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Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts

Main Report

Prepared by
Senior Seismic Hazard Analysis Committee (SSHAC)
R. J. Budnitz (Chairman), G. Apostolakis, D. M. Boore, L. S. Cluff, K. J. Coppersmith, C. A. Cornell, P. A. Morris

Lawrence Livermore National Laboratory

Prepared for
U.S. Nuclear Regulatory Commission
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U.S. Department of Energy
Engineering and Operations Support Group
Office of Defense Programs
19901 Germantown Road
Germantown, MD 20874-1290

Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, CA 94304-1395

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ABSTRACT

Probabilistic Seismic Hazard Analysis (PSHA) is a methodology that estimates the likelihood that various levels of earthquake-caused ground motion will be exceeded at a given location in a given future time period. Due to large uncertainties in all the geosciences data and in their modeling, multiple model interpretations are often possible. This leads to disagreement among experts, which in the past has led to disagreement on the selection of ground motion for design at a given site.

In order to review the present state-of-the-art and improve on the overall stability of the PSHA process, the U.S. Nuclear Regulatory Commission (NRC), the U.S. Department of Energy (DOE), and the Electric Power Research Institute (EPRI) co-sponsored a project to provide methodological guidance on how to perform a PSHA.

The project has been carried out by a seven-member Senior Seismic Hazard Analysis Committee (SSHAC) supported by a large number other experts.

The SSHAC reviewed past studies, including the Lawrence Livermore National Laboratory and the EPRI landmark PSHA studies of the 1980's and examined ways to improve on the present state-of-the-art.

The Committee's most important conclusion is that differences in PSHA results are due to procedural rather than technical differences. Thus, in addition to providing a detailed documentation on state-of-the-art elements of a PSHA, this report provides a series of procedural recommendations.

The role of experts is analyzed in detail. Two entities are formally defined—the Technical Integrator (TI) and the Technical Facilitator Integrator (TFI)—to account for the various levels of complexity in the technical issues and different levels of efforts needed in a given study.

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SPONSOR'S PERSPECTIVE

Probabilistic Seismic Hazard Analysis (PSHA) has become an increasingly important tool for aiding design and decision making at all levels in both the private sector and government. The level of sophistication applied to PSHA has increased dramatically over the past 27 years since the technique was first introduced in the literature. As more and more people and groups implemented and used PSHA in different forms, it became clear to the sponsors of the Senior Seismic Hazard Analysis Committee (SSHAC) report that the time had arrived to establish more uniform and up-to-date guidelines for future PSHA studies.

The need for such guidelines is threefold:

1. As the situation stands today, it is often the case that multiple PSHA studies are available for the same geographic region. However, due to differences in implementation, results of these studies often differ by substantial amounts for the same physical location. Further, because of the amount of technical information and complex combination of techniques utilized, it is not always simple to determine the source of these differences and which answer should be used.

2. Potential sponsors of a PSHA study are faced with the difficulty of determining the appropriate level of a proposed PSHA to ensure stable results that meet the sponsor's needs.

3. The cost to perform a PSHA study can be quite large. The sponsors of this report expected that a suitable set of guidelines could be developed to assist the potential user in choosing the appropriate level of analysis consistent with the overall goals and resources available. Given the need to conserve resources, issuing such guidelines to optimize future PSHA studies in accordance with the sponsor's need takes on added importance.

Overall, the sponsors saw a need for more stability in the PSHA process, both for nuclear and non-nuclear applications, in dealing with future needs for using PSHA to establish seismic hazard levels throughout the United States.

Comparative evaluations have shown that the differences between PSHA studies are often not technical, but due to the information gathering and assembly process used in the study. The integration of the different types of information required in a PSHA (geologic, seismotectonic, probability and statistics, information theory, and decision making) presents significant inter-disciplinary challenges and requires a project structure and process that assure proper integration. The skills required to be a good integrator and evaluator are not necessarily the same skills needed to be a good scientist. Our observation is that although many PSHA practitioners are trained experts in one or more fields, the PSHA divergence issue can partly be explained by a lack of integration and evaluation skills so important to the PSHA product. We believe this is true at all levels of PSHA, and these skill requirements may be most acute at the simpler levels of seismic hazard analysis not associated with critical facility assessments where typically the PSHA analysts must complete their work.

This report addresses the integration and evaluation issues that should be considered and focuses on the process of integration required in a PSHA. The SSHAC's investigations have led to the conclusion that technical facilitation and integration is a necessary component for the proper implementation of a PSHA in some instances. In most of these cases, it is anticipated that following the approaches outlined in the report will bring about more consistent interpretations that are supported by the data or bulk of scientific thought. However, if an outlier interpretation persists, it is our firm belief—in agreement with the SSHAC —that the approaches outlined will allow for essential downweighting of that interpretation. This is

preferable to the stiff adherence to an equal weighting scheme, which can result in the final seismic hazard being driven by a single outlier input.

The issues that are raised and discussed in the SSHAC report, especially but not exclusively the process issues, apply in varying degrees to any PSHA project, and should be at least considered by sponsors and analysts before undertaking a PSHA. While the primary focus of SSHAC was on siting critical facilities, it is believed that all PSHA projects should attempt to achieve several primary objectives: 1) proper and full incorporation of uncertainties, 2) inclusion of the range of diverse technical interpretations that are supported by available data, 3) consideration of site- specific knowledge and data sets, 4) complete documentation of the process and results, 5) clear responsibility for the conduct of the study, and 6) proper peer review. Regardless of the level of the study, the goal in the various approaches is the same: to provide a representation of the informed scientific community's view of the important components and issues and, finally, the seismic hazard.

For these reasons, the sponsors believe that the SSHAC report is complete in terms of outlining the process a principal investigator should follow to complete a PSHA. Indeed, the report provides for technical flexibility where such flexibility is needed and, at the same time, encourages standardization of technical approaches and procedures as much as is feasible.

The future utility of PSHA in decision making depends to a large degree on our ability to implement the process in a meaningful and cost-effective way. Development of the SSHAC guidelines was planned with this goal in mind.

EXECUTIVE SUMMARY

Probabilistic seismic hazard analysis (PSHA) is a methodology that estimates the likelihood that various levels of earthquake-caused ground motions will be exceeded at a given location in a given future time period. The results of such an analysis are expressed as estimated probabilities per year or estimated annual frequencies. The objective of this project has been to provide methodological guidance on how to perform a PSHA. The project, co-sponsored by the U.S. Nuclear Regulatory Commission, the U.S. Department of Energy, and the Electric Power Research Institute, has been carried out by a seven-member Senior Seismic Hazard Analysis Committee (SSHAC), supported by a large number of other experts working under the Committee's guidance, who are named in the following "Acknowledgments" section.

The members of the Senior Seismic Hazard Analysis Committee (SSHAC) are:

Dr. Robert J. Budnitz (Chairman)	President Future Resources Associates, Inc.
Professor George Apostolakis	Massachusetts Institute of Technology previously at University of California, Los Angeles
Dr. David M. Boore	Seismologist U.S. Geological Survey
Dr. Lloyd S. Cluff	Manager, Geosciences Department Pacific Gas & Electric Company
Dr. Kevin J. Coppersmith	Vice President Geomatrix
Dr. C. Allin Cornell	C. A. Cornell Company
Dr. Peter A. Morris	Applied Decision Analysis, Inc.

The scope of the SSHAC guidance is intended to cover both site-specific and regional applications of PSHA (more broadly, applications in both low-seismicity and high-seismicity regions) in both the eastern U.S. and western U.S. Although the sponsors' primary objective is guidance for applications at nuclear power plants and other critical facilities, the methodological guidance applies in whole or in part, on a case-by-case basis, to a broad range of applications.

The SSHAC guidance involves both technical guidance and procedural guidance, with a strong emphasis on the latter for reasons explained below. Therefore, the audience for the report includes not only analysts who will implement the methodology and earth scientists whose expertise will support the analysts, but also PSHA project sponsors—those decision-makers in organizations such as private firms or government agencies who have a need for PSHA information and are in a position to sponsor a PSHA study.

Note that our guidance is not intended to be "the only" or "the standard" methodology for PSHA to the exclusion of other approaches; there are other valid ways to perform a PSHA study. Likewise, our formulation should not be viewed as an attempt to "standardize" PSHA in the sense of freezing the science and technology that underlies a competent PSHA, thereby stifling innovation. Rather, our guidance is intended to represent SSHAC's opinion on the best current thinking on performing a valid PSHA.

The most important and fundamental fact that must be understood about a PSHA is that the objective of estimating annual frequencies of exceedance of earthquake-caused ground motions can be attained only with significant uncertainty. Despite much recent research, major gaps exist in our understanding of the mechanisms that cause earthquakes and of the processes that govern how an earthquake's energy propagates from its origin beneath the earth's surface to various points near and far on the surface. The limited information that does exist can be—and often is—legitimately interpreted quite differently by different experts, and these differences of interpretation translate into important uncertainties in the numerical results from a PSHA.

The existence of these differences of interpretation translates into an operational challenge for the PSHA analyst who is faced with (1) how to use these different interpretations properly, and (2) how to incorporate the diversity of expert judgments into an analytical result that appropriately captures the current state-of-knowledge of the expert community, including its uncertainty.

The SSHAC studied a large number of past PSHAs, including two landmark studies from the late 1980s known as the "Lawrence Livermore (LLNL)" study and the "Electric Power Research Institute (EPRI)" study, both of which broke important new methodological ground in attempting to characterize earthquake-caused ground motion in the broad region of the U.S. east of the Rocky Mountains. Most important, the mean seismic hazard curves presented in the reports for most sites in the eastern U.S. differed significantly. However, the median hazard results did not differ by nearly as much. We now understand that differences in both the inputs and the procedures by which the two studies dealt with the inputs were among the key reasons for the differences in the mean curves. At the time this was not understood, and the differences between the mean curves caused not only considerable consternation, but launched several efforts to understand what might underlie the differences and attempts to update the older work.

Ultimately, the inability to understand all of the differences between the LLNL and EPRI hazard results—and the concomitant need for an improved methodology going beyond the late-1980s state-of-the-art—led directly to the formation of the SSHAC to perform this project. However, although the Committee studied both the LLNL and EPRI projects carefully to obtain methodological insights (both positive and negative), it did not undertake a forensic-type review to identify past "errors." Rather, it attempted to draw more broadly upon the entire body of PSHA literature and experience, including of course the LLNL and EPRI projects along with many others, to formulate the guidance herein.

In the course of our review, we concluded that many of the major potential pitfalls in executing a successful PSHA are procedural rather than technical in character. One of the most difficult challenges for the PSHA analyst is properly representing the wide diversity of expert judgments about the technical issues in PSHA in an acceptable analytical result, including addressing the large uncertainties. This conclusion, in turn, explains our heavy emphasis on *procedural* guidance.

This also explains why we believe that *how a PSHA is structured* is as critical to its success as the technical aspects—perhaps more critical because the procedural pitfalls can sometimes be harder to avoid and harder to uncover in an independent review than the pitfalls in the technical aspects. Finally, this also explains why *one of the key audiences for this report is the project sponsor*, who needs to understand the procedural/structural aspects in order to initiate and support the desired PSHA project appropriately.

This Executive Summary will conclude with a brief overview of what the SSHAC believes are its most important findings, conclusions, and recommendations in the procedural area. Because we recognize that several very important pieces of technical guidance concerning the earth-sciences aspects of PSHA will not be discussed in this Executive Summary, the SSHAC requests that readers turn to the full report to review the technical guidance. The key procedural points follow:

1) SSHAC identifies and describes several different *roles for experts* based on its conclusion that confusion about the various roles is a common source of difficulty in executing the aspect of PSHA involving the use of experts. The roles for which SSHAC provides the most extensive guidance include the expert as *proponent* of a specific technical position, as an *evaluator* of the various positions in the technical community, and as a *technical integrator* (see the next paragraph).

2) SSHAC identifies four different types of consensus, and then concludes that one key source of difficulty is failure to recognize that 1) there is not likely to be "consensus" (as the word is commonly understood) among the various experts and 2) no single interpretation concerning a complex earth-sciences issue is the "correct" one. Rather, SSHAC believes that the following should be sought in a properly executed PSHA project for a given difficult technical issue: (1) a representation of the legitimate range of technically supportable interpretations among the entire informed technical community, and (2) the relative importance or credibility that should be given to the differing hypotheses across that range. As SSHAC has framed the methodology, this information is what the PSHA practitioner is charged to seek out, and seeking it out and evaluating it is what SSHAC defines as *technical integration*.

3) SSHAC identifies a hierarchy of complexity for technical issues, consisting of four *levels* (representing increasing levels of participation by technical experts in the development of the desired results), and then concentrates much of its guidance on the most complex level (level 4) in which a panel of experts is formally constituted and the panel's interpretations of the technical information relevant to the issues are formally elicited. To deal with such complex issues, SSHAC defines an entity that it calls the Technical Facilitator/Integrator (TFI), which is differentiated from a similar entity for dealing with issues at the other three less-complex levels, which SSHAC calls the Technical Integrator (TI). Much of SSHAC's procedural guidance involves how the TI and TFI functions should be structured and implemented. (Both the TI and TFI are envisioned as roles that may be filled by one person or, in the TFI case, perhaps by a small team).

4) The role of *technical integration* is common to the TI and TFI roles. What is special about the TFI role, in SSHAC's formulation, is the *facilitation* aspect, when an issue is judged to be complex enough that the views of a panel of several experts must be elicited. SSHAC's guidance dwells on that aspect extensively, in part because SSHAC believes that this is where some of the most difficult procedural pitfalls are encountered. In fact, the main report identifies a number of problems that have arisen in past PSHAs and discusses how the TFI function explicitly overcomes each of them.

5) For most technical issues that arise in a typical PSHA, the issue's complexity does not warrant a panel of experts and hence the establishment of a TFI role. Technical integration for these issues can be accomplished—indeed, is usually best accomplished—by a TI. In fact, SSHAC has structured its recommended methodology so that even the most complex issues *can* be dealt with using the less expensive TI mode, although with some sacrifice in the confidence obtained in the results on both the technical and the procedural sides.

6) One special element of the TFI process is SSHAC's guidance on sequentially using the panel of experts in different roles. Heavy emphasis is placed on assuring constructive give-and-take interactions among the panelists throughout the process. Each expert is first asked, based on his/her own knowledge (yet cognizant of the views of others as explored through the information-exchange process), to act as an *evaluator*; that is, to evaluate the range of technically legitimate viewpoints concerning the issue at hand. Then, each expert is asked to play the role of *technical integrator*, providing advice to the TFI on the appropriate representation of the composite position of the community as a whole.

Contrasting the classical role of experts on a panel acting as individuals and providing inputs to a separate aggregation process, the TFI approach views the panel as a team, with the TFI as the team leader, working together to arrive at (i) a composite representation of the knowledge of the group, and then (ii) a composite representation of the knowledge of the technical community at large. (Neither of these representations necessarily reflects panel consensus—they may or may not, and their validity does *not* depend on whether a panel consensus is reached.)

The SSHAC guidance to the TFI emphasizes that a variety of techniques are available for achieving this composite representation. SSHAC recommends a blending of behavioral or judgmental methods with mathematical methods, and in the body of the report several techniques along these lines are described in detail. A key objective for the TFI is to develop an aggregate result that can be endorsed by the expert panel both technically and in terms of the process used.

7) The TFI's integrator role should be viewed not as that of a "super-expert" who has the final say on the weighting of the relative merits of either specific technical interpretations or the various experts' interpretations of them; rather, the TFI role should be seen as charged with characterizing both the commonality and the diversity in a set of panel estimates, each representing a weighted combination of different expert positions. SSHAC thus sees the TFI as performing an integration assisted by a group of experts who provide integration advice.

8) Thus, the TFI as facilitator structures interaction among the experts to create conditions under which the TFI's job as integrator will be simplified (e.g., either a consensus representation is formed or it is appropriate to weight equally the experts' evaluations of the knowledge of the technical community at large). In the rare case in which such simple integration is not appropriate, additional guidance is provided. In the main report, guidance is presented on two possible approaches involving (i) explicit quantitative but unequal weights (when it becomes obvious that using equal weighting misrepresents the community-as-a-whole); and (ii) "weighing" rather than "weighting", in cases when the experts themselves, acting as evaluators and integrators, find fixed numerical weights to be artificial, and when it is appropriate to represent the community's overall distribution in a less rigid way.

9) The SSHAC guidance gives special emphasis to the importance of an independent peer review. We distinguish between a participatory peer review and a late-stage peer review, and we also distinguish between a peer review of the process aspects and of the technical aspects for the more complex issues. We strongly recommend a participatory peer review, especially for the process aspects for the more complex issues. This paper details the pitfalls of an inadequate peer review.

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Although the intellectual responsibility for the report rests solely with the seven SSHAC members, the task could not have been accomplished without the diligent and very capable contributions of a large number of others who worked in a collaborative mode under the SSHAC Committee's overall direction. These other experts, some of whom ghost-wrote entire subsections or appendices of the report, were:

Don L. Bernreuter, Lawrence Livermore National Laboratory

Michael P. Bohn, Sandia National Laboratories (DOE Project Manager; lead author for the Glossary)

Auguste C. Boissonnade, Lawrence Livermore National Laboratory

Martin W. McCann, Jack Benjamin & Associates Inc. (lead author for Chapter 7)

Robin K. McGuire, Risk Engineering Inc. (author of Appendix G)

Richard W. Mensing, Logicon-RDA (lead author for Chapter 6; author of Appendix D; contributor to Chapter 4 and Appendix A)

Jean B. Savy, Lawrence Livermore National Laboratory (NRC Project Manager)

Gabriel R. Toro, Risk Engineering Inc. (major contributor to Chapter 5; author of Appendices F and I; contributor to Chapter 4 and Appendices A and B)

The SSHAC project organized four different workshops that were attended by a large number of experts representing a variety of disciplines. The participants, who are all listed in the workshop descriptions (see Appendices A, B, C, and H), deserve our thanks for contributing so significantly to the project.

We would also like to thank Norman Abrahamson for contributing an excellent piece of guidance that we have taken the liberty to incorporate herein as Appendix E.

The National Academy of Sciences/National Research Council organized a special "Panel on Seismic Hazard Evaluation" under its Committee on Seismology with the charter to review our report. This review was supported by the U.S. Nuclear Regulatory Commission. The Panel's review comments on our draft report of November 11, 1994 were especially helpful in focusing the SSHAC on key issues that needed extra attention. Besides the NAS/NRC Panel's review, we had the benefit of informal review comments on the November draft from about a dozen other specialists and organizations for which we are very grateful. The comments of the NAS/NRC Review Panel, which were published separately by the National Academy Press, are included in this report as an Appendix to Volume 1.

Finally, the logistical work of pulling the report together, based on input from many different authors typing on many different word processors, was accomplished in an outstanding manner by Rosa I. Yamamoto of LLNL, whose skill and dedication the SSHAC gratefully acknowledges.

1. INTRODUCTION

1.1 The SSHAC

In order to provide technical guidance on the subject of a *methodology for Probabilistic Seismic Hazard Analysis* (PSHA), a "Senior Seismic Hazard Analysis Committee" (SSHAC) was formed in early 1993 under the three-way sponsorship of the U. S. Department of Energy (DOE), the U. S. Nuclear Regulatory Commission (NRC), and the Electric Power Research Institute (EPRI).[1] The SSHAC has carried out this project as a working committee, and its members, the seven authors of this report, are jointly responsible for the report's contents.

To support the committee's work, a large number of experts on various technical subjects have been working under the committee's direction on specific topics integral to the effort.[2] These experts are listed in the Acknowledgments section.

The specific *objective* of this project, which will be discussed in more detail below, is to provide *methodological guidance on how to perform a PSHA*. Both technical guidance and procedural guidance are provided, with a strong emphasis on the latter. Why such guidance is necessary is discussed below.

1.2 Background

PSHA is an analytical methodology that estimates the *likelihood* that various levels of earthquake-caused ground motions will be exceeded at a given location in a given future time period. The results of such an analysis are expressed as estimated probabilities per unit time or estimated frequencies (such as expected number of events per year).

Unfortunately, this objective of estimating earthquake-caused ground-motion frequencies can be attained only with significant uncertainty. Despite extensive advances in seismic knowledge in recent years by a large and active community of researchers around the world, there are still major gaps in our understanding of the mechanisms that cause earthquakes, and of the processes that govern how an earthquake's energy propagates from its origin beneath the earth to various points near and far on the surface. These gaps in understanding mean that, when a PSHA is performed, there are inevitably significant uncertainties in the numerical results.

The uncertainties arise for a host of reasons, but the most important is that even in the regions where earthquakes occur fairly frequently so that scientists have a basic understanding of the tectonic setting—such as in coastal California—the scientific data base (specific fault locations, orientations, slip rates, energy dissipation mechanisms, etc.) is still limited. In fact, major new insights arise whenever there is another large earthquake. In regions where large earthquakes are very uncommon—such as along much of the U. S. eastern seaboard or in the American Great Plains—the data base is even less able to support scientific understanding of what might cause earthquakes, because, despite significant recent advances in knowledge, not even the sources or mechanisms of earthquakes are well understood.

This lack of understanding has operational implications for the analyst charged with performing a PSHA. Specifically, <u>there often exist wide differences of legitimate scientific opinion</u> on many of the key inputs into a PSHA. The limited information from actual earthquakes, either observed by humans (with or without modern instruments) or inferred from the paleoseismic record, can be—and often is—interpreted quite differently by different experts. These differences of interpretation translate into important uncertainties in the PSHA's numerical results, and make these results less useful for many potential applications of PSHA. Operationally, a PSHA analyst is faced with how to use these different interpretations properly,

[1]Some members of the SSHAC have been supported by NRC funds directly, some members by NRC through contracts with Lawrence Livermore National Laboratory, and other members by DOE funds through contracts with Sandia National Laboratories.

[2]Contractually, these experts have been supported variously by NRC, DOE, and EPRI.

incorporating the diversity of expert judgments into an analytical result that appropriately captures the current state-of-knowledge including its uncertainties.

For the Committee, addressing this situation has been a challenge. In developing guidance for performing a PSHA we have had to face two different (although related) tasks:

(i) developing technical guidance, drawn from the earth sciences, concerning the scientific issues involved in performing a PSHA; and

(ii) developing procedural guidance, drawn mostly from disciplines outside the earth sciences (although anchored in the specific details of PSHA and based largely on PSHA experience), concerning how to cope with the diversity of opinion among the experts about the technical issues.

Because this situation was recognized from the start, the three sponsors of this project (DOE, NRC, and EPRI) established a broad-based committee, supported by a broad-based group of other scientists and engineers, with expertise not only in all of the major earth-science disciplines but also in the other key areas. The resulting guidance in this report is comprised of a mix of both earth-sciences guidance and procedural guidance. If a successful PSHA project is to be carried out, there is heavy emphasis on the importance of the latter. This is because it is often more difficult to execute the procedural aspects properly (including how expert interpretations are used) than the technical aspects, and because there exists far less procedural guidance in the literature.

Note that our guidance is not intended to be "the only" or "the standard" methodology for PSHA to the exclusion of other approaches; there are other valid ways to perform a PSHA study. Likewise, our formulation should not be viewed as an attempt to "standardize" PSHA in the sense of freezing the science and technology that underlies a competent PSHA, thereby stifling innovation. Rather, our guidance is intended to provide not only up-to-date technical guidance for the analyst, but also procedural guidance that we believe is crucial to the successful execution of a PSHA project today and for the next several years.

Because our sponsors are interested in applications for siting and regulation of nuclear power plants and other nuclear facilities, we have considered their interests throughout the project. However, as discussed below, we believe that the resulting methodology should be useful, in whole or in part depending on the issues, for other PSHA applications as well. In Chapter 3, we distinguish among four different levels of study in a PSHA.

1.3 History

The discipline of PSHA has evolved over several decades. Early empirical statistical methods (for example, Milne and Davenport 1969) have been largely replaced by the analytical/numerical models initiated by Cornell (Cornell 1968), and further refined by many researchers in subsequent years.

Many site-specific and regional mapping applications have been made around the world. The need to consider the uncertainty in parameters and models was recognized early on. The SSHAC members have drawn on their extensive experience in such studies, both large and small in terms of the resources expended.

The systematic, explicit incorporation of the diversity of expert interpretations on a regional basis was pioneered by a Lawrence Livermore National Laboratory study (Bernreuter et al. 1981) that examined several U.S. sites with operating nuclear power plants. The methods therein were later applied to several DOE sites. The expert interpretation aspect of PSHA was then addressed more formally in two major PSHA projects in the mid-1980s, both breaking major new ground on several fronts. Today they remain significant landmarks. The "Livermore" and "EPRI" studies included a PSHA on a broad regional basis covering the entire central and eastern United States:

(i) The "Livermore" study (Bernreuter et al. 1989) was sponsored by the U.S. Nuclear Regulatory Commission and executed by a

team at the Lawrence Livermore National Laboratory. Its objective was to develop seismic hazard curves for the 69 sites in the eastern U.S. (east of the Rocky Mountains) at which nuclear power plants were then operating. It accomplished this by performing a broad regional study, and then extracting the 69 site-specific seismic hazards from the regional PSHA information. It called upon a large number of experts, whose interpretations of the earth-sciences information were individually elicited using a formal expert-elicitation process and then combined together by the LLNL team to produce the PSHA results. Separate elicitation processes were used for the seismic-source characterization and the ground-motion aspects.

(ii) The "EPRI" study (EPRI 1989) was sponsored by the Electric Power Research Institute. Its objective was to develop seismic hazard curves for most of the sites in the eastern U.S. (east of the Rocky Mountains) at which nuclear-power plants were then operating, although a few of the sites covered by the Livermore study were not covered. Like the Livermore study, the EPRI analysis was a broad regional study, which then calculated the site-specific seismic hazards from the regional PSHA information. For the seismic-source part of the analysis, the EPRI study utilized a large number of geoscientists who were grouped into several different seismic-source teams whose interpretations of the earth-sciences information were elicited, team-by-team, using a formal expert-elicitation process. The ground-motion part of the analysis was performed using a weighted combination of models developed by the analyst team. The seismic-source and ground-motion information was then combined together by the EPRI group to produce the PSHA results.

Although the Livermore and EPRI studies were similar in many ways, both technically and procedurally, they also differed significantly in a few areas. As mentioned, both broke important new ground, primarily with respect to the implementation processes used but in many substantive technical areas as well, and today both are key landmarks in the history of PSHA. However, for our historical purposes here, the most important fact about these two studies is that the *Livermore and EPRI mean seismic hazard curves for most sites in the eastern U. S. differed significantly*. This led, for several years after both studies were published, to considerable consternation and several efforts to understand what might underlie the differences. The reason for the consternation was that the differences between the Livermore and EPRI results had important implications for policy in a number of areas. However, no completely satisfactory explanation for these differences emerged, despite several important studies (both Livermore-EPRI comparison studies and new PSHA studies at various sites) that cast useful light on various technical and procedural issues.

Ultimately, although there was a strong feeling in the PSHA community that procedural issues rather than technical earth-sciences issues per se were an important reason for the differences, the inability to understand all of the differences between the Livermore and EPRI hazard results led directly to the formation of the SSHAC to perform this project. Originally, some of the sponsors and participants proposed that one key study objective should be to "resolve" the differences between the Livermore and EPRI studies. However, the Committee quickly realized that the new project would be most useful if it were forward-looking rather than backward-looking—specifically, if it could pull together what is known about PSHA in order to recommend an improved methodology, rather than specifically attempting to figure out which of the two studies was "correct," or which specific problems with either study were most important in affecting that study's specific results.

Therefore, although the Committee has carefully studied both the LLNL and EPRI studies (along with other past PSHAs) to obtain methodological insights, both positive and negative, we did not undertake a forensic-type examination to identify past "errors" or their implications. More broadly speaking, the Committee has attempted to draw

upon the entire body of PSHA literature and experience, which is of course much more extensive than the LLNL and EPRI projects, as important as they have been.

The above discussion is a natural introduction to a presentation of the SSHAC project charter and objectives, which are discussed next.

1.4 Objective of the Project

At the inception of the project, the three sponsors (DOE, NRC, and EPRI) provided an "objective" for the SSHAC effort, as follows:

> "The objective is to develop implementation guidelines, including a recommended methodology, suitable for the performance of PSHA for seismic regulation of nuclear power plants and other critical facilities."

Operationally, the SSHAC has taken its charter to be:

> To describe an up-to-date PSHA methodology, including guidelines and recommendations, that can guide the analyst both technically and procedurally.

Because PSHA results can be so important for both engineering design and public-policy decision-making, a goal of this project is that the PSHA methodology will ensure the stability of the numerical results for a reasonable period of time (five to ten years) or until significant new technical information presents itself.

This goal will be achieved by (i) ensuring that the assessment is based on unbiased interpretations of available data and information, and (ii) explicitly identifying and evaluating the uncertainties in the PSHA inputs, including both data and model inputs, and incorporating them in the composite measure of the uncertainty in the results.

1.5 Audience for the Report

This report has been written with four different audiences in mind:

- analysts who will implement the PSHA methodology (and for whom the specific guidance has been written);
- earth scientists whose expertise will be drawn upon by the analysts, and who will require an understanding of the entire PSHA process in order to participate most effectively in a PSHA project;
- technical reviewers who will be called upon to review a PSHA study, either to advise a study's sponsors of its validity or to provide support for a regulatory decision;
- PSHA project sponsors, meaning decision-makers in entities such as private firms or government agencies, who have a need for PSHA information and who are in a position to sponsor a PSHA study. Such sponsorship includes both financial and institutional sponsorship, and we have both in mind.

The first three audiences should be interested not only in the broad guidance but also in the specific technical details. The fourth audience, although perhaps not as interested in the detailed guidance about how to determine seismic sources or ground-motion attenuation, should be interested in how the committee envisions that a PSHA project must be put together, how the process is expected to work for different levels of effort, how to avoid the known pitfalls observed in past studies, and how to set realistic expectations as to the validity of the results.

1.6 Conditions and Limitations on the Guidance

In order to bound the scope, the Committee and its sponsors decided on several conditions and limitations that are important for any reader to understand. The principal ones are:

- Types of applications: In the past, probabilistic seismic-hazard analyses have been used in at least four quite different ways. These different types of applications, all of which are contemplated in the SSHAC guidance, are:

(i) to understand the seismic *hazard* at a specific site in order to establish site-specific safety regulations;

(ii) to guide the establishment of *specific criteria for the seismic design, evaluation, and/or retrofit* of a facility;

(iii) to provide the *hazard input* to a comprehensive probabilistic seismic-risk assessment for a facility, either existing or in the design stage; and

(iv) to support development of regional *seismic-hazard maps* used in broad applications such as building codes.

Of course, depending on the application, different levels of effort may be indicated.

- Breadth of application: Although the emphasis in the formal statement of objective is on "seismic regulation of nuclear power plants and other critical facilities," the SSHAC methodology can clearly be used more broadly. In fact, SSHAC has contemplated various broader applications from the start. Any attempt to apply the methodology to regions, sites, or facilities that are significantly different from "nuclear power plants and other critical facilities" should evaluate the methodology's applicability on a case-by-case basis, because SSHAC's preferred approach may not always apply directly to other facilities. However, the issues that are raised and discussed here, especially but not exclusively the procedural issues, apply in varying degrees to any PSHA project, and should be at least considered by sponsors and analysts before undertaking almost any PSHA. (See Section 5.1 for a description of four study levels that SSHAC has identified.)

- Site-specific vs. regional applications: PSHA can be applied not only to specific sites but also to broad regions. Both applications are contemplated in the SSHAC guidance.

- East and west: The SSHAC methodology is intended for application in both the eastern U.S. and western U.S. (more broadly, in both low-seismicity and high-seismicity regions of the country). Even though the specifics of implementation differ in detail in these two very different regions, the procedural aspects should be similar.

- Probabilistic vs. deterministic seismic-hazard analysis This project addresses the methodology for performing probabilistic seismic-hazard analysis. A number of non-probabilistic approaches to understanding seismic hazards are widely practiced and have considerable value in some applications. These non-probabilistic methods are usually called "deterministic" methods. Although it has been tempting to develop information about the similarities and differences between PSHA and some of the most widely-used deterministic methods, the Committee has explicitly not done so at the direction of the sponsors.

1.7 Philosophy of the Project

Although there is general concurrence among PSHA practitioners regarding the purpose and goal of a PSHA, experience has demonstrated the importance of establishing a sound philosophical approach for conducting the analysis. We believe that a well-defined philosophy establishes the foundation for developing the rules and guidance that are provided here.

We have identified five elements of our philosophy that merit discussion in this introductory chapter, and these will be discussed next:

- The level of prescription
- Stability
- The use of "experts" and the meaning of "consensus"
- Transparency
- Performing a PSHA using different levels of effort

The level of prescription: The SSHAC has attempted to provide explicit guidance, and,

where feasible, prescribed approaches for performing a PSHA. Sometimes, our guidance will require a certain methodological approach, while at other places we will recommend, or perhaps suggest, how the analyst should proceed, or in some cases we may merely allow a particular approach. This hierarchy in the guidance ("require," "recommend," "suggest," and "allow" and their opposites) is intended to be as explicit as the Committee believes can be supported by the information available. We realize that, because we have developed this guidance primarily with nuclear-power-plant and other nuclear-facility applications in mind, the hierarchical structure may not apply directly in other applications.

Sometimes, there will be several alternative approaches to a particular element in the PSHA methodology. Where the committee judges that these are equivalent, the guidance has attempted to identify one approach among the alternatives and to require or recommend it. This is not intended to denigrate the validity of the alternative approaches, but by narrowing the options we do intend to provide for a degree of uniformity, which will enhance the technical community's ability both to compare the work of different PSHA practitioners and to review it more easily. The SSHAC wishes to avoid the implication that using PSHA approaches *other than the one recommended here* would be invalid. Nevertheless, the Committee believes that the *issues* raised and dealt with herein should be considered by every PSHA sponsor and analysis team.

Stability: By following SSHAC's guidance, a PSHA practitioner should be able to provide reasonable assurance that the numerical hazard results will be stable for a reasonable period of time following the completion of the PSHA (unless significant new seismic information, which could occur at any time, calls for a major revisitation). This stability is important to both the technical and the policy-making community, and is achieved by ensuring the integrity of the process, involving two crucial elements: (i) completeness of the earth-science information used in the analysis, and (ii) a thorough evaluation of the uncertainties in professional interpretations of that information. As discussed below, SSHAC believes that without such an evaluation, the user—whether the technical user or the policy user—is not adequately served.

The use of "experts" and the meaning of "consensus": In writing the guidance in Chapter 3, the Committee has given careful attention to the role of "experts" in the PSHA process. As Chapter 3 describes, we have identified several different types of experts and roles for experts, ranging from the narrow type (a substantive expert in a very specific technical subject) to the very broad type (an expert with experience across a technical field); and also ranging from the role of proponent of a particular interpretation to that of an evaluator of the full state-of-knowledge of a subject. A given PSHA project will utilize various types of experts in various different roles that SSHAC believes must be kept clearly separate, even if the same individual often changes roles in different phases of the same PSHA project.

In Chapter 3, we also dwell at length on the issue of "consensus," identifying four different types of consensus and describing how each plays its specific role in a PSHA project. The SSHAC believes it important to emphasize here that, given the existence of differing interpretations of the technical information input in a PSHA, there is not likely to be a "consensus" (as that word is commonly understood by lay readers) among the various experts that a single interpretation of the earth-sciences information is the "correct" one. This is the case for both seismic sources and seismic ground-motion attenuation.

Rather, the following should be sought in a properly-executed PSHA project for a given technical issue: (i) a representation of the legitimate range of technically supportable interpretations among the entire informed technical community, and (ii) the relative importance or credibility—read "weight" even if not a numerical weight—that should be assigned to the differing hypotheses across that range. As SSHAC has framed the methodology (see the detailed discussion in Chapter 3), the PSHA practitioner is charged to seek out this information, whether by "sampling" a sub-set of

the community of experts or, if financially restricted, by drawing upon only the literature and his/her own judgment.

Transparency: The results of a PSHA serve a range of users with different needs. To assure that all of these needs are met, the information that is generated as part of the PSHA must be documented in a transparent way. Transparency of the PSHA, including not only the input data and models used but also the process employed and the results obtained, satisfies the needs of (i) the earth scientist who is interested in understanding the scientific issues, (ii) the engineer who must understand how the ground motion predicted at a given site has been derived, and has been related to the magnitudes and distances of the contributing earthquakes, (iii) the technical reviewer who must be satisfied with the completeness and scientific integrity of the earth-science interpretations and of the PSHA process, and (iv) the decision-maker concerned with the stability and integrity of the results as a whole.

Documenting the PSHA, including both the methodology and the results, in a transparent way allows all of these users to see how the constituent parts of the assessment fit together. This will reduce the apparent level of complexity generally associated with these assessments.

Performing a PSHA using different levels of effort: We have concentrated our methodology-development work on guidance for a sponsor and analysis team whose financial and personnel resources would be sufficiently large that they would not significantly limit the scope of the PSHA. This is appropriate as a starting point, because some applications are so important that the sponsors can afford to devote upwards of a million dollars or more to the PSHA and the science upon which it is based.

However, the committee recognizes that some sponsors may not be able to devote such vast resources to a PSHA project, or may not even require a PSHA assessment of very large potential ground motions that would be associated with very rare events. In these cases, a scaled-down approach may be appropriate. To assist such sponsors, we have attempted to differentiate those elements of a PSHA that are essential to its success—that must be incorporated—from those elements where it may be feasible to compromise, accepting more uncertainty (and concomitantly, less confidence in the results) as the result of a smaller project scope. In any case, the basic constituent elements of a PSHA are the same in all applications, even if the process is different.

The committee emphasizes, however, that wherever we have indicated that certain types of compromises are acceptable, we nevertheless insist that there be no compromise in the rigor with which the PSHA is undertaken. Only the size of the residual uncertainties (which in any event will be large, even for the most expensive PSHAs) may be compromised; and even here, our committee requires that a careful characterization of both the source and size of the uncertainties be part of any PSHA.

1.8 Uncertainties in PSHA

In the introductory section 1.2 above, we mentioned that the results of PSHA, as defined for the purposes of this report, are expressed in terms of likelihoods—estimated probabilities in a given time period or estimated frequencies—that earthquakes producing various sizes of ground motion will occur at a given site or in a given region.

The SSHAC has adopted a probabilistic formulation for dealing with seismic hazards that embeds uncertainties in the core of the methodology. This has forced the Committee to try to deal directly with *all* of the various uncertainties that characterize our current state-of-knowledge.

Although the optimism of science in general leads some to believe that nearly all of the "uncertainties" in PSHA that we will deal with in this report are ultimately amenable to reduction, we recognize that for practical purposes many of them cannot be thought of or dealt with in this way. We define two different classes of uncertainties:

- Those that we will call *epistemic* are lack-of-knowledge uncertainties arising because our

scientific understanding is imperfect *for the present*, but are of a character that in principle are reducible through further research and gathering of more and better earthquake data.

- Those that we will call aleatory—"random" in character—are uncertainties that for all practical purposes cannot be known in detail or cannot be reduced (although they are susceptible to analysis concerning their origin, their magnitude, and their role in PSHA).

In the seismic case, it is helpful to consider a mental model in which some thousands of years of an earthquake catalog and site-specific ground-motion recordings were made available. In this case, the former epistemic uncertainty would be reduced to near zero, whereas the forecast of the maximum ground-motion at the site in the next year would remain subject to aleatory uncertainty.

The division between the two different types of uncertainty, epistemic and aleatory, is somewhat arbitrary, especially at the border between the two. This is because, conceptually, some of the processes and parameters whose uncertainties we will characterize here as aleatory ("random") may be partially reducible through more elaborate models and/or further study. However, for our purposes here, we will relinquish such a hope or expectation, and will treat some of the uncertainties in various processes and parameters as unknowably aleatory.

The conceptual difference between epistemic and aleatory uncertainty is an important element of SSHAC's approach to PSHA. In the chapters of this report that follow, we will provide methodological guidance that incorporates uncertainty analysis at the core of the approach, and that therefore cannot be implemented without an understanding of how uncertainties of both types are dealt with. Especially in light of the fact that our knowledge of earthquake phenomena is still so incomplete, which necessitates that the PSHA analyst must deal with diverse expert interpretations of the insufficient information that does exist, we wish to reinforce here, in the introductory chapter, that a PSHA that follows the rest of our guidance but that does not deal appropriately with both the epistemic and the aleatory uncertainties must be considered inadequate.[3]

This exhortation does not imply that every PSHA study must undertake a highly refined uncertainty analysis in order to be valid. Depending on the application, the uncertainty treatment may be adequate while relying largely on experience in similar situations and the judgments of the analysts for its support. However, the SSHAC approach emphasizes that unless the analysis team deals with the major uncertainties instead of "ducking" them, the PSHA results will not be complete, and the full description of the problem faced will not have been communicated to the users of the results.

1.9 Introductory Comments on a Few Other Issues

Regulatory applications: Another SSHAC objective is to develop a methodology that satisfies, when necessary, NRC requirements for nuclear-power-plant siting, including the ability to be reviewed by the NRC staff and adjudicated in an administrative hearing. Meeting this objective will allow the methodology to be used in other similar regulatory or quasi-regulatory settings, including those contemplated by DOE for its reactor and non-reactor facilities.

However, SSHAC has not given significant attention to the specific ways in which PSHA results have been used in the past, or may be used in the future, in the regulatory arena. Each sponsor of a particular PSHA study must work together with the project team to direct the project's efforts at those applications—regulatory or otherwise—that are that study's intended use. This includes such crucial issues as the scope of the project, any special documentation requirements, the relative emphasis on mean or median hazard results as the more important (if appropriate), and so on. In particular, it is not known to us whether the results of a given PSHA

[3]In certain applications, the objective is simply the mean annual hazard (that is, the expected value with respect to epistemic uncertainty). In this case, the result is not sensitive to the distinction between the two uncertainty types, but both must still be captured to obtain the correct value.

performed using the SSHAC guidance will be useful for nuclear-power-plant regulatory purposes.

Seismic hazard expressed in terms of ground motion: The SSHAC has thought about seismic hazards principally in terms of the ground motion that would occur at a given site. This ground motion can be expressed in many different ways (response spectral ordinates, peak acceleration, etc.) that are discussed in detail in the body of this report. Generally, the results of a PSHA are expressed in terms of the likelihood in one year that a certain level of ground motion may be exceeded, usually called the "probability of exceedance."

Seismic hazard at a rock outcrop vs. local site effects: Local site effects must be considered in any site-specific application to a facility, and some guidance on them is provided here. However, the SSHAC sponsors decided early in the effort that the principal emphasis should be on recommending a methodology to obtain the seismic hazard (ground motion) at a hypothetical (or actual) hard-rock outcrop at a given site.

Uncertainty: As discussed above, the Committee believes that a PSHA that does not deal with the various uncertainties properly is not useful for nearly all the contemplated applications. Therefore, the Committee has given special attention to guidance on this subject, which has turned out to be one of the major issues in the project.

1.10 Criterion for Success of the SSHAC Project

With PSHA, even cookbook-type methodological guidance allows flexibility in implementation. Of course, such flexibility means that different teams inevitably will interpret and apply the methodology differently. Early in the project, the Committee agreed that a key criterion for success of the SSHAC project would be that the recommended PSHA methodology, when independently applied by different groups, would yield "comparable" results, defined as results whose overlap is within the broad uncertainty bands that inevitably characterize PSHA results. For this to be true, we believe (as discussed above) that the uncertainties in the methodology must be confronted and dealt with head-on. No PSHA analyst should attenpt less, and no PSHA sponsor should accept less.

Furthermore, if the results of two such studies turn out not to be "comparable," following the guidance herein will provide a framework within which the differences can be identified and debated in a structured manner.

1.11 Road Map to the Report

The report is organized into several Chapters. Following this Introduction, Chapter 2 contains an overview of the PSHA methodology. Next, Chapter 3 provides the crucial guidance on structuring a PSHA project, including how experts are used and how the peer review process should be structured. The next two chapters present the methodology for characterizing both seismic sources (Chapter 4) and ground-motion attenuation (Chapter 5). This is followed by a discussion of the methodology for producing the PSHA results (Chapter 6) and guidance on obtaining insights from the results and on documenting the project (Chapter 7). A glossary and comprehensive list of references complete the report.

Material too detailed or outside the scope of the main report can be found in the Appendices.

2. OVERVIEW OF THE PSHA METHODOLOGY

2.1 The Basic Probabilistic Model

The model of the randomness (or aleatory uncertainty) of the behavior of the earth that underlies virtually all probabilistic hazard analysis is by now very familiar to scientists and engineers working in the field. The SSHAC endorses this model for all but certain uncommon cases where the information available may permit or require specific deviations. As with any effective representation of nature, the model below represents a compromise between complexity, availability of information, and sensitivity of the results.

The objective is to estimate the mean frequency per unit time or, alternatively, the probability in a given future time period that a specified level of some ground motion parameter will be exceeded at a site of interest. For example, the result might be the annual probability that the 1 hertz spectral acceleration at the site exceeds 0.3g. In general, one will seek this probability for a range of levels, i.e., as a function of the ground motion parameter value. Also, a suite of different ground motion descriptors will be studied, e.g., spectral accelerations for several different oscillator frequencies. We will focus here, however, on the simplest case.

The components of the aleatory model are those that (i) characterize the seismicity in the vicinity of the site, and (ii) represent the ground motion prediction of the effect at the site should an earthquake of given size (magnitude) occur a given distance from the site. These two general subjects will be dealt with in great detail in Chapters 4 and 5. For our purposes here we presume that the seismicity is represented by a set of s independent "sources" each with spatially homogeneous seismicity and that the ground motion prediction is characterized by a function g(m,r) that yields the mean value of the (natural) log of the ground motion parameter, lnA, given the magnitude, m, and the distance, r, of the event. To a first approximation, this function increases linearly in magnitude and decays logarithmically with distance. Further, the variability (event to event and site to site) observed in ground motion data is represented by a Gaussian distribution on lnA with standard deviation σ. σ is often assumed to depend on m.

For any given source of seismicity, the model assumes that earthquake events of "engineering interest," i.e., those above a magnitude threshold such as 5.0, occur with a mean annual rate ν. Further we assume that these events occur at relative frequencies, $f_M(m)$. This probability density function has a corresponding CCDF (complementary cumulative distribution function), $G_M(m)$, which is the fraction of events with magnitude m or greater. The common assumption is that the form of $f_M(m)$ is exponential:

$$f_M(m) \propto e^{-\beta m} \text{ for } m_o \le m \le m_u \qquad (2.1)$$

in which m_o is the lower threshold and m_u is the upper bound magnitude, the largest magnitude that this particular source is capable of producing, while β is the parameter that determines the relative frequency of larger to smaller events. This parameter is, within a constant, the traditional b value of the familiar Gutenberg-Richter relationships: $\beta = \ln(10)b \cong 2.3b$. In certain applications this exponential magnitude frequency distribution may be supplemented by a "characteristic magnitude" distribution; this implies superposing a "spike" or narrow rectangular bar of frequency density at or about the value of this characteristic size; this size is usually m_u.

Finally the assumption that the source is spatially homogeneous implies that any point within that source is equally likely to be the hypocenter of the event. From this knowledge and the geometry of the source relative to the site, one can deduce a function $f_R(r)$ that describes the relative frequency of different site-to-earthquake distances. In plan view the geometry of the source may be a line (fault) or arbitrarily shaped area. The rupture may be considered to be simply a point or a line (a fault in plan view) of a length that depends on the magnitude. In the latter case the distribution on

distance (defined typically as the closest distance between site and fault) would also depend on magnitude, $f_R(r \mid m)$.

Then, of all those events of magnitude m at distance r from the site, the ground motion assumptions above imply that the fraction that causes ground motion greater than or equal to level **a** is

$$\Phi'\left(\frac{\ln a - g(m,r)}{\sigma}\right)$$

in which $\Phi'(\cdot)$ is the CCDF of the standard unit normal. Therefore the fraction of all events on the source that equal or exceed **a** is

$$\iint \Phi'\left(\frac{\ln a - g(m,r)}{\sigma}\right) f_R(r|m) f_M(m)\, dr\, dm$$

The mean annual frequency of such events is simply this fraction times ν, the mean rate of all events.

Then, to consider all s sources, we need simply sum the mean rates from each source leading to the following expression for λ(**a**) the mean annual rate of events with site ground motion level **a** or more:

$$\lambda(a) = \sum_{i=1}^{S} \nu \iint \Phi'\left(\frac{\ln a - g(m,r)}{\sigma}\right) f_R(r|m) f_M(m)\, dr\, dm \qquad (2.2)$$

in which the subscripts on all the factors within the sum (ν, f_R, f_M, and even possibly g(m, r) and σ) are deleted for simplicity. This is the basic equation of probabilistic seismic hazard analysis. It is the simple algorithm by which the many important pieces of the total puzzle are finally integrated.

Under the additional assumption that the events in every source follow independent Poissonnian processes, the mean rate λ(**a**) can be used to compute the probability of exceedance in any time interval of length t:

$$P[A > \mathbf{a} \text{ in time t}] = 1 - e^{-\lambda(\mathbf{a})t} \qquad (2.3)$$

in which P[·] is read "the probability of the event that." Note that for the small probabilities of usual interest in PSHA problems the value of λ(**a**)t is small relative to unity, in which case the probability in Eq. 2.3 is approximately equal to simply λ(**a**)t. In different words the annual probability is approximately equal to the mean annual rate. Therefore the two phrases are used virtually interchangeably in common PSHA and in this report.

In certain problems it may be important to recognize that some of the events, such as the "characteristic" events, are not Poissonian in their temporal stochastic behavior. In this case it is usually sufficient (Cornell and Winterstein 1988) to replace the mean rate ν of such events by the time interval average of what is called the hazard function h(τ) which is a function of the time elapsed since the last such event on the source. It is in this case that one must distinguish carefully between the probability (Eq. 2.3) and the mean rate (Eq. 2.2). The *probability* is the appropriate item to calculate and report.

Further, it should be recognized that the spatially homogeneous areal source model used in many applications is not a physical characteristic of the earth but a simplified mathematical representation of a field of seismogenic structures that the earth scientist believes can be approximated adequately for hazard estimation purposes by such a model. Its application in practice will be discussed in Chapter 4.

2.2 Primer on Uncertainties

2.2.1 Introduction

The purpose of this section is to introduce several concepts and the associated terminology essential to the framework adopted for PSHA. We discuss both the nature of physical models ("models of the world")—recognizing that they can be either deterministic or probabilistic depending on the application—and our knowledge and ability to model the phenomena (the "world") of interest. We then acknowledge that models themselves, as well as the parameters appearing in them, may be uncertain and we introduce probabilities to express these uncertainties. The uncertainties that are part of the model of the world, if any, are called *aleatory* uncertainties (other names are

"stochastic" or "random" uncertainties). Even under "perfect information," i.e., when the model has been validated and the numerical values of its parameters are known, these aleatory uncertainties are still present (for a given model).

The uncertainties that stem from our lack of knowledge concerning the validity of the models and the numerical values of their parameters are referred to as *epistemic* uncertainties (in the literature, they have been referred to as simply "uncertainties"). As information is collected, the epistemic uncertainties are reduced. We prefer to use the terms aleatory and epistemic because they have a unique interpretation; alternatives (e.g., "uncertainty" for "epistemic") have multiple meanings.

We also discuss in this section the concept of model uncertainty in more detail, as well as the display and communication of the various types of uncertainty.

2.2.2 Deterministic and Aleatory Models of the World

The "model of the world" is the mathematical model that is constructed for the physical situation of interest, such as the occurrence and impact on a system of a physical phenomenon. The "world" is defined as "the object about which the person is concerned" (Savage 1972). Occasionally, we will refer to the model of the world as simply the model, or the mathematical model. Constructing and solving such models is what most physical scientists and engineers do. There are two types of models of the world, deterministic and probabilistic. A simple example of a deterministic model is the function g(m,r) that yields the mean value of the logarithm of the ground motion parameter at a specified site given the magnitude, m, and the distance, r, of the earthquake (see Section 2.1).

Many important phenomena cannot be modeled by deterministic models. For example, the actual ground motion parameter A can not be predicted precisely. We then construct models of the world that include this uncertainty. A simple example is the normal distribution (Section 2.1), i.e.,

$$\Pr(A > a) = \Phi'\left(\frac{\ln a - g(m,r)}{\sigma}\right) \tag{2.4}$$

where $\Phi'(\cdot)$ is the CCDF of the standard unit normal.

The interpretation of this probability is the following: if we consider very many earthquakes all at a distance r from the site and of magnitude m, the fraction of events leading to a ground motion parameter A (the "random variable" of this problem) exceeding a given value a will be very close to this probability.

The uncertainty described by the model of the world is sometimes referred to as "randomness," or "stochastic" uncertainty. Stochastic models of the world are also called *aleatory* models [aleatory: of or depending on chance, luck, or contingency (Webster's 1988)].

In addition to the two examples from the model for ground motion cited above, we recognize that the representation of seismicity by a number of "sources" each with a specified mean rate of seismicity along with eq. (2.1) for the magnitude distribution of an earthquake occurring in a given source is an aleatory model.

2.2.3 The Epistemic Model

There are two additional types of uncertainties associated with a (deterministic or aleatory) model of the world. The model itself (or, the hypotheses behind it) may involve approximations, so that its predictions deviate by a fixed but unknown amount from observed values of the predicted quantity. The second type is associated with uncertainties about the numerical values of the parameters of a given model, e.g., the parameter β of eq. (2.1).

The *epistemic* probability model represents our knowledge regarding the numerical values of the parameters and the systematic over- or under-predictions of the model [epistemic: of or having to do with knowledge (Webster's 1988), see also Paté-Cornell and Fischbeck (1992); in risk assessment, this probability distribution function (pdf) is also referred to as a "state-of-knowledge" pdf (Kaplan and Garrick 1981)].

The epistemic model for the deterministic model of the world that consists of seismic sources allows alternate boundaries for each source. Each alternate map is associated with an epistemic probability. The upper-bound magnitude m_u of each source is assigned its own epistemic probability distribution. Similarly, for the ground motion model, eq. (2.4), the function g(m,r) itself is uncertain (epistemic model uncertainty); multiple alternatives are often considered. The value of the standard deviation σ of the aleatory model is also uncertain (epistemic parameter uncertainty).

We note that the probability distributions that reflect epistemic uncertainty are the ones that are "updated" as empirical evidence is gathered. For a given model, the updating of the epistemic distributions of its parameters is done using Bayes' theorem, as shown in numerous references, e.g., Lee (1989), Benjamin and Cornell (1970), Winkler and Hays (1975), and Apostolakis (1990). It can be shown that, when the empirical evidence is very strong, these epistemic distributions become delta functions about the exact numerical values of the parameters. At this point, no epistemic uncertainty about the numerical values of the parameters exists and the only uncertainty in the problem is the aleatory uncertainty in the model of the world. The latter can never be removed (unless, of course, we happen to change the model of the world).

The types of uncertainty that we have presented are defined from what can be called the "probabilist's" point of view. We have associated epistemic uncertainties with models and their parameters only, while aleatory variables appear in the model of the world. Unfortunately, this clear distinction cannot be maintained in PSHA, because the engineering use of the term "parameter" is not consistent with this formulation. For example, the stochastic ground motion model (Electric Power Research Institute 1993) includes what are called these parameters, such as the stress drop, $\Delta\sigma$, that are assumed to have both kinds of uncertainty.

In the formulation that we have presented, quantities such as $\Delta\sigma$ would be called aleatory variables and they, as well as their assumed probability distributions, would be part of the (aleatory) model of the world. The moments (or other parameters) of these aleatory distributions would, in turn, be assigned epistemic probability distributions. Having made this distinction clear, we must follow common engineering practice and call these quantities "parameters" of the models. Thus, a parameter in an engineering model may have related to it both aleatory and epistemic probability distributions. We still, however, make a distinction between, on one hand, quantities that deal with model uncertainty (see, for example, the discussion on D below), and parameters, such as $\Delta\sigma$, on the other. The term "model uncertainty" is used for the former, while "parametric uncertainty" is reserved for the latter. As an example, Table 5-2 in Chapter 5 shows this classification in the context of ground-motion models.

We point out that, even though we have discussed probabilities appearing in the model of the world and the epistemic model, and we have given them different names, leading philosophers of science and uncertainty (e.g., De Finetti 1974; De Groot 1988) believe that, conceptually, there is only one kind of uncertainty; namely, that which stems from lack of knowledge. Aleatory and epistemic uncertainties are a convenient way to distinguish between uncertainties that cannot be reduced (for a given model) and uncertainties that can be reduced as new knowledge is acquired.[1]

2.2.4 More on Model Uncertainty

Consider the case of a single deterministic model of the world which calculates the quantity y_c. Furthermore, we know that there are significant model uncertainties associated with this prediction. One way to describe this situation is to introduce a parameter D into the model of the world which may be multiplicative or additive. For example, we may assert that the actual value

[1]The distinction between aleatory and epistemic uncertainty may at first appear inconsistent with the Baysian view of probability, but, in fact, it is entirely consistent with this view. Aleatory uncertainties may be thought of as frequencies of a set of exchangeable events or as frequency distributions of an exchangeable set of continuous random variables. If the frequencies or frequency distributions are uncertain, it makes perfect sense to assess probability distributions over the unknown frequencies or parameters of the unknown frequency distributions.

may be obtained as $y_a = Dy_c$. In this case, the parameter D is multiplicative (this is, for example, how the EPRI stochastic ground motion model treats part of model uncertainty). This parameter may be interpreted as the ratio of the true value over the predicted value (by the model). Note that we still may assign both aleatory and epistemic uncertainty distributions to the parameters of the deterministic model that produces y_c.

The quantity D is a deterministic parameter of the model of the world. However, its numerical value may be uncertain, therefore, in the epistemic model we represent this uncertainty by a probability density function (pdf) g(d).

Let us consider again the implications of this formulation in terms of a thought experiment. After even one observation, the exact value of D will be known (since all epistemic uncertainty will have been eliminated) and it will represent the systematic bias of the model prediction y_c. This systematic bias is due to the incompleteness (or other shortcomings) of the deterministic model.

The EPRI (1993) engineering model of ground motions is an example of this formulation. The ground-motion amplitude (peak acceleration or spectral acceleration at a certain frequency) is given by

$$\ln A(m,r) = g(m,r) + \varepsilon_e + \varepsilon_a \qquad (2.5)$$

where g(m,r) represents a median attenuation equation, e_e is an epistemic variable with zero mean, and ε_a is a zero-mean aleatory variable. In this example, the additive quantity ε_e plays the role of D and it represents lack of knowledge about the difference between g(m,r) and the logarithm of the true median amplitude for this magnitude and distance. The aleatory variable e_a represents event-to-event and site-to-site scatter due to smaller-scale details of the earthquake source processes and of wave propagation through a heterogeneous crust. Note that in terms of actual observations, the observed scatter is due to both epistemic and aleatory uncertainty and one observation alone would not suffice to remove all epistemic uncertainty. This treatment in terms of model and parameter uncertainty was formalized by Abrahamson, Somerville, and Cornell (1990).

The issue of model uncertainty has been investigated in other applications of risk assessment also. An example from fire risk assessment is given in Siu and Apostolakis (1981 and 1985), in which the updating of the (epistemic) distribution of D is also investigated using Bayes' theorem.

Alternate formulations of model uncertainty have also been proposed. In one such formulation (Apostolakis 1990 and 1993), a number of models calculating $y_{c,j}$, j=1,...,n, are considered corresponding to a set of n hypotheses H_j, j=1,...,n. In the context of ground motion prediction, these alternative hypotheses may represent empirical attenuation equations derived by different investigators using somewhat different data sets and functional forms, attenuation equations derived using different methods (e.g., empirical vs. stochastic), or attenuation equations derived using a stochastic model and varying some key assumption or parameter in a discrete manner.

Another example of discrete hypotheses is in the specification of seismic sources (or seismic source maps). A certain tectonic feature may or may not be active (according to an activity probability, P_a). If it is active, uncertainty about its true geographic extent is typically represented by multiple alternative geometries with associated weights.

Discrete hypotheses with weights are used frequently in PSHA because they are flexible and they are intuitive. Under certain assumptions, a set of model weights can be developed that reflect the relative forecasting accuracy of approximate models. In Appendix J, we develop this view in more detail in the context of some simple opinion aggregation models that are useful for gaining insight.

An alternate interpretation of model uncertainty is offered in Winkler (1993) and Morris (1971). The outputs from a number of models are viewed as information that is to be processed using Bayes' Theorem. This formulation avoids the issue of

developing probabilities regarding the acceptability of models; this approach has not yet been used in risk assessment. The difficulty lies in its implementation, as Winkler states.

2.2.5 Communication of the Uncertainties

Having discussed the concepts of the model of the world and of the epistemic model, we must now address the question of how to communicate these results to others (possibly, decision makers).

To make the discussion concrete, let us consider the (aleatory) probability of no events in the interval (0, t) [see also eq. (2.3)], i.e.,

$$P[\text{no occurrences in } t] = \exp(-\lambda t) \qquad (2.6)$$

Furthermore, suppose that the rate λ has a discrete epistemic distribution given by the following set of doublets: $\{10^{-2}, 0.4\}$ and $\{10^{-3}, 0.6\}$, i.e., we judge that this rate can be either 10^{-2} per year with probability 0.4 or 10^{-3} per year with probability 0.6. The probability of zero occurrences in a period (0, t) can be calculated using eq. (2.6) and is given by a set of doublets: $\{e^{-0.01t}, 0.4\}$ and $\{e^{-0.001t}, 0.6\}$. The two terms in these doublets resulting from the use of eq. (2.7) represent aleatory uncertainty, while the probabilities 0.4 and 0.6 represent epistemic uncertainty.

A frequently used "point" estimate is the mean value of the probability of no occurrences, i.e., $(0.4e^{-0.01t} + 0.6e^{-0.001t})$. This is called the predictive probability of zero events in a period (0,t). Note that we have not considered any model uncertainty in this example.

We note that the use of the average (predictive) value for decision making can create problems, especially when the epistemic uncertainties are very large, as is frequently the case with model uncertainties [see eq. (2.6)]. This is because the average value can be greatly affected by high values of the variable, even though they may be very unlikely. The average value is only a summary measure of the full uncertainty, which is expressed by the set of doublets. In particular, when the epistemic uncertainty is very large, it would be incomplete to report only the average to the decision maker. In our example, reporting all the doublets to the decision maker communicates the full epistemic uncertainty.

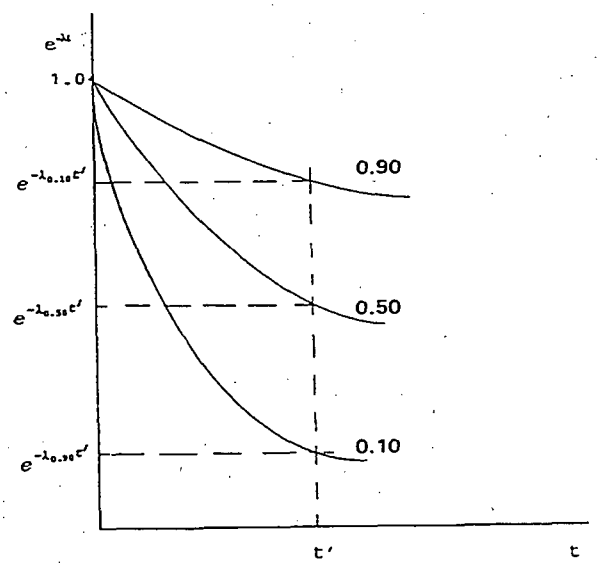

Figure 2-1 A family of aleatory curves displaying epistemic uncertainty

The simple example presented above captures the essence of the uncertainties that we have considered. Other, more realistic, cases can be easily constructed. For example, let us assume that the aleatory model is still given by eq. (2.6), but now the epistemic distribution of λ is a continuous pdf. It is then customary to display a family of curves for various values of λ (Kaplan and Garrick 1981). For example, Figure 2-1 shows three curves produced from eq. (2.6) with λ being equal to the 10th, 50th, and 90th percentiles of its pdf. Also shown are three values of the aleatory probability for a given t' (the analogy with the doublets discussed above can be seen). The interpretation of the curves is as follows: after a very long time, all epistemic uncertainty will have disappeared and the value of λ, and, therefore, the actual curve $e^{-\lambda t}$, will be known. At the present time, we judge with probability 0.90 that this "true" curve will be below the curve labeled "0.90" in the figure.

Figure 2-2 shows the results of a PSHA in this format. The interpretation is just as above. For example, we are 0.85 confident that the "true" seismic hazard curve will turn out to lie below the curve labeled "85th."

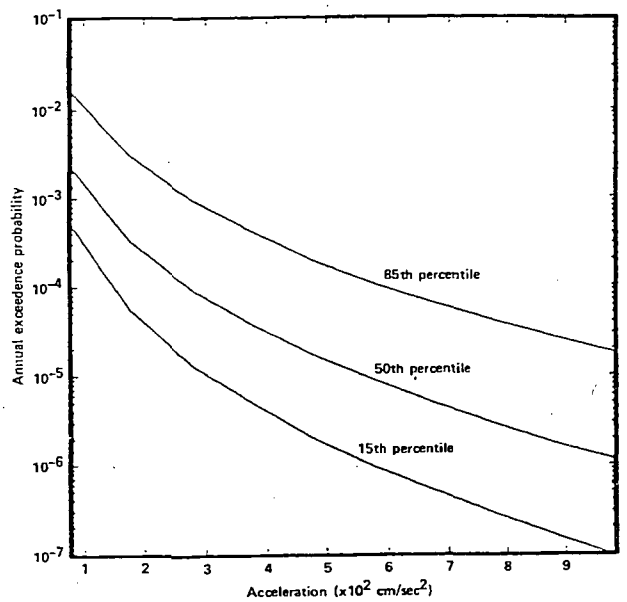

Figure 2-2 A typical family of seismic hazard curves

2.2.6 Further Comments on the Distinction between Aleatory and Epistemic Uncertainties

A recent paper by Veneziano (1994) questions the value of distinguishing between aleatory and epistemic uncertainties. The author claims that this distinction is ambiguous for geologic hazards and raises the issue of the time-dependence of this formalism. Veneziano argues further that what really matters to decision making is the total uncertainty, that is, what we have called the predictive distribution in the last section.

To address these concerns we note that there are both theoretical and practical reasons for this distinction. The theoretical foundation was provided by de Finetti in 1937 (de Finetti 1974; Press 1989). He first introduced the concept of *exchangeability*; an infinite sequence of random variables $X_1,\ldots,X_j,\ldots$ is said to be exchangeable, if the joint distribution of any finite subset of these variables is invariant under permutations of the subscripts. A special and familiar case is when these variables are independent and identically distributed. De Finetti's theorem states that, if the X_j are binary variables, the predictive distribution of r "1's" (for example, r "successes") in n exchangeable trials is given by

$$P[r \text{ "1's" in n trials}] = \int_0^1 \binom{n}{r} \theta^r (1-\theta)^{n-r}\, dF(\theta) \qquad (2.7)$$

where $F(\theta)$ is some proper cumulative distribution function on (0, 1). Furthermore, the limit of the relative frequency (r/n), as n becomes large, is θ. This equation shows that the predictive distribution of r "successes" in n exchangeable trials may be obtained as if the trials were independent conditional on θ. In our previous terminology, we would say that the model of the world is the binomial distribution (in this case) and it is obviously aleatory. The epistemic model is the mixing distribution $F(\theta)$. It is this distribution that is updated as evidence becomes available. This theorem can be extended to general random variables and is the cornerstone of the subjectivistic (Bayesian) theory of probability.

While this theorem is fundamental, it does not tell us how to separate aleatory from epistemic uncertainties in actual applications. In the above example of binary variables, e.g., the familiar coin-tossing experiment, it is fairly obvious that the assumption of exchangeable trials is reasonable, therefore the natural candidate for the model of the world is the binomial distribution appearing in eq. (2.7). In a practical situation, the assumptions that may be used in the model of the world may not be obvious. It is useful to briefly discuss what really happens in practice.

In modeling a physical situation of interest, we do not decide *a priori* how to separate the uncertainties. In fact, the question does not even arise. What we do is build the best model that we can making assumptions that are defensible. If we decide that certain aspects of the problem require a probabilistic treatment, we introduce the appropriate models that capture our knowledge about these uncertainties. This is what physical scientists do.

After the model of the world is completed, the formalism that we have adopted requires that the

analysts answer several questions, such as: "Are the basic assumptions of the model valid?" "Are there alternate assumptions that one may adopt?" "Are the numerical values of the parameters of the model known?" In the simple example of eq. (2.7), the only question that is asked is the last one. It is at this point that a new set of uncertainties may be identified. Recognizing this reality and to facilitate *communication* we introduce the term epistemic uncertainties for this new set and we refer to the uncertainties in the model of the world as aleatory. From this perspective, we can now say that this distinction *occurs naturally* and it is not made in advance. Therefore, a clear prescription as to how to separate the two types of uncertainty (other than what we have already said) cannot be given *a priori*. Furthermore, the different terminology is not intended to imply that these uncertainties are of a fundamentally different nature.

The benefits from the formalism are far greater than just the facilitation of communication. By demanding that the analysts ask the preceding questions, this approach imposes a *discipline* on the analysis that has been found to be invaluable in practice. The interpretations of aleatory and epistemic uncertainties that we have discussed in earlier sections are new to most modelers and practitioners and using these concepts forces the analysts to really delve into the details of the models and consequences of various assumptions. An example from the NUREG-1150 studies will clarify this point.

In studying how large power reactors behave in postulated accidents, one important issue is the internal pressure that would cause the large containment building that surrounds the reactor to fail catastrophically. In the NUREG-1150 study of the Peach Bottom 2 reactor, a boiling water reactor, the approach to understanding at what pressure the containment would fail was to ask a group of experts to provide their judgments (Amos et al. 1987).

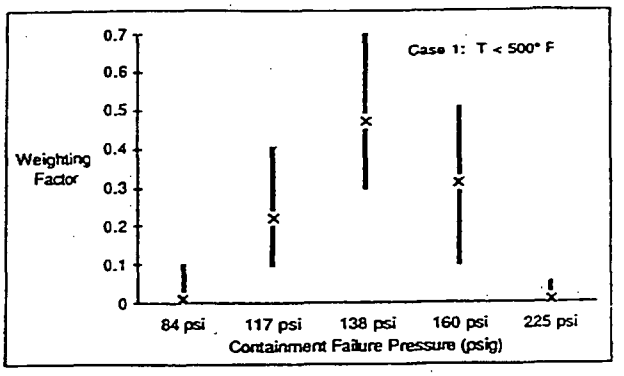

Figure 2-3 Weighting Factors for Containment Capacity for Low Temperature Conditions [NUREG/CR-4551/Volume 3, Figure 4-1]

Figure 2-3 shows the expert-supplied probabilities ("weighting factors") for the containment failure pressure (given certain conditions). Five pressure values are being considered. This model of the world implies that one of these pressures will actually turn out to be the true one and, at this time, we do not know which value it will be, i.e., the model of the world is deterministic. It is stated in Appendix A of the report that there might be some randomness about each value and that "there was a great deal of discussion concerning this issue due to the difficulties in defining the meaning of the failure pressure distributions derived for this issue. Each reviewer had a somewhat different interpretation of the input that was being required, as well as of the use of the input in the Limited Latin Hypercube sensitivity analysis." This means that the experts debated the validity of the assumption that the model of the world was deterministic (that only one value was the true failure pressure). It was finally decided that the aleatory variability was "generally small" and it was dropped from further analysis. We note that, if the group had decided to include aleatory uncertainty in the model, the question asked of the experts would have been "what is the fraction of times that failure occurs at each of these pressures and what is your uncertainty about this fraction?" The results of Fig. 2-3 are responses to a different question, i.e., "what are your probabilities that the true failure pressure will be one of the five values shown in the figure?"

The predictive distribution contains all the uncertainties and is the one that is used in formal decision theory to evaluate the expected utilities. What the presented formalism does is allow for the systematic assessment of this distribution. In practice, the epistemic uncertainties themselves may suggest possible actions, such as delaying the actual decision and doing more research to reduce the magnitude of the epistemic uncertainties.

As discussed in previous sections, new information is used to update the epistemic model using Bayes' theorem. This is based on the fundamental assumption that the models of the world with which we begin the analysis do not change. This is not the way engineering models, especially the ones employed in risk assessments, evolve in time. New evidence and advances in science very often lead to new models. In these cases, the old formulation does not apply anymore and one must start with new models of the world and ask, again, the above questions to assess the epistemic uncertainties associated with these new models. Thus, the new predictive distributions will be evaluated in the same manner as before. It is evident, therefore, that models used in present analyses may be used only for a limited time depending on how sound their assumptions are. For example, the models for PSHA that this report presents and the associated guidance for hazard assessment are expected to be useful for the next several years. When new scientific advances necessitate a significant change in the models of the world, then the structure of the analysis will change and the formalism that we have discussed will apply to this new structure.

3. STRUCTURING AND IMPLEMENTING A PSHA

3.1 Introduction

The success of a PSHA project is principally determined by how it is structured and implemented to derive inputs; in particular, how this structure and implementation account for different technical interpretations of the available evidence and uncertainties. Despite the importance of these issues—that is, *how* the PSHA is conducted, rather than what goes into the analysis—very little written guidance has been developed. Such guidance should not only incorporate the evolving concepts related to uncertainty treatment and expert elicitation in general, but, perhaps more importantly, should draw on the experience base developed over the past decade or more in carrying out seismic hazard analyses.

PSHA inputs involve multiple issues, e.g., ground motion models, ground motion uncertainty, seismic source identification, seismicity parameters, etc. The complexity, importance and diversity of judgments within the appropriate scientific community regarding any one of these issues vary between study location (east vs. west U.S.), range of the study (site-specific vs. regional), and other factors.

3.1.1 Principle 1: The Basis for the Inputs

A basic principle defined by the Committee is that *the underlying basis for the inputs related to any of these issues must be the composite distribution of views represented in the appropriate scientific community.* Expert judgment is used to represent the informed scientific community's state of knowledge. Of course, it is impractical—and unnecessary—to engage an entire scientific community in any meaningful interactive process. Decision makers must always rely on a smaller, but representative, set of experts. Thus, we view an expert panel as a sample of the overall expert community and the individual Technical Integrator (defined later) as the expert "pollster" of that community, the one responsible for capturing efficiently and quantitatively the community's degree of consensus or diversity.

Regardless of the scale of the PSHA study, the goal remains the same: *to represent the center, the body, and the range of technical interpretations that the larger informed technical community would have if they were to conduct the study.*

3.1.2 Principle 2: A Clear Definition of Ownership

Another principle defined by the Committee with respect to deriving inputs is that *it is absolutely necessary that there be a clear definition of ownership of the inputs into the PSHA* (and hence ownership of the results of the PSHA). Therefore, this precludes the PSHA being performed by an analyst who simply accumulates inputs (either from the literature or eliciting the judgments of one or more experts) without establishing his/her responsibility for and ownership of aggregated results. That is, it is important that the analyst be an integrator in the sense of establishing his/her ownership of the results.

The number and size of PSHAs conducted over the past decade scales very much like an earthquake recurrence curve: hundreds of "small-magnitude" hazard studies are conducted annually to evaluate ground motions at the sites of new or existing conventional facilities (e.g., buildings, pipeline terminal facilities, hospitals); tens of "moderate-magnitude" studies are conducted for more critical facilities (e.g., high-rise buildings, nuclear production facilities, offshore platforms); and a few large-magnitude studies have been conducted over the past decade for highly critical and/or highly regulated facilities (e.g., nuclear power plants, high-level waste repositories). Given the nature of the "PSHA-experience recurrence curve," our collective experience base is decidedly skewed toward the smaller-scale studies. However, the sponsors of the SSHAC project are interested in guidance that is skewed toward application for more critical facilities.

Despite an emphasis on large-scale studies for critical facilities, SSHAC has devoted considerable time and effort in reviewing past PSHAs of all scales and applications in order to

learn which processes have worked, the pitfalls, and the processes that appear to hold the most promise in future application. One example of SSHAC's research effort is the Seismic Source Characterization (SSC) Workshop (see Appendix H), in which the focus of the discussions was on *process* issues: the manner in which SSC experts should be elicited, the degree of expert interaction desired, the value of workshops, methods for combining the interpretations of multiple SSC experts, etc. In SSHAC's ground motion workshops, concepts related to facilitation of workshops, roles and interactions of experts, and aggregation of expert interpretations were "tested" through a real application.

The two basic SSHAC principles discussed above—(1) inputs should represent the composite distribution of the informed technical community and (2) ownership of inputs established by an integrator—SSHAC recommends that the derivation of inputs be conducted by one of two approaches, either by a Technical Integrator (TI) approach or a Technical Facilitator/Integrator (TFI) approach. Appropriate definitions of these approaches and SSHAC recommendations of the structures of these approaches as a function of the importance, complexity, diversity of views and contentiousness of an issue is the subject of Section 3.1. Sections 3.2 and 3.3 outline the TI and TFI approaches, respectively. Because it has never been fully implemented, hence not documented, the TFI discussion in Section 3.3 (and Appendix J) is more comprehensive. Section 3.4 discusses peer review and summarizes SSHAC recommendations with regard to peer review of the TI and TFI approaches to deriving inputs on any issue related to PSHA. It should be noted that detailed guidance for implementing the TI and TFI approaches for seismic source characterization are found at the end of Chapter 4 and detailed guidance for implementing the TI and TFI approaches for ground motion assessment is given at the end of Chapter 5.

3.1.3 Definitions and Roles of Technical Integrator (TI) and Technical Integrator/Facilitator (TFI)

To outline clearly the Committee's recommended approaches to the PSHA input issues, it is necessary to define some important terms and concepts.

3.1.3.1 Project Sponsorship and Leadership

- The *Project Sponsor* is the entity that provides the financial support for the project, hires the study team (including the project leader), and "owns" the study's results in the sense of property ownership.
- The *Project Leader* (often one individual, but possibly a small team) is the entity that takes managerial and technical responsibility for organizing and executing the project, oversees all other project participants, and "owns" the study's results in the sense of assuming intellectual responsibility for the project's overall technical validity. The Project Leader makes decisions regarding the level of study of particular issues (discussed below).

3.1.3.2 Integrators

Two types of integrators are considered:

- *Technical Integrator (TI)*: a single entity (individual, team, company, etc.) who is responsible for ultimately developing the composite representation of the informed technical community (herein called the community distribution) for the issues using the TI approach. As discussed later, this could involve deriving information relevant to an issue from the open literature or through discussions with experts.
- *Technical Facilitator/Integrator (TFI)*: a single entity (individual, team, company, etc.) who is responsible for aggregating the judgments and community distributions of a panel of experts to develop the composite distribution of the informed technical community for the issues using the TFI approach. The key differences between the TI and TFI approaches are (i) the facilitator role of the TFI in which he/she is responsible for

facilitating the discussions and interactions between experts and (ii) the use of "evaluator" experts, who act as individual integrators, in the development of the community distribution.

In the context of these discussions we use the term *interpretation* to denote a technical hypothesis (i.e., without epistemic uncertainty), and *evaluation* to denote a weighted set of hypotheses or interpretations. The evaluation process, then, is focused on epistemic uncertainties.

3.1.3.3 PSHA Issues

By reviewing past hazard studies and experimenting with "new" approaches, SSHAC has formulated a spectrum of approaches to structuring a PSHA. It is concluded that all approaches attempt to achieve several primary objectives. These objectives include: proper and full incorporation of uncertainties, inclusion of a range of diverse technical interpretations, consideration of site-specific knowledge and data sets, complete documentation of the process and results, clear responsibility for the conduct of the study, and proper peer review.

It is recognized that PSHA can, and should, be conducted for a wide variety of reasons and at various scales. There is nothing inherently "wrong" with the calculated results that come from a modest hazard analysis conducted by a single contractor; nor does the use of multiple experts in a large-scale project guarantee that the hazard results are more defendable (particularly if done poorly). They are, however, more likely to capture accurately the scientific community's information. The choice of the level of PSHA is often driven by the level of uncertainty and contention associated with a particular project, as well as the amount of resources available for the study. It is further recognized that particular components or *issues* of the PSHA (e.g., the slip rate on a particular fault, the maximum magnitude, or the amplitude of near-field ground motions) may have variable degrees of contention and/or uncertainty.

Table 3-1 Degrees of PSHA Issues and Levels of Study

ISSUE DEGREE	DECISION FACTORS	STUDY LEVEL
A Non-controversial; and/or insignificant to hazard	•Regulatory concern •Resources available •Public perception	**1** **TI** evaluates/weights models based on literature review and experience; estimates community distribution
B Significant uncertainty and diversity; controversial; and complex		**2** **TI** interacts with proponents & resource experts to identify issues and interpretations; estimates community distribution
C Highly contentious; significant to hazard; and highly complex		**3** **TI** brings together proponents & resource experts for debate and interaction; TI focuses debate and evaluates alternative interpretations; estimates community distribution
		4 **TFI** organizes panel of experts to interpret and evaluate; focuses discussions; avoids inappropriate behavior on part of evaluators; draws picture of evaluators' estimate of the community's composite distribution; has ultimate responsibility for project

As used here, an issue may be one or a combination of input issues, e.g., an issue may only be ground motion models for median values, or an issue may include both the ground motion model for the median as well as the aleatory uncertainty in the ground motion. Table 3-1 illustrates the process of identifying the key technical PSHA issues and deciding the level of study that should be devoted to addressing the issues. It is assumed that individual issues or components of a PSHA can be evaluated separately, although, commonly in the past, the decision regarding the level of study has applied to the entire hazard analysis. In the left-hand column of the table, the degrees of issues are shown as A, B, and C. In deciding the degree of an issue, there are several considerations such as:

- the significance of the issue to the final results of the PSHA
- the issue's technical complexity and level of uncertainty
- the amount of technical contention about the issue in the technical community
- important non-technical considerations such as budgetary, regulatory, scheduling, or other concerns.

Degree A issues are non-controversial and/or have no significance to the seismic hazard results; Degree B issues are more controversial, complex, and significant to the hazard results; Degree C issues are often highly contentious, complex, and most significant to the hazard results. Obviously, there is a continuum of degree so that the three levels identified represent a coarse partition of the range of issue degrees. Some judgment must be made when classifying any particular issue for a given study.

For each issue (or for the PSHA as a whole), a decision must be made regarding the level of study that will be conducted to address the issue. The decision usually involves factors such as the regulatory framework, the resources (money and time) available to conduct the study, perceptions (including both the public and other stakeholders) of the importance of the project, and scheduling constraints.

3.1.3.4 Experts

Because of limited data, it is often necessary to interact with experts to derive necessary information regarding an issue. For purposes of PSHA issues, three types of experts, not necessarily mutually exclusive, are identified: proponents, evaluators, and resource experts. An important distinction is made here in the roles of experts as "proponents," as "evaluators," and as "resource experts." A *proponent* is an expert who advocates a particular hypothesis or technical position. The proponent role is common in science, whereby an individual evaluates data and develops a particular hypothesis to explain the data. The proponent's position is then challenged technically by his peers in professional debates and in the literature to see if it stands up to a variety of observations. The proponent of the hypothesis detaches himself professionally from the success or failure of the hypothesis; that is, although he argues for the viability of the hypothesis, he recognizes that it may ultimately be proven wrong. With time, the hypothesis will gain increasing support with additional data or will lose favor in the scientific community.

An *evaluator* is an expert who is capable of evaluating the relative credibility of multiple alternative hypotheses to explain the observations. The evaluators are expected to evaluate all potential hypotheses and bases of inputs from proponents and resource experts and provide 1) their own input and 2) their representation of the community distribution. The evaluator recognizes that the evaluation occurs at a particular point in time and, as a result, the viability of any particular hypothesis is uncertain and may not be proven until some time in the future. To evaluate the alternatives, the evaluator considers the available data, listens to proponents and other evaluators, questions the technical basis for their conclusions, and challenges the proponents' positions. In the end, the evaluator is able to assign relative credibilities to the alternative hypotheses. He recognizes, too, that no single hypothesis is likely to be the ultimate truth—it is only a current representation. Therefore, he finally may, for example, assign a smooth continuous (epistemic) uncertainty distribution over that parameter (e.g.,

the median peak acceleration of a magnitude 6 at 10 kilometer distance or the long-term slip rate on a fault) to which each hypothesis (model/interpretation/data set) assigns a unique value, and for which a finite set of weighted hypotheses would imply a simple discrete uncertainty mass function.

A *resource expert* is a technical expert with particular knowledge of a particular data set of importance to a PSHA. Commonly, a resource expert will have site-specific experience that will be of use to the evaluators. For example, a resource expert for a site-specific hazard analysis might be a geologist who has mapped and evaluated nearby faults. A resource expert might also have expertise in particular methodologies or procedures of use to the evaluators. For example, a resource expert may have developed new procedures for evaluating the completeness of earthquake catalogs or for processing catalogs to identify foreshocks and aftershocks.

3.1.3.5 Study Level

Table 3-1 summarizes four levels of study to address issues, which are shown roughly in order of increasing resources and sophistication. The TI and TFI roles are outlined for the various levels. Because the TFI, by definition, involves the "facilitation" of multiple experts, the TFI role does not appear until the Level 4 analysis. The TI, on the other hand, varies in his/her role from basing judgments on his own experience and literature to obtaining input from communication with other experts.

The roles and activities associated with the TI show increasing input from technical experts with increasing level. For example, at Level 2, the TI reviews the literature and contacts those individuals who have developed interpretations or who have particular site experience. At Level 3, however, the TI gains additional insight by bringing together the experts and focusing their interactions. In these sessions, the experts could have an opportunity to explain their hypotheses and data bases. Further, proponents or advocates of particular technical positions can defend their positions to other experts.

In the context described above, the Level 2–4 analyses involve the input from proponents who have developed technical interpretations regarding particular issues of importance to PSHA. Levels 2 through 4 differ in the degree to which these proponents are questioned directly and/or are given a forum for expressing their views. In Levels 1 to 3, the TI plays the role of the "evaluator." In Level 4, a group of expert "evaluators" is identified and their judgments are elicited. The TFI is responsible for identifying the roles of the proponents and evaluators and for ensuring that their interactions provide an opportunity for focused discussion and challenge.

It is important to note that in all four levels of hazard analysis, the responsibility for the success or failure of the analysis rests with the TI or the TFI. In the Level 1-3 analyses, the responsibility is clear inasmuch as the TI develops judgments and hazard inputs based on information gathered from others. In the Level 4 analysis, resources permit and the situation dictates multiple evaluators and hence a TFI to take responsibility for the aggregated product. The TFI must organize and manage interactions among the proponents and evaluators, must identify and mitigate problems that might develop during the course of the study (e.g., an expert who is unwilling or unable to play the evaluator role), and must ensure that the evaluators' judgments are properly represented and documented. In both the TI and TFI approaches, proper peer review must be conducted to review the process and substance of the study.

In the TI approach, it is clear that the *intellectual responsibility* for the study lies with the TI. Intellectual responsibility is defined as the responsibility not only for the accuracy and completeness of the results, but also for the process used to arrive at the results. In the TFI approach, *both* the TFI and the experts have intellectual responsibility for the results. The TFI has a further burden of ensuring that the process is properly implemented. In most cases, peer reviewers are expected to provide an *endorsement* of the process and results of the study. An endorsement is an affirmation that the particular

project meets his/her standards of quality, thoroughness, and validity.

Regardless of the level of the study, the goal in the various approaches is the same: to provide a representation of the informed scientific community's view of the important components and issues and, finally, the seismic hazard. ("Informed" in this sense assumes, hypothetically perhaps, that the community of experts were provided with the same data and level of interaction as that of the evaluators). This is done by the TI in the Level 1-3 studies, with various levels of input from representatives of the community and their literature. In the Level 4 analysis, multiple evaluators provide their review and synthesis of the available data and formulate interpretations that represent their assessments and uncertainties. As will be discussed in Section 3.3.4, the evaluators will be asked to represent both their own interpretations and uncertainties (Stage I elicitation) and their view of the informed community's composite interpretation (Stage II elicitation). In the latter sense, they are themselves each acting as integrators in evaluating the community's views.

Because there have been relatively few Level 4 studies (EPRI and LLNL are examples), there is not a large experience base on which to build guidance. Further, the adoption of the TFI process introduces certain new ground and processes for structuring expert interaction for which detailed guidance must be developed. For this reason a large part of this chapter is devoted to implementation advice for the TFI. In contrast, the TI process is much more common and founded in application. Therefore, the discussion devoted to the TI approach is more limited and based on numerous examples.

3.2 The Technical Integrator (TI) Approach

3.2.1 Introduction

PSHAs in which a single entity is responsible for specifying all inputs into a PSHA, as well as performing the necessary calculations, uncertainty analyses, and documenting the process and results have considerable precedence. In most of these applications, the specified inputs are developed and therefore owned by the single entity, that is, a TI or Technical Integrator. In most of these applications there has not been a formal elicitation of expert judgments. The single entity is the sole evaluator of the information available—either published, as espoused by proponent(s) or described by resource experts—and, hence, is sole developer of the representation of the community distribution. This feature applies to all three levels of study and is one of the distinguishing differences between the TI approach and the TFI approach in which a formal panel of evaluator experts is used jointly as (i) sources of their personal inputs, and (ii) source of representation of the community distribution. The distinction between the three levels of study using the TI approach is a matter of level of resources used by the TI to develop his/her representation of the community distribution.

In modest (Level 1) studies, the TI utilizes the interpretations found in the published literature, supplemented by informal discussions with other researchers. For example, consider a site-specific PSHA for a bridge site in southeastern Illinois whereby the engineers are interested in evaluating the integrity of the structure when subjected to 500-year ground motions. The TI should review the literature for previous hazard studies that have been conducted in the area (e.g., the EPRI and LLNL studies, the national hazard map by the USGS, studies by the Illinois Department of Transportation, recent studies of seismicity in the New Madrid seismic zone, recent paleoseismic studies in the Wabash Valley, etc.) The goal in these reviews is to understand and, in turn, represent in the hazard analysis the present level of knowledge and uncertainty in the seismic environment of the bridge site. Peer review for a Level 1 study can be quite modest (say 10% to 20% of the total effort), but still serves the valuable function of providing review of the process followed and review of the data and interpretations.

Assuming that the study was a Level 2 study (which implies additional resources), the TI would communicate with the authors of published studies and other local experts who have expertise

in the region or in regional ground motions. The goal in these interactions would be to hear and understand the technical positions taken by various proponents of particular hypotheses. For example, the TI might probe the basis of interpretations taken by a paleoseismologist who is advocating the view that his data set in the Wabash Valley suggests that large-magnitude earthquakes strike the region on the average every 250 to 500 years. What is the basis for identifying the paleoearthquakes? What evidence suggests that these events are large? What are the uncertainties in the age estimates? What do others think about these data and conclusions? In the course of these exchanges, the TI would evaluate the viability and credibility of the various hypotheses with an eye toward capturing the range of interpretations, their credibilities, and uncertainties. In effect, the TI is acting as an "integrator" of the various interpretations and is attempting to provide an overall assessment that would represent the *informed scientific community's view* of the subject, if the community were to make such an assessment. This goal should be common to all Levels of PSHA, whether a Level 1 TI approach or a Level 4 TFI approach.

To complete the example, assume that the bridge in Illinois is the largest suspension bridge in the Midwest and that the issue of large-magnitude paleoearthquakes has been deemed by the U.S. Department of Transportation as a critical issue that must be addressed in order for the state to qualify for federal retrofit funds. In this case, the project sponsor/project leader may conclude that this issue is a degree "C" issue, following the categorization discussed previously. Further, he may chose to conduct a Level 3 study focusing on the paleoseismic issue, feeding into a Level 1 PSHA for the remaining issues. To conduct the Level 3 analysis, the TI would bring together the technical experts and proponents of various hypotheses for debate and interaction in, perhaps, one or more workshops. The TI would focus the debates in a way that would highlight the issues of most significance to the PSHA (e.g., indicators of the magnitude, location, and recurrence of paleoearthquakes). The TI would probe the viability of the arguments for and against the hypotheses and would attempt to encourage active interaction of the advocates of various technical positions. The result of this process would be a representation developed by the TI of the diversity of interpretations and their uncertainties.

A key aspect of the TI approach is the use of peer review to assure that the process followed was adequate and to ensure that the results provide a reasonable representation of the diversity of views of the technical community. Peer review has long been a cornerstone of quality assurance procedures for PSHA. Usually peer review is conducted in the final *late-stages* of the project and involves the review of draft and final project documents. In recent years, through large projects such as the Diablo Canyon Power Plant Long Term Seismic Program, DOE's New Production Reactor studies, and the Caltrans Seismic Hazard Evaluations for the San Francisco Bay Area bridges, the process of a *participatory* peer review has been developed and implemented. In this approach, the peer reviewers are actively involved in reviewing the project throughout its implementation. In this way, the peer reviewers are able to provide advice regarding changes in the course of the study as it evolves. They are thus in a better position to evaluate the process of the study and not just the final results. Of course, this entails some loss of independence of the reviewers (see Section 3.4 for a more detailed discussion of peer review).

In application, the TI approach has been most commonly applied to site-specific seismic hazard analyses, and less commonly to regional seismic hazard analyses. Often, site-specific analyses include site-specific data that have been developed with the particular purpose of evaluating the seismic hazard. For example, the PSHA for the Diablo Canyon Long Term Seismic Program and the PSHA for Rocky Flats DOE site both included geologic or geotechnical data gathered with the specific purpose of evaluating the site ground motions. Because of this focus on site-specific information, the TI approach has been well-suited to directly incorporating this information into the hazard analysis through a thorough review by the responsible TI. The TFI approach, which includes the assessments by

multiple experts, requires the review of all pertinent data sets by the multiple experts in order for them to make an informed assessment. The additional resources required to do so are usually not available and/or the project sponsor decides that value gained for the additional resources are not required for the particular project.

3.2.2 The TI Process

This section summarizes the recommended process that should be followed according to the TI process. The guidance provided here is general and is not elaborate. This reflects the fact that the TI approach has common application and is well-tested. Detailed guidance is provided for seismic source characterization and ground motions applications in Sections 4.4 and 5.6, respectively. In the following discussion, the steps of the process are presented with an assumption of a moderate-scale (Level 2) analysis. The reader can infer that a Level 1 analysis would involve lesser activity and a Level 3 analysis would involve additional activities, particularly with regard to the communication with experts within the technical community.

Step 1 Identify and select peer reviewers

The Project Leader, perhaps in conjunction with the Project Sponsor, is responsible for identifying and selecting peer reviewers. Selection criteria for the peer reviewers includes such attributes as the following:

- Earth scientist having a good professional reputation and widely recognized competence based on academic training and relevant experience.
- Understanding of the general problem area through experience collecting and analyzing research data for the same or comparable environments.
- Availability and willingness to participate as a named peer review panel member, including a commitment to devoting the necessary time and effort to the project.
- Personal attributes that include strong communication and interpersonal skills, flexibility and impartiality, and the ability to simplify and generalize.

Peer reviewers, particularly those involved in a "participatory peer review" (see Section 3.4), should be prepared to question and provide meaningful guidance to the Project Leader and the TI (or TFI) on both the process being followed and the technical substance of the project. The project should be conducted such that the peer reviewers will endorse the process and the substance of the project at its completion.

Step 2. Identify available information and design analyses and information retrieval methods

The TI is responsible for assembling all relevant technical data bases and other information important to the hazard analysis. This includes any site-specific data that may have been gathered specifically for the hazard analysis (e.g., geologic maps, results of fault studies, geotechnical properties of soils, etc.). The TI also identifies technical researchers and proponents that he/she intends to contact during the course of the study to gain insight into their positions and interpretations (in a Level 3 analysis, the TI identifies those individuals that he intends to assemble for discussions and interactions). In addition, the TI defines the procedures and methods that will be followed in conducting the hazard analysis.

Step 3. Perform analyses, accumulate information relevant to issue and develop representation of community distribution

This Step is the heart of the TI work. Specifically, the TI is responsible for understanding the entire spectrum of technical information that can be brought to bear on the issue at hand. This includes the written literature, recent work by other experts, and other technical sources. In advanced technical work, it is always the responsibility of the investigator to learn about the most recent advances in the field, often by direct contact with other experts via personal correspondence, personal meetings, telephone conversations, and so on. In a Level 3 study, members of the technical community are also brought together and the TI orchestrates interactions and, possibly, workshops to focus the discussions on the technical issues of most significance to the hazard and to be sure that he is aware of the diversity in interpretations for these key issues. The TI uses

all of this information to develop a community distribution of the range of uncertainty for the particular issues being addressed.

Step 4. Perform data diagnostics and respond to peer reviews

Interactive peer review during the analysis is very important. The TI can use the peer review team as a sounding board to learn whether the full range of technical views has been identified and assimilated into the project. If key aspects are difficult to resolve because different technical views exist among respected experts, the peer reviewers are vitally important. Peer review of the process depends on the type of peer review used (see Section 3.4). If participatory peer review is applicable, on-going review would occur after steps 2, 3, and 4 with appropriate response to the reviews.

The fact that experts are not brought into the process in a formal sense, as in the TFI approach, means that the TFI guidance on "expert buy-in" does not apply directly. However, it does apply indirectly, and that aspect of the TFI guidance should be studied (subsection 3.3). Specifically, if the TI develops a controversial interpretation that represents an integration of diverse technical views of differing experts, it is very important that an attempt be made to obtain the views of the specific advocates of the various technical positions involved. The peer reviewers can verify that this contact has been fulfilled and that the various interpretations are properly represented. In SSHAC's opinion, if these experts can "buy into" the process that the TI has used to integrate the different views, the credibility of the ultimate result of the TI's effort will be significantly strengthened.

A variety of sensitivity analyses should be carried out and shared with the peer reviewers to understand the most significant issues, sources of uncertainty, and data sets used to address the issues.

Step 5. Document process and results

This step is vital to an understanding of the study by third parties. Although relatively straightforward, it is important to emphasize that the TI be attentive to the documentation guidance in Chapter 7.

3.3 The Technical Facilitator/Integrator (TFI) Approach

3.3.1 Introduction

In a significant enhancement to current practice, we introduce the concept of the Technical Facilitator/Integrator (TFI). The TFI is a single entity who has the responsibility and is empowered to represent the composite state of information regarding a technical issue of the scientific community. In the TFI process, the selected experts act, not as proponents of one specific viewpoint, but as informed *evaluators* of a range of hypotheses and models. Separately, the experts on the panel also play the role of *integrators*, providing advice to the TFI on the appropriate representation of the composite position of the community as a whole.

The TFI process is centered on the precept of thorough and well-documented expert interaction as the principal mechanism for integration. Much of the "work" in the TFI process occurs in the context of face-to-face expert information and viewpoint exchanges that take place over a series of carefully structured meetings and workshops.

In contrast with the classical role of experts on a panel as individuals providing inputs to a separate aggregation process, the panel is viewed as a team, with the TFI as team leader, working together to arrive at, first, a composite representation of the knowledge of the group and, second, a composite representation of the knowledge of the community at large (these representations may or may not reflect panel consensus). The process is transparent to the experts at all stages in contrast with previous PSHA studies in which some experts have complained that the aggregation process was a "black box."

The TFI conducts individual elicitations and group interactions, and with the help of the experts themselves, integrates data, models, and interpretations to arrive at the final product—a

full probabilistic characterization of seismic hazard. Together with the experts, the TFI "owns" the study and defends it as appropriate.

The TFI is a special role that only comes into play in a Level 4 analysis in which an issue is complex and controversial enough to warrant the challenge and expense of a suite of multiple integrators. The advantages of bringing increased wisdom and experience to bear on a difficult problem come at the cost of having to aggregate, or in some way represent, the judgments of a set of diverse experts—a problem that has been a source of major difficulty in past PSHA projects. On future projects that warrant Level 4 analyses, the TFI process described below offers some new and unique advantages over previous PSHA multiple-expert processes.

The distinction between the novel roles of experts as evaluators and integrators and the traditional role of experts as proponents of a particular scientific point of view is fundamental to the TFI process and is not well-defined in current multiple-expert use literature and applications. The TFI methodology does rely heavily, however, on relevant published decision science research, and incorporates our best understanding of state-of-the-art methods for eliciting and aggregating expert judgments. Moreover, the TFI concept is based on a detailed review of the problems and issues of past studies, particularly the large EPRI and LLNL PSHA studies of the late 1980's and early 1990's (discussed in Section 3.3.2.2 below).

The remainder of this section focuses on two unique TFI roles: 1) the TFI as a Technical Facilitator who structures and guides the interaction of a panel of experts, each of whom evaluates the full range of models and interpretations, supported by expert proponents who explain and defend specific models and interpretations, and 2) the TFI as a responsible integrator whose objective is to develop a composite characterization for the expert community based on the panel's inputs. The TFI Integrator role is not that of a "super-expert" who has the final say on the weighting of the relative merits of a set of (proponent) models and positions; rather, the TFI attempts to characterize both the commonality and diversity in the set of panel estimates, each of which may itself represent a weighted combination of proponent models and positions. The TFI can be viewed as performing an integration assisted by a group of experts who provide integration advice.

TFI Responsibilities

In carrying out the two roles, the TFI conducts a systematic process, which entails a number of specific responsibilities:

- **Facilitator** —structures and documents full information, data and judgment exchange; stages effective, professional face-to-face debates and interactions in critical areas; ensures that the group identifies all strengths and weaknesses of key data and modeling approaches; elicits formal evaluations from each expert; creates conditions that enable a direct, non-controversial integration of the experts' judgments.
- **Integrator** —develops a final composite assessment (in explicit probability distributions that can be incorporated in the PSHA calculations); explains and defends this assessment before the panel; obtains feedback and concurrence (to the maximum degree possible); explains and defends the composite representation to the outside, i.e., to other experts, the peer reviewers, and all interested parties (e.g., policy makers and regulators).

It is clear that the TFI must have the stature and expertise to deal authoritatively with the multiplicity of disciplines and individuals. It is doubtful that one individual can be identified who will possess all of the qualities required of a TFI. It is more reasonable to anticipate that the TFI will consist of a small group of individuals, typically, two or three. At least one individual should have "substantive" knowledge of the subject matter, e.g., seismic source characterization or ground motion modeling; as a "specialist," he or she should be at least as qualified as the members of the panel on the technical issues. Another role (often another individual) will be that of a "PSHA expert" who knows how PSHA works and how the experts' inputs might affect the final results. One of the

substantive experts must be comfortable in the role of group facilitator (defined below). Finally, one member of the TFI team should be an "elicitation" expert (sometimes called a "normative" expert), i.e., an expert on individual- and multiple-expert elicitation processes, as well as in decision analysis and probability theory, especially on methods for processing evidence.

Goals of the TFI Process

In applications and presentations of the TFI process, observers have often asked the following questions:

> Does the TFI process always result in a consensus among experts?
>
> If not, are the expert judgments equally weighted?
>
> If, for some reason, the expert judgments aren't equally weighted, then what?
>
> Who chooses the weights and how?

These questions are natural because most if not all existing multiple-expert processes have a single objective, such as "achieve consensus," or, "elicit and then equally weight individual judgments," or, "have the principal investigator choose the best judgment or even the best model."

In contrast, the TFI process does not operate with a single preset objective but rather proceeds through a pushdown list of objectives, attempting to achieve the simplest, least controversial end state possible. In designing the TFI process, we recognized that the answer to each question depends critically on the objectives of the exercise and on the specific issue being addressed. For example, while consensus and equal weights are highly desirable, they are only appropriate under certain conditions (described below). However, these conditions can be controlled and SSHAC believes that equal weights, at least, can usually be attained with sufficiently structured intensive expert interaction. Also, we shall describe different types of consensus, each of which has an *a priori* different likelihood of being achievable.

Notice carefully that each expert, as in Level 3, documents and takes technical responsibility for his or her personal interpretation. The TFI is ultimately responsible for ("owns") the composite representation of the expert community, which is based on the individual expert evaluations as well as the expert-as-integrators estimates of the community distribution. The TFI is responsible for documenting and defending how the composite representation was developed, be it by equal weighting of the individual expert estimates of the community distribution or, if necessary, by means more appropriate to the particular circumstances.

Thus, rather than pre-specifying the outcome of the integration process, the TFI as Facilitator structures interaction among the experts to create conditions under which the TFI's job as Integrator will be easy (e.g., either a consensus representation is formed or equal weights are appropriate). In the rare case in which simple integration is not appropriate, additional guidance is provided.

Expert Roles

Title	**Individual Evaluator**	**Integrator**	**Proponent**	**Resource Expert**
Product	Individual Interpretation	Estimate of Community Distribution	Presentation of a Model	TFI Assistance

Reader's Guide

The TFI process includes four separate expert roles. As previewed above, the two primary roles for panel members are "Evaluator" and "Integrator," but both panel and non-panel member experts will, on occasion, be asked to play the role of "Proponent," and an important non-panel member expert role is that of "Resource Expert" who assists the TFI in a number of important activities (described below). To assist the reader, the table below summarizes these roles and their products:

The remainder of 3.3 and its companion Appendix J are written at two levels with some intentional redundancy. The first three subsections provide a basic understanding of the TFI process and its rationale. They are organized as follows:

3.3.2 Historical Context and Motivation for TFI Approach

- 3.3.2.1 General Approaches to Expert Use
- 3.3.2.2 Historical PSHA Approaches to Expert Use —Lessons Learned

3.3.3 Underlying Logic of TFI Process

3.3.4 TFI Elicitation Process

An important adjunct to this section, Appendix J, provides additional guidance, including background on the principles underlying the TFI process and presentation of a set of specific implementation tips and traps. It is organized as follows:

Appendix J. Guidance on TFI Principles and Procedures

- Section 1. Guidance on Historical Approaches to Expert Use
- Section 2. Guidance on Facilitation
- Section 3. Guidance on Integration
- Section 4. Guidance on the Two-Stage Elicitation Process

Appendix J's additional guidance is written at a more technical level and is "must reading" for potential TFI's who need detailed how-to-do-it instructions, and for expert-aggregation specialists who wish to delve more deeply into the expert-aggregation issues underlying the TFI approach.

3.3.2 Historical Context

To place the TFI approach in perspective, it is useful to review existing approaches to the use-of-experts problem. We start with a brief overview of general schemes and then focus on previous PSHA studies, highlighting some of the lessons learned that led to the TFI approach. This section is a condensed version of Section 1 of Appendix J, which goes into greater depth and includes specific references to related work.

3.3.2.1 General Expert Use Approaches

Historically, two basic types of expert use processes have been used in general practice, mostly focusing on the problem of aggregating the judgments of multiple experts:

- Mathematical Schemes, in which expert inputs are combined using a mathematical formula, and
- Behavioral Schemes, in which aggregation is accomplished through consensus building or some type of qualitative judgment by an individual or negotiated group decision

A great variety of mathematical schemes have been proposed and reviewed in the decision science literature, ranging from linear and logarithmic opinion pools, equal and non-equal weights on expert probability distributions, weights on the parameter values of underlying probability distributions, and Bayesian models (references are provided in Section 1 of Appendix J). Most behavioral schemes are centered around some type of group facilitation process in which the group, through either structured or unstructured interaction, is given the objective of reaching complete agreement on some technical issue.

Mathematical aggregation has several advantages. The logic is transparent and completely checkable. Combination formulas can isolate and separate specific assessments of dependence, expertise, and overlap, so that sensitivity studies

are straightforward. Unfortunately, given the current state of the art, there are several substantial disadvantages to mathematical aggregation. Mathematical models are not advanced enough to include all the factors that are important.

Classic consensus-building processes are usually designed to encourage a group to reach consensus on a technical issue, such as the best estimate of median ground motion for a region or the annual frequency of characteristic magnitudes for a fault. The major advantage of this type of scheme is that, if the information exchange is full and unbiased, and if the result truly reflects each expert's state of information, then the consensus result is appropriate, credible and non-controversial. Unfortunately, there are several problems with such methods. The overriding concern is whether the result is a true consensus that accurately reflects the diversity of education, experience and reasoning within a group, or whether it is more the result of negotiation and strong personalities. There is also the risk of understating the appropriate range of uncertainty by suppressing discussion of differences and focusing on points of agreement.

Should consensus on a technical issue be an objective? In theory, where there is substantial uncertainty, this type of consensus should rarely occur. In practice, technical consensus is better viewed as a convenient result, not as an objective. For example, in the SSHAC ground-motion workshops, the experts, even after thorough group interaction, had diverse judgments about which ground-motion model they would use if they had to use only one (for a given magnitude, distance and frequency). However, when asked to assign weights to the range of models, the weighting schemes were remarkably similar.

SSHAC believes that it is very important, whatever process is used, not to force unwarranted technical consensus that appears to be agreement but that does not reflect the state of information of any single reasonable individual. The SSHAC process is oriented towards potential consensus of a very different sort, that is, consensus on the best composite representation of the knowledge of the scientific community.

3.3.2.2 Historical PSHA Approaches to Expert Use —Lessons Learned

In seismic hazard analysis, both mathematical and behavioral schemes have been used. The analysts typically decide at which level aggregation will take place (e.g., at the ground motion prediction level and/or at the overall seismic hazard level) and they employ mathematical combination formulas, either explicitly (e.g., equal or unequal weights on expert probability distributions), or implicitly (e.g., Monte Carlo sampling, implying equal weights, perhaps after removing an outlier, implying a zero weight).

Motivation for TFI Approach

The previous PSHA exercises most relevant to the multi-expert situation were the large EPRI and LLNL studies (Chapter 5 on Ground Motion describes relevant aspects of these studies). SSHAC was fortunate to have the extensive cooperation of project leaders and participants in both studies. They openly and willingly discussed the strengths and weaknesses of those projects; indeed, many of the key EPRI and LLNL participants made substantial contributions to this report. The successful ideas from these projects and other sources, such as (Otway and von Winterfeldt 1992); (Meyer and Booker 1991), (Cooke 1991) and (DeWispelare, Herre, Miklas and Clemen 1993), provided much of the foundation for the SSHAC TFI approach. However, detailed analysis of the previous studies also pointed to some areas for potential improvement, which led directly to the TFI concept:

- Overly Diffused Responsibility Previous studies sometimes lacked a well-defined single entity, responsible for the composite results. Responsibility was typically diffused over a large group of experts, analysts and stakeholders in a nebulous way. In contrast, the TFI has explicit overall responsibility for the final PSHA product. In all cases, of course, the individual experts are responsible for their own interpretations and evaluations.
- Insufficient Face-to-Face Expert Interaction Previous PSHA studies have sometimes not involved sufficient, nor sufficiently

structured, expert interaction. While experts were queried and interviewed, there was insufficient time for intensive face-to-face technical interaction among experts, and little opportunity for structured technical discussions to clarify issues, challenge and defend positions, and resolve unintended differences. Past projects demonstrate that the experts' limited experience with probabilistic models and statistics requires a strong facilitator to probe into technical details to avoid unintentional characterizations of expert interpretations, and also to detect and correct an expert who is acting as a proponent rather than an objective evaluator.

In the EPRI and LLNL studies, some experts felt dissociated from the final results. SSHAC's workshops confirmed that emphasis on expert interaction as the principal mechanism for integration helps to ensure that both the panel and the TFI feel "ownership" of the composite results —all major agreements and disagreements are represented explicitly.

- Inflexible Aggregation Schemes Previous PSHA studies (as well as most other major studies employing multiple-expert elicitation) have generally not taken sufficient advantage of state-of-the-art concepts and principles from the fields of expert elicitation and aggregation. For example, most PSHA studies have made *a priori* decisions to apply equal weights to multiple-expert judgments. As we shall discuss below, equal weights are both desirable and often appropriate, but only if the expert-interaction process is carefully designed to ensure appropriate conditions for equal weights, and only if a careful check is made after the interaction to ensure that these conditions have been met (in some prior studies, the conditions for equal weights were clearly not met). Although there are no universal algorithms or recipes for aggregating judgments, SSHAC's recommended process incorporates key principles from the large body of helpful research and practice in expert aggregation into guidelines for the TFI.

- Imprecise or Overly Narrow Objectives Previous PSHA studies (and, again, virtually all previous multiple-expert studies) have generally not distinguished well between the ultimate objective of a composite representation of the panel itself and a composite representation of the expert community as a whole. This distinction can be crucial with respect to important issues, such as how to deal with panel experts with outlier opinions. Fortuitously, representing the overall community is not only a more desirable objective, but is actually more likely to be an achievable one.

- Outlier Experts Previous PSHA and multiple-expert studies have dealt awkwardly or not at all with the contentious issue of "outlier experts," experts who make interpretations that are significantly different than the those of the rest of the panel and that are not well supported by logic or data. Treatment of outlier experts can have a major impact on the final hazard distribution; indeed, this issue was a primary motivation for the TFI process.

- Insufficient Feedback Following the elicitation of expert judgments—but prior to finalization of the assessments—the experts should be presented with the results of their evaluations. This feedback is in the form of the calculated final results, interim results, and numerous sensitivity analyses. As an example of past problems, it has been shown in some studies that the assessment of earthquake recurrence parameters (a and b-values) without feedback can lead to problems. This is because, in addition to uncertainties in the values of the two parameters individually, the parameters are usually correlated with each other and this correlation needs to be specified (e.g., the probability that high values of a should occur with high values of b). Feedback could include the range of recurrence curves derived from the assessment of a and b-values and derived recurrence intervals for particular magnitudes.

3.3.3 Underlying Logic of TFI Process

We summarize here the basic structure of the basic TFI process. Figure 3.1 provides a "roadmap" for the process logic. Reading left to right, the tree indicates increasingly less desirable final process outcomes. Paths with an arrowhead indicate desirable (and expected) process outcomes. The TFI's job is to organize a process that will exit the tree at the earliest possible point, while at the same time making sure that this is a legitimate stopping point.

The TFI's Fundamental Objective

To understand the "tree" TFI process and its potential outcomes, it is essential to understand the unique objective of the SSHAC process: that is, to use the panel to represent the overall scientific community's state of knowledge. The underlying premise is that the primary objective for public policy making is not capturing the judgment of any individual expert (including the TFI), nor even capturing the composite judgment of any specific subset of experts (including the panel), but rather, capturing as best possible the composite judgment of the overall scientific community of informed experts. Characterizing the panel's own knowledge is an essential intermediate goal, but not the final product.

Of course, it is impractical to engage an entire scientific community (often hundreds or even thousands of scientists for a given issue) in any meaningful interactive process. Decision makers must always rely on a smaller, but representative, set of experts. Thus, the panel is viewed as a sample of the overall expert community.

Section 3.3.4 describes a two-stage elicitation process in which the panel members are asked in Stage I to represent their own positions as independent evaluators of data, models and interpretations (the traditional role of a scientist); and in Stage II, to play the role of integrators who attempt to represent the composite position of the community as a whole. This two-role distinction may appear subtle at first, but it has important practical implications for the process outcomes.

The following discussion is organized around the tree in Figure 3-1. In describing the possible process outcomes, we highlight some especially useful working principles for the TFI to apply at each stage; the reader should be aware, however, that in application, the TFI can "mix and match" the principles throughout the process. Also, these and other process guidelines are described in more detail in Section 2 of Appendix J.

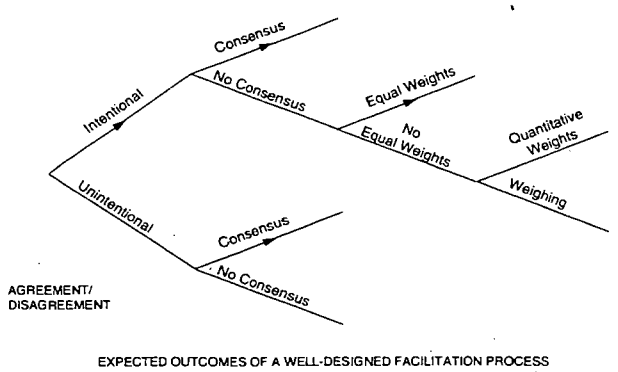

Figure 3-1 TFI Process Logic

Outcome 1: Consensus

The most desirable end state is consensus among the expert panel, but only if the experts truly agree after a full and intensive information exchange and interaction. There are two equally inappropriate outcomes the TFI must avoid: 1) the group achieving an artificial consensus that is not real (unintentional agreement) and 2) the group appearing to have substantial disagreements that are caused only by semantics and confusion rather than by substantive scientific differences (unintentional disagreement).

Types of Consensus

A key question we must address before proceeding is, "Consensus on what?" Consider the following possible types of consensus:

<u>Consensus Type 1</u>:

> Each expert believes in the same deterministic model or the same value for a variable or model parameter.

This could reflect agreement on a scalar parameter like the speed of light or density of the earth's crust, or agreement on a deterministic model and its parameters (e.g., ground motion attenuation as a function of distance), or sometimes just agreement on a functional form

(e.g., the attenuation curve is logarithmic). Importantly, this could reflect agreement within practical limits such that the final hazard distribution is insensitive to differences. This type of technical consensus represents the common use and meaning of the word, but is often an artificial objective and difficult to achieve.

Consensus Type 2:

> Each expert believes in the same probability distribution for an uncertain variable or model parameter.

This could reflect agreement about a probability judgment, the probability distribution resulting from a single model, or agreement on appropriate weights for a range of probabilistic models or positions. This type of technical consensus is also difficult to reach, but may be achievable for some issues after removal of unintentional differences by an appropriately facilitated TFI process (see below).

Consensus Type 3:

> All experts agree that a particular composite probability distribution represents them as a group.

Note that a group may agree on their composite representation, even if individuals have different positions. This type of consensus is generally easier to achieve than Types 1 and 2, especially if the experts recognize that substantial diversity among individual panel estimates tends to imply a wide range of overall uncertainty.

Consensus Type 4:

> All experts agree that a particular composite probability distribution represents the overall scientific community.

SSHAC seeks Type 4 consensus, which is potentially the easiest type of consensus to achieve. In the process of seeking Type 4 consensus, a useful intermediate step is to seek Type 3 consensus.

There is reason to be far more optimistic that the TFI process can achieve legitimate Type 3 or 4 representational consensus than one would be for an expert panel to achieve more traditional Type 1 or 2 technical consensus. In the TFI process, the issue is not consensus on scientific issues, which is almost impossible to achieve; acting as integrators, the experts only have to agree on the appropriate composite representation of the overall scientific community. As demonstrated in the SSHAC workshops, it is far easier for a group of experts—when they have legitimate scientific disagreements—to agree on how to represent the informed community's legitimate diversity of opinion about a seismicity or ground motion issue, than it is for the experts to agree on specific technical issues.

Here are some process principles especially useful in the early stages of the TFI process:

Experts as Evaluators, not Proponents Viewing the experts as evaluators (Stage I) who provide both interpretations of a range of data and models for the TFI is an attractive alternative compared to viewing the experts as proponents, advocating their own models or assessments. Although the TFI might sometimes ask a panel expert to act temporarily as a proponent, this is solely for the purpose of explaining a particular model, not for the purpose of creating a permanent advocate.

Emphasis on Expert Interaction The TFI must conduct structured, facilitated discussions among the panel experts in which the focus is on underlying models and hypotheses, not on individual experts. The process evolves in stages, and in each stage there are intensive group interactions preceded and succeeded by TFI interaction with individual experts. Guidelines for how to conduct this interaction were developed and tested in the two SSHAC ground motion workshops (these are documented in Chapter 5 and Appendices A and B).

Isolate Sources of Disagreements Experts may disagree: about underlying scientific hypotheses and principles; about interpretations of different available data sets; about the values of model parameters; and, even with agreement on models, data and parameter values, about the ranges of the epistemic uncertainties that affect seismic hazard. Paradoxically, isolating and focusing discussion about the different potential types of disagreement

may actually move the group toward agreement on scientific issues. In the SSHAC workshops, the process of isolating sources of disagreement uncovered many common points of agreement and revealed a number of points of unintended disagreement. One participant remarked at the end, "It is astonishing how much everyone now agrees."

Active Listening A useful facilitation model is the concept of "active listening," in which a person's reasoning is not considered fully understood unless each listener, whether or not they agree with the reasoning, can explain it back to the person who made the point. It is extremely important for the TFI to summarize points of agreement and disagreement, encouraging active listening and frequently playing back a clear summary of the conversation during the meeting.

Tone of the Interaction It is critical for the TFI as a facilitator to set the right tone. Two elements are critical: first, establish that the purpose is not to choose the best model or answer. The TFI concept is founded on the premise that there is no one correct model or answer, no single "winner" or "loser." Second, the purpose is not to achieve consensus (of any type, but especially Types 1 and 2). Consensus may occur, but it is important psychologically for the participants not to feel that the process is failing if everyone does not agree.

Outcome 2: Equal Weights

When the panel members do not share the same composite representation of the community, the TFI must define the composite distribution. The TFI is neither constrained to use any fixed aggregation formula nor, in particular, to weight all expert inputs equally. Nevertheless, equal weighting has significant advantages and the TFI process is explicitly designed to create conditions under which equal weights will be appropriate. The attraction of equally weighting expert judgments is that it avoids at least two extremely difficult issues. First, one need not make what can be a very charged—and difficult to defend in the regulatory arena —judgment (Who is the best expert?), and second, one need not make what can be very difficult assessments (If not equal weights, what?)

It is essential for the TFI to understand clearly when equal weights are appropriate and when they are not. As we shall discuss, intensive interaction is perhaps the most effective way to create conditions under which equal weights are appropriate. In past seismic hazard and other public policy studies, equal weights were often used without this intensive interaction and without careful analysis of whether equal weights were appropriate. This can be dangerous in the seismic hazard arena: because of the logarithmic nature of key components of the seismic hazard calculation, equally weighting an indefensibly high probability given by one outlier expert can (as it has in some studies) swamp out the impact of all the other experts. The result is an answer that no one, not even the outlying expert, believes is representative of the overall community.

In the classic expert-use problem (see Appendix J for details), there are two fundamental conditions that must hold for equal weighting to be appropriate: first, the experts must either be completely independent —i.e., rely on independent data bases and models (this is virtually impossible), or be equally interdependent (expert dependence is more carefully defined in Appendix J). By exposing the expert panel to all models and data bases, the TFI process encourages equal interdependence. Second, the experts must be equally credible. In the TFI process, experts are methodically screened for their ability to be excellent scientific evaluators (see Section 3.3.4 for details on panel selection).

The Committee's methodological goal of representing the state of knowledge of the overall community of experts imposes another important condition that must be satisfied for equal weights to be appropriate. A set of n equally weighted experts, in order to represent the informed diversity in the whole community, must reflect an unbiased sample of the overall expert population. If, for example, an expert evaluator insists on giving weight to only one model, thereby acting as a proponent rather than an informed evaluator, giving that expert equal weight among the n experts overrepresents the strength of his or her position in the community. To understand this,

suppose that the group could be expanded to the size of the entire community by adding (n-1) new experts (i.e., the size of the community is (2n-1)). Then, the proponent would still be the only one holding his or her position, and weighting the experts equally would result in the appropriate weight for this position of 1/(2n-1). On the other hand, assuming that the (n-1) original representative expert positions are replicated by the new experts, equally weighting the non-proponent experts results in a weight of 2/(2n-1) for each of the unbiased positions, twice that of the proponent's weight. (Note that changing an individual expert's weight from 1/n may or may not change the composite representation significantly depending on how strongly hazard estimates based on his or her position deviate from the hazard estimate based on the composite distribution of the other n-1 experts.) Outlier experts are discussed further below.

Panel Selection and Removal For a Level 4 study, it is critically important to select a diverse group of experts, large enough to ensure that all credible points of view are represented, including all fundamental interpretations and modeling approaches. Using equal weights implicitly assumes that each expert is "standing in" for a much larger community of equally qualified experts. Thus, it is important that the set of experts be capable of representing the overall expert community as a whole.

Two of the most serious practical problems occur 1) when a expert behaves as a proponent, rather than an evaluator and 2) when an expert is not prepared and in some way does not live up to his or her professional time and work commitments. Careful panel selection using explicit selection criteria will greatly reduce the chance of encountering these problems. Nevertheless, SSHAC also recommends strongly that the TFI develop and discuss in advance with the panel formal criteria for dropping members from the panel (see Section 3.3.4 for more details). In the event of a problem, a determination is made by the TFI in close consultation and with the support of the overall panel.

Structure before numbers The focus in initial interactions should be on the logic of different basic approaches, rather than on variations of the same approach. There should be more dialogue at the level of structure than at the level of numbers. This avoids disagreement over small numerical issues local to the specific panel, and focuses on community—level issues that matter. As the interaction evolves, numbers become increasingly useful to the extent that they show how different modeling approaches work over ranges of applications and data and how much disagreements matter. A related lesson from the SSHAC workshops is that it is crucial to investigate early issues involving data underlying a model or its parameter values in order for the group to understand well the different model results and expert positions.

Sensitivity Analysis There is no reason to down-weight an expert's composite representation if the final answer is insensitive to the weight given to his or her position. If the expert's answer is not dramatically different than the average of the other positions, or if it results in a lower-than-average hazard probability (the hazard calculation is logarithmic), then it will likely not have an appreciable effect on the overall hazard calculation, especially the mean hazard curve. In this case, even if the TFI feels an expert's position is "over-represented" by an equal weight, it is not worth the time, energy and possible controversy involved to down-weight that expert.

Outcome 3: Explicit Quantitative Weights

In any practical project, the number of experts (call it "n") is small relative to the larger population of equally qualified experts. If the TFI believes that if the panel were expanded to the size of the overall community, an expert's position would not be representative of 1/n of the community, then to give that expert's position weight 1/n would misrepresent the diversity in the overall community. In this case, unequal weighting may be appropriate. The situation need not be contentious and should be viewed as primarily a process issue. The relevant question is, "Is the expert's position, which is already a weighted combination of models, representative?" not the more personally threatening question, "Is the expert's scientific position correct?" The Committee believes that in the rare case in which

the representativeness issue arises, the expert should be given every opportunity to defend his or her position as being representative to the other experts and peer reviewers (especially participatory peer reviewers).

The issue of unequal weights is, of course, pertinent to the individual experts who will almost certainly want to give different weights to different models. In this case, the expert aggregation literature has some useful guidelines the TFI can pass on to the experts for how to determine these weights (Appendix J).

Outlier Experts The issue of outlier experts has been especially contentious in past multiple-expert studies and deserves extra attention here. For our purposes, an outlier expert is defined by two conditions: a) he or she makes an interpretation far different than the rest of the panel and b) the expert cannot support the interpretation with solid data or reasoning (from the points of view of the TFI and the other panel members). A past PSHA study provided an example of an expert who attached probability of unity to Modified Mercalli Intensity (MMI) XII earthquakes throughout the Northwestern U.S. If the objective were limited to developing a composite representation of, say, a five-person panel, then the TFI is in a logical "trap" since the outlier expert does, in fact, represent 1/5 of the panel. Moreover, the outlier expert was selected carefully as being *a priori* as equally qualified as the other experts. Common sense says that the MMI XII expert should be down-weighted, but how can this be justified after the fact without superimposing the TFI's own scientific judgment on the process?

The perspective of developing a composite representation of the overall community of scientists affords a way out of the logical trap. When asked to identify other supportive experts, the outlier may even agree that he or she is the only one out of a hundred seismicity experts who would attach significant probability to a MMI XII earthquake. To represent the overall community, if we wish to treat the outlier's opinion as equally credible to the other panelists, we might properly assign a weight of 1/100 to his or her position, not 1/5.

Expert Aggregation Checklist Section 3 of Appendix J reviews a set of basic issues relevant to both expert aggregation (directly relevant to the TFI) and model aggregation (relevant to the TFI in guiding the experts as evaluators). The TFI should be aware of and carefully consider each aggregation issue at each stage of the process before final decisions are made concerning issues like equal or non-equal weights.

Outcome 4: "Weighing" rather than "Weighting"

Rarely, even after extensive interaction, will a situation call for some type of asymmetric treatment of expert-as-integrator representations. More commonly (but still relatively rare), the experts themselves, in their role as evaluators of models or proponent positions, may find simple fixed numerical weights to be inadequate. An example is in the ground motion arena in which many experts believe that the weights on different models should be a function of magnitude, frequency and distance (see the Ground Motion appendices). But there are even rarer situations in which explicit model weighting of any type is artificial, in which case an expert must "weigh" alternative models in a more general sense. A simple example will help to explain this concept. Two proponents have provided a TFI with their probability distributions on a scalar quantity y. These cumulative distribution functions (CDFs) are shown in Figure 3-2. The experts A and B have also supplied the reasoning (qualitative arguments) underlying their CDFs. If the TFI is constrained to use equal weights, he or she will do what the NUREG-1150 methodology required (Hora and Iman 1989) and will produce the curve labeled EW. For each value of y, the EW ordinate is one-half the sum of the ordinates of the curves A and B. The qualitative arguments that the experts have supplied play no role in this aggregation scheme, except, perhaps, to give legitimacy to the individual distributions.

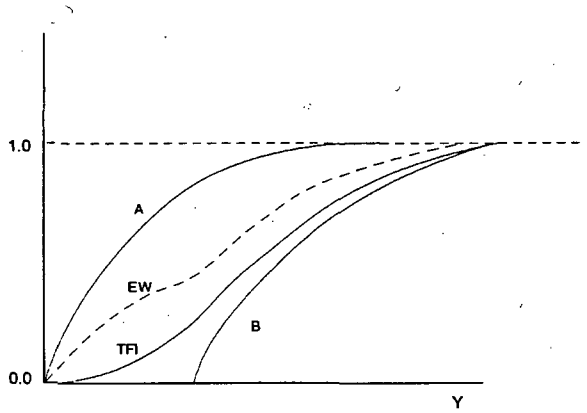

Figure 3-2 An Example of Behavioral Aggregation

Suppose now that the TFI studies these arguments carefully and finds that the reason why the two curves differ is the disputed applicability of a piece of evidence: Expert A believes that this evidence is convincing, while Expert B believes that it is not relevant. The experts are fully aware of this disagreement, and have discussed each other's rationales, but they are not willing to change their curves. Let us further assume that the TFI reaches the conclusion, based on the experts' interpretations, that the disputed evidence is most likely irrelevant at very low values of y, but cannot be completely dismissed for moderate values. The TFI, therefore, produces the curve labeled "TFI" to reflect this state of knowledge. This curve is presented to the experts and their subsequent arguments are evaluated by the TFI who may adjust the composite curve to reflect this feedback. Finally, the TFI reports the composite curve and the reasons that have led to its derivation (which, of course, includes reporting the individual curves and arguments, so that others may judge the validity of the whole exercise). This concept is consistent with Kaplan's idea of a "skillful user" (Kaplan 1992). It is easy to see why requiring the TFI to use explicit weights for this aggregation scheme would be artificial. Furthermore, this approach can mitigate contention based on different parties' complaints that their positions were not understood, because the explicit issues will have been explained and the TFI's reasoning documented, so that discussions on the merits can occur in an open context.

The Committee believes that while a "weighting" approach is not required of TFI's or TI's, explicit equal or unequal numerical weighting is highly desirable (if feasible) for several reasons: 1) Explicit weighting provides a decomposition in which different evaluations can be explicitly compared, 2) requiring explicit weights from experts tends to lower the possibility of eliciting extreme non-defensible opinions, and 3) there are probabilistic models (see Appendix J), albeit simplified, that provide theoretical underpinnings to the weighting process (as applied to either experts or models).

3.3.4 The TFI Process

We describe below a seven-step process for the TFI to follow to bring a multiple-expert project from problem definition to a successful conclusion. The seven steps are rather traditional, but some important novel aspects of the implementation are specific to the TFI process.

In particular, the goal of forming a composite representation of the scientific community suggests a natural two-stage elicitation procedure. We review this first because it provides useful context for not only the elicitation step, but for the expert selection, training, and aggregation steps as well.

Two-Stage Elicitation Procedure

A useful conceptual model of the expert panel is that it is an informed, independently-thinking sample of n evaluators who are representing a much larger community of N similarly informed evaluators (more precisely, representing the community's position if all in the community were equally informed, where "informed" includes a full understanding of relevant site - specific details). The TFI's problem is to collect information from the size n sample ($n < N$) in order to estimate the characteristics of the larger size N population. In many ways this is a classical problem in statistics, and many statistical insights apply directly. Section 4 of Appendix J presents a simplified mathematical version of this conceptual model.

The conceptual model suggests a two-stage process in which the expert panel members play two distinct roles. Here we highlight the elicitation process for each role. Appendix J provides for each stage a specific suggested list of the estimates and probability assessments required of the experts. Appendices A and B provide implementation details in the context of the two SSHAC ground-motion workshops.

Stage I Panelists as Independent, Informed Evaluators, Representing Themselves

Typically, the objects of a given elicitation are the parameters of an aleatory model, such as the mean rate or rupture velocity during an event or the median ground motion for a given distance and magnitude or even the (aleatory) standard deviation of the ground motion. The experts are asked to provide two types of assessments:

a) Each expert provides his or her best estimate (e.g., mean value). This is based on an evaluation of the full range of models, evidence, data and proponent positions in the community. The assessments are performed in the context of thorough facilitated interaction (including sharing of all relevant local or site-specific information) as described in Step 6 (analysis, aggregation, and resolution of disagreements).

b) Each expert assesses his or her epistemic uncertainty in the mean estimate. This is also based on thorough interaction; in particular, each expert is exposed to the full range of other panel-member estimates, which should often lead to appropriately wide distributions if there is substantial disagreement.

If the TFI's goal were to represent the panel's composite knowledge, the elicitation would stop here (after sufficient interaction, iteration, etc.). In fact, it is useful at this stage to construct an initial composite representation of the panel, but this is an intermediate product. A second stage builds additional information useful for extrapolating from the panel to the overall scientific community.

Stage II Panelists as Integrators, Representing the Overall Expert Community

In this stage, the panelists act as integrators (see Section 3.2), providing two types of assessments, based in large measure on what they learned from first-stage interactions with the other panel members:

a) Each expert provides an estimate of what the composite mean of the entire informed community would be; that is, assuming that an extensive elicitation were performed in which the community were provided the same information base and opportunity for interaction as the panel itself.

b) Each expert assesses an estimate of what the composite uncertainty in the community would be if an extensive elicitation were performed.

The Stage II assessments provide the TFI with information a) about each expert's judgment about how well his or her individual interpretation represents the overall community (it is entirely reasonable for a expert to say, "I recognize and can defend that my estimate is lower than the community average"), and b) about whether the panel believes its composite judgment is biased relative to the overall community.

The Stage II elicitation, since it is based largely on information generated in Stage I, should consume substantially less resources and time than the Stage I elicitation.

Seven-Step Process

The TFI must be involved in all aspects of a multiple-expert project in order to be able to take responsibility for the final product and to ensure that the involved experts take intellectual responsibility for the results. Based on their NUREG-1150 experience, Keeney & von Winterfeldt (1991) describe a seven-step process:

Step 1 Identification and selection of the technical questions

Step 2 Identification and selection of the experts

Step 3 Discussion and refinement of the issues

Step 4 Training for elicitation

Step 5 Group interaction and individual elicitation

Step 6 Analysis, aggregation, and resolution of disagreements

Step 7 Documentation and communication

Step 5 in Keeney and Winterfeldt's process was labeled "Elicitation." We have generalized the step to accommodate our special focus on group interaction.

Most of the discussion in the literature on multiple-expert applications, e.g., in Otway and von Winterfeldt (1992); Meyer and Booker (1991) and Cooke (1991), can be accommodated by this list of seven steps. In a project similar in spirit to the SSHAC project, DeWispelare and others (DeWispelare, Herre, Miklas and Clemen 1993) implemented an analogous formal expert elicitation process in their Yucca Mountain future-climate study.

We shall use the seven-step paradigm as a convenient way to structure our discussion of the TFI process; however, we pay special attention to the most unique SSHAC step, Step 6, where the TFI must act as both a facilitator for expert interactions (Step 6a) and as an integrator (Step 6b) responsible for producing a final composite representation of the expert panel.

Step 1. Identification and Selection of the Technical Issues

For our purpose here, a technical question is one that must be answered by the formal elicitation of expert judgments. Examples of questions from PSHA are the definition of the seismic source boundaries and the value of the maximum earthquake magnitude for each source in the seismicity portion of the study, and the median of the ground motion variable (PGA or spectral velocities) in the ground motion portion of the study. Clearly, such questions must have significant impacts on the results. Depending on the scope of the analysis and given the expense involved in a formal exercise, the TFI must develop criteria as to how the questions will be selected (relevant guidance is given in the seismicity and ground motion sections of this report). Some of the questions may be resolved by simply proposing a answer and soliciting comments from peers. The TFI should seek outside advice, e.g., from the study's sponsors and selected experts, when the questions are selected.

Step 2. Identification and Selection of the Experts

Attempting to define precisely who is an expert is not fruitful. In general, a candidate panelist must have a good professional reputation among his or her peers. In some recent studies (Trauth, Hora, and Guzowski 1993), a nomination process has been adopted, in which a long list of potential candidates is developed by consulting the archival literature and by asking technical societies, government organizations, as well as knowledgeable experts to submit names of researchers and practitioners. SSHAC strongly recommends this type of formal nomination process, and the development of a formal set of criteria for both selecting and potentially removing potential panel members.

For example, the following criteria were used to select the seismic source characterization experts for the ongoing Yucca Mountain seismic hazard analysis:

- Strong relevant expertise as demonstrated by professional reputation, academic training, relevant experience, and peer-reviewed publications and reports
- Willingness to forsake the role of proponent of any model, hypothesis or theory, and perform as an impartial expert who considers all hypotheses and theories and evaluates their relative credibility as determined by the data
- Availability and willingness to commit the time required to perform the evaluations needed to complete the study
- Specific knowledge of the Yucca Mountain area, the Basin and Range Province, or ground motion characterization
- Willingness to participate in a series of open workshops, diligently prepare required evaluations and interpretations, and openly explain and defend technical positions in

interactions with other experts participating in the project

- Personal attributes that include strong communication skills, interpersonal skills, flexibility and impartiality, and the ability to simplify and explain the basis for interpretations and technical positions.

In the same study, the following guidelines have been established for the removal of an expert from the panel:

"The need to consider removing an expert can only arise for failure to perform according to the commitments and demands of the project as stated in the expert selection criteria."

One or more of the following could prompt the need to consider removing an expert:

1) The person demonstrates unwillingness to perform as an expert evaluating credible models, hypotheses, or theories relative to the degree they are supported by data. This might be considered to be demonstrated if a person becomes a proponent of a single model, theory, or hypothesis to the exclusion of all others, or is unwilling to be guided by the data in making interpretations or expressing uncertainty.

2) The person is unwilling or finds it impossible to commit the time required to perform the evaluations needed to complete the study. This might be reflected in the person consistently being unprepared for workshops or interactive meetings with the Facilitation Team and/or consistently failing to meet established schedules for deliverables.

3) The person is unwilling to interact with other members of the project in an open and professional manner. This might be demonstrated by the person assuming a hostile and aggressive posture toward other members of the project or being uncooperative and disruptive in the workshops or interactions with the Facilitation Team."

A formal, well-documented selection and removal process can be extremely useful in highly charged political arenas in which the TFI must anticipate charges of bias. The TFI should play the principal role in creating nomination and removal criteria and in selecting the group, supported by the sponsors and possibly an advisory committee of experts.

It is important to ensure that the final group represents a broad spectrum of scientific expertise, technical points of view, and organizational representation. There are additional considerations as well. In the TFI process, evaluation ability and experience is especially important for the experts as informed evaluators. Also, the selection process should be influenced by the way the elicitation of the judgments will be handled. If the TFI plans to interact with the experts individually, it is important to select experts who are (or, are willing to become) somewhat familiar with the big picture, i.e., what PSHA is all about and how their input will be utilized. If, on the other hand, the TFI plans to form several teams of experts and interact with each team as a sub-group, then the concern should be making sure that each team includes all the necessary disciplines, e.g., for seismic source characterization issues, seismology, geophysics and geology. The need for each expert to have a broader perspective is not as pressing in the team case.

The advantage of forming teams is that, in highly multidisciplinary problems, each team can be chosen to have the necessary expertise to handle the problem. A drawback may be the presence of a strong personality who forces his or her judgment on the team, although an effective TFI will discern this and intervene to prevent it from happening. Furthermore, the presence of several teams provides additional assurance that a representative spectrum of scientific judgments will be obtained (i.e., assurance that the teams themselves can act as evaluators and integrators). In multidisciplinary problems, individual experts could have access to a supporting staff. Of course, the more elaborate the structure of the expert panels, the more costly the process. In the end, the

TFI will bear responsibility for both the selection process and the expert-panel structure.

Step 3. Discussion and Refinement of the Technical Issues

The TFI will hold a first meeting with the experts to discuss the technical questions that have been selected in Step 1 and to make sure that everyone understands them as intended (more meetings may be held, if necessary). The TFI needs to make sure that all experts have access to major sources of relevant data. An interaction of this kind is very important, because experience, for example, in the Ispra Benchmark Exercises on probabilistic assessments (Amendola 1986), has demonstrated that a major contributor to apparent disagreements is misinterpretation of the problem and its boundary conditions. Past experience in the LLNL/EPRI and other PSHA projects was similar. SSHAC workshops on seismic source characterization and ground motion confirmed that the participating experts felt strongly that detailed discussions and exchange of information prior to the actual elicitation were critical to the success of the exercise (see also the discussion on Step 6a below).

Through these interactions, the experts have an opportunity to provide input to the formulation of the technical questions and the precise formulation of the elicitation questions that will be asked. This formulation usually involves the decomposition of an issue into other issues that are judged to be easier to analyze. For example, one may wish to ask questions directly about a specific ground motion parameter or one may decide to consider several alternative models that estimate the parameter value, formulating the issues in the context of these models, i.e., asking questions about the numerical values of the parameters of these models, such as the expected stress drop.

The TFI's role in this step is primarily one of a technical facilitator (for more details on this subject, see Step 6a below). The TFI takes a proactive role by collecting and disseminating relevant information and by raising questions and encouraging all experts to learn the PSHA language and participate in the process. For example, this meeting offers a good opportunity for the TFI to discuss with the experts the concepts of aleatory and epistemic uncertainty (see Chapters 1 and 2 of this report). Such conceptual subtleties must be discussed so that the experts will have a clear understanding of the issues with which they are dealing (the Ground Motion appendices document such discussions).

Keeney and von Winterfeldt (Ref. 1991) recommend, and SSHAC agrees, that after the first meeting the experts should be given time to reflect on the issues and on the discussions that will have taken place at that meeting. They should then provide feedback to the TFI.

Besides the obvious benefits of eliminating misunderstandings, this step also influences the degree to which strong disagreements will surface during the processing of the judgments (Step 6, discussed below). We expect an informed group of experts that has debated the issues prior to the actual elicitation to be more likely to cooperate with the TFI in the formulation of the final composite judgment.

Step 4. Training for Elicitation

This step of the process is carried out by the elicitation experts of the TFI Team. The basic premise is that domain or substantive experts, i.e., experts on the relevant physical sciences, are not necessarily experienced at producing probability distributions that reflect their true state of knowledge. The language of probability may be foreign to them or they may be susceptible to various biases (Tversky and Kahneman 1974; Meyer and Booker 1991, Cooke 1991). Moreover, they should be familiarized with problem-structuring tools, such as influence diagrams (Shachter 1988; Oliver and Smith 1990; Call and Miller 1990) and logic trees (Coppersmith and Youngs 1986; National Research Council 1988).

The reluctance of some experts to speak in probabilistic terms may be overcome by explaining what probabilities are designed to do and by discussing some simple rules and exercises. The distinction between aleatory and epistemic uncertainty should be further explained in terms of concrete examples.

The possible biases may be characterized as being motivational or cognitive. Of course, the possibility of an expert having a motivation to distort his or her judgments deliberately should have been a factor in the selection of the experts (Step 2). Note that this does not necessarily mean that the TFI team should ignore candidates with motivational biases, just that these experts should properly play the role of proponents, not evaluators; in fact, the arguments that such proponents advance may be very useful to the panel's deliberations, even though the expert is known to be biased. The facilitation process described below is explicitly designed to expose and eliminate bias among panel members insofar as possible.

Cognitive biases, such as overconfidence and location bias, i.e., the reporting of narrower-than-justified probability distributions and the systematic over- or under-estimation of scalar quantities, have been discussed extensively in the cited literature. The TFI should explain to the experts the existence and nature of these biases in the hope that their impact will be minimized.

Step 5. Group Interaction and Individual Elicitation

An important aspect of the TFI process is the individual elicitation of probability judgments from individual experts. It is important to note, however, that the individual elicitations should be preceded by and followed by an important set of group interactions. We first address some individual elicitation issues and then discuss the relationship of individual elicitation to the group interactions.

We will not devote much space to individual elicitation here only because it is dealt with extensively elsewhere (including the references cited above). However, we do not want to minimize the importance of obtaining an accurate probability statement from each individual expert on all uncertainties of interest. Such a statement is useful, not only for characterizing each expert's position in a form usable for seismic hazard analysis, but also for ensuring full and unambiguous communication among the expert panel.

The actual elicitation process should be conducted with in-depth, face-to-face individual interviews, possibly supplemented by (but not replaced by) the use of preliminary questionnaires. When expert teams are employed, it is important to elicit the team as a group, possibly supplemented by preliminary individual interviews. The structure of the questions to be asked depends on the subject and will be developed by the TFI by taking into account the relevant literature.

A relevant point here is that the decision analysis literature advises that the experts should be asked to express opinions only on observable (at least in principle) quantities. In particular, this advice says that questions on event rates and moments of distributions should be avoided , because they are not "observable." Such a requirement would not allow the TFI to ask questions about the rate of occurrence of earthquakes in a seismic source, nor about the logarithmic standard deviation of the ground motion variable. This would be a mistake in the PSHA context, because the experts are very comfortable with these quantities. Asking the experts questions on "observable" quantities is based on the assumption that this would help them work with quantities that are easier to visualize and understand. In the earthquake community, long experience with data and analyses have made the experts very comfortable with the quantities cited above, so that related questions are meaningful to them.

An important element of the process, regardless of whether or not expert teams are formed, is the extensive use of consistency checks and providing feedback to the experts regarding the possible implications of their judgments. The idea is to challenge the experts and to invite self-scrutiny as much as possible. This is a key function of the TFI both as an informational resource to the expert group and as a facilitator of the group interactions and is discussed in detail in Step 6a below.

Before and after the individual elicitations, a number of types of group interactions need to take place. Chapters 4 and 5 present specific examples of types of workshops and meetings that enable these interactions. Here, we review briefly some generic interactions that are essential to success:

Information Meetings

There need to be informational meetings of at least three types (although not necessarily separated in time):

1. Background on objectives of study and overview of TFI process

   The experts need to understand the TFI process and their different roles in it. The experts must also understand clearly the distinction between the Stage I elicitation objectives and the Stage II elicitation objectives (as described above and expanded in Section 4 of Appendix J). In particular, assessing the possible scientific positions of the overall expert community will require a new way of thinking for most experts, so special care must be taken to ensure that the questions are well-defined, meaningful and thoroughly explained.

2. Background on the specific problem

   Depending on the scope of the study, the panel needs to be briefed by site or regional specialists who provide local or problem-specific knowledge that the panel members will not generally have. Also useful are presentations by local proponents and, possibly, site visits to give the panel first-hand familiarity with the study area. The experts should be encouraged to interact and exchange ideas and interpretations with the specialists.

3. Background on Hazard Analysis

   To be maximally effective, the experts must understand how their judgments will be used. They should be provided with a review of basic hazard methodology, the role of probabilistic judgments and the importance of sensitivity analysis.

Issue Interaction and Data Needs Review

The experts should work together to define and discuss the important issues on which uncertainty needs to be quantified—i.e., those variables that will require individual elicitation. Using the process described in Appendix J, the TFI structures interaction among panel members, specialists and proponents, facilitates debate and keeps the group focused on the sensitive parameters and issues.

It is also important to provide the experts with a detailed review of existing data and literature. The experts should be permitted to request additional data summaries and additional reports and papers.

Post-elicitation Feedback and Interaction

The TFI should summarize the result of the individual elicitations and provide this information as feedback to the entire panel. Panelists should be encouraged to amend their estimates, if they wish, after observing the other experts' judgments. Finally, it is often quite beneficial to conduct a post-elicitation group interaction to enable the experts to ask questions or address important differences or new issues arising out of the individual elicitation. Also, it is useful to structure group interaction to exchange viewpoints in preparation for individual expert-as-integrator assessments of the community distribution (Stage II) which must logically follow after the Stage I expert-as-evaluator assessments.

Step 6. Analysis, Aggregation, and Resolution of Disagreements

This step is where the SSHAC process deviates most from prior PSHA studies and the multiple-expert-use literature. Recall that the TFI has two fundamental roles: that of a Facilitator whose job it is to ensure that the knowledge, data and models of the expert community are fully and accurately elicited, and that of an Integrator whose job it is to ensure that the diverse information is integrated into a form useful for decision making that is a consistent and accurate representation of the state of information of the expert community. Because aggregation, if necessary, must follow the analysis of disagreements, it is natural to divide Step 6 into two successive steps: Step 6a, "The Role of TFI as a Facilitator," and Step 6b, "The Role of TFI as an Integrator."

Step 6a. The Role of TFI as a Facilitator

The TFI facilitation process is designed to encourage both the TFI and the experts to

understand explicitly the data bases and reasoning upon which different model estimates and expert interpretations are predicated. Moreover, it also demands explicit understanding concerning the rationale underlying each expert's uncertainty assessments.

SSHAC believes that successful integration is best achieved through proper facilitation of intensive interaction; hence, in the TFI process, the facilitation role of the TFI is paramount. A number of facilitation tips were provided in the previous sections. A longer list with more comprehensive discussion of facilitation principles and guidelines for potential TFIs is provided in Section 2 of Appendix J.

Step 6b. The Role of TFI as an Integrator

There are no cookbook formulas for integration (see Section 3 of Appendix J), but there are many useful concepts and models that can be used by the TFI. Even in the facilitation role, it is critical for the TFI be aware of certain key expert aggregation issues. Appendix J summarizes a set of fundamental expert-aggregation issues, including:

- Different Degrees of Expertise
- Outliers
- Non-Independent Experts
- Equal Weights
- Non-Equal Weights
- Level of Aggregation

The SSHAC process requires the TFI to be familiar with these issues and models, and to review them at each stage of the process (hence the need for an elicitation expert as part of the TFI team). There are three basic reasons for this:

1. The TFI must have a basic understanding of expert-aggregation issues in order to steer the expert interaction process to result in the simplest possible (e.g., equal weights) integration procedure. Moreover, the issues provide a checklist for the TFI to use in determining when it is appropriate to halt the process.
2. If it is determined that non-equal weights or "weighing" of the experts-as-integrators composite representations is the appropriate integration procedure, the aggregation issues and models provide useful information for how to do the non-equal weighting or weighing.
3. For experts acting as individual evaluators who must weight scientific models and interpretations, the aggregation issues and associated aggregation models can be directly useful. Since the experts are unlikely to be familiar with aggregation concepts, the TFI will need to use the aggregation issues and models to guide the experts in defining and assessing the weights.

We emphasize that the TFI does not need to use any prescribed, rigid combination formula, such as a fixed weighting scheme. Nevertheless, mathematical expert aggregation models have an important supporting role in the TFI process. A number of simplified expert-aggregation models are presented in Appendix J, Section 3. Also included is a new mathematical model specifically relevant to the TFI process. The TFI utilizes these models to check the implications of various assumptions, so that the ultimate aggregation (even if purely behavioral) will be sound and defensible. For example, the TFI may choose to process some disputed evidence using a number of aggregation models to illuminate the numerical impact of specific assumptions. This approach was used in Chibber, Apostolakis, and Okrent (1994) to estimate the pressure increment in the Sequoyah nuclear power plants containment vessel breach. The inputs from three experts, as reported in NUREG-1150 (Hora and Iman 1989), were processed using Bayesian methods under a number of assumptions regarding the degree of dependence among the experts, as well as the amount of their systematic biases.

Step 7. Documentation and Communication

The primary incentive for the formal elicitation of expert judgments is to supply credibility to the study. It is evident, therefore, that an essential element in accomplishing this is carefully and

thoroughly documenting every step of the process, as well as the results. It is important that each expert panel member document not only his or her own scientific position, but also his or her estimate of the community position. These detailed records will also prove invaluable when the TFI presents and defends the study to third parties, including regulatory agencies. Documentation is discussed in more detail in Chapter 7.

3.4 Peer Review

SSHAC recommends that peer review be conducted in both the TI and TFI processes. The purpose of the peer review is to provide assurance that a proper process has been followed, that the study incorporates the diversity of views prevailing within the technical community, that uncertainties have been properly considered and incorporated into the analysis, and the documentation of the study is clear and complete. Peer review has a long history of application in quality assurance for scientific endeavors including seismic hazard analysis. Classically, peer review is conducted by 1) one or more technical peers of the study participants who are "independent" of the study, and 2) at the end of the project. In recent years, experience on several large projects has shown that the active "participation" by peer reviewers throughout the course of the study can provide valuable input to the process being followed and can serve to define mid-course corrections that can improve the quality of the final product. This experience and these concepts are described in the guidance provided below.

3.4.1 Structuring the Peer-Review Process

If a PSHA project is to be successful, the crucial need for a strong peer review process cannot be overemphasized. What this means, in practice, is that the peer reviewers must be "peers" in the true sense: recognized experts on the subject matter under review. In the discussion below, we will assume that the Project Sponsor has assembled a peer-review panel, headed by a chairman who is responsible for writing the panel's reports (with the provision for the expression of minority views if appropriate). However, the Sponsor may in some cases use individual peer reviewers not assembled into a panel. For example, in a Level 1 analysis a review by a single peer reviewer may be sufficient to assure reasonable quality.

We will also assume that the peer-review panel reports are addressed to the Project Sponsor or the Project Leader, depending on the sponsor's desires, provided that the peer reviewers can act, and feel that they can act, to provide independent comments.

3.4.1.1 Participatory vs. Late-Stage Peer Review

In order to lay the foundation for our recommendations, we differentiate between two different types of peer review:

- A participatory peer review is an ongoing review that provides the peer reviewers with full and frequent access throughout the entire project. The process is structured to seek peer-review comments at numerous stages, and includes peer-review interaction with both the study team and, if appropriate, with the consultants and/or experts whose input is important to the final product. The principal benefit of a participatory peer review is that, if problems are discovered, the opportunity exists for a mid-course correction without the need for work to be substantially redone at the end. One limitation: peer reviewers might lose their objectivity as they interact with the project over time.
- A late-stage peer review is a review that occurs only after the project has been almost completed. Usually, such a review takes place when a draft of the final report has been prepared, or when the project's bottom-line results are close to being in final form. Sometimes, a late-stage peer review can examine an intermediate-stage result when it has been almost completed. The principal characteristic of a late-stage peer review is that, if major problems are discovered, the work may need to be substantially redone, without the mid-course-correction benefits of a participatory peer review. The use of a late-stage review is, therefore, a "gamble"—usually an informed gamble, of course—on the part of the sponsors that major problems

will not be discovered. A late-stage review has the benefit of a perception of complete independence.

Although these types of peer review are discussed separately here, it is possible for any given PSHA to include *both* a participatory and late-stage peer review.

3.4.1.2 Technical Peer Review vs. Process Peer Review

In the context of a PSHA project, we also need to distinguish between two different PSHA areas that require peer review:

- Technical peer review is the review of the earth-sciences aspects of a PSHA study: seismic-source characterizations, ground-motion models, the completeness and quality of the data set used to derive these inputs, etc. It also includes review of the PSHA calculation methods, the final seismic-hazard results and the sensitivity studies analyses. Reviewing this aspect requires expertise in the relevant earth sciences and calculational methodologies.
- Process peer review is the review of how the PSHA study is structured and executed. Because a PSHA must rely so heavily on expert interpretations of the admittedly inadequate earth-sciences information, the process peer review must concentrate on assuring that consideration of the uncertainties and the elicitation and incorporation of expert judgments is done well. Reviewing this aspect requires expertise in expert elicitation, statistical analysis, and related disciplines, as well as adequate familiarity with the technical issues and methods involved in a PSHA project.

3.4.2 Recommendations Concerning Peer Review

We have described two different methods for peer review, and two different subjects that require peer review:

- peer-review methods:
  - participatory peer review
  - late-stage peer review
- subject matter:
  - technical peer review
  - process peer review

We also have described two different approaches to address the complex technical issues involved in a PSHA project, the TFI and TI approaches. There are 4 different combinations of peer review structures to discuss for each of the two approaches. Table 3-2 contains a summary of our guidance concerning peer review.

Rationale: SSHAC's rationale for the peer-review guidance in Table 3-2 is as follows:

When structuring a peer review for the TFI approach, SSHAC recommends a participatory peer review over a late-stage peer review. When structuring a process peer review, SSHAC strongly cautions that a late-stage review can be very risky because accomplishing the process correctly is vital, and there are many process pitfalls that could benefit from a mid-course correction. In a technical peer review, SSHAC recommends a participatory review; however, this is not a strong recommendation—we believe that a late-stage technical peer review can be sufficiently effective, because the interactions among the various experts during the elicitation process, if done correctly, can provide many of the benefits of a participatory technical review.

When structuring a peer review for the TI approach, SSHAC believes that a participatory peer review is strongly recommended, if not essential. This recommendation holds for both the technical peer review and the process peer review. Although the process aspects using the TI approach may often be uncontroversial, SSHAC's reasoning is that, because the TI is conducting the entire analysis "in-house," there are significant opportunities for problems with both the technical and process aspects, and a late-stage review can be risky. For the technical aspects, the risk can sometimes be smaller (and more manageable) than for the process aspects, provided that the technical issues are not too contentious. For the process aspects, SSHAC believes that the risks associated with a late-stage review are likely to be great.

Table 3-2 SSHAC Recommendations on How to Structure the Peer Review Process

APPROACH	SUBJECT MATTER	METHOD	SSHAC RECOMMENDATION
TFI	Technical	Participatory	Recommended
		Late-stage	Can be acceptable
	Process	Participatory	Strongly recommended
		Late-stage	Risky: unlikely to be successful
TI	Technical	Participatory	Strongly recommended
		Late-stage	Risky but can be acceptable
	Process	Participatory	Strongly recommended
		Late-stage	Risky but can be acceptable

4. METHODOLOGY FOR CHARACTERIZING SEISMIC SOURCES

4.1 Introduction

This chapter summarizes important considerations in characterizing seismic sources for PSHA. Seismic Source Characterization (SSC) refers to the component of PSHA in which the locations, size, and frequency of future earthquakes are estimated. Because it is not yet possible to predict the location, size, and timing of the *next* earthquake, analysts attempt to determine the average *rate* of earthquake occurrence and use this rate as an indication of the likelihood or probability of future earthquake occurrence. The indication of rate, then, is a distinguishing feature of PSHA and a key parameter to be assessed for earthquake sources.

SSC is a multi-disciplinary activity that entails various aspects of the earth sciences including seismology, geology, and geophysics. The multi-disciplinary nature of source characterization means that a variety of expertise is required. Further, because of the limited knowledge of earthquake processes, the judgments of earth sciences experts (either formally or informally elicited) are required.

The three key elements of seismic source characterization are

- **Seismic source locations/geometries** Seismic sources are depicted in map form and represent locations within the earth's crust that have relatively uniform seismicity characteristics. Variations in the estimates of the geometries of sources reflect uncertainties in the spatial distribution of future seismicity. The probability of activity is assessed for each seismic source. Seismicity parameters (recurrence and Mmax) are specific to each seismic source.
- **Maximum earthquake magnitude** Maximum magnitudes (Mmax) are the largest magnitudes that a seismic source is capable of generating. Mmax is the upper-bound magnitude to the earthquake recurrence (frequency–magnitude) curve.
- **Earthquake recurrence** Earthquake recurrence is the frequency of occurrence of earthquakes having various magnitudes. Recurrence relationships or curves are developed for each seismic source and reflect the frequency of occurrence (usually expressed on an annual basis) of magnitudes up to the maximum.

The methods that are used to assess these three elements are different and, as a result, the three-part subdivision above will be used in the subsequent discussions of methodology.

The purpose of this chapter of the report is twofold: (1) to summarize the seismic source characteristics that are required for PSHA, and (2) to review approaches that can be used to characterize the epistemic uncertainties in SSC. These two sections of the chapter are not intended to be discussions of the "how-to" of seismic source characterization. The published literature provides reasonably complete discussions of the methods and scientific bases for characterizing sources for PSHA (e.g., Schwartz, 1988; Reiter, 1991; Coppersmith, 1991). These methods will be briefly summarized here. Likewise, various methods have been used to quantify the epistemic uncertainties in the elements of SSC and require only summary mention. Effort will be made, however, to distinguish among alternative methods for characterizing uncertainties, to recommend preferred approaches, and to note the pitfalls of these methods.

Section 4.4 of this report contains recommended methods for implementing SSC that incorporate expert judgment in quantifying uncertainties. The section is a principal focus of the SSC discussion because very little documentation of such methodologies exists in the literature. Further, it is the responsibility of SSHAC to review the methodologies and to make recommendations that are particularly appropriate to PSHA and its various components, including SSC.

A challenge in developing guidance for SSC is the requirement that the SSHAC-recommended

methods be appropriate for all parts of the United States. The approaches to source characterization, perhaps more than any other aspect of PSHA, depend upon the earthquake environment being considered. (Note that this is not strictly a function of "eastern" versus "western" U.S.; most of the western U.S. is characterized by low rates of seismicity, and some areas of the eastern United States are seismically active). In highly active areas of the western United States, the locations and geometries of seismic sources (in this case faults) are usually less uncertain than the recurrence rates appropriate for the sources; in turn, the recurrence rates are almost exclusively based on geologic data. Seismicity data play an important role in identifying sources and specifying the recurrence of small-magnitude events. In the low-activity eastern United States, geometries of seismic sources (typically area sources) are often highly uncertain and recurrence rates are derived almost exclusively from observed seismicity data, which are mostly small-magnitude earthquakes. Detailed analyses and procedures required for characterizing source geometries and recurrence, eastern United States versus western United States will not be enumerated; rather, this chapter will focus on methods for addressing the uncertainties associated with each and, in this way, find some common ground. The discussion of seismic sources is divided along the lines of various source types, as opposed to tectonic environments, which should assist in the application of the methods.

Section 4.2 summarizes the seismic source characteristics that are required for PSHA, and Section 4.3 discusses methods for characterizing epistemic uncertainties in SSC. Section 4.4 presents recommended methods for incorporating expert judgment in source characterization.

4.2 Seismic Source Characteristics Required for PSHA

The seismic source characteristics that must be assessed for probabilistic seismic hazard analysis are described below. The types of sources and the means of characterizing their earthquake behavior varies with the seismotectonic environment. Therefore it is useful to consider first the types of seismic sources that might be defined and then center the discussion on methods for these particular types of sources. Seismic sources can be categorized into four basic source types, shown in Figure 4-1:

Type 1 Faults, represented as lines or planes

Type 2 Area sources enclosing concentrated zones of seismicity

Type 3 Regional area sources

Type 4 Background area sources.

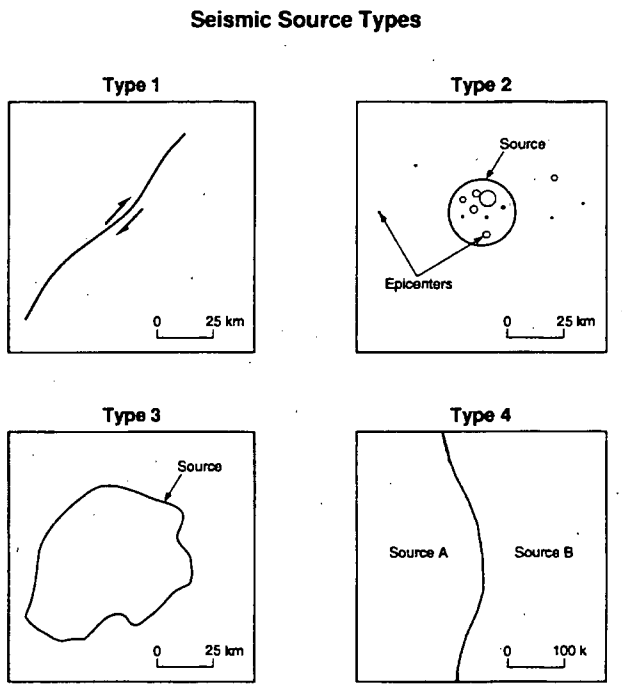

Figure 4-1 Diagrammatic representation of the four general types of seismic sources discussed in the text. Type 1 is a fault source and Types 2 - 4 are area sources. Type 2 is a source whose boundary encloses a zone of concentrated seismicity; Type 3 is a source defined by regional seismotectonic characteristics; and Type 4 is a regional background source (note scale).

Although these categories are arbitrary, they are useful in discussing the various data and methods used to characterize them. The basic source characteristics for all source types are the same (i.e., location, maximum magnitude, and recurrence); however the particular parameters and data sets that are used to define these

characteristics may be quite different. For example, slip rate is an important parameter for a fault source, but it is not applicable for a regional area source.

Although this section presents the source characteristics required for PSHA, it does not present a detailed description of the manner in which these characteristics can be assessed. For comprehensive descriptions of methods and the scientific basis for characterizing earthquake sources, refer to the published literature (e.g., Schwartz, 1988; Reiter, 1990; Coppersmith, 1991).

The following discussion is divided into the three principal components of seismic source characterization: source location and geometry, maximum earthquake magnitude, and earthquake recurrence. It should be recognized that, because of limitations in data, it will not be possible to assess all of the characteristics described below as part of any given seismic hazard analysis. For example, paleoseismic data may not be available to evaluate recurrence rates for a particular seismic source. However, the discussion here is given in terms of a reasonably complete set of alternative approaches. It is recognized that other characteristics besides those discussed are likely important to earthquake ground motions (for example, dynamic stress drop and the coseismic distribution of slip on a fault). However, these characteristics are not yet commonly included (at least explicitly) in probabilistic seismic hazard analysis.

4.2.1 Seismic Source Locations and Geometries

A seismic source is a construct developed for seismic hazard analysis as a means of approximating the locations of earthquake occurrences. A seismic source is defined as a region of the earth's crust that have relatively uniform seismicity characteristics, and is distinct from those of neighboring sources. It is possible to allow for some variation of seismicity parameters (a- and b-values) within a given seismic source. Typically, however, the distribution of Mmax and the probability of activity (defined below) are assumed to be uniform within a seismic source.

Each seismic source must be defined by its location in order for the distance distribution to a site of interest to be calculated in the hazard analysis. In theory, the level of detail necessary to describe the location and geometry of sources can be uniform for large regions. In practice, however, the level of detail in specifying the locations and geometries of seismic sources can vary as a function of distance from the site. Because the amplitude of ground motions attenuates with distance from the source, at large distances even large-magnitude earthquakes will not result in significant ground motions at the site. From the standpoint of seismic hazard analysis, this means that the inclusion of these distant sources in the analysis is not required because they do not contribute to site ground motions.

This means that there are distances beyond which detailed source characterization is not necessary. For example, for a site in the western United States (with its attendant attenuation), it is likely that sources more than about 300 km from a site of interest do not need to be considered; "detailed" source characterization need only be carried out within, say, 100 km from the site. "Detailed" source characterization would include specifying the mapped location and three-dimensional geometries of faults. At greater distances, the effect on hazard from faults and area sources is similar. Thus faults and small area sources at larger distances can usually be generalized as large area sources. Further, if fault sources (or Type 2 localized area sources) are nearby they will likely be most important to the hazard results and will, therefore, preclude the need to characterize sources in detail out to large distances.

To provide guidance on this issue, the following source-to-site distances are suggested for detailed source characterization and source identification, as a function of whether or not nearby faults are present:

Western U.S.	Source-to-Site Distance (km)
Maximum distance for source identification	300
Distance for detailed source characterization	
Faults within 50 km of site	100
No faults within 50 km of site	150
Eastern U.S.	**Source-to-Site Distance (km)**
Maximum distance for source identification	500*
Distance for detailed source characterization	
Faults within 50 km of site	200
No faults within 50 km of site	300

* In certain cases, where a highly active distant source is present, capable of generating large-magnitude earthquakes (e.g., New Madrid), distances up to 1,000 km may need to be considered.

For example, for a site in the eastern United States that has faults (or localized sources) within 50 km of the site, seismic sources should be characterized out to distances of about 200 km of the site. The difference between the western and eastern U.S. is related to differences in the ground motion attenuation between the two regions.

The "western U.S." is defined roughly as the region of Mesozoic–Cenozoic deformation of the earth's crust lying west of the Rocky Mountain front. The definition of locations and geometries varies with source type between faults (type 1) and area sources (types 2–4), as discussed below.

Fault Locations and Geometries (Source Type 1)

At a minimum, the location of fault sources must be identified in map view. Usually a fault map depicts the line of intersection of faults with the ground surface. In the case of blind faults that do not intersect the surface, the location of the shallowest extent of the fault should be indicated on the fault maps. With the occurrence of the 1983 Coalinga earthquake and the 1994 Northridge earthquake has come an increasing recognition of the important contribution that blind or buried faults can make to seismic hazard, particularly within regions of compressional tectonics.

Faults may be represented as "line" sources using the fault maps or, if sufficient information is available, by three-dimensional fault planes. The need to characterize the three-dimensional geometry of a source is greatest where the source-to-site distance is small. For example, if a fault is less than 10 km from a site, the direction and amount of dip away from or toward the site can have a large impact on the source-to-site distance.

A primary geometric characteristic is the dip angle, expressed by convention as 90 degrees for vertical faults and decreasing as the fault approaches the horizontal. The direction of dip must also be specified.

The updip and downdip extent of the fault within the seismogenic crust must also be specified for three-dimensional faults. Because seismic hazard analysis attempts to portray the earthquake generation process, a three-dimensional rupture is assumed to occur during earthquake generation. The area of this rupture, as measured on the fault surface in square kilometers, is directly proportional to earthquake magnitude. Empirical relationships, such as that given by Wyss (1979) and Wells and Coppersmith (1994) describe the area of rupture for given magnitudes. In order to model the occurrence of earthquake ruptures for hazard analysis, an estimate must be made of the downdip extent of the fault within the

seismogenic part of the crust. Such an estimate is commonly developed by considering the maximum focal depths of seismicity in the vicinity of the fault or in the region.

Another characteristic of faults that must be assessed is the style of faulting, generally defined as strike-slip, normal, and reverse faulting. This assessment can come from geologic studies of the fault, focal mechanisms from associated seismicity, or tectonic considerations (Coppersmith, 1991).

Area Source Locations and Geometries (Source Types 2–4)

It is universally true that earthquakes are the result of differential slip on faults. However, in many areas, such as most of the eastern U.S., the identification of the causative faults giving rise to seismicity is problematic. To accommodate this uncertainty in fault location, area sources were invented and have common application in PSHA. It is recognized that a homogeneous area source used in PSHA is not a physical characteristic of the earth's crust but is a simplified representation of one or more seismogenic structures whose location is unknown. The area-source boundaries enclose regions that earth scientists believe are relatively uniform with respect to the PSHA application.

Although the data used in their identification can be significantly different, the depiction of area sources is essentially the same for all source types discussed. Seismic sources are defined by their boundaries shown on maps. Although these boundaries may be considered "fuzzy" boundaries (Bender 1986), most commonly they are assumed to be sharp and to define differences in the maximum magnitude and recurrence rate between one zone and another. (An exception is variation in recurrence parameters within an area source). As discussed previously, area source boundaries can be defined by a variety of characteristics including concentrations of seismicity, changes in tectonics, and geologic boundaries.

Although the source map is the only required product, an assessment be made of the depth distribution of seismicity (which defines a seismogenic volume) is also recommended, particularly if the depth is anomalous relative to other regions. Also, the expected style of faulting should be evaluated. Uncertainties in source boundaries are incorporated into the hazard analysis through the identification of alternative source configurations, each with its own relative weight or credibility.

Data Used to Define Source Locations and Geometries

The identification of seismic sources is a critical part of seismic hazard analysis and involves a wide range of data types and scientific interpretations. The purpose of this section is to identify the types of data that can be used to develop source interpretations and to provide an indication of the relative usefulness that various types of data may have in making source assessments. No requirement is being made that all data discussed be developed for all hazard analyses—some hazard studies may require more data than others depending on the scope of the analysis. It is a requirement, however, that all *available* data of the type indicated be considered in characterizing seismic sources. Gathering additional data is a function of their importance to the analysis, potential benefits to be gained from further reducing uncertainties, and the like.

Table 4-1 summarizes the types of data used to define each of the four types of seismic sources and the relative usefulness of each data type. Relative usefulness in this context means the degree to which that particular type of data provides a strong technical basis for the source definition. For example, if fault sources are being identified, a map of young (Quaternary) faults is judged to provide a strong basis for defining fault sources in hazard assessment, whereas a map of older (pre-Quaternary) faults is judged to provide a relatively weak basis for defining fault sources. Likewise, the nature and spatial patterns of instrumental seismicity are most important in defining Type 2 and 3 area sources, while various types of geological structural data play a lesser role. Note that, in real application, the quality of various data can vary significantly. This variation can have an important impact on its usefulness in source definition.

Table 4-1 Data Used to Assess Seismic Source Locations and Geometries and Their Relative Usefulness

TYPE OF SOURCE	DATA/BASIS FOR SOURCE	RELATIVE USEFULNESS/ CREDIBILITY (1: high, 3: low)
Type 1: Faults	Mapped fault with historical rupture	1
	Mapped Quaternary fault at surface	1
	Mapped localized Quaternary deformation, inferred fault at depth	2
	Borehole evidence for fault, especially in young units	2
	Geophysical evidence (e.g. seismic reflection) of fault at depth	2
	Map of pre-Quaternary faults	3
Type 2: Concentrated Zone	Concentrated zone of well-located instrumental seismicity	1
	Mapped fault(s) at surface or subsurface in proximity to seismicity	1
	Zone of historical/poorly located seismicity	2
	Structural features/trends parallel to seismicity zone	2
	Focal mechanisms/stress orientation	3
	Rapid lateral changes in structures/tectonic features	3
Type 3: Regional Zone	Changes in spatial distribution/concentration/density of seismicity	1
	Regions of genetically-related tectonic history	1
	Regions of similar structural styles	2
	Changes in crustal thickness or crustal composition	2
	Regions of different geophysical signature	3
	Changes in regional stresses	3
	Changes in regional physiography	3
Type 4: Background Zones	Regional differences in structural styles/tectonic history	1
	Major physiographic/geologic provinces	1
	Changes in character of seismicity	3

4.2.2 Maximum Earthquake Magnitudes

The maximum earthquake magnitude that a seismic source is capable of generating defines the upper bound to the earthquake recurrence relationship. Because the assessment of the maximum magnitude often includes approaches different from those used to evaluate the remainder of the recurrence relationship, maximum magnitudes and earthquake recurrence assessments are discussed separately.

Faults (Source Type 1)

There are two basic approaches to assessing maximum magnitudes for fault sources: constraints provided by historical seismicity and provided by estimates of maximum dimensions of rupture. In most cases, the historical record for individual faults is short relative to recurrence intervals for the largest earthquakes; thus the probability that the historical record includes the maximum event is usually small. However, if the historical record includes a significant earthquake that can be associated with the fault (say, a surface-rupturing event such as the 1857 earthquake on the San Andreas fault), it may provide an estimate of the maximum magnitude. In cases where the historical event was associated with coseismic rupture, the extent of that rupture can be evaluated geologically relative to other constraints on the maximum rupture dimensions.

Earthquake magnitude is well-correlated with rupture dimensions. It follows that if rupture dimensions associated with a maximum earthquake on a fault can be estimated, the maximum magnitude can be assessed. Fault rupture parameters that have been shown empirically to be correlated with earthquake magnitude include rupture length, rupture area, maximum surface displacement, and average surface displacement (Slemmons, 1977; Bonilla and others, 1984; Wells and Coppersmith, 1994). The evaluation of these parameters for an individual fault includes paleoseismic investigations of the extent of past ruptures and other geologic constraints (see discussions in Schwartz and Coppersmith, 1988; Schwartz, 1989; Coppersmith, 1991). Commonly, a number of potential rupture dimensions can be estimated (e.g., rupture length, rupture area, displacement per event) and a magnitude estimated for each. Paleoseismic data regarding the number of events and rupture dimensions are usually associated with considerable uncertainty. The final maximum magnitude estimate for a fault source should be a distribution of magnitude values. The distribution should reflect the uncertainties in the estimates of rupture dimensions and their relative credibilities. Any constraints provided by the historical seismicity record can also be included in the maximum magnitude distribution.

Area Sources (Source Types 2–4)

The assessment of maximum earthquake magnitudes for area sources is particularly difficult because the physical constraint most important to the assessment—the dimensions of fault rupture—is not known. As a result, the primary methods for assessing maximum earthquakes for area sources usually include a consideration of the historical seismicity record and analogies to other sources.

In assessing the maximum earthquake, the historical seismicity record takes on great importance—particularly in terms of the locations and sizes of older earthquakes. Extensive studies of the distribution of intensities, and relationships between isoseismal distributions and magnitude, have been initiated with the ultimate goal of using them in evaluating the size and location of older events.

Studies of the sizes of historical earthquakes associated with the area source of interest should be made. It is possible that, after the historical record has been examined, it will be concluded that the record provides no particular constraint on the estimate of maximum earthquake for the source. Alternatively, the maximum historical earthquake for the zone may be assessed as a lower bound or best estimate of the maximum magnitude for the source. In cases where the maximum historical earthquake has not been assessed to be equivalent to the maximum possible earthquake, past practice has included adding an increment of one-half magnitude unit or one intensity unit to the maximum historical earthquake. This practice implies that, because the

historical record does not include the maximum event, the recurrence interval for the maximum possible event is longer than the historical period. Thus, the addition of a magnitude unit is equivalent to a shift to longer recurrence intervals on the recurrence relationship for the source (an approximate recurrence interval of 10 times the historical record, for typical b-values).

Other considerations in assessing maximum earthquakes for area sources are analogies to other sources. The source of interest may be tectonically similar to another source such that their maximum earthquakes are also deemed to be similar. For example, in past practice in the eastern U.S., the tectonic association of certain large-magnitude historical earthquakes, such as the 1886 Charleston earthquake, was evaluated relative to the possibility that such an earthquake could occur in other sources having similar tectonic characteristics. At present, the tectonic characteristics that are most important to controlling maximum earthquakes are not well-known, but could include whether or not the source is characterized by past rifting or extension (Johnston and Kanter, 1990). Recently completed studies (EPRI, 1993) have examined the possible tectonic constraints on maximum earthquakes within sources in stable continental regions.

In some cases, it may be possible to incorporate considerations of possible rupture dimensions into assessments of maximum magnitudes for area sources. The lengths of zones of concentrated seismicity (source type 2) may be assessed to represent maximum lengths of rupture. The dimensions of tectonic elements within a source may also provide physical constraints on maximum earthquakes. For example, a source that is defined as including a region of crustal deformation may include a consideration of the dimensions of faults within the deformation zone.

The uncertainties associated with the assessment of maximum earthquake magnitudes for area sources must be incorporated into a probability distribution for each source. The technical basis for the assessment and the associated data must be fully documented.

4.2.3 Earthquake Recurrence

Earthquake recurrence relationships express the annual frequency (which is usually assumed to be constant in time) of earthquakes having various magnitudes up to the maximum magnitude and they must be developed for each seismic source. The methods for developing these relationships are usually different for fault sources than for area sources.

Faults (Source Type 1)

The development of recurrence relationships for fault sources can include information from both the historical seismicity record and the geologic record. Typically, observed seismicity provides constraints on the frequency of small-magnitude events and the slope of the recurrence curve; the geologic record provides the frequency of larger-magnitude events.

To use observed seismicity to estimate earthquake recurrence first requires that an assessment be made of which events can be associated with the fault of interest. For instrumentally recorded earthquakes, a corridor around the fault should be specified that accounts for the dip of the fault and the epicentral location uncertainties. Associations with older historical earthquakes must consider uncertainties in epicentral locations.

The use of observed seismicity for recurrence assessment, for either faults or areal source zones, must account for incompleteness in the catalog as a function of magnitude, location, and time. The recurrence rate that is needed for seismic hazard analysis is the rate of independent main shocks, which are typically assumed to be distributed randomly in time. Therefore, dependent events (foreshocks, aftershocks, clusters) must be removed for use in the hazard analysis.

In plotting recurrence from observed seismicity (for example, Figure 4-2), it is helpful to indicate the average or mean frequency at particular magnitudes as well as to indicate the statistical variability of the frequency estimate for that magnitude (e.g., Weichert, 1980). Such a plot, expressed for example with 5- and 95-percent confidence limits, typically shows the progressively larger errors with increasing

magnitude. This is directly due to the occurrance of progressively fewer events as the magnitude increases.

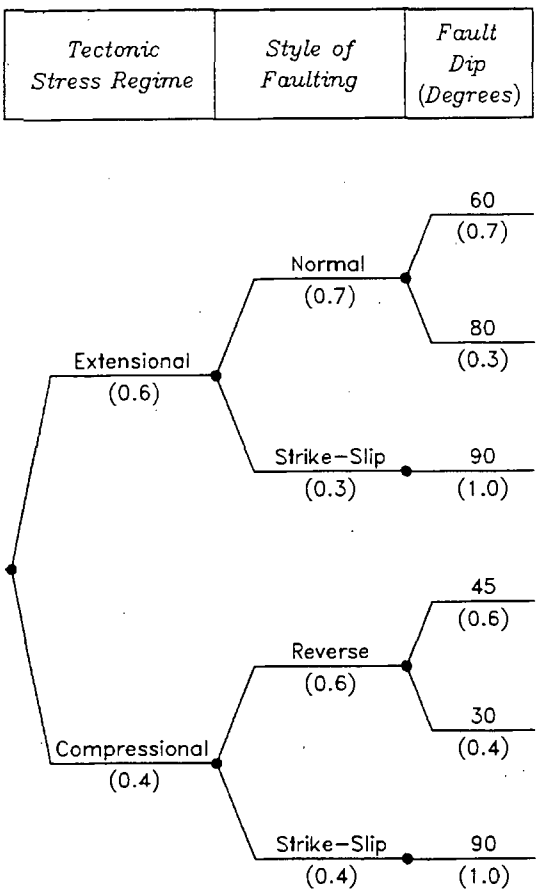

Figure 4-2 Example logic tree illustrating the manner in which assessments of the tectonic model can affect assessments of seismic source characteristics such as source geometry. In the example, the assessment of the tectonic model (in this case the nature of the regional stress regime) affects the assessments of the expected style of faulting and, in turn, the dip of faults.

Geologic data often provide valuable information regarding the recurrence of larger-magnitude earthquakes. Paleoseismic data can provide assessments of the recurrence intervals associated with earthquakes that have ruptured the surface. In using paleoseismic data, the uncertainties the recurrence intervals and the magnitudes of the paleoseismic events should be included. Another type of geologic constraint on earthquake recurrence is provided by the fault slip rate. The slip rate can provide an estimate of the average rate of release of seismic strain energy. (See Coppersmith, 1991 for discussion of the use of slip rate for recurrence estimation.) To use the slip rate, it must be partitioned into various earthquake magnitudes according to a magnitude-distribution model. Two alternative models are the truncated exponential model and the characteristic earthquake model (Youngs and Coppersmith, 1985). The characteristic earthquake model appears to be more valid for describing the recurrence behavior of individual faults (e.g., Schwartz and Coppersmith, 1984; Youngs and others, 1993). Both the exponential and the characteristic earthquake model require an estimate of the b-value in the exponentially distributed part of the recurrence curve. This estimate is commonly derived from the average b-value in the region based on observed seismicity. The uncertainties in slip rates and magnitude-distribution models should be incorporated and documented.

A suggested representation of earthquake recurrence relationships for individual faults is to indicate the frequency of observed earthquakes, with associated statistical error bars, the recurrence intervals from paleoseismic data, and the mean recurrence curves derived from the slip rate and magnitude-distribution model (Figure 4-2).

Area Sources (Source Types 2–4)

The assessment of earthquake recurrence for area sources commonly relies heavily on catalogs of observed seismicity. To maximize their utility, seismicity catalogs should be reviewed for uniformity in designation of magnitudes and for completeness as a function of magnitude, location, and time. The association of older historical events with particular seismic sources should be assessed bearing in mind the location uncertainties. For example, whether a large-magnitude historical earthquake, such as the 1886 Charleston earthquake, occurred in one source or another may be important to estimates of recurrence within those sources.

The observed seismicity rates can be plotted as mean frequencies for each magnitude, along with the statistical uncertainties due to the number of

events within each magnitude bin (e.g., Figure 4-2). Using these observed data, with the maximum magnitude estimate, a recurrence curve is fit. A reasonable method for curve-fitting is the maximum likelihood method because it accounts for the decreasing number of points as magnitude increases. The result is a recurrence curve that expresses the recurrence rate for various-magnitude earthquakes up to the maximum. Various methods for expressing the uncertainty in recurrence curves are discussed in Section 4.3. An appropriate magnitude-distribution model for area sources is a truncated exponential distribution.

The degree of variation, or "smoothing," of the a- and b-values within an area source can be specified. Uniform a and b throughout the source represents maximum smoothing, and different levels of smoothing can be identified. Guidance on the use of spatially varying recurrence parameters within a seismic source is given in Section 4.3.5.

4.3 Characterizing Epistemic Uncertainties in Seismic Source Characterization

Section 4.2 presented the basic elements of seismic source characterization that are required for PSHA. All of the elements discussed are uncertain and this epistemic uncertainty can be addressed in a variety of ways. In this section, approaches to characterizing the uncertainties in SSC are discussed.

4.3.1 Seismic Source Location and Geometry

Two basic approaches have been commonly applied in characterizing the uncertainties in source location and in specifying the activity of sources: alternative maps of seismic sources each associated with a relative weight, and alternative configurations of a seismic source each associated with a relative weight or probability of activity. Both of these approaches are acceptable and the preference for one or the other depends upon the SSC expert.

Probability of activity is an expression of the likelihood that a particular seismic source is seismogenic or capable of generating significant earthquakes. This assessment is most commonly made for individual faults, but has also found application (for example, in the EPRI eastern United States study) in assessing particular area sources interpreted on the basis of various tectonic features. In many cases, there may be uncertainty regarding whether or not seismic sources shown on source maps are active. Hence an assessment of the probability of activity must be made. An equivalent assessment is the probability of existence of a particular source zone.

The activity of fault sources is commonly assessed using the criteria developed from regulatory experience. For example, the concept of fault "capability," which is given in NRC's geologic siting criteria for nuclear power plants (10 CFR Part 100, Appendix A), is a common basis for assessing activity of faults. Fault activity assessment usually involves criteria that are believed to provide an indication of the potential for future earthquake occurrence. Such criteria include spatial association with past earthquakes, evidence for geologically recent displacement, structural association with other active faults, and the like. The relative usefulness of these various criteria is often quite different and should be identified.

The probability of activity of source zones has been evaluated in two alternative, equally credible, ways in the EPRI and LLNL studies for the eastern U.S. In the EPRI approach, tectonic features that might be seismogenic were identified and their probability of activity assessed. The criteria for assessing the activity of a feature are first identified and defined. Criteria include such attributes as spatial association with large- or small-magnitude earthquakes, evidence of geologically recent slip, orientation relative to the regional stress regime, and the like. The relative weight or relative value of each criterion in assessing the probability of activity is evaluated generically in a "tectonic feature matrix." Then these criteria are applied to each feature to assess its probability of activity. The seismic sources interpreted from the tectonic features (i.e., "feature-specific source zones") are then assigned

a probability of activity equivalent to that of the feature.

In the LLNL study, the probability of activity is defined as the probability of "existence" of a particular source zone. In practice, rather than making the assessment on a source-by-source basis, alternative source maps are developed—each map having its own probability of existence or credibility. The hazard calculations include this probability in combining the alternative maps. The probability of activity/existence expresses the uncertainties in the locations and geometries of seismic sources for the PSHA. In all applications of the probability of activity or existence, the criteria for making the assessment must be documented, the relative value of the criteria must be evaluated, and the basis for the assessments must be documented.

In expressing the probability of activity it is important to specify clearly the criteria that are being used to evaluate the activity and the relative weight that the criteria have in the evaluation. In the EPRI procedure, the criteria and their relative weight were specified using a "tectonic feature matrix" and were used to evaluate a large number of features. In addition, dependencies among sources may need to be indicated. In some cases, for example, one interpretation of the configuration of a seismic source may be judged to be mutually exclusive with another configuration, or one interpretation may be judged to depend on other interpretations. In these cases, additional assessments that describe these dependencies need to be made in order to properly combine all of the sources in the seismic hazard analysis (EPRI, 1989).

Another way in which tectonic interpretations are linked with seismic source geometries is through considerations of tectonic models. Alternative tectonic models for a region may imply different source geometries. For example, alternative tectonic models for a region may imply that mapped faults are either high-angle strike-slip faults or low-angle thrust faults. The uncertainty in tectonic models should be treated first in terms of alternative models, each with its relative weight. Then the alternative source geometries that are implied by these models can be developed as a function of each particular tectonic model. The resulting alternative tectonic models can be summarized in a logic tree format (see example in Figure 4-2).

Uncertainties in all of the parameters defining the geometry of individual sources can be characterized using weighted alternative parameter values or estimated continuous distributions. These parameters include maximum depth of seismogenic crust, focal depth distribution, fault dip angle and direction, total fault length, and updip and downdip extent (for blind faults).

4.3.2 Maximum Earthquake Magnitude

Maximum earthquake magnitude is a parameter for each seismic source. As such, its uncertainty can be defined by discrete alternative values with relative weights or using a continuous probability distribution. In addition to direct assessments of Mmax, it is also common to display and incorporate the uncertainties in the parameters and models that were used to derive the maximum earthquake as well. For example, maximum magnitudes for fault sources are typically estimated based on estimated maximum dimensions of rupture, including maximum surface rupture length, subsurface rupture length, maximum displacement, and average displacement. These rupture dimensions are, in turn, empirically related to earthquake magnitude. For a given fault having data related to each of these dimensions, it may be useful to express the relative weight to be given to each of the them in assessing the maximum earthquake. In addition, if multiple segmentation models are used to estimate rupture length, these models should each be associated with a relative weight. Clearly, a logic structure is a convenient way to express the relative weights applied to various approaches and parameters used to assess the maximum magnitude. Using a logic tree format, the maximum magnitude distribution for the source is simply a probability distribution of the type shown in Figure 4-3. The discrete Mmax distribution can be used directly in the seismic hazard analysis.

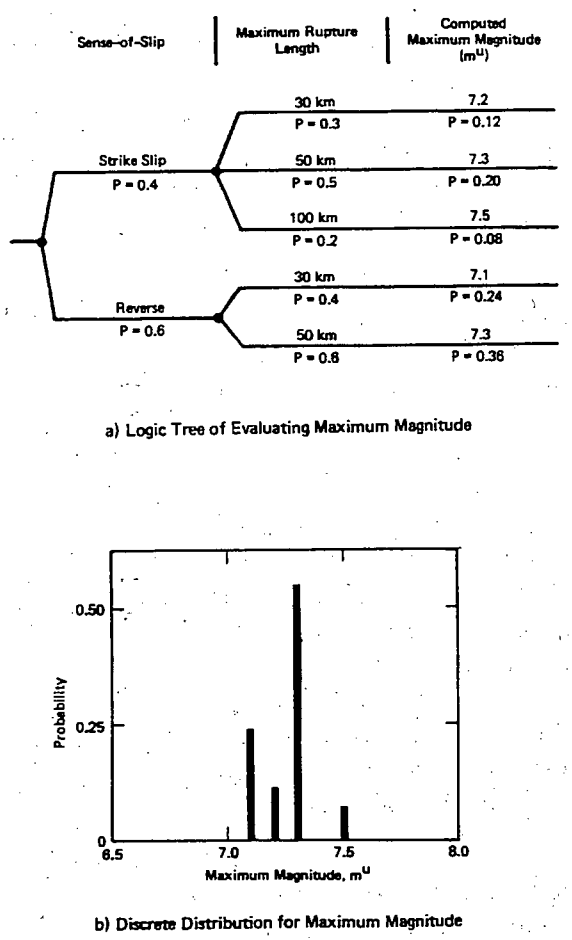

Figure 4-3 Example logic tree showing the manner in which assessments of fault rupture dimensions, and associated uncertainties, leads to a probabilistic distribution of maximum magnitude. In the example, the sense of slip on the fault is uncertain and the expected maximum displacement per event is assessed conditional on the sense of slip. Each displacement value is related empirically to earthquake magnitude. The probability associated with each magnitude on the end branches is the product of the probabilities on the branches of the logic tree leading to the end branch. The result of the analysis is a discrete distribution of maximum magnitude, which can be used directly in the PSHA.

For assessing the Mmax of area sources, the procedures discussed in Section 4.2 are used, and a distribution of Mmax is usually assessed directly. An approach for assessing Mmax for sources in the eastern United States has been proposed by EPRI (1993), which is based on tectonic analogies between the eastern United States and other stable continental regions worldwide. In the procedure, a *prior* distribution of Mmax is assessed based on a statistical analysis of the global data base, and this distribution is updated based on source-specific information.

4.3.3 Earthquake Recurrence

Earthquake recurrence for individual seismic sources is defined by the a-value (also called the activity rate), b-value (slope of the recurrence curve expressing relative number of exponentially distributed small- and large-magnitude earthquakes), and Mmax. As discussed in Section 4.2, alternative magnitude distribution models are often important for describing the recurrence behavior of individual faults. The goal of uncertainty characterization for recurrence is to define the range of variation of the frequency-magnitude distribution. There are several ways to do this, depending on the type of seismic source.

Consider first area sources, for which the basis for recurrence estimation is observed seismicity. The first source of uncertainty is the magnitude of earthquakes contained within any catalog. As discussed in Chapter 5, the preferred magnitude for PSHA is moment magnitude and, until the eastern United States catalog can be translated to moment magnitude, Nuttli magnitude (m_{bLg}) . In the eastern United States, most of the catalog of instrumental earthquakes is given in terms of Nuttli magnitude, although the M>4.5 historical earthquakes have been converted to moment magnitude using isoseismal areas (Johnston and others, in EPRI, 1993). Johnston and others provide uncertainty estimates in the moment magnitudes for each of the historical earthquakes in Johnston's catalog. Likewise, EPRI (1989) considered the uncertainty in the m_{bLg} estimates in the catalog and propagated that uncertainty into the recurrence analysis. Commonly, recurrence curves for sources are fit to observed data using a maximum likelihood procedure, to account for variations in the number of earthquakes in each magnitude bin. The statistical variability in the mean recurrence within each magnitude bin can be defined using Weichert's method (1980). Based on the observed earthquake counts (accounting for catalog incompleteness) and based on the

assumptions above, a plot can be developed showing the observed counts by magnitude, the variability in mean rate at each magnitude bin, and a maximum likelihood fit to the observed data. An example is shown in Figure 4-4. If the seismic source is very active and has generated a large number of earthquakes throughout a range of magnitudes, then the recurrence relationship derived directly from observed data may be sufficient to describe the uncertainties in recurrence for the source. Unfortunately, this is rarely the case. Typically, the observed earthquakes are few in number and small in magnitude. Hence, additional effort is required to assess the uncertainty in recurrence parameters.

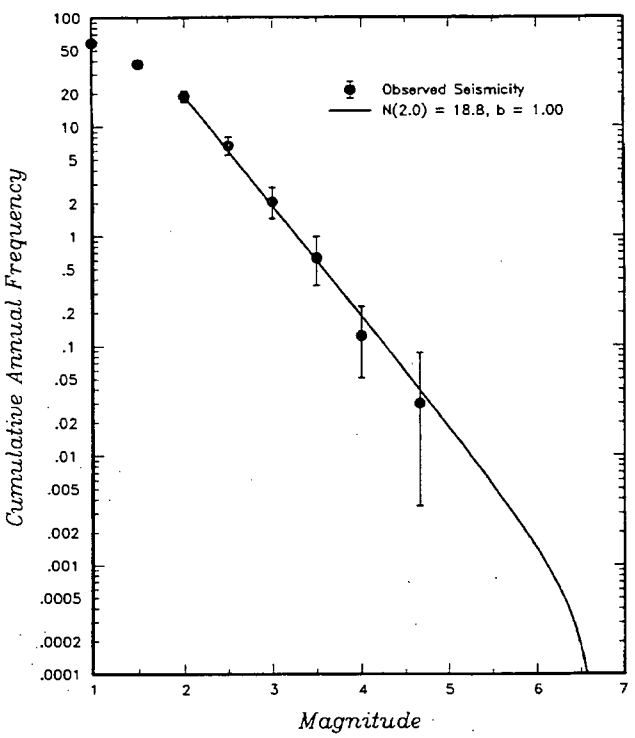

Figure 4-4 Example recurrence curve and observed seismicity for an area seismic source. The curve is the maximum likelihood truncated exponential recurrence relationship. The dots denote the mean annual frequency of observed earthquakes and the vertical error bars denote the 90% confidence interval on the cumulative rate of observed earthquakes (corrected for completeness). The parameters of the truncated exponential recurrence relationship are the cumulative annual frequency of events larger than magnitude 0 (the a-value), and the slope of the $\log_{10}$ frequency-magnitude recurrence curve, b.

Two alternative approaches have been used to describe the uncertainties in recurrence relationships (e.g., Savy et al. 1993). (Again, we are discussing an area seismic source and assume an exponential magnitude distribution). In the first approach, uncertainties in a-values and b-values are defined, including the correlation between the two parameters. Experience in the 1989 LLNL study (and corrected in the 1992 study) has shown that unintentional combinations of a- and b-values can result if the correlations between a and b are not defined. For example, suppose that one expresses the mean and uncertainty in a-value and the mean and uncertainty in b-value for a particular source. Unless the correlation between the two variables is specified, there may be combinations of a- and b-values that lead to unintended recurrence rates (e.g., a high a-value may be combined with a low b-value, resulting in high rates for large-magnitude earthquakes).

In the second approach, frequencies or recurrence intervals are assessed at particular magnitude levels. In the LLNL (1992) approach, these frequencies were elicited at two levels: at lower magnitudes where observed data are present and at larger magnitudes close to the maximum. The uncertainty in the frequency estimate can be described by a best estimate and a range of values. The net effect of this approach is also to eliminate unintentional extreme recurrence distributions that can result from assessing a-values and b-values independently.

The choice of the magnitude distribution model is usually based on the type of seismic source being considered: the exponential magnitude distribution is commonly considered appropriate for area sources (which presumably contain multiple faults), and the characteristic earthquake model is commonly considered appropriate for individual faults. There may be cases where the choice of the magnitude distribution model is uncertain. For example, a relatively small area source that includes a highly active zone of seismicity (e.g., the New Madrid seismic zone) may be characterized by either an exponential distribution (because of its areal extent) or a characteristic distribution (because the seismicity may be dominated by a single fault).

For fault sources, the uncertainties in earthquake recurrence are generally related to uncertainties in the models and parameters that are used to make the assessment. For example, a common approach to assessing earthquake recurrence is the use of fault slip rate, whereby the fault slip rate (which is uncertain) is multiplied by the area of the fault (also uncertain) and the rigidity of crustal rocks to arrive at a total average seismic moment rate. This seismic moment rate is then partitioned into earthquakes of various sizes according to a magnitude distribution model such as the characteristic earthquake model. Alternative approaches to estimating fault-specific recurrence are the use of paleoseismic recurrence intervals (having uncertainties in both the intervals and the sizes of the paleo-events) and geodetic strain data (uncertainties much like slip rate data). In all of these cases, a logic tree procedure is an effective way to sequence the models and parameters leading to the recurrence estimates and to propagate the uncertainties into the recurrence distributions. For fault sources, the observed seismicity is usually too sparse to provide a strong constraint on the recurrence rate, but, for more active faults, could control the recurrence rates in the lower magnitude part of the distribution.

4.3.4 What SSC Information is Elicited and What is Calculated?

The purpose of this section is to summarize information that must be elicited from SSC experts and describe which information can be calculated by the hazard analyst. The goal here is to provide an idea of the types of tasks that SSC experts should be prepared to accomplish.

At a minimum, the SSC experts should be prepared to provide the following:

- Seismic source map and alternative maps or alternative source configurations and the probability of activity for each.
- Any source activity dependencies (i.e., the assessment that one source is active if another is active).
- Focal depth distribution for all sources.
- Three-dimensional geometries for faults and associated uncertainties.
- Maximum magnitude distribution for all sources.
- Designation of an earthquake catalog for each source. Time periods over which the catalog is complete (either zero or fractional).
- Choice or approval of a magnitude distribution for each source. Where appropriate, multiple models should be specified with weights, or distributions of parameter values should be given (if one model is used). If the exponential model

  (Log N = a - bM) is used, an a-value and b-value must be specified, and the expert should use either:

  — pairs of values with weights

  — joint distributions of a and b with the correlation specified

  The magnitude distribution may vary in space within a source area.
- For faults, the expert may specify the distribution as above, or may use slip rate, b-value and magnitude distribution to specify the recurrence rate. These parameters can be readily transformed to magnitude recurrence information by the analyst. As is the case for areal sources, either discrete or continuous distributions may be used, but correlations must be specified.

4.3.5 Considerations on the Spatial Variation of Seismicity Within a Seismic Source Philosophical Basis and Implications of the Assumption of Homogeneous Seismicity

It has been assumed in many seismic-hazard studies that seismic sources of types 2, 3, and 4 have homogeneous seismicity; i.e., that the a-value and the b-value are the same for all points within the seismic source. According to this assumption, if the seismicity catalog were extensive enough over time, one would observe the same density of earthquakes (events per unit

area) in any small area within a given source. This assumption has two very important implications on the calculated seismic hazard, as follows:

1. On the mean hazard. All sites located within a homogeneous seismic source (and sufficiently far from the source boundary) will have the same mean hazard due to this source, regardless of the spatial distribution of historical earthquakes within the seismic source.

2. On the statistical uncertainty in hazard. The activity rate and b value for this seismic source are calculated using all the historical earthquakes in the source. The statistical uncertainty in the rate and b value are lower than they would be if this source was sub-divided into two or more smaller sources.[1]

These two effects are particularly important for large seismic sources of regional or tectonic-providence dimensions (i.e., source types 3 and 4).

The assumption of homogeneity is almost always made for the sake of simplicity (i.e., fewer parameters are required) and is driven more by ignorance than by a firm belief in homogeneity (e.g., the expert does not sub-divide this large source because he/she does not know how to sub-divide it, not because he/she thinks it has homogeneous seismicity). If a seismic source (particularly sources of types 3 and 4) is defined on a basis other than patterns of seismicity (see Table 4-1), there is no reason for the assumption of homogeneity to be valid.

In any seismic hazard analysis, the assumption of homogeneous seismicity must be justified and alternative assumptions may have to be included in the model of seismic sources. As a minimum, one must confirm that the assumption of homogeneous seismicity is not inconsistent with the spatial distribution of historical seismicity, using the statistical tests to be described below or other appropriate statistical techniques. If the assumption of homogeneity is not consistent with the data, and the source is a significant contributor (>30%) to the hazard at the site, the source should be sub-divided into more homogeneous sub-sources or the assumption of constant rate and b throughout the source must be relaxed by using the EPRI approach (see EPRI 1986; VanDyck 1986) or a similar approach.

Statistical Tests for Homogeneity

The following simple statistical test indicates whether the assumption of homogeneous seismicity is consistent with the spatial distribution of historical seismicity within a seismic source. The test consists of the following five steps:

1. Sub-divide the seismic source into smaller sub-sources using, for example, the 1-degree or 0.5-degree grid used by EPRI (1986).

2. Calculate the observed historical earthquake rate in each sub-source.

3. Calculate the expected number of earthquakes using the homogeneous model in each sub-source, considering the sub-source area, the length of the catalog, and the catalog-completeness assumptions.

4. Compare the expected and observed numbers of earthquakes in each sub-source and flag those sub-sources with statistically significant differences. Figures 4-5 and 4-6 illustrate this test. Figure 4-5 shows the source and its historical seismicity; Figure 4-6 shows the flags associated with the 10% and 2% significance levels.

5. Examine the number and pattern of flags to determine if the assumption of homogeneous seismicity is consistent with the catalog. If α is the significance level used in step 4, one would expect approximately a fraction α of the sub-sources to have the associated flags. Too many flags indicate that the assumption of homogeneous seismicity is inconsistent with the catalog; too few flags indicate that the catalog is too limited to provide any indication about spatial patterns of seismicity. Even if the number of flags is not unexpected,

[1] As a rule of thumb, the coefficient of variation in the activity rate is approximately $n^{-1/2}$ where n is the number of earthquakes in the seismic source. The standard deviation in the b value is also proportional to $n^{-1/2}$.

the concentration of positive or negative flags in a certain portion of the source is an indication that the assumption of homogeneous seismicity is inconsistent with the catalog (at a spatial scale larger than the grid size)[2]. In Figure 4-6, the number of flags clearly indicates that the assumption of homogeneous seismicity is not consistent with the spatial pattern of seismicity in the catalog.

This test is implemented in the EQPARAM code developed by EPRI (EPRI 1986). The code estimates seismicity parameters under assumptions of homogeneous or spatially varying parameters, but it may be easily used to perform these tests only. Also, this test is relatively easy to implement as a stand-alone code.

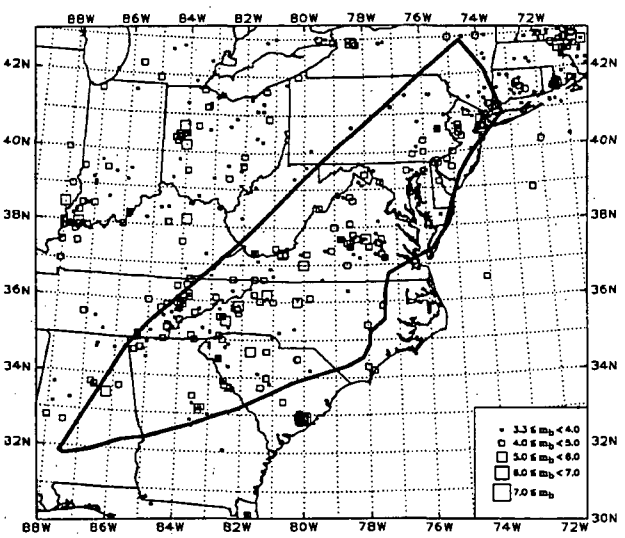

Figure 4-5 Map showing a background source for the southern Appalachians and the historical seismicity in the EPRI catalog.

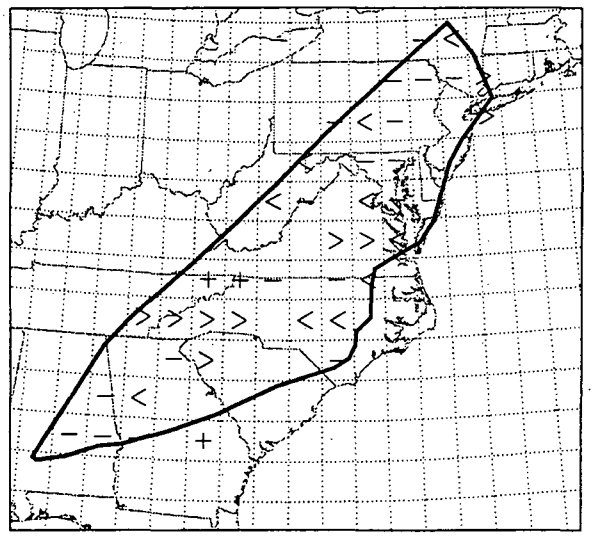

Figure 4-6 Diagnostic flags from the statistical test of homogenaity of seismicity for the source shown in Figure 4-5. "+" ("-") indicate that the observed count in a sub-source is significantly higher (lower) than predicted at the 10% significance level; ">" ("<") indicate that the observed count is significantly higher (lower) at the 2% level. Approximately 8% (i.e., 10-2) of the sources should have ± flags; 2% of the sub-sources should have ">" or "<" flags.

Special Circumstances Requiring Models with Spatial Variability

Even if the above statistical tests do not reject the assumption of homogeneous seismicity, there may be situations where this assumption alone may not be sufficient for the characterization of seismic hazard and its uncertainty at a site. The following two criteria are proposed in this regard.

Spatial variability should be considered for a seismic source, even if the assumption of homogeneous seismicity is not rejected, if the following two conditions apply:

1. Earthquake count in the source. The earthquake count is very small, so that it provides little indication about the spatial distribution of seismicity in the source (e.g., some sub-sources contain one to three events, others contain none).

and

[2]This test is not a really a spatial-homogeneity test. Rather, it is a series of univariate significance tests. Thus, the test requires some interpretation from the expert or analyst in Step 5. On the other hand, the test is easy to implement, intuitive, and very informative. Other tests for spatial homogeneity are available in the literature (e.g., Ripley 1981).

2. Percent contribution to seismic hazard at the site (based on preliminary seismic-hazard results). The source contributes more than 30% of the seismic hazard at the site (for any exceedance probability or ground-motion measure of interest).

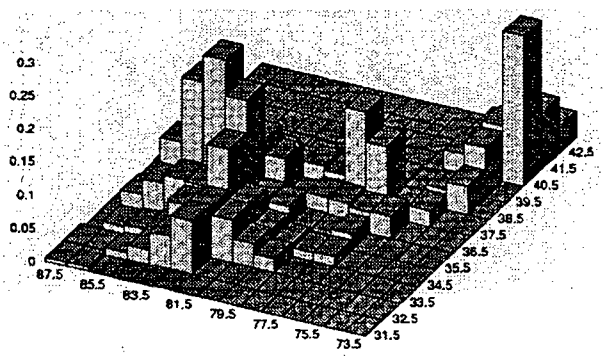

Figure 4-7 Spatial distribution of rate (m_b>3.3) per unit area (events/yr/deg^2) for the source of Figure 4-5, obtained with the assumption of low smoothing on *a* and high smoothing on *b*.

The motivation for requiring the use of spatial variability, even though it is not required by the catalog, is that the objective of a seismic-hazard study is to quantify both the mean hazard and its uncertainty.

Spatially Varying Seismicity Parameters: EPRI Model

The EPRI model for spatially varying seismicity parameters is presented here as one possible model for relaxing the standard assumption of homogeneous seismicity parameters throughout the seismic source. Another possibility is simply to sub-divide the seismic source into a few sub-sources, so that the seismicity becomes more homogeneous[3].

The EPRI model sub-divides the seismic source along a one-degree latitude-longitude grid, resulting in sub-sources of dimensions of one square degree or less. Values of a and b are estimated for each sub-source. This model can accommodate observed spatial variations of historical activity within a given source. This approach constitutes a moderate departure from traditional seismic hazard analysis, in the sense that it assumes (or can assume) a relatively smooth spatial variation of the activity rate. Also, each sub-source retains all the properties of the seismic sources of traditional seismic-hazard analysis. This model may be considered as intermediate between historical and conventional seismic hazard analysis.

In order to avoid problems with sub-sources that have low or no earthquake counts, and to reduce the uncertainty in the estimates of a and b, smoothing assumptions are introduced, which impose dependence between the seismicity parameters in adjacent sub-sources. Thus, the seismicity parameter in one sub-source depends, to some extent, on the earthquake counts in adjacent sub-sources within the same source. Conceptually, the smoothing assumptions may be interpreted as prior distributions on the degree of spatial roughness of a and b within the seismic source. Because this is not an easy concept, experts typically specify multiple values of the smoothing parameters, with associated weights, as an indication of their subjective uncertainty about the appropriate prior distribution.

Smoothing is specified separately for a and b. The smoothing assumptions range from full smoothing to no smoothing. Full smoothing on both a and b is the same as assuming that seismicity in the source is homogeneous; no smoothing on both a and b is the same as treating each sub-source as a separate source. Typically, b is assumed to be smoother than a, because b has been observed to be more geographically stable. The statistical test described earlier provides guidance for the selection of smoothing assumptions.

The seismicity parameters a and b for each sub-source are estimated using maximum penalized likelihood, where the penalty terms represent the smoothing assumptions. The result is a pair of "maps" for a and b within the source. As an example of the type of results obtained, Figure 4-7 shows the activity rates for the source in Figure 4-5, calculated under the assumption of low smoothing on a and high smoothing on b. Because the equivalent number of parameters

[3]One potential problem with the approach of sub-dividing the source into a few sub-sources is the choice of where to subdivide. Unless there are sharp contrasts in seismicity or obvious boundaries suggested by the the geology or geophysics, the choice of boundaries may lead to biases.

being estimated is larger than when homogeneity is assumed, the associated statistical uncertainty is higher. This uncertainty depends on the earthquake counts in the various sub-sources and on the smoothing assumptions; lower smoothing leads to more uncertainty in seismicity parameters. This higher uncertainty is not necessarily undesirable, because it may be more realistic.

Analytical calculation of the statistical uncertainty in the seismicity parameters is difficult because the smoothing introduces correlation. One simple way to quantify this uncertainty is by using a technique known as "bootstrapping," where artificial catalogs are generated (using the actual catalog or the estimated seismicity model) and maps of a and b are calculated for each artificial catalog. One then propagates this uncertainty into hazard space by calculating the seismic hazard associated with each alternative map of a and b.

The statistical uncertainty in the hazard—due to statistical uncertainty in spatially varying models of seismicity—must be quantified as part of the hazard calculations as described above. In fact, this statistical uncertainty may often be more important than the uncertainty about the proper level of smoothing.

The EQPARAM software package (EPRI 1986) performs all the calculational steps described above, including bootstrapping. Some further enhancements to these techniques have been proposed and tested (Veneziano and Luna Pais 1986; Veneziano and Chouinard 1987), the most significant enhancement is the optimal selection of smoothing parameters. These enhancements are not currently implemented in EQPARAM.

Appendix I contains detailed examples showing the a and b maps obtained under different smoothing options, the associated statistical uncertainties, and the effect of these uncertainties on the calculated seismic hazard.

4.3.6 Significant Changes in Hazard due to Seismic Source Characteristics

A significant amount of effort must go into seismic hazard analysis to obtain meaningful results, and this effort should be used in the most efficient way possible. To this end, it is important to examine which SSC parameters contribute significantly to seismic hazard, and to determine when changes in those parameters make significant differences to the computed hazard. The identification of important parameters can then be made on an informed basis so that maximum effort can be guided toward evaluating those SSC parameters that make the most difference to the hazard.

The real benefit in considering which parameters contribute to significant changes in hazard comes from being able to concentrate on the evaluation of important parameters (both in the sense of the best estimate and of the uncertainty) while neglecting, or treating in an approximate fashion, other parameters that are not significant or are only marginally significant. Thus, consideration of significant parameters involves both an evaluation of what drives the seismic hazard in the sense of the best-estimate hazard, and what contributes significantly to uncertainties in hazard.

To these ends, the Committee has formulated a procedure to guide the evaluation of which SSC parameters deserve the most scrutiny. The procedure is presented in Appendix G. Also given in Appendix G are a series of hazard analyses conducted by Risk Engineering and LLNL for a set of conditions related to source-to-site distances, focal depth distribution, maximum magnitudes, earthquake magnitude distributions, b-values, and a-values (activity rate). The goal of these analyses was to determine the relative importance of certain SSC parameters and combinations of parameters relative to the best-estimate hazard and the contributions to the uncertainty in the hazard (as a function of the structural period of the ground motion estimate and probability level). Some of the important conclusions of these analyses (which are given fully in Appendix G) are the following:

- Uncertainty in fault location causes a moderate sensitivity for most sites for high-frequency ground motions, and less sensitivity at low frequencies. For source zones, this applies to sites located outside the

source, but especially near the source boundary.

- Sensitivity to depth distribution is negligible except at small source-to-site distances (less than 50 km).
- Sensitivity to maximum magnitude is largest at large source-to-site distances. It increases with ground motion amplitude, and is largest when the mean Mmax values are lower. (The sensitivity is greater when the mean Mmax is 6.0 rather than 7.5 for fixed a- and b-values).
- Sensitivity to the b-value is moderate, except at small source-to-site distances (less than 25 km).
- Sensitivity to whether an exponential or characteristic magnitude distribution is used depends on whether a slip rate constraint or a seismicity constraint is used to fix the rate of activity (a-value). If a slip-rate constraint is used, the maximum sensitivity occurs for very close or very distant sites. If a seismicity constraint is used, calculations at all distances are sensitive to the choice of the model.

4.4 Specific Expert-Elicitation Guidance on Seismic Source Characterization

4.4.1 Introduction

Seismic source characterization involves assessment of the location, rates, and maximum size of future earthquakes, which are variable, i.e., have aleatory uncertainties. Also, there is sparse historical evidence in most areas as well as limited understanding of the mechanisms associated with earthquake occurrences. Thus, our ability to model earthquake occurrences is subject to epistemic uncertainty. Because of the limited experience and understanding there is a diversity of interpretations of seismic source characteristics within the informed technical community and, for purposes of PSHA, it is necessary to capture the community distribution of source characteristics. Thus, as discussed in Chapter 3, SSHAC recommends using either the TI or TFI approach to derive the SSC inputs for a PSHA. The study level (1-4) will depend on the scope of the study and the expected complexity and contentiousness of the SSC.

The approaches discussed below are consistent with the general guidelines and concepts regarding the TFI and TI approaches discussed previously in Chapter 3. However, the procedures and methods discussed in this section are specific to SSC and differ somewhat from those procedures outlined for incorporating judgments related to ground motions (Section 5.6). For example, an essential and first step in seismic source characterization is the identification of seismic sources. In most regions of the U.S., the interpreted geometry of seismic sources will vary with the source characterizer and, therefore, each expert's map of sources will be different. The subsequent characterization of these sources (e.g., by recurrence parameters) will be specific to the particular interpretation of the expert. Because of this, there is no easy way to compare the results of the characterization from one expert to the next directly. More importantly, there is no easy way to integrate the results of the analysis at an intermediate step (say, the seismic source maps), nor can the final results of the seismic source characterization be readily combined, other than at the final step of the seismic hazard analysis. An exception might be in highly active tectonic environments in which the seismic source maps among various experts (reflecting active faults) might be very similar. Also, it may be possible to arrive at a consensus source map that a group of experts can all endorse. In this case, the uncertainties in scalar quantities (e.g., the slip rate on a particular fault) may be amenable to integration across multiple experts. In the future it may be desirable to move SSC in a direction that allows for more integration at intermediate levels of the analysis; for example, through the development of consensus seismic source maps for regions of the U.S.

A SSHAC-sponsored workshop designed to examine the pros and cons of SSC expert elicitation methodologies (see Appendix H) is the resource for the following discussion. The participants at the workshop were SSC experts who themselves have been elicited as part of

several seismic hazard analyses. As such, their experience represents a unique data base from which to draw conclusions about which SSC elicitation approaches "work" and which "don't work." Many of the elements of the recommended SSC expert elicitation methodology find support in the conclusions drawn by the experts at the workshop, as well as reviews by SSHAC of several PSHA projects conducted for both regional and site-specific applications.

In discussing the recommended methodologies for incorporating SSC expert judgment, the section begins with recommended approaches to quantifying SSC expert judgments using either the TFI approach or the TI approach, then considers how the approaches may vary as a function of the resources available for the project (resource-intensive versus modest resources) and the application (site-specific versus regional hazard assessment).

From the standpoint of seismic source characterization for PSHA, the Committee concludes that either the TFI or TI approaches can be used to quantify SSC characteristics and uncertainties, depending on the expected contentiousness of SSC in the region of interest. Because of SSHAC's emphasis on capture of the diversity of interpretations within the informed technical community, we will emphasize Study Levels 3 and 4, discussed in Section 4.4.3 and 4.4.2 respectively, based on the use of multiple experts as the primary sources of inputs. Modifications, assuming only limited resources and site-specific versus regional studies, are discussed in Section 4.4.4.

4.4.2 The TFI Approach

The TFI approach to deriving SSC inputs for a PSHA is to be used for those studies in which there is considerable diversity of interpretations of the seismic sources and/or the seismicity in the region of interest. Use of the TFI approach is based on the premise that representation of the community distribution of SSC's is best derived by eliciting inputs from a panel of experts, acting as evaluators and individual integrators. The products of the elicitation are:

- Alternative seismic source maps and distributions of seismic source characteristics from each expert representing his/her SSC with uncertainty

and

- Alternative seismic source maps and distributions of seismic source characteristics describing each expert's view of the informed technical community's distribution of seismic sources and seismicity.

An important TFI function is to facilitate during the workshops prior to the elicitation and involve proponents, resource experts, and evaluators. These workshops must include discussions of the historical data bases of earthquakes, geologic and tectonic models regarding the localization of seismicity, models of seismic source interpretations, frequencies and distributions of magnitudes of earthquake, as well as methods and procedures for analyzing and summarizing the historical data for use in developing SSCs.

Another important part of the TFI process is the elicitation of inputs from the evaluator experts. Because the experts need to provide descriptions of aleatory uncertainty and to describe their epistemic uncertainties in providing these descriptions, it is essential that the elicitation involve individual interviews. It is also important that experts be educated and trained in the concepts of aleatory and epistemic uncertainties as well as in ways of formulating and quantifying their epistemic uncertainties. The basic steps in the recommended methodology for SSC are given below in terms of the specific application to SSC.

1. Conduct careful expert selection The process of expert selection should be based on a clear set of criteria aimed at capturing a full range of diversity of expert interpretations.

2. TFI role The technical facilitator/integrator should play a strong role, running workshops and expert interactions, monitoring the behavior and participation of the experts, conducting calculations and sensitivity analyses, documenting the final results, and taking intellectual responsibility for the results of the project.

3. Provide a uniform data base to all experts SSC-related data sets, as defined by the experts themselves, should be provided to all of the experts in formats most useful to the experts.

4. Conduct multiple expert interactions Interaction among SSC experts is strongly recommended, through such vehicles as workshops, small working meetings, etc.

5. Elicit SSC judgments from experts Individual expert elicitations should be conducted through person-to-person interviews. Elicitations of expert teams is also acceptable.

6. Conduct sensitivity analyses and submit feedback to experts Following the elicitations, extensive sensitivity analyses should be conducted by the TFI and provided to the experts. They then should interact again as a group to review their interpretations.

7. Finalize SSC interpretations and combine at hazard level Integration/aggregation of SSC interpretations usually occurs at the hazard level. The TFI should create the proper conditions, through the application of 1 through 6 above, to combine the expert judgments using equal weights. Allowance should be made for cases where unequal weights are appropriate (see Section 5.3).

8. Peer review An active or "participatory" peer review should be conducted throughout the study with the particular focus of the process that was followed in conducting the SSC assessment.

Each of these components of the methodology is discussed below.

Expert Selection Because the TFI approach relies on the direct judgments of SSC experts as basic input to the PSHA, the selection of the experts is very important. Further, a desirable outcome of the SSC expert elicitation procedure is to develop a strong, defendable basis for equally weighting the interpretations of the SSC experts when combining the assessments for the hazard analysis. A key part of that basis is that the experts were selected according to a set of criteria that ensure high-caliber, equally-qualified experts.

Two equally acceptable alternatives for expert selection are that it be carried out by the TFI or by the project peer panel. In either case, the entire expert selection process must be thoroughly documented, such that an independent third party could review and understand the procedure followed based on the documentation.

The criteria for selecting the SSC experts must be established and documented. Important criteria should include: geologist or seismologist with a strong professional reputation and widely recognized competence based on academic training and relevant experience, tangible evidence (e.g., peer-reviewed publications and reports) of relevant studies and experience, and availability and willingness to commit the full time and effort needed for the study. In addition, the individual must be willing to forsake the role of a "proponent" espousing a particular hypothesis for that of an "evaluator" who considers all viewpoints and evaluates their relative credibility. In addition to selection criteria for individuals, the project leader should ensure that the experts as a group represent diversity in technical interpretations, areas of technical expertise, and institutional and organizational backgrounds.

If the SSC elicitation will be conducted with teams rather than individuals, the experts should be selected such that a diversity of views and expertise is represented across the teams. In addition, the experts should be informed that they will be working in a team environment.

Following development of the selection criteria, a large pool of potential experts should be identified. This can be done by identifying a few potential experts first and then asking each of them for their nominations. Alternatively, an independent panel may nominate potential experts. The large pool is then narrowed down to a smaller number (about 7 to 15 experts for regional studies, perhaps fewer for site-specific studies) depending on the range and diversity of views. These individuals should then be contacted and informed fully of the purpose of the study, the

specific assessments that they will be asked to make, the manner in which their assessments will be used in the PSHA, and the time and effort that they will need to devote to the project. Either lack of availability or insufficient motivation to commit to the required level of effort are sufficient grounds to exclude that expert from consideration.

At the start of the project, the TFI should establish and discuss with the experts the criteria that would be used to remove an expert from the panel. As discussed in Section 3.3, these criteria would include such problems as the lack of commitment on the part of one of the experts to devote sufficient time to the project, an expert who refuses to forsake the role of a proponent for that of an evaluator, an expert who lacks the interpersonal skills to interact with the other experts in a professional manner. The responsibility for monitoring the performance of the experts lies with the TFI and he, along with the Project Leader and Sponsor, are responsible for the removal of an expert from the panel.

Role of the TFI The TFI role implies proactive participation in dealing with the SSC experts and their elicitation. The TFI team includes a technical peer of the experts and can take a leadership role in selecting the experts, organizing and directing the workshops and other expert interactions, facilitating expert interactions, and monitoring the participation of the experts. Behavioral approaches to achieving integration include active participation in workshops, challenging the interpretations of the experts, looking for areas of consensus among the experts, weeding out differences of opinion due to misunderstandings or definitions, etc. As an example, the TFI should be responsible for developing the sensitivity analyses and feedbacks that are provided to the experts following their elicitations but prior to finalization. This is an opportunity for the TFI to focus the discussion on the implications of the assessments to the hazard results, and the technical basis for the diversity of interpretations.

The TFI approach as applied to SSC may differ somewhat from the TFI approach outlined for ground motions (Section 5.6). In particular, the role of the TFI in integrating the interpretations of the SSC experts occurs primarily through the process of selecting, training, and interacting among the experts (i.e., the seven key elements of the TFI approach discussed earlier). Because there is, as yet, no apparent way to combine SSC expert's seismic source maps (except, perhaps, in highly active areas where the fault locations might be agreed upon, or other cases where a set of sources can be chosen), there is no way to, in turn, develop a distribution of recurrence parameters that properly expresses the range of interpretations across the experts. In contrast, it may be possible to develop these types of distributions on ground motion values for a given set of magnitude and distance combinations. Thus, the role of the TFI in the ground motion case can include an appropriate 'weighing' of the alternative interpretations to arrive at a distribution for certain parameters. In SSC, each expert develops a set of seismic sources and associated parameters (and their uncertainties). These assessments can only then be combined at the end or hazard level, and such combination will require a "weighting" of the interpretations from the various experts. The TFI is responsible for selecting and implementing the scheme for integrating the SSC expert's interpretations. Recommended methods for this integration are discussed further below.

Despite the differences in detail of the TFI approach for ground motions and SSC assessment, they are founded on the same premise: a fundamentally important component to the integration of multiple expert judgments is interaction among the experts. Interaction is a mechanism for resolving unintentional disagreements, presenting interpretations, challenging the interpretations of others, reviewing data bases, and, ultimately, for assisting the experts in their evaluations. Expert interaction is discussed further below.

Data Bases A major responsibility of the TFI is to provide a comprehensive and uniform data base to the experts. Early in the study, the experts and the TFI should identify a comprehensive set of technical issues that will need to be addressed in the source characterization. The data needed to

address those issues should then be identified by the experts in a workshop forum. Formats should be specified, responsibilities assigned for data retrieval, and a realistic schedule established for data compilation. Depending on the wishes of the experts, much of the data base may be amenable to compilation and transfer in digital form to the experts. Care should be taken to clearly define the data needs in terms of "raw" data and any processing that is required by the experts. Any data processed according to the request of a single expert should be made available to any other expert who may desire it. The objective of this effort, which for large regional studies can be very resource-intensive, is to provide all of the experts equal access to the data that are most pertinent to the assessments that they will need to make. Although most of the data base effort will occur early in the project, provision should be made to allow for additional data requests or data processing later in the project.

Expert Interactions Interaction among the SSC experts is a fundamentally important aspect of the SSHAC methodology. Time for expert interaction should be allowed in workshops, small group meetings, and informal communication. Source characterization experts are few in number, often rely on the same data bases, and interact frequently as part of their professional activities. Therefore, the interactions recommended here are a natural scientific extension of the way that earth scientists formulate their ideas about seismic sources.

The purposes of SSC workshops are the following:

- Identify technical issues of greatest importance to PSHA
- Specify the data needed to address these issues
- Educate the experts on the available data and seismotectonic interpretations (resource experts, who themselves are not elicited, may make presentations at the workshop)
- Educate the experts on the methods and procedures that are available to characterize seismic sources and clearly specifying how their assessments will be used in the seismic hazard analysis
- Train the experts on expert elicitation procedures
- Review, technically challenge, and defend SSC hypotheses and interpretations
- Complete behavioral integration of expert interpretations
- Include observation by those not directly involved in the elicitations (e.g., sponsors, regulators, etc.)

The discussion and challenge of interpretations in SSC varies with the topic being considered. For example, seismic source maps developed by experts in the eastern United States are commonly quite different. In a workshop setting, experts can discuss the technical basis for the configuration of their source zones. However, because the sources drawn by any two experts are different, it is difficult to directly compare and challenge the interpretations. Likewise, because recurrence parameters are associated with particular seismic sources, it is often difficult to challenge the parameter values for a given source zone. In contrast, the seismic source maps in active areas are often quite similar among multiple experts. For example, the major faults are usually depicted and characterized. In these cases, the SSC experts are able to discuss and challenge the SSC interpretations made for particular faults, and to directly compare alternative interpretations. For example, the slip rate and recurrence intervals on the San Andreas and Hayward faults could be discussed and debated in a workshop environment.

The number of workshops and their content will vary with the particular study but must cover, at a minimum, the following areas: 1) identification of technical issues and data bases to address them, 2) available data and seismotectonic interpretations relevant to the study region, 3) available procedures and methods for defining seismic sources, specifying earthquake recurrence, estimating maximum magnitudes, and characterizing the uncertainties in these assessments, 4) procedures that will be followed

in eliciting expert judgments and for monitoring the performance of the experts, and 5) feedback of preliminary interpretations and sensitivity analyses.

The schedule, content, and conduct of SSC workshops are the responsibility of the TFI. Ample time must be provided to prepare for each workshop. Responsibilities for presentations should be given well in advance, and written materials should be provided prior to the workshop. During the workshop, the TFI should lead the technical discussions and ensure that all topics are given adequate time for consideration. It may be useful to have "proponents" advocating particular hypotheses or viewpoints present their technical arguments. The TFI must maintain a balance between rigid control and free-wheeling discussion. Less-vocal participants should be encouraged to voice their opinions. The goal of the workshop is communication, education, and reduction of unintentional disagreement.

In addition to workshops, other small meetings may be held to ensure progress and assist the experts. Individual experts may wish to work as small teams to develop their interpretations and to get feedback from their peers. The TFI may need to provide guidance regarding SSC-related procedures. If a team approach is being followed, these small meetings will likely be conducted within the team.

Workshops are effective mechanisms for the free exchange of data and interpretations. They are not recommended as a vehicle for performing the actual elicitations. However, it may be useful to conduct "example elicitations" in a workshop or meeting format to illustrate the manner for eliciting expert judgments, the procedures for quantifying uncertainties, and the methods for documenting the assessments.

Elicitations of SSC Experts The elicitation of either individual experts or of teams of experts is acceptable, although the procedures for doing so differ somewhat.

Assuming that the experts have received training in elicitation procedures and, as appropriate, have undergone example elicitations to provide a degree of comfort in the process, it is recommended that individual experts be elicited in small interview sessions. Present at the sessions should be the expert, the TFI team consisting of the technical expert and an elicitation expert with experience in subjective probability assessment. It is also acceptable to have other "resource specialists" (say, with specialized knowledge of statistics, tectonics, etc.) available to provide information to the expert. Every effort should be made to put the expert at ease in the elicitation and to maintain flexibility in the questioning to allow the expert to express his/her interpretations and uncertainties in his/her own way. The elicitation is not a final examination; the expert may bring any resource material that he/she feels will assist in making the assessments.

It is important for the individual being elicited to be discouraged from playing the role of a "proponent" who advocates a single hypothesis or viewpoint. The role of an "evaluator" is to evaluate the technical merits of all hypotheses and to assess the relative credibility of each. In doing so it is expected that multiple hypotheses will have some level of credibility to the expert, and the credibilities can be readily quantified using subjective probabilities. As discussed in Section 3.3, it is useful to have two stages of elicitation: a Stage I elicitation in which the expert plays the role of an evaluator who represents his own range of knowledge and uncertainty, and then a Stage II elicitation in which the expert is asked to represent his/her assessment of the diversity of views that result from questioning the larger <u>informed</u> technical community. A purpose of the second elicitation is to identify those cases where an expert may recognize that his interpretation is significantly different from his perceptions of the interpretations that the scientific community would have if they were similarly informed.

Elicitation of SSC expert judgments using written questionnaires is not recommended. Experience has shown that they are often subject to different interpretations and can be confusing. It is acceptable and even desirable, however, to provide a written questionnaire to the expert prior to an interview session for information purposes

only as a means of focusing attention on the pertinent SSC issues.

The elicitation must be carefully documented, including both the interpretations and uncertainties expressed by the expert and the technical bases for the interpretations. A recommended procedure is for the TFI to record in writing the elicitation and, subsequent to the session, provide the written documentation to the expert for review and revision. Acceptable, but less preferred, alternatives are to record the session electronically and provide a summary of the transcription to the expert, or to require that the expert furnish the written documentation following the session. Experience has shown that these alternatives are not as efficient as the preferred approach.

It is possible that the interview session, which is usually an exhausting experience for the expert, will not cover the entire source characterization required for the analysis. Alternative, equally acceptable, remedies for this problem are the following: conduct a follow-up elicitation session to complete the assessment, or allow the expert to complete the assessment privately and provide the results at a later time. In order for the latter approach to work, the elicitation session must have covered the entire spectrum of source characteristics for several sources in the interview session (presumably the sources of greatest significance to the hazard). The expert can then complete similar assessments for the remaining sources.

Another expected circumstance is the case where an expert may feel uncomfortable with answering a particular element of the assessment, usually because of a lack of experience or expertise in a particular area. It is recommended that the SSC analysis allow for the expert to decline answering questions in these areas. To do so, the SSC analysis should, prior to the elicitation, have made every effort to select the proper experts and to educate the experts. Failing this, procedures should be established for dealing with the problem and these should be communicated to the experts prior to the elicitation. For example, if the expert declines to define seismic sources in geographical regions remote from his/her past experience, the expert could use sources defined by the other experts. If the expert declines to provide certain parameters for his/her sources, an agreed-upon 'default' methodology for estimating the parameter should be invoked. Obviously, this is a difficult problem in the SSC area, but because of the multi-disciplinary nature of the problem, is one that should be anticipated. The use of multi-disciplinary expert teams is one way to mitigate the problem.

In some cases, the expert may prefer to specify a methodology or procedure for calculating a particular parameter, rather than provide a direct assessment of the parameter value itself. This is acceptable and provision should be made for the TFI to conduct the calculation in a timely manner (if possible, at the interview session itself) then ask the expert to review the calculation.

Despite the small experience base on which to make the recommendation, it is advised that teams of experts be elicited in the interview session. Questions will be posed to the team as a whole and the team as a unit will be responsible for developing a consensus interpretation and uncertainty distribution that captures the diversity of their individual views. Clearly, depending on the questions being asked, some members of the team will defer to others at different points in the assessment and this is acceptable. It is the responsibility of the TFI to lead the team through the assessment and to emphasize that the team's responsibility is not to reach agreement on each issue, but to develop a range of assessments (e.g., alternative seismic source configurations, distributions of recurrence parameters) that effectively captures the thinking of the team as a whole. It is expected that the team elicitation will be more time consuming than individual interviews and may require multiple sessions to complete. Documentation must be conducted in the same manner as for individual interview sessions.

Feedback and Sensitivity Analysis Following the elicitations and prior to the final seismic hazard calculations, the preliminary results of the elicitations and a variety of sensitivity analyses should be prepared by the TFI, provided to the experts, and discussed in a workshop format. The

purpose of this exercise is to (1) allow each expert to see the preliminary interpretations made by the other experts, (2) understand the implications that the assessment has to the seismic hazard calculations, (3) identify the key SSC assessments that are most important to the hazard results, and (4) compare the "predicted" seismic source characteristics to "observed" data. The following examples show the types of results that might be provided to each expert in advance of the feedback workshop:

- Seismic source maps and seismicity parameters for all experts
- Mean and fractile seismic hazard curves based on the assessments of each expert
- Plots showing the relative contributions of each seismic source, magnitudes, and distances to the mean hazard
- Plots showing the contributions of various SSC uncertainties to the total variance in the seismic hazard results
- Comparisons of the predicted recurrence rates for each source with the observed seismicity for various completeness periods
- Comparisons of the total predicted regional recurrence rates with the observed seismicity rates
- Sensitivity analyses showing the variability in mean hazard as a function of assessed ranges of seismicity parameters.

The TFI should review the results with each expert and identify possible problems or inconsistencies. For example, an expert's interpretations might predict that the rate of seismicity (say, the number of M>5 earthquakes per year) is significantly larger than or smaller than the observed rate from historical seismicity. The TFI should review the technical basis for the expert's assessment, ensure that the expert is aware of the difference between his estimate and the historical record, and provide an opportunity for the expert to revise his assessment if desired. There are certain key assessments in SSC that are subject to possible misinterpretation or "error" unless the expert is educated by the TFI. These assessments are discussed in Chapter 3 on Seismic Source Characterization. One example is the assessment of the recurrence parameters a and b. Assignment of values to these parameters (and their uncertainties) without consideration of the correlation between the parameter values can lead to some unintended combinations of a and b-values and their associated recurrence rates. It is the responsibility of the TFI to identify possible problem areas and, through questioning the expert, ensure that there are no unintended results.

At the feedback workshop, each expert should be provided the opportunity to discuss his/her interpretations and evaluations with the other experts focusing on the technical basis for the assessment. The TFI is required to lead a constructive scientific debate, to look for areas of consensus, to resolve misunderstandings or different assumptions, and to assist the experts in making explicit assessments. The experts are expected to challenge and defend different interpretations. The TFI should focus the discussions on those aspects of the interpretations that are most important to the seismic hazard results (for example, the recurrence rate per-square-kilometer for the "host zone" containing the site). As in previous workshops, the feedback workshop is vital to ensuring interaction among the experts, which in turn is a key mechanism for the behavioral integration of the experts' assessment.

At the workshop, it should be emphasized that the assessments are preliminary and, following the workshop, the experts will be encouraged to make any changes that they feel are appropriate in light of the discussions and feedback that they have received. It should be emphasized by the TFI that there is no need nor any desire for the experts to agree with each other after having seen where their assessments stand relative to the other experts' assessments. Rather, it is important for each expert to understand the *technical reasons* why his evaluations fall where they do relative to the others and to be sure that these reasons make sense to him.

Finalize SSC Assessments and Integrate

Following the workshop, the experts should

finalize their interpretations and documentation. It is unlikely that another elicitation session will be required to do so, but it may. The TFI should take the responsibility for ensuring that the finalization is done properly and in a timely manner.

Two mechanisms are used to integrate the interpretations of the SSC experts: (1) behavioral integration related to interactions of the experts throughout the project, and (2) weighting of the expert interpretations. The first mechanism should be the primary mechanism for integrating SSC interpretations. Further, it is desirable for the TFI to be in a position to combine the SSC interpretations using equal weights, unless compelling reasons exist for unequal weighting. To integrate SSC expert interpretations properly, the TFI should have accomplished the following during the process:

- Selected highly qualified experts
- Established the commitment of each expert to the project and worked to motivate the expert throughout the project
- Disseminated a comprehensive and uniform data base to all of the experts
- Educated the experts in all aspects of seismic source characterization, including areas of limited expertise, and trained the experts in elicitation methodologies
- Facilitated interaction of the experts such that a free exchange of data and interpretations occurred as did scientific debate of all hypotheses
- Allowed for experts to decline answering certain elements of the assessment for which they did not feel qualified
- Provided feedback and sensitivity analyses to the experts, checked for unintentional errors, and facilitated discussion and challenge of preliminary interpretations
- Provided an opportunity for each expert to modify his assessments in light of feedback from the TFI and interactions with the other experts
- Obtained explicit agreement from each expert (or team) that the other experts' (teams') interpretations are understood and are valid alternative interpretations/representations

If the above recommended criteria have been met, the TFI should have created the proper conditions to apply equal weights to the SSC expert evaluations. However, it is recognized that certain circumstances may arise that would signal the need for unequal weights (see discussion in Section 3.3). If these or similar conditions arise, it is the responsibility of the TFI to communicate to the expert the concern and provide an opportunity for improved performance.

The goal in the procedures described in Section 3.3 and applicable to SSC is <u>not</u> to arbitrarily assign unequal weights to SSC evaluations. In fact, it is anticipated that in most cases the assignment of equal weights will be highly defensible. However, the procedures are designed to provide the TFI a mechanism to deal with particular "problem" circumstances where unequal weighting is more appropriate. As discussed, the procedure should only be applied in cases where unequal weights leads to significant differences in the hazard results. The calculated seismic hazard results for both the equal weights and unequal weights must be documented as part of the SSC report.

Peer Review The advantage of the TFI approach is that the active interaction of SSC experts provides for a de facto "peer review" of the technical substance of the SSC assessment. The TFI approach is designed specifically to encourage the presentation and technical challenge of hypotheses. In addition to this informal technical peer review, it is also recommended that an explicit process peer review be conducted. The focus of the peer review would be the implementation of all approaches and methods for the SSC assessment, including selecting the experts, compiling and distributing data, eliciting experts, etc. The recommended peer review procedure is a "participatory" peer review, whereby the peer reviewers interact with the TFI throughout the study and gain first-hand knowledge of the assessment through this interaction. A "late-stage" peer review, although

acceptable, may not be sufficient to identify any necessary mid-course corrections in the project. The results of the peer review should be documented and included with the final report.

4.4.3 Technical Integrator (TI) Approach

The TI approaches (Study Levels 1 through 3) for deriving SSC inputs have been applied, in the past, primarily to site-specific studies. The particular level used depends on the amount of published information available and/or the diversity of interpretations within the informed technical community about the seismic sources and seismicity relevant to the region of interest.

For parallelism with the TFI discussion (Section 4.4.2), the discussion below describes a Level 3 study. The basic elements of the TI approach to SSC, assuming a participatory peer review, are the following:

1. Select peer reviewers A panel of peer reviewers is selected by the sponsor in the same way that the group of experts was selected following the "expert" approach.

2. TI assembles all data bases and defines SSC procedures SSC-related data bases are compiled by the TI (for site-specific studies this may involve collecting new data). Methods and procedures are selected for the SSC analysis and reviewed by the peer reviewers.

3. TI conducts SSC analysis The TI conducts the source characterization with the requirement that a wide range of technical interpretations be represented and included.

4. Peer reviewers interact with TI The peer reviewers meet frequently with the TI to review and criticize the compiled data base, the procedures to be followed, and the interpretations being made on source characteristics.

5. Peer reviewers submit written review of preliminary analysis A draft SSC analysis, which fully documents all of the assumptions, methods, and assessments, is submitted to the peer review panel. The peer reviewers provide written comments on the draft report keeping in mind their charge to verify a full range of alternative interpretations.

6. Review comments are addressed by the TI Written responses to peer reviewer comments are prepared by the TI and changes are made to the analysis. The TI report is finalized. The peer review panel submits its endorsement of the final report.

Each of the above steps is discussed below.

1. Peer Reviewer Selection Because they will actively participate in reviewing the elements of the SSC analysis and will be asked to endorse the process and results, peer reviewers should have the same high qualifications that are required of the experts in the TFI approach. Likewise, in large complex studies, the peer reviewers should agree to a significant commitment of time and effort. Therefore, the peer reviewers should be selected by the sponsors in the same manner as discussed previously and, as a group, it is desirable that they be similarly balanced.

2. Data Bases and SSC Procedures SSC-related data bases should be compiled and formatted in the same manner as the TFI approach. The peer review panel can be instrumental in helping to define data needs and availability. In site-specific studies, various types of site data may exist and may need to reviewed and evaluated for their accuracy and pertinence to the SSC analysis. For example, geologic mapping and boreholes may exist in the site vicinity but may not have been gathered for purposes of earthquake evaluation. Their usefulness will need to be evaluated by the TI. In some circumstances for site-specific studies, certain critical data may need to be gathered in order to reduce uncertainties in the SSC and seismic hazard analysis. For example, if a fault has been identified in the immediate site vicinity, but no data are available to evaluate its activity, the peer reviewers can assist the sponsor in deciding whether new data collection is required.

The methods and procedures that will be used to characterize seismic sources and to quantify uncertainties should be identified. These can then

be reviewed by the peer reviewers prior to making assessments.

3. Conduct of SSC Analysis The TI takes the responsibility for conducting the source characterization assessment and is responsible for representing the informed technical community's full range of credible interpretations of the source characteristics. To achieve this, the TI must be familiar with and document all published or otherwise available interpretations of seismotectonics that might affect SSC; acknowledged experts should be contacted to obtain their views on possible interpretations; and any available site-specific data should be factored into the assessment. Throughout this process, the TI should be receiving input from the peer reviewers on possible alternative interpretations. The entire SSC analysis should be documented fully in a draft report, including the technical basis for all assessments and their uncertainties. The draft report should include sensitivity analyses that display the results of alternative SSC interpretations.

4. Interactions with Peer Reviewers The peer reviewers should meet frequently with the TI to review all aspects of the analysis. Their role is to inform the TI of available data and interpretations being made that might have an impact on the SSC analysis, to express their own interpretations as experts, to examine and suggest refinements to methods and procedures being followed by the TI, and to ensure that a wide range of technical interpretations is being represented. In reviewing the TI's work, the peer reviewers may recommend to the sponsors that significant new data be gathered or new analyses be undertaken that will strengthen the technical basis for the conclusions drawn. If such data are gathered, the peer reviewers may assist the TI in designing the data collection or analysis effort and in reviewing the results.

5. Peer Review of Draft Report Upon completion of draft documentation of the SSC analysis, a report is submitted to the peer reviewers. Here, standard peer review procedures should be followed to prepare written comments that relate to the process, assessments, and documentation prepared by the TI. The clear advantage of a participatory peer review process is that by this stage of the project, the peer reviewers are thoroughly familiar with the data bases available, the SSC procedures being used, and the technical basis for the assessments made. Likewise, the TI is aware of potential concerns that the peer reviewers may have and has sought to address them in the draft report. Much of the review will focus, then, on how effectively the documentation captures the assumptions made and analyses carried out. One or more meetings should be held with the peer reviewers and the TI to clarify the comments made on the report to minimize the need for subsequent review/revise cycles.

6. Resolution of Review Comments and Finalization of Report The normal resolution process for peer review comments should be followed, which includes addressing each comment, revising the report and, if necessary, the analysis, and preparing written documentation describing the manner in which each comment has been addressed. Again, interaction with the peer reviewers will have served to clarify the basis for each comment and provide for a clear resolution of remaining concerns. The final SSC report is then submitted to the sponsor.

The final step in the peer review approach is a written endorsement of the SSC study by the peer review panel. Their endorsement should extend to those aspects of the study where they were able to provide a direct, substantive review of the procedures and results.

4.4.4 Modifications to the Recommended Approaches

The recommended approaches (TFI and TI approaches) discussed above for incorporating SSC expert judgments are appropriate for most seismic hazard applications that SSHAC anticipates for the sponsors of the study. However, it is possible that the approaches may be modified to accommodate different needs. For example, the approaches discussed above are resource-intensive (Level 3 and 4 studies) and are, therefore, most appropriate for large-scale studies for critical facilities.

To provide some guidance for alternative applications, the following discussion considers how the approaches might be modified for more modest studies and for regional or site-specific analyses.

4.4.4.1 Resource-Intensive versus Modest Resources

This issue recognizes that some seismic hazard analyses will need to be conducted under limited budgets and time constraints (particularly, for less-critical facilities or for applications where there is interest in only higher probability levels). The trade-off in conducting more modest studies is not in the quality of the SSC assessment, but in the ability to verify the level of quality using multiple representatives (experts) from the SSC community. For example, a key attribute of the recommended approaches is assurance that a full, documented representation of the range of scientific interpretation is incorporated into the SSC assessment. Any seismic hazard analysis, of any scale, must strive to achieve this goal. However, the more modest SSC analyses will provide less assurance to an independent third-party reviewer that, in fact, the goal has been achieved.

In general, the levels of analysis discussed in Section 3.1 (Levels 1 through 4) scale with resources available. Therefore, a TFI approach, which is Level 4, requires considerable resources in most cases. However, we here discuss some of the ways that both a TFI and a TI approach might be modified to account for modest resources.

TFI Approach

- Reduction in the number of experts who will conduct the analysis (say 3 to 4 experts).
- Reduction in the number of expert interactions. The number of workshops could be reduced, or eliminated altogether and replaced with smaller working meetings to review data bases, interpretations, and preliminary results
- Reliance on readily available data bases. Published and readily retrievable data bases could be made available to the experts (e.g., existing earthquake catalogs). Data processing might be reduced.

The reduction in scope discussed above would result in less of the desirable attributes of the TFI approach itself: use of multiple experts to represent the technical community, intensive interaction of the experts to resolve unintended disagreements and review/challenge interpretations, and formal elicitation of a representative sample of the informed technical community.

The focus of the TFI approach would remain one of using the judgments of experts directly to characterize seismic sources and to quantify the uncertainties.

TI Approach

- Reduction in the number of peer reviewers and less participation. A "late-stage" peer review process could be adopted whereby the reviewers do not interact with the TI during the course of the study, but review and comment on the draft report.
- No new data collection or data processing. The TI would base the SSC assessment on available data only and would not gather new data. Data processing might be reduced.

Other reductions in resources could, perhaps, be accomplished in the analysis itself. For example, the number of sensitivity analyses could be reduced. In no case, however, can the quantification or incorporation of uncertainties be significantly reduced in scope. Even the more modest seismic hazard studies must attempt to incorporate uncertainties.

4.4.4.2 Regional versus Site-Specific Studies

The application of the seismic hazard analysis can be for regional seismic hazard assessments (e.g., contours of hazard levels over regional scales) or for site-specific applications at particular facilities. The recommended approaches are appropriate for either application. However, experience leads us to provide preferences for particular applications.

For the following reasons, large, regional studies (say, of the eastern U.S.) might best be conducted using the TFI approach; site-specific studies might best be conducted using the TI approach. In terms of source characterization, seismic sources are commonly identified based on regional data sets (seismicity maps, fault maps, tectonic maps, geophysical maps). Because local small faults and sources do not have much significance in regional hazard results, detailed characterization of small-scale features is usually not attempted. Experts for regional studies, therefore, are required to have a strong knowledge of seismotectonics over geographically extensive areas. Although they may have detailed knowledge of specific local areas, their regional knowledge is most important. In contrast, experience with site-specific hazard studies has shown that the hazard is often dominated by a few local sources. Further, a few key characteristics of these local sources are often the most important (e.g., fault slip rate, geometry). As a result, experts for site-specific studies are required to have a detailed knowledge of the local seismotectonics and otherwise "minor" local sources. The need for this local knowledge limits the number of possible experts. Commonly, a TI takes the responsibility of assembling all of the available data sets and making the assessments. In doing so, the TI can draw on site-specific knowledge and expertise from, for example, scientists who have worked in the site area. The peer review of these TI assessments should entail a review of both the methodologies used by the TI as well as the use that has been made of local site-specific data sets. Hence, even if the peer reviewers do not have the site-specific expertise of the TI, they can contribute to the overall quality of the hazard analysis.

In past studies, there have been significant differences in the amount of new data that have been collected to provide a basis for the SSC assessment, ranging from no new data collection to extensive programs, including geologic field studies (designed to focus on significant seismic sources and to reduce uncertainties in their characterization). Differences in data collection appear to be tied to the regional versus site-specific issue. Regional hazard studies typically have a limited program of new data collection, although processing of existing data can require significant effort. Conversely, site-specific SSC studies usually include at least a limited, focused program of new data collection. For some site-specific studies (e.g., Diablo Canyon Long-Term Seismic Program), "scoping studies" (preliminary hazard analyses based on existing knowledge) have been carried out with the specific purpose of identifying the data collection activities that will have the most importance to the hazard results.

Another circumstance to consider is the case where a site-specific study is being conducted within a region for which a regional seismic hazard study has already been completed. An example might be a facility site in eastern Oregon, where a regional seismic hazard map has recently been completed for the state. Because the focus of the regional map was, in fact, on the regional variation of seismic sources, it is unlikely that local faults and sources have been considered. In these cases, either the TFI or the TI approach could be used first, to review the basis and applicability of the regional sources identified for the regional study, and second, to identify and characterize the local seismic sources of importance to the site. If the results of the site-specific study differ significantly in seismic sources or characteristics (and thereby hazard values) than the regional study, it is important to document the reasons for those differences. The differences may be due to an evolution in understanding of earthquake sources (e.g., the identification of a previously unknown source) or to differences in the manner in which uncertainties have been treated. A goal in seismic hazard analysis should be, over the long term, stability in estimates of seismic hazard both regionally and locally. As the science evolves and new findings are incorporated into the hazard analysis, the differences in the resulting hazard values should be understood and documented.

5. METHODOLOGY FOR ESTIMATING GROUND MOTIONS ON ROCK

5.1 Introduction

This chapter discusses the estimation of ground motions for use in probabilistic seismic hazard analysis. The chapter is divided into two major portions. The first portion comprises Section 5.2 through 5.5 and discusses the ground-motion measures considered in PSHA, the explanatory variables in current use, the various methods for prediction of ground motions, and the treatment of uncertainty. The recommendations from this portion are summarized in Section 5.6. The second portion comprises Section 5.7 and discusses issues of expert elicitation regarding ground motion models. The calculation of site response is not discussed, in spite of its importance, because this issue is outside the scope of the SSHAC study.

Computations of seismic hazard require a specification of earthquake occurrence and size, discussed in the previous chapter, and the ground shaking from earthquakes as a function of, at least, magnitude and distance. Unlike most deterministic studies, PSHA requires the ground motion as a continuous function of magnitude and distance. Furthermore, in general it is not enough to give the expected median value of the ground shaking; the aleatory uncertainty of the shaking, as well as the epistemic uncertainty in the median value, must also be specified. This chapter discusses the estimation of ground shaking for use in PSHA.

In many situations, there are not enough recordings of ground motion to allow a direct empirical specification of ground shaking. As a result, estimates are based on a variety of methods, using different assumptions and models that are calibrated and verified using various data sets. This can lead to widely differing motions for a particular magnitude and distance. In the face of such diversity, an important task in our study is to recommend a methodology for obtaining ground motions that adequately capture the uncertainty in the estimates and is defensible in a regulatory arena.

The Committee recognized at an early stage that it could not recommend a particular model or even a particular class of models. It is very likely that the models will change with time, as new data become available and as methods are refined to account better for existing data and for improvements in our understanding of how the earth works. We felt it more valuable to recommend *procedures* for obtaining the ground motions, procedures that will be as applicable ten years from now as they are today.

The scope of this chapter includes ground-motion estimation on hard-rock sites throughout North America, for distances, magnitudes, and frequencies of relevance for engineering design and structural response. Generally the magnitudes of interest will be above 5.0, the distances will be up to several hundred kilometers, and frequencies of response will range from 0.5 Hz to several tens of Hz.

Although SSHAC considers site effects to be one of the most important factors affecting the amplitudes and durations of ground motions (aside from the earthquake magnitude, of course), the project scope was restricted to motions on rock sites. We assume that site-specific applications will consider the expected modifications of the ground motions for the local site conditions. Local site conditions include the geologic materials below the surface as well as topographic irregularities of the ground near the site. The model for site effects should consider soil nonlinearity, if appropriate.

In discussing ground-motion prediction, it is common to divide North America into two regions—western and eastern. It is also important to divide North America on the basis of the availability of ground-motion data, because this determines the preferred methods for ground-motion prediction. In this sense, what is often loosely referred to as western North America is actually coastal California, from which most strong-motion data have been obtained. Ground-motion prediction in other parts of California or western North America suffers from the same (or

even a greater) lack of data as does eastern North America (in fact, a large number of useful ground-motion recordings have been obtained from southeastern Canada and the northeastern United States). Predictions of ground motions in regions lacking sufficient data for a direct empirical estimation must be based on similar methods, using different parameter values to represent differences among geographic regions. For this reason, we emphasize methods more than regions in our discussions.

We have organized this chapter along traditional lines, first discussing measures of ground motion, followed by sections on explanatory variables and methods for obtaining ground motions. We have not attempted to give a comprehensive and in-depth treatment of these subjects. This is not a textbook for predicting strong ground motion; we have provided references for those interested in the details of the prediction methods.

The heart of SSHAC's ground-motion contribution to PSHA is given in the final two sections of this chapter. Section 5.5 discusses the definition and estimation of uncertainty in ground-motion predictions, and section 5.7 contains SSHAC's recommendations for obtaining estimates of strong ground motion for PSHA.

5.2 Ground-Motion Measures

Although a time series of the ground shaking is needed for an exact analysis of nonlinear, dynamic behavior of structures or soil deposits, most PSHA studies characterize ground shaking in terms of a few ground-motion measures. The most common measures are peak ground acceleration (*PGA*) and a few (typically 6) ordinates of the response spectrum. This characterization is sufficient for most applications.

Peak ground acceleration is defined as the maximum absolute amplitude of a ground acceleration time series. It is easy to obtain from analog records and is used to define lateral forces and shear stresses in equivalent-static-force procedures (e.g., those specified in building codes) and liquefaction analyses. Being controlled by the highest frequency content in the spectrum, however, *PGA* is very sensitive to processes that can alter the high-frequency content, such as local geologic conditions and instrument response, and furthermore is not easily related to any particular range of ground-motion frequencies; in any earthquake, the *PGA* can be controlled by different frequencies at different distances from the earthquake. In addition, the frequencies that dominate the peak acceleration in a particular record are often not in the range of those most important for structural response. Peak accelerations in excess of 5 *g* have been measured from rockbursts in mines, but these motions were dominated by frequencies near 400 Hz. For these reasons we recommend that *PGA* not be used to determine design spectra for most applications. A much more useful measure of ground motion is the response spectrum.

Response spectra describe the response of a single-degree-of-freedom damped elastic oscillator to ground shaking. A number of different measures have been used, referred to by a confusing variety of symbols and terms. The one most commonly used for PSHA is the peak spectral acceleration, *PSA*, defined as:

$$\mathrm{PSA} = \left(\frac{2\pi}{T}\right)^2 S_d \qquad (5.1)$$

where S_d is the maximum displacement of the mass of an elastic, viscously-damped, single-degree-of-freedom oscillator with undamped natural period *T*, relative to its point of attachment to the ground. In most applications, the damping is taken to be 5 percent. When PSA is plotted as a function of frequency or period, the result is a response spectrum. Because the response of many structures can be well-approximated by that of a single-degree-of-freedom simple harmonic, damped oscillator, the characterization of ground shaking as a response spectrum is immediately useful. Once a response spectrum is defined, the maximum acceleration, and thus the force, to which a structure is subjected is easily determined by scaling the appropriate value off the spectrum. Because of its simplicity, the response spectrum has been universally adopted as the standard method of defining earthquake motions for purposes of performing dynamic analyses of

simple elastic and inelastic structures. Furthermore, we anticipate that future editions of building codes will use response spectral ordinates at a few selected periods, rather than peak acceleration, as a basis for seismic zonation (Algermissen et al. 1991).

In spite of their usefulness, response spectra have some limitations. First, they provide the response of a linear oscillator. Studies of nonlinear response require a more complex representation of the ground shaking (e.g., Kennedy et al. 1984; Sewell 1988; Krawinkler et al. 1991; de Bejar and Ganapathi 1992). Second, although PSA can be calculated for any frequency, a non-zero *PSA* does not imply ground-motion energy at the frequency of the oscillator. For example, if shaken by ground motion with frequencies no higher than, say, 5 Hz, the response of a 100-Hz oscillator will simply reproduce the ground acceleration. Finally, because of the process by which they are constructed, response spectra do not have the same properties as Fourier spectra. In particular, the ratio of two response spectra is not the same thing as the ratio of Fourier spectra. For example, ratios of response spectra from the same event do not cancel the effect of the source.

The ground shakes in both horizontal and vertical directions, and in addition spatial variations can produce rotations of the ground. Generally, *PSA* are only computed for the horizontal ground shaking. It is not sufficient, however, simply to specify that the *PSA* is for horizontal shaking, since the shaking can be in two spatial directions. Usually the specification is for either the geometric mean or the larger of two horizontal orthogonal components of motion placed randomly with respect to the orientation of the fault that produced the motion. It is important to be specific about the particular definition, for there are systematic differences in the motion between various definitions (e.g., Boore and Joyner 1988).

Less emphasis is usually placed on the vertical component of motion. The vertical component is often estimated from the horizontal component using a rule-of-thumb, for example, where the vertical is about 2/3 of the horizontal. Such rules should be used with caution, however; for the actual ratio may depend on the frequency of motion, the local site conditions, the focal mechanism, and the distance from the event (e.g., Atkinson 1993a; EPRI 1993). If important, we recommend that vertical motions be obtained from independent analyses, in the same manner as for the horizontal motions (e.g., Abrahamson and Litehiser 1989).

5.3 Explanatory Variables in Ground Motion Models

5.3.1 Introduction

This section discusses the quantities that serve as input to ground-motion attenuation models. The discussion focuses on the current state of practice and on anticipated developments over the next five years. These explanatory variables in ground-motion attenuation equations fall into three general categories, as follows: (1) size and other characteristics of the earthquake (typically magnitude), (2) location of the site relative to the earthquake (typically distance), and (3) site characteristics.

5.3.2 Background

In general, the addition of a new explanatory variable X in the ground-motion model is justified from the point of view of seismic hazard analysis if the following three conditions are satisfied:

1. Introduction of X in the ground-motion model results in a significant reduction in the scatter of the ground-motion residuals (observed minus predicted amplitudes), as measured, for example, by a 10 percent reduction in the residual standard deviation.

2. There is the ability to characterize the probability distribution of parameter X for future earthquakes affecting a given site.

3. The probability distribution of parameter X in future earthquakes affecting a given site must be significantly different from the distribution in the sample data used in the development of the ground-motion model. If the two distributions are similar, the explicit introduction of parameter X in the ground-motion model and in the seismic-hazard

integration will not have an effect on the hazard. This condition is somewhat less critical than the other two. One may be justified in introducing parameter X because it makes the model more robust, or because it may allow for future site-specific updating of the hazard if the site-specific probability distribution of X becomes better known.

There is a relationship between the number and type of explanatory variables in an attenuation equation and the associated uncertainties (both aleatory and epistemic). This relationship will be discussed in Section 5.5.

5.3.3 Characterization of the Earthquake Source

5.3.3.1 Magnitude

Magnitude is the most commonly used measure of earthquake size for the purpose of seismic hazard analysis. There are a large number of magnitude scales in use. It is imperative that the ground-motion attenuation equations and the source characterization use the same magnitude scale.

Most magnitude scales are instrumental. Magnitude is calculated from the peak amplitudes and distances from the earthquake sources to seismographs of a certain type that recorded the earthquake (the process is analogous to applying an attenuation function in reverse, solving for magnitude given amplitude and distance). Moment magnitude, unlike instrumental magnitudes, has the advantage that it is related to a well-defined physical characteristic of the earthquake source (i.e., the seismic moment). In practice, seismic moment is not observed directly and, like instrumental magnitudes, it must be calculated from indirect observations (e.g., seismograph recordings, geologic or geodetic measurements), and the calculation of seismic moment from these observations often requires assumptions about seismological models and their parameters.

Magnitudes for pre-instrumental earthquakes are determined from macro-seismic measurements such as epicentral intensity, felt area, or the extent of liquefaction, using empirically derived conversions. Issues of magnitude conversion are discussed in numerous references (see Johnston et al. 1993; EPRI 1986).

Current practice as to the choice of magnitude scale for seismic hazard analysis is different for different regions of North America and for different earthquake sizes.

- East of the Rocky Mountains, Nuttli's (1973) m_{bLg} (also called m_{Lg} or m_N) magnitude is the most commonly used magnitude (e.g., this is the primary magnitude in the EPRI 1986, catalog). This is the magnitude in current use by seismograph networks in the region. Pre-instrumental earthquakes have been converted to m_{bLg} using empirically-based relations that use intensity as the fundamental observable (e.g., EPRI 1986). The choice of alternative conversion relations for pre-instrumental earthquakes is one potential source of differences among seismic hazard studies (see Toro et al. 1992). There are several deficiencies in current procedures for calculating and reporting m_{bLg}. For instance, no distinction is made in some catalogs between m_{bLg} and teleseismic m_b. Also, no account is taken of the instrument types (for instance, American stations typically calculate m_{bLg} using short-period WWSSN seismographs, which peak near 1 Hz, while Canadian stations use ECTN seismographs, which have a broader bandwidth). There are also variations in observatory practice, as some stations use Nuttli's (1973) equation, while others use variants of that equation. All these factors lead to moderate but systematic regional biases in m_{bLg} estimates.

- For western North America, the local magnitude M_L or an approximation to that magnitude has been used since its introduction by Richter in 1935 (Richter 1935). In the last 15 years, however, Hanks and Kanamori's (1979) moment magnitude **M** has been commonly used and is now the preferred magnitude for moderate and large earthquakes. The moment magnitude generally correlates well with other magnitudes over limited ranges of earthquake size. For magnitudes between about 3 and 6,

M is approximately equal to the M_L magnitude used by seismograph networks in California (Hanks and Boore 1984). For large, but not great, earthquakes, **M** is approximately equal to the surface-wave magnitude M_S. The issue of determining **M** for historical earthquakes is of less importance in the west because the historical catalog is shorter than in the east, and because there are more instrumental data as a result of higher activity rates.

There is a trend towards the use of **M** in central and eastern North America. This trend is motivated by several factors, as follows: (1) the deficiencies in the calculation and reporting of m_{bLg} mentioned above, (2) the preference for predicting ground motions using the stochastic and physical ground-motion models, in which the seismic moment is a fundamental model parameter (e.g., Atkinson and Boore 1995; EPRI 1993)[1], and (3) the benefits of using one magnitude scale for all of North America, thereby eliminating a non-physical distinction between east and west.

In addition, moment magnitude is the magnitude used for the GSHAP (Global Seismic Hazard Analysis Program 1993) worldwide seismic-hazard study.

The conversion to moment magnitude for seismic hazard studies is justified if the overall uncertainty in the calculated seismic hazard is reduced; this may be verified quantitatively through statistical analysis of events for which both mblg and **M** are available. This uncertainty involves both uncertainty in the conversion of the earthquake catalog to moment magnitude (especially for large earthquakes with no instrumental data) and in the attenuation equations. Regarding the first issue, recent work on the characterization of large intra-plate earthquakes (Johnston 1995a,b,c, in press) has provided estimates of moment magnitude for the tectonically-stable region of North American earthquakes above **M** 3.9 for pre-instrumentally recorded earthquakes (for which only intensity data are available) and above **M** 3.5 for instrumentally-recorded events. The scatter in these relationships is generally lower than for conversions to m_{bLg}. Regarding the second issue, attenuation functions in terms of m_{bLg} and of **M** have comparable scatter (as characterized by the residual standard deviation) for high-frequency ground-motion measures (i.e., $f > 2.5$ Hz), and the M-based equations have lower scatter for low-frequency ground-motion measures (EPRI 1993; Atkinson 1995). In conclusion, there are significant advantages in converting to moment magnitude as the measure of earthquake size for seismic-hazard analysis and we recommend a gradual transition towards the use of **M** for seismic hazard studies in all regions of the United States. Appendix C contains a more complete discussion of these issues.

Another interesting alternative to the use of m_{bLg} is the high-frequency magnitude m recently proposed by Atkinson and Hanks (1995). The main advantages of this magnitude scale are that it is (1) more directly related to high-frequency ground motions than are the other magnitude scales, and (2) it correlates very well with felt area, thus allowing reliable estimation of magnitude for large, pre-instrumental events. Although we consider this scale to have much promise for use in PSHA, we cannot recommend its use at this time; it must be better understood and accepted before it is used as the magnitude scale for seismic hazard analysis.

5.3.3.2 Other Source Characteristics

Another source characteristic that affects ground motion is the tectonic regime where the

[1] Physical and stochastic models use seismic moment as the basic measures of the size of the earthquake. Thus, in order to predict ground motions for a given m_{bLg} using these models, one needs a relationship for seismic moment given m_{bLg}. Often, these relationships are obtained using the model itself, by predicting the amplitude recorded at a hypothetical seismograph at a certain reference distance, and then applying Nuttli's (1973) equation to calculate m_{bLg} as a function of amplitude and distance. The resulting relationship is sensitive to the assumptions of the model (particularly Q), the choice of seismograph, and the choice of reference distance. An alternative is to derive the relationships between m_{bLg} and seismic moment empirically. Unfortunately, these two approaches can lead to large differences for large earthquakes. The empirical data can be fit well by a linear relation in the range for which data are available. The model-based relationships agree with the empirical relationships in this region, but predict curvature for larger earthquakes. Sufficient data are lacking to resolve the differences at the larger magnitudes. These differences can translate into large differences in predicted ground motions.

earthquake occurs (i.e., intraplate, plate margin, or subduction zone). This characteristic is not typically included explicitly (as a parameter) in attenuation equations because most attenuation equations are applicable to a single tectonic regime. Instead, tectonic regime is used implicitly as an explanatory variable by the selection of the attenuation equations applicable to the region of interest. If a site is affected by earthquakes from different tectonic regimes, it may be required to use different attenuation equations for the source zones associated with the different types of earthquakes.

Other source characteristics that affect ground-motion amplitudes are focal mechanism (strike slip, reverse, or normal), and source depth. Focal mechanism is typically not used as an explanatory variable, although it has been used in some attenuation functions for California (e.g., Campbell and Bozorgnia 1994; Sadigh 1993). Depth is seldom included explicitly as an explanatory variable.

5.3.4 Characterization of Site Location Relative to the Earthquake

5.3.4.1 Distance

Figure 5-1 illustrates the most common definitions of distance used in attenuation functions and in seismic hazard analysis.

For small and moderate earthquakes, the dimensions of the earthquake rupture are negligible compared to the distance from the earthquake to the site (except, perhaps, for earthquakes in the host source zone). In this case, two definitions may be used: hypocentral (or focal) distance, and epicentral distance. These two definitions of distance are consistent with the use of areal source zones in seismic hazard analysis. Consistency must also be maintained in the treatment of depth. If the attenuation function uses epicentral distance, the areal source zones must be specified as having zero depth. If the attenuation function uses hypocentral distance, the seismic source must have a non-zero depth (or, preferably, a probability distribution of depth).

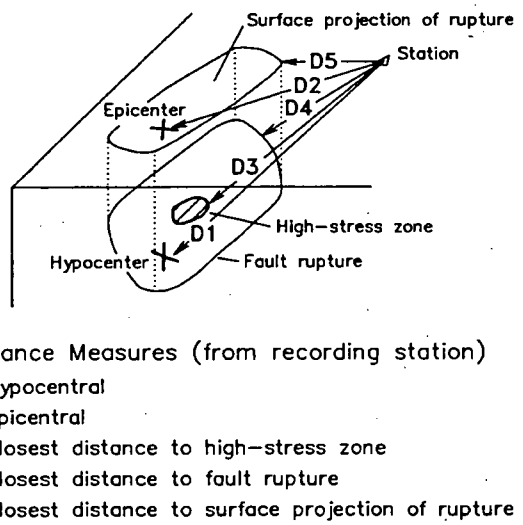

Figure 5-1 Diagram illustrating different distance measures used in predictive relationships (from Shakal and Bernreuter 1981).

If the dimensions of the earthquake rupture are of the order of ten kilometers or more, point-source idealization of the seismic-energy release may become inappropriate. In these situations, some form of closest distance to the rupture should be used. Figure 5-1 illustrates the shortcomings of the hypocentral and epicentral definitions of distance when the rupture is long. Of the three definitions of distance that consider the spatial extent of the rupture, the distance to the slipped fault (also called distance to the seismogenic rupture), and the closest horizontal distance from the station to the point on the earth's surface that lies directly over the rupture are commonly used. These definitions of distance are consistent with the use of fault seismic sources with extended ruptures. Consistency must also be maintained between the definition of distance and the geometric representation of earthquake occurrences. Attenuation equations that use distance to the surface projection of the rupture require (as a minimum) line models of the fault trace. The other definitions require three-dimensional models of the fault plane.

5.3.4.2 Other Characteristics

At least one seismic hazard study has considered the location of the site relative to an earthquake with a reverse focal mechanism, under the

assumption that ground motions are different for the up-thrown and down-thrown blocks (PG&E 1988). In addition, some attenuation equations under development predict different amplitudes for the up-thrown and down-thrown blocks (Somerville and Abrahamson 1995, in press).

Directivity is the theoretical tendency for higher ground-motion amplitudes when the rupture propagates toward the site. Some empirical studies show evidence for directivity effects (e.g., Boatwright and Boore 1982; Campbell 1987), but these effects are usually not seen at the frequencies of interest in this study (i.e., $f > 0.5$ Hz). Directivity effects are often obvious in data from large earthquakes at lower frequencies (e.g., Benioff 1955; Gutenberg 1955; Kanamori et al. 1992; Somerville and Graves 1993; Velasco et al. 1994) and may be important in seismic-hazard studies for low-frequency structures such as base-isolated structures, suspension bridges, or tall buildings. Attenuation equations in current use do not include directivity effects as an explanatory variable, although to the extent that such effects are in the data, they will be included implicitly as scatter in empirically-based equations. Theoretical models often show directivity effects, and simplified theoretical models, such as the commonly-used stochastic model, might incorporate directivity implicitly in deriving model parameters from empirical data (e.g., Boore and Joyner 1989).

5.3.5 Characterization of Site Response

Site effects are best treated on a site-specific basis, because these effects may substantially change the amplitude and frequency content of ground motion and because data on the dynamic characteristics of the site are always gathered for important facilities. Guidance on methods for site-specific evaluation of site effects is beyond the scope of this report; the reader is referred to EPRI (1993), Martin (1994), and other engineering literature on site-response calculations, including the treatment of soil nonlinearity. Nevertheless, a short discussion of the generic characterizations of site response is included here because these may be of use for preliminary studies or for studies involving low-risk facilities.

Some attenuation equations include terms describing site conditions (see Joyner and Boore 1988, for a review). Initially those terms consisted of dichotomous variables (rock or soil; e.g., McGuire 1978; Joyner and Boore 1981). Other studies distinguish among different soil depths by considering the depth to basement rock (Trifunac and Lee 1979; Campbell 1987). Boore et al. (1993 1994a) consider the combined effect of soil depth and soil impedance by using the average shear-wave velocity over the top 30 meters of the soil column.[2]

Other studies have developed amplification factors for various soil types and depth categories (Bernreuter et al. 1989; Boore and Joyner 1991; EPRI 1993). These amplification factors are used to modify the rock attenuation functions or the rock hazard results.

Note that it is important to be precise about what constitutes a rock site. For example, for the SSHAC elicitation of ground motion (Appendix B), a rock site was defined to be one whose time-weighted shear velocity in the upper 30 m is 2800 m/s. A hard-rock site such as this may be appropriate for glaciated portions of eastern North America, but for many other sites what is commonly taken for rock will have much lower shear velocities in the upper 30 m. In such cases, careful consideration of differences in local rock velocities must considered before importing results from other regions; a "site effect" may have to be developed for the rock. For example, a sample of California sites that were classified as rock (based on their geological description) had a geometric-average shear-wave velocity of 650 m/s.

5.3.6 Introduction of Other Explanatory Variables into the Hazard Analysis Calculations

Magnitude and distance are the only ground-motion explanatory variables used in a majority of seismic hazard studies and the available calculational methods are designed to integrate over the aleatory (i.e., random) distribution of

[2]Actually, the quantity used is the harmonic or "time-weighted" average of the velocity, i.e., 30 m divided by the travel time through the upper 30 m of the profile.

earthquake magnitudes and locations. These calculational methods also consider epistemic uncertainty (i.e., ignorance) about the true form of these distributions.

Additional explanatory variables have been used in ground-motion models for recent seismic hazard studies. This practice will become more widespread as more data become available and ground-motion models become more sophisticated. If the value of an explanatory variable applicable to the site (or to a site-source pair) is not known (either because the value is anticipated to vary from event to event or because of incomplete knowledge), it is important to consider that uncertainty explicitly. If the value is expected to vary from event to event (i.e., aleatory uncertainty), one should integrate over the values of the explanatory variable in the calculation of the exceedance probabilities (as is done with magnitude and distance). Because the standard calculational methods for seismic hazard analysis do not integrate over variables other than magnitude and location, it is usually easier to perform this integration prior to the hazard analysis. This integration will change the median prediction of the ground motion and the distribution about that median. If the uncertainty about the explanatory variable is epistemic, it is easier to incorporate it in the conventional seismic-hazard analysis.

5.4 Methods for Predicting Ground Motions

This section contains a brief discussion of the various common components that must be included in ground-motion prediction models (other than those based strictly on data). Any particular model can be built from the various elements that are cascaded together to make the predictions.

A matter of terminology must be cleared up now. By "methods" we mean a general class or way of predicting ground motions. A particular application of a method to derive ground motions, either explicitly in the form of a table of values or equations, or implicitly as a procedure or algorithm from which ground motions can be computed, is referred to as a "model." These "models" often are associated with the names of the authors who derived the model. For example, Toro and McGuire (1987) and Boore and Atkinson (1987) are two models using the stochastic method.

By focusing on the components of models, we have removed the temptation to judge, rank, recommend, or advise against particular models. This is more properly the task of the elicitation process discussed in Section 5.7. References to specific models and some discussion of their advantages and disadvantages can be found in the discussions of the workshops held during the course of this project (Appendices A and B).

We first start with a description of methods that rely on data. Next, we discuss aspects of methods that must rely on a mix of theory and data; models based on these methods are currently the most commonly used procedures for predictions of ground motions outside of coastal California. We conclude with remarks regarding the use of scaling spectral shapes to obtain ground motions. This last subsection is the only one in this section containing any significant recommendations—in general we recommend that the use of scaled spectral shapes be avoided. Even though the spectral shapes are usually determined from analysis of empirical data, we placed this section last because the peak acceleration needed to scale the shapes can come from any method—empirical or theoretical.

For those readers seeking more details about various methods, we recommend consulting the original research papers, as well as reviews such as Joyner and Boore (1988), Atkinson and Boore (1990), Reiter (1990), and Boore et al. (1994b). In addition, the quadrennial reviews of strong motion seismology published by the American Geophysical Union can be very useful (e.g., Joyner 1987; Anderson 1991).

5.4.1 Empirical Methods

This topic divides naturally into those methods that use instrumental data and those that use intensity data. We discuss the use of instrumental data first.

Methods that Use Recorded Ground-Motions

In some site-specific and deterministic applications, ground motions can be determined directly by choosing a suite of motions from earthquakes of similar size, fault type, and distance from the site. If the data are available, nothing more need be done. This use of observed data is not particularly relevant for PSHA, which requires the prediction of ground motions for a continuum of magnitudes and distances. In this situation, the obvious choice is to use regression analysis to fit a functional form to the set of ground-motion recordings. Details about this method can be found in a number of places, including Boore and Joyner (1972), Campbell (1985), Joyner and Boore(1988), Boore et al. (1993 1994), Sadigh (1993), Campbell (1993), and Campbell and Bozorgnia (1994). Even with similar data available, differences can arise in the results because of different data winnowing, different choices for the explanatory variables, and different assumptions regarding the functional form. The equations are directly useful when the PSHA is being performed in the region for which the data were obtained, and the results are also useful as a means for checking and calibrating theoretical methods. The method suffers from several weaknesses, all related to the lack of data for various magnitudes and distances. It is well known that few data are available at close distances for large events, but perhaps less well known is the limitation at distances beyond about 100 km. The ground motions at these distances are small enough that not all operational instruments are triggered, even for large events. This can lead to biases in the regression results and uncertainty in the form of the attenuation equations for the greater distances. For use in PSHA, the equations must be capable of predicting motions beyond the distance at which the bias might appear, and therefore the attenuation equations determined strictly from empirical data may have to be extended using theoretical models or data from small earthquakes recorded on sensitive seismological networks.

Methods that Use Intensity Data

Because it is often the only information related to the ground shaking from large earthquakes in regions characterized by low seismicity, seismic intensity has been used in the past to predict ground shaking in future earthquakes (see, e.g., Trifunac and Brady 1975; Veneziano 1988). The present consensus that emerged from the ground-motion workshops (see the Appendices) is that intensity should no longer be used as the principal means for obtaining ground motions. The principal weaknesses are that intensity is a fairly crude, qualitative measure of ground shaking, and the correlations between intensity and ground shaking, needed to derive equations for spectral or peak accelerations, are very poor. This leads to significant uncertainty in the motions. Also, these relationships between intensity and instrumental ground motion are region-dependent, magnitude-dependent, and distance-dependent. In addition, there are pitfalls in the process of substituting one regression into another, as required in order to construct an attenuation equation for PGA or response spectra from intensity attenuation equations (e.g., Cornell, Banon, and Shakal 1977; Veneziano 1988; Risk Engineering 1991). These limitations might be overcome to some extent if ground motion and earthquake magnitude never entered the picture. This would be the case if seismicity were expressed in terms of epicentral intensity and if the product of the analysis were hazard curves for various intensities. This scenario, however, is not applicable to the PSHA studies of interest to SSHAC because a characterization of seismic hazard in terms of intensity is of no practical use in setting design levels or in seismic PRA studies. This scenario is applicable to earthquake loss studies, which routinely use loss functions in terms of intensity.

Intensity data and intensity attenuation equations are useful, however, as consistency checks for the predictions (especially for large magnitudes) obtained from attenuation equations based on modeling and/or instrumental data.

The use of intensity has recently experienced a renewal of interest as a means for estimating seismic moment (e.g., Hanks and Johnston 1992; Johnston 1995b; Bollinger et al. 1993) and high-frequency Fourier spectral levels of the ground shaking (Atkinson and Hanks 1995); see also section 5.3.3.1. These approaches make use of

data from events for which both intensity observations and instrumental magnitudes are available. Thus, this process ensures consistency with relationships such as that of Nuttli and Herrmann (1984). These estimates of source strength can then be used with theoretical models of the ground shaking to obtain predictions of ground shaking that potentially have less uncertainty than those produced by the direct use of intensity. We think that this very promising use of intensity has an important role in PSHA in many regions of North America.

5.4.2 The Components of Non-Empirical Methods

Introduction

For most applications, sufficient data are lacking to be able to use the purely empirical methods. Instead, ground motions are predicted by methods that generally combine theoretical and empirical aspects: the theory gives functional forms with parameters that are determined from data, if possible, or are specified by analogy with other regions or from experience.

Hind- vs. Fore-Sight Prediction. Before continuing, we point out that for the ground-motion component of PSHA, the fundamental task is to predict the statistical distribution of ground motion for future earthquakes as a function of magnitude and distance (at the least, this would be the mean and the standard deviation of the ground-motion measure). Many seismological studies are focused on hind-sight predictions of ground shaking in individual earthquakes for which records of ground motion have been obtained. The purpose of these studies is usually to infer the details of the seismic source—the geometry of the source and the distribution of slip across the fault as a function of space and time. When done for enough earthquakes, the results of such studies can be used to develop statistical distributions of the source properties that might be used for the type of ground-motion predictions needed by PSHA. Furthermore, the methods used to construct synthetic seismograms can be used in a forward sense to predict motions from future earthquakes, but to be useful for future earthquakes, many simulations are required to estimate the parameters of the statistical distribution of ground motion. This can be a computationally intensive exercise. This approach will become more viable as data from more earthquakes are accumulated and as computing power increases.

Pieces of the Puzzle. The methods usually break the task of estimating ground motions into three pieces: the source, the path, and the site (the division between the latter two is somewhat artificial—the site is usually that part of the path within a few kilometers of the point at which ground motion is predicted or observed). Later in this subsection we discuss the various ways that these pieces are treated.

The Issue of Complexity. It is clear from looking at observed ground shaking that the motions are usually chaotic, particularly at high frequencies. Simple models in which a fault with uniform slip is embedded in a constant-velocity half space do not produce enough complexity in the motions (although such models have been used for many years in studies of motions at periods much longer than of concern in engineering). A key issue is how the various methods incorporate the complexity and randomness in the motions. Some methods attempt to model the actual complexities of the earth, while others might be classified as phenomenological models with functional forms that are guided by insights from physical models and parameters that can be adjusted to fit data. A fundamental precept of the latter methods, whether or not explicitly stated, is that the earth's dynamics and structure are too complicated to model deterministically, particularly for a future event.

Low vs. High Frequency. Before embarking on a discussion of the pieces of the puzzle, we remind the reader that the applicability and necessity of a method are often related to the frequency of the motions that are being predicted. As mentioned earlier, simplified models of the source and path are adequate if very long periods are being modeled, motions whose wavelengths are much greater than the size of the earthquake source and most of the earth's heterogeneities. This frequency regime is of no interest for PSHA. On the other hand, motions with periods of several seconds

during the course of this study (Appendices A and B).

5.4.3 The Use of Fixed Spectral Shapes Anchored to PGA

Introduction

One of the approaches for obtaining a representation of seismic hazard as a function of structural frequency is to perform the seismic hazard calculations for PGA only and then use an independently obtained spectral shape or a standard spectral shape to convert the PGA to spectral accelerations or velocities at all frequencies of interest. This approach maybe viewed as assuming a ground-motion model in which spectral acceleration at any frequency f is given by C(f)xPGA(M,R), where C(f) is independent of magnitude and distance. This approach was commonly used in the past.

This section begins by describing the main factors that affect the spectral shapes of earthquake ground motions. Considerations about these factors are then used to support the recommendation that fixed spectral shapes not be used in seismic-hazard analysis (except for studies of limited or very-limited scope).

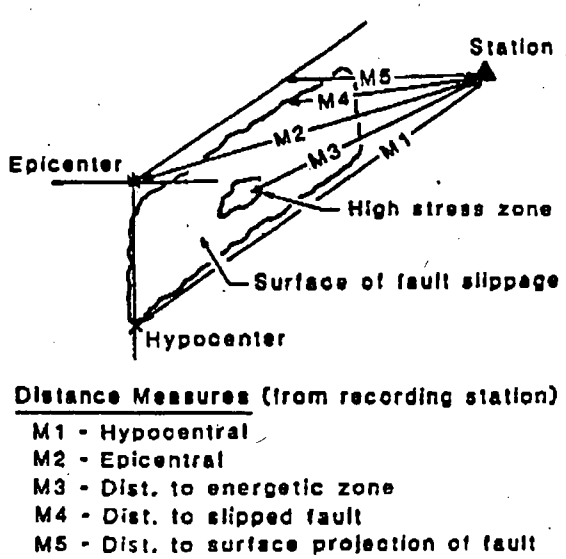

Figure 5-2a Diagram illustrating different distance measures used in predictive relationships (from Shakal and Bernreuter 1981).

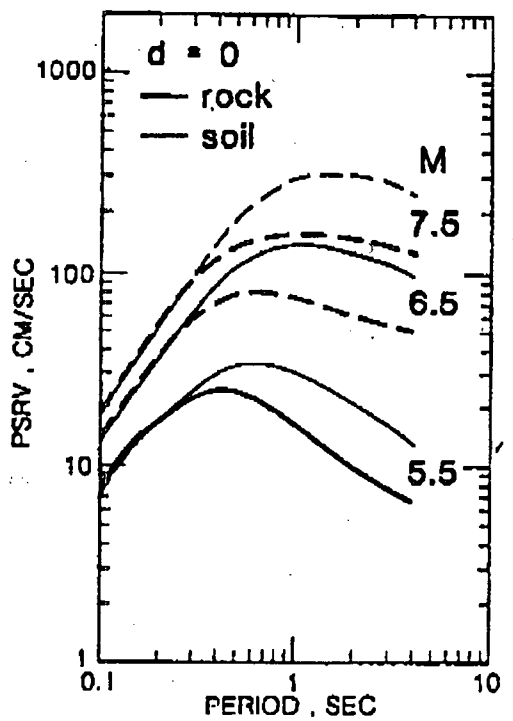

Figure 5-2b Predicted pseudovelocity response spectra for zero epicentral distance and several values of moment magnitude. Source: Joyner and Boore 1988.

Factors Affecting Spectral Shapes

Magnitude

Larger earthquakes generally break a larger portion of the earth's crust and have longer durations than smaller earthquakes. As a result, larger earthquakes are more effective at producing lower-frequency ground motions and have a higher proportion of low-frequency energy relative to the high-frequency energy than smaller earthquakes. Figure 5-2 shows the effect of magnitude on spectral shapes. The effect of magnitude on spectral shapes is also obvious by examining the magnitude coefficients in attenuation functions for spectral acceleration and for PGA (e.g., Boore et al. 1993; Toro et al. 1995): the coefficients for 1 Hz spectral acceleration are approximately twice as large as those for PGA.

As an illustration, consider the calculation of seismic hazard of a hypothetical 1 Hz structure located in a region with maximum magnitude in the range of 6.0 to 6.5. If we use a spectral shape based on earthquakes with magnitudes near 7.0, we implicitly assume that the ratio *PSA*(1 Hz)/*PGA* is the same for the earthquakes affecting the site as for the magnitude 7.0 earthquakes used to construct the standard spectral shapes commonly used (we will return later to the standard spectral shapes). We know from seismological theory and observation, however, that this ratio is lower for the earthquakes that threaten our hypothetical structure, due to the effects of magnitude.

High-Frequency Energy

Earthquake ground motions at rock sites in the western United States have little energy at frequencies higher than 20 Hz (Hanks 1982). In contrast, a number of ground-motion records obtained at hard-rock sites in the central and eastern U.S. have significant energy at frequencies as high as 50 Hz. This high-frequency energy affects the spectral accelerations at high frequencies (f>20 Hz) as well as the PGA, but it does not affect spectral accelerations at lower frequencies. These differences are generally explained as the result of less damping in the upper crust (Hanks 1982; others), but alternative interpretations have been proposed (e.g., Papageorgiou 1988). The shape of the power spectrum at high frequency is often parameterized by the frequency f_{max} (Hanks 1982) or the attenuation time κ (Anderson and Hough 1982).

As a result of these differences in high-frequency energy, the high-frequency portion of the response spectrum is very different for these two types of earthquakes as illustrated in Figure 5-3.

Considering a hypothetical structure with a 1-Hz resonant frequency in the eastern United States, we note that earthquakes in the central and eastern U.S. have similar 1-Hz amplitudes and higher PGA than California earthquakes of the same moment magnitude. Thus, the *PSA*(1 Hz)/PGA ratio is lower (nearly 50% lower, according to Figure 5-3) for the the central and eastern U.S. earthquake. As a result, using a California spectral shape (with its higher *PSA*(1Hz)/PGA ratios) with a proper central and eastern U.S. PGA attenuation function will lead to overestimation of the hazard for the hypothetical 1 Hz structure in the central and eastern U.S.

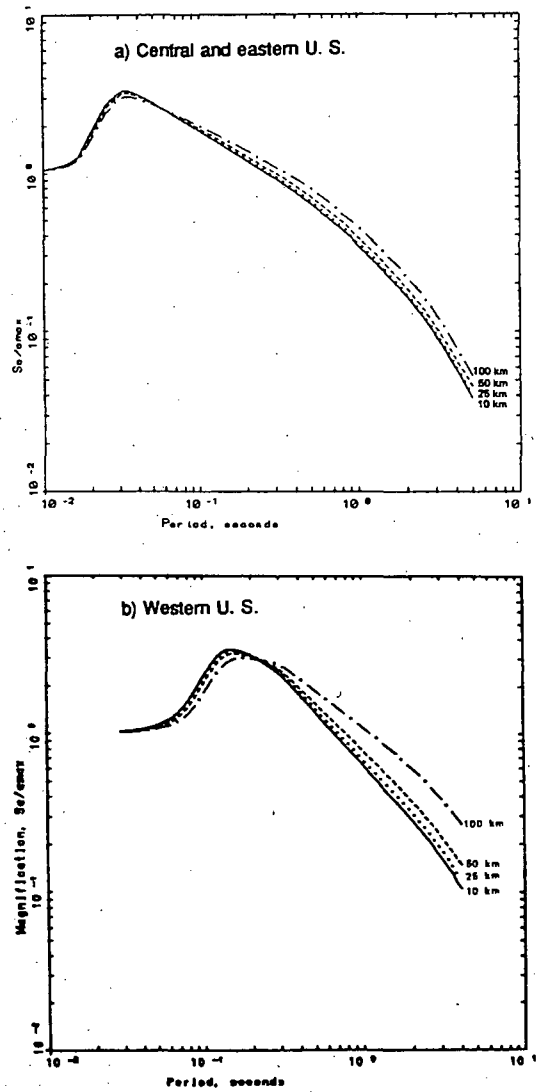

Figure 5-3 Comparison of spectral shapes for the central and eastern U.S. (CEUS) and the western U.S. (WUS) for moment magnitudes 6.5. Source: Silva and Green (1989).

Distance also has an effect on high-frequency energy, due to anelastic attenuation (i.e., damping) in the earth's crust. High-frequency waves go through more cycles as they travel a certain distance, so they undergo more attenuation. This phenomenon becomes important

may be of interest, and for these motions deterministic models of the propagation path can be adequate, although even for this case unknowable complexities of the source may require a probabilistic treatment of the source.

Source

Introduction. The seismic source is described fundamentally by the specification of the slip across the fault plane as a function of space and time. This information is never available for future earthquakes, and therefore the methods for treating the source use various approximations to obtain the seismic radiation from faults. One class of methods sums subevents over a finite fault, and another represents the fault by an equivalent point source. The latter can still be applied to faults of moderate size as long as the source characterization and the distance measure used in the hazard calculations are consistent with the method for predicting the ground motions.

Summations Over a Finite Fault. In methods treating the source as a fault with finite, nonzero extent, the motions are generally calculated by summing and lagging the motions from many subevents distributed over a fault plane with a particular orientation and size. In the sense of a Monte Carlo study, the motions for many realizations of the subevents can be combined to provide the ground-motion distribution needed for PSHA. These subevents can be defined in a number of different ways. Some methods use records from actual earthquakes as the subevents (e.g., Somerville et al. 1991; see also Appendix E). A number of others generate a random slip distribution with prescribed properties (many studies have done this, a recent example is Herrero and Bernard 1994). Finally, some methods do not attempt to simulate a physical distribution of slip over the fault plane, but instead use simple subevents, with the needed complexity contributed by adding together the motions from a distribution of these subevents (many small ones and a few whose dimensions are comparable to that of the target event; e.g., Zeng et al. 1993).

Equivalent Point Source. This popular subset of models of the Stochastic Models method, often referred to, in the literature, as "stochastic models," describes the radiation from a fault in terms of ground-motion spectra whose amplitude and shape are given by smooth, relatively simple functions, and whose phase is quasi-random, such that the motions are distributed in time over a duration related to the size of the source and the distance from the source to the site (e.g., Hanks and McGuire 1981; Boore 1983; Toro and McGuire 1987). The amplitude spectra can be obtained by fitting functional forms to data (e.g., Atkinson 1993b), but more often are taken from physically-motivated seismological models of the source. The most common is the single-corner frequency, ω^2 model; this model is usually, but not completely accurately, referred to as the "Brune" model (after Brune (1970)). Joyner (1984) has published a two-corner extension of the model to account for a breakdown in the self similarity of seismic sources. No attempt is made in the equivalent point-source models to account for the distribution of motions around a fault of a particular orientation; usually a simple scalar factor, taken from studies such as Boore and Boatwright (1984), is used to represent the effect of rays leaving the source in many directions. Because a randomization is not needed for many subevent distributions over a given fault plane and for many orientations of the fault plane, the computational requirements of the equivalent point-source methods are almost trivial.

Path

As seismic energy leaves the source, it is subject to modification enroute to the site. In some methods, this modification is captured by using empirical Green's functions—recordings of small events at a site that have traversed the specified path. Such Green's functions are of little use for PSHA, however, for seldom are sufficient Green's functions available for a specific site of interest. Instead, most often the modification is parameterized by the multiplication in the frequency domain of two factors. The first is a simple geometrical spreading (often frequency-independent) to model the elastic wave-propagation effects. The simplest form of this model assumes propagation in a uniform whole space and predicts a decay proportional to 1/r; a

straightforward modification makes this decay proportional to $1/\sqrt{r}$ at distances greater than 100 km to account for multiple reflections of waves trapped in the earth's crust (Herrmann 1985). The second is a representation of anelastic attenuation, usually given by a function of the form exp $(-\pi f r / Q c)$, where c is the shear-wave velocity and the quality factor Q can be frequency dependent:

$$Q = Q_0 (f / f_0)^{\eta} \qquad (5.2)$$

where usually $f_0 = 1$. The parameters for the anelastic attenuation are usually obtained from studies of wave propagation in the region of interest.

More realistic models of geometrical spreading are now in use. For example, somewhat more complicated functional forms than 1/r can be fit to existing data (e.g., Atkinson and Mereu 1992). Another class of models uses wave propagation in a layered earth to account for the path complexities. These include computationally-rapid high-frequency approximations that try to capture the essential modifications due to the earth's layering (e.g., Ou and Herrmann 1990; EPRI 1993), generalized ray theory (Somerville 1992), and full-wave calculations that compute the complete wave motions for a layered earth (Saikia 1994). The latter two methods are computationally intensive, and the basic assumption of plane layering is in many cases a very gross approximation to reality. Furthermore, even if the earth were plane-layered, it is unlikely that the properties of the layering would be known in sufficient detail to account for propagation of high-frequency waves. For these reasons, the motions computed for full-wave methods, although mathematically precise, may not give *a priori* predictions of ground motion that are any more accurate than the methods that treat the path in a much simpler manner. Recognizing that full-wave methods may not produce sufficient complexity in the motions, some recent studies are adding an empirically-determined filter to the simulations to account for the scattering of waves due to geologic complexities not included in the computational models (e.g., Horton 1994).

At long periods (which are important for base-isolated structures, suspension bridges, or tall buildings) the full-wave methods become more attractive because the path is more deterministic at this larger scale (see Helmberger et al. 1993). A hybrid approach, which uses a full-wave method for long periods and a more stochastic method for short periods has been utilized for this purpose (Saikia and Somerville 1995).

Anelastic attenuation has only a moderate effect on PSHA for frequencies below 10 Hz, especially in the central and eastern U.S. where anelastic attenuation is lower. Although geometrical spreading and anelastic attenuation are treated as separate phenomena, they are strongly coupled in practice, because ground motion is affected by both. Given the amount of data and their scatter, it is typically impossible to resolve the two effects; all that is known is their combined effect.

Site

As mentioned earlier, site effects can have a first-order effect on ground motions. This can be the case even for sites that are nominally founded on hard rock. In fact, at least one study suggests that there is more ground-motion uncertainty in rock sites than in soil sites (Abrahamson and Sykora 1994). It is very important in elicitation of ground motions to be specific about what is meant by "hard-rock"; in our workshops, we specified this to be sites underlain by material for which the time-weighted shear velocity exceeded 2800 m/s.

Examples

Because each piece of the ground-motion puzzle can be treated in so many different ways, many ground-motion models can be obtained. It is because of this diversity that a well-developed elicitation process is necessary to obtain the ground motions needed for PSHA. We devote Section 5.7 and a good part of Chapter 3 to this need. Some discussion of the strengths and weaknesses of a number of specific models for the predictions of ground motions in the central and eastern U.S., circa 1994, is contained in the discussions of the ground-motion workshops held

at distances of more than 50 km and has only a minor effect on seismic hazard.

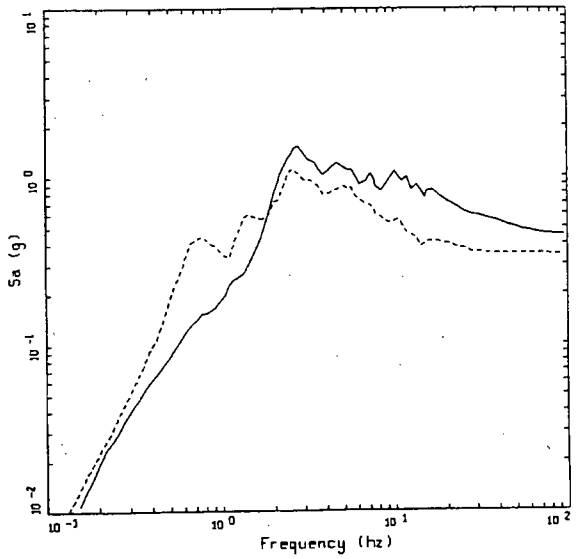

Figure 5-4 Response spectra (5% damped) recorded at Gilroy 1 (rock: solid line) and Gilroy 2 (soil: dashed line) during the 1989 Loma Prieta earthquake (the log average of two horizontal components is plotted). Source: EPRI 1993.

Site Response

Site responses may have a dramatic effect on spectral shapes. Figure 5-4 illustrates the effect of site response on spectral shape by comparing the spectra from records obtained at two nearby stations: one on firm soil, the other on rock.

Deep-soil sites tend to amplify low-frequency motions (for which amplification effects are dominant) and to dampen high-frequency motions (for which damping effects are dominant). The net effect on peak acceleration is typically small, but the effect on spectral shapes may be dramatic. Shallow-soil sites have little effect on low-frequency energy and tend to amplify high-frequency energy and PGA (for which elastic resonance effects due to trapped energy are dominant).

The data used to develop some standard spectral shapes (e.g., the NRC Regulatory Guide 1.60, U.S. Atomic Energy Commission 1973 and NUREG 0098, Newmark and Hall 1978) contain a large number of records from deep-alluvium sites in California. As a result, these spectral shapes may overestimate the PSA(1 Hz)/PGA ratios for rock sites.

Use of Spectra Associated with Certain Percentiles

A common practice in the development of spectral shapes is to select representative records, normalize or scale all records to a common PGA, compute their response spectra, and calculate the normalized spectrum associated with the 84 percentile. That is, at each frequency the calculated value of the normalized spectral acceleration is higher than the normalized spectral accelerations in 84 percent of the selected records. This practice was followed in the development of the NRC Regulatory Guide 1.60 spectrum (U.S. Atomic Energy Commission 1973; see also Blume et al. 1973).

At frequencies associated with the PGA, there is no scatter among the spectra because all spectra have been normalized to a common PGA. As one moves to lower frequencies (i.e., away from peak acceleration), the scatter among the selected spectra increases due to the effects of magnitude, high-frequency energy, and site response discussed earlier. Thus, the 84 percentile spectrum deviates substantially from the median normalized spectrum. Returning to the hypothetical 1-Hz structure, the PSA(1 Hz)/PGA ratio is much higher for the 84-percentile spectrum than for the median spectrum[3]. This difference is not the result of justified conservatism in the face of uncertainty; rather, it is the result of conservatism combined with a sub-optimal procedure for the estimation of low-frequency spectral accelerations (see also Cornell 1993).

Not all standard spectral shapes in current use are associated with 84 percentiles. For instance, the NUREG-0098 median spectral shape (Newmark and Hall 1978) is often used.

5.4.4 Recommendations

It is recommended that the representation of seismic hazard as a function of structural

[3]Recall that the PSA(1 Hz)/PGA ratio in the median spectrum may already be too high, due to the effects mentioned earlier.

frequency be obtained directly through attenuation functions (or equivalent formulations) that predict spectral acceleration as a function of structural frequency, rather than using a fixed spectral shape anchored to a value of PGA. This recommendation implies that separate seismic-hazard calculations must be performed for each frequency, but this is not a problem with today's computational capabilities. This is also the only way to capture the manner in which the various seismic sources contribute differently to hazard at the different structural frequencies.

The recommended approach also requires more input than a PGA hazard analysis, because it requires attenuation equations for spectral accelerations at multiple frequencies. This is less of a problem at present than in the past for the following two reasons: (1) most ground motion records of interest are routinely digitized and processed (making the response spectra available), and (2) there has been significant progress in the use of seismology-based models of ground motion, which can readily provide estimates of spectral accelerations.

In cases where the limited scope of the study makes it necessary to use fixed spectral shapes, these shapes should be developed on a site-specific basis, using records that are representative of the seismic exposure, κ values, and soil conditions of the site. The site-specific spectral shape should be associated with a median normalized shape. Also, it may be desirable to use spectral acceleration at some intermediate frequency, rather than PGA, as the reference ground-motion measure used for anchoring.

In practice, it is nearly impossible to find a sufficient number of records (i.e., more than 10) that meet all the required conditions (the exception is portions of California and similar areas with high seismic activity and dense network of strong-motion instruments). In addition, the level of effort is not too different from that associated with a seismic hazard analysis for multiple spectral accelerations.

A simpler approach is to use existing attenuation functions or seismological ground-motion models to construct the site-specific spectral shape. These attenuation equations or ground-motion models used for this purpose must have sufficient basis (either empirical or based on sound theory) for predicting spectral accelerations at the magnitude, distance, and structural frequency of interest. This approach is also more economical than the approach described above.

Standard spectral shapes may be used in studies of limited scope only if they are shown to be consistent with the above conditions or if they are shown to be conservative, as long as this conservatism is not burdensome to the owner or operator of the facility.

Standard spectral shapes may be used in studies of very limited scope, without having to show their applicability.

5.5 Characterization of Uncertainty in Ground-Motion Predictions

5.5.1 Types of Uncertainty

This section presents a description of the types of uncertainty in ground-motion predictions. The taxonomy of uncertainty used by some ground-motion analysts is somewhat more elaborate than the one presented in Chapters 1 and 2. Although this taxonomy should not be mandated, it is included here because it provides useful insights into the causes of uncertainty and allows the quantitative calculation of that uncertainty.

The distinction between aleatory and epistemic uncertainties was introduced in Chapters 1 and 2; it is repeated here for emphasis.

Epistemic Uncertainty. Uncertainty that is due to incomplete knowledge and data about the physics of the earthquake process. In principle, epistemic uncertainty can be reduced by the collection of additional information.

Aleatory Uncertainty. Uncertainty that is inherent to the unpredictable nature of future events. It represents unique details of source, path, and site response that cannot be quantified before the earthquake occurs. Given a model, one cannot reduce the aleatory uncertainty by collection of additional information. One may be able,

however, to quantify the aleatory uncertainty better by using additional data[4].

From the point of view of the ground-motion analyst who is using physical models, the total uncertainty in predicted ground motions is often partitioned in a manner that may be considered orthogonal to the above partition (see Abrahamson et al. 1990), as follows:

Modeling Uncertainty. Represents differences between the actual physical process that generates the strong earthquake ground motions and the simplified model used to predict ground motions (Abrahamson et al. 1990, call this modeling+random uncertainty). Modeling uncertainty is estimated by comparing model predictions to actual, observed ground motions.

Parametric Uncertainty. Represents uncertainty in the values of model parameters (e.g., stress drop, anelastic attenuation) in future earthquakes. Parametric uncertainty is quantified by observing the variation in parameters inferred (usually in an indirect manner) for several earthquakes and/or several recordings.

It is important to recognize that the distinction between modeling and parametric uncertainty is model-dependent. For instance, one may reduce the scatter in the predictions by making the model more complete, thereby introducing new parameters in the model. Unless these new parameters are known *a priori* for future earthquakes and for the site of interest, there will be additional parametric uncertainty, thereby transferring some modeling uncertainty into parametric uncertainty, without varying the total uncertainty.

Both the modeling and parametric uncertainties contain epistemic and aleatory uncertainty. For instance, observed scatter that is not accounted for by the model and varies from event to event is aleatory modeling uncertainty, whereas statistical variability in the calculated bias that introduces uncertainty about the accuracy (or unbiasedness) of the model (due to limited data) is epistemic modeling uncertainty. Similarly, the event-to event variation in stress drop is aleatory parametric uncertainty, whereas the imperfect knowledge about the probability distribution of stress drops from future earthquakes (e.g., What is the median stress drop for M 7 earthquakes?) is epistemic parametric uncertainty. Table 5-1 illustrates this two-way partition of total uncertainty. The different types of uncertainty are illustrated by way of a more concrete example. The Hanks-McGuire ground-motion model (Hanks and McGuire 1981; Boore 1983, etc.) may be used to predict spectral acceleration for a given magnitude and distance and for given values of the model's physical parameters; i.e.,

$$\ln[Amplitude\} = f(\mathrm{m,r}: \Delta\sigma, Q, f_{max}) \qquad (5.3)$$

where the stress drop $\Delta\sigma$, the quality factor Q, and the frequency f_{max}, are physical parameters of the model.

When one applies this model to well-studied events in well-studied regions (for which the parameter values have been determined), and compares predictions to observations, one observes some scatter and possibly some bias, addressed below, because the physical model contains only a crude representation of source and path effects. This scatter represents aleatory modeling uncertainty (i.e., observed scatter not explained by the physical model). In order to include this scatter in our predictions, the physical model above is used to construct an aleatory model of the form

$$\ln[Amplitude\} = f(\mathrm{m,r}: \Delta\sigma, Q, f_{max}) + \varepsilon_{\text{aleatory modeling}} \qquad (5.4)$$

where $\varepsilon_{\text{aleatory modeling}}$ is a zero-mean random quantity that represents the observed scatter not explained by the physical model.

[4]An example may clarify these definitions. Consider a Gaussian random quantity X with mean μ and standard deviation σ. The value of μ represents the deterministic component of X. The value of σ represents aleatory uncertainty in X. The probabilistic modeler's uncertainty about the true values of μ and σ (due to a small statistical sample or to alternative hypotheses about the nature of X) represents epistemic uncertainty in X.

Table 5-1 Partition of Uncertainty in Ground-Motion Prediction

		Seismic-Hazard Analyst	
		Epistemic	Aleatory
	Modeling	Uncertainty about the true model bias (i.e., to what extent model has tendency to over- or under-predict observations)	Unexplained scatter due to physical processes not included in the model
	Parametric	Uncertainty about the median stress drop for the central and eastern U.S., depth distribution, etc.	Event-to-event variation in stress drop or focal depth, etc.

Because we need to make predictions for future earthquakes (for which the stress drop and other model parameters are not yet known), those predictions will contain additional uncertainty: aleatory parametric uncertainty. Knowing the aleatory, event-to-event and site-to-site, variation in the parameters, one can calculate the associated aleatory uncertainty in ground-motion amplitude by using the methods of derived distributions (Benjamin and Cornell 1971). Referring to Section 2.2, we note that the aleatory modeling and aleatory parametric contributions are combined into ε_a in Equation 2-5.

Epistemic uncertainty in the above prediction also comes in two forms, as follows. The limited data, and the scatter in these data, do not allow us to quantify any systematic biases in the physical model's predictions for given parameter values. Small biases are obscured by the scatter in the observations, unless one has observations from many events and sites. It may also happen that most of the data fall outside the (m,r) ranges of engineering interest. This uncertainty is epistemic modeling uncertainty. In addition, the aleatory distributions of the model parameters are not known exactly (e.g., What is the median stress drop for ENA earthquakes?); this introduces epistemic parametric uncertainty. Referring to Section 2.2, we note that the epistemic modeling and epistemic parametric contributions are combined into ε_e in Equation 2-5.

Appendix F describes how these concepts are used in the context of the various types of ground-motion models and how the various components of uncertainty are estimated in practice.

The distinction between epistemic and aleatory uncertainties is common practice in PSHA (see Chapter 2) and should be maintained throughout the process of characterizing uncertainty in ground-motion predictions. The distinction between modeling and parametric uncertainties is a useful tool for the quantitative determination of the epistemic and aleatory uncertainties in the context of physical models, but it is not required. In fact, this latter distinction is internal to the ground-motion modeling and is not carried downstream into the seismic hazard calculations.

Site-Specific Perspective on Uncertainty. In ground-motion studies, the limited availability of data forces the investigator to use data from large geographical areas[5]. Any undetected geographic trends in the data are implicitly counted as part of the aleatory parametric uncertainty. (Also, undetected geographic variations in the model bias are implicitly counted as aleatory modeling

[5]In physical models, data on different parameters may be collected at different geographical scales (e.g., one may use stress-drop data from all of ENA, while using Q data from a smaller region).

uncertainty). Thus, the scatter one obtains from regional data applies to a site chosen at random.

In seismic hazard studies for a given site, one is interested in ground motions from certain seismic sources (with their particular distributions of stress drop and source depth and their preferred focal mechanisms), which are propagated through a certain portion of the earth's crust (over a radius of say, 100 km, with its particular Moho depth, Q, and upper-crust velocity profile), and are further modified by the local geologic conditions beneath that specific site (with its particular amplification, resonance, κ, and degradation properties). If one takes this perspective, much of the geographic variations that were implicitly counted as aleatory uncertainty should be counted instead as epistemic, thereby decreasing the aleatory uncertainty and increasing the epistemic uncertainty.

If site-specific information on any of these parameters is obtained (from geophysical or geotechnical studies, regional Q studies, weak-motion recordings, etc.), the epistemic parametric uncertainty will be reduced accordingly (and there will likely be a change in the central value of the parameter).

This site-specific perspective is, in principle, the proper perspective for all seismic-hazard studies, regardless of the level of effort, and regardless of the availability of site-specific data. In practice, however, it may be difficult to quantify *a priori* how much of the aleatory parametric uncertainty in a parameter is associated with geographic variation and should be treated as epistemic.

This site-specific perspective is particularly important for site effects, because the site-response parameters (shear-wave velocity profile, stiffness-and damping-degradation curves, and κ) have a significant effect on ground motions. Also, these parameters are determined as part of the site-characterization studies for important facilities. Thus, one would expect a significant reduction in epistemic uncertainty (and a significant, but unknown *a priori*, change in the median ground-motion prediction) when site-specific site-response information becomes known and is used to update ground-motion predictions. This is true for both soil and rock sites, as there appears to be significant differences in the response of different rock sites.

5.5.2 Propagation of Parametric Uncertainties

Let $X_1, X_2, \ldots X_n$ be aleatory quantities representing uncertain parameters of the ground-motion model (e.g., stress drop, Q). Aleatory uncertainty in the values of $X_1, X_2, \ldots X_n$ for a given event and site is represented by probability distributions with parameters[6] (e.g., means and standard deviations) $\Theta_1, \Theta_2, \Theta_3, \ldots \Theta_m$. Uncertainty in the values of $\Theta_1, \Theta_2, \Theta_3, \ldots \Theta_m$ represents epistemic uncertainty, and is also represented by probability distributions. Also let

$$\ln[\text{Amplitude}] = f(m,r;X_1,X_2,\ldots X_n) + \varepsilon_{\text{epistemic modeling}} + \varepsilon_{\text{aleatory modeling}} \quad (5.5)$$

represent the ground-motion model, including modeling uncertainty. The propagation of parameter uncertainties into uncertainties in ground-motion amplitudes (i.e., finding the distribution of ln[Amplitude] as a function of only m and r) is one of derived probability distributions (see Benjamin and Cornell 1970). It may be performed using logic trees, Monte Carlo simulation, or other appropriate methods. Because epistemic and aleatory uncertainties must be kept separate, this propagation must be performed in a nested manner. The innermost step consists of calculating the distribution of ln[Amplitude(m,r)]for given values of $\Theta_1, \Theta_2, \Theta_3, \ldots \Theta_m$, and $\sigma_{\text{aleatory modeling}}$, by integrating over all possible values of the aleatory quantities given $\Theta_1, \Theta_2, \Theta_3, \ldots \Theta_m$, and $\sigma_{\text{aleatory modeling}}$. In practice, one often calculates the mean and standard deviation of ln[Amplitude(m,r)] rather than the full distribution. The outer step is to calculate the epistemic distribution of the mean and standard deviation calculated above, when $\Theta_1, \Theta_2, \Theta_3, \ldots \Theta_m$, and $\sigma_{\text{aleatory modeling}}$ are allowed to vary based on their respective probability distribution.

6We use the word parameter with two different meanings in this paragraph. The first time we mean a physical (or perhaps empirical) parameter such as stress drop (aleatory), the second time we mean a parameter of a probability distribution such as median stress drop (epistemic).

The result of this exercise is a model of a form that may be used in the seismic-hazard calculations, i.e.,

$$\ln[\text{Amplitude}(m,r)] = g(m,r) + \varepsilon_{epistemic} + \varepsilon_{aleatory}$$

where $\varepsilon_{epistemic}$ and $\varepsilon_{aleatory}$ have zero mean. We can write the following expressions for the quantities appearing in the above equation.

- Mean value of ln[Amplitude(m,r)] and epistemic standard deviation of ground motion amplitude.

$$g(m,r)=E_{\Theta}\{E_{X|\Theta}[f(m,r,x)]\}$$

$$\sigma_{epistemic} = \left[\mathrm{Var}_{\Theta}\left\{E_{x|\Theta} f(m,r,x)\right\} + \sigma^2_{epistemic\ modeling}\right]^{1/2} \quad (5.6)$$

- Mean value and epistemic standard deviation of the variance of $\varepsilon_{aleatory}$:

$$\sigma^2_{aleatory} = E_{\Theta}\left\{\mathrm{Var}_{x|\Theta}[f(m,r,x)]\right\} + \sigma^2_{aleatory\ modeling}$$

$$\sigma_{\sigma^2_{aleatory}} = \left[\mathrm{Var}_{\Theta}\left\{\mathrm{Var}_{x|\Theta}[f(m,r,x)]\right\} + \mathrm{Var}_{stat.}\left[\sigma^2_{aleatory\ modeling}\right]\right]^{1/2} \quad (5.7)$$

In the above equations, E_X [ ] and Var_X [ ] represent the expectation and variance operators, Θ represents the vector of $\Theta_1, \Theta_2, \Theta_3, \ldots \Theta_m$, and X represents the vector of $X_1, X_2, \ldots X_n$, and we assume that $\varepsilon_{aleatory\ modeling}$ and $\varepsilon_{epistemic\ modeling}$ have zero mean. The last term in the last equation represents statistical uncertainty in the value of $\sigma^2_{aleatory\ modeling}$. The above equations show the nested nature of these calculations, with the conditional integrations over $X|\Theta$ on the inside and the integrations over Θ on the outside.

One may choose not to integrate over a few of the more important epistemic uncertainties, leaving those uncertainties explicitly in the model (in which case one would have to provide the conditional values of the above four quantities). Those uncertainties would then be considered explicitly in the seismic hazard calculations. This has the advantage that one can calculate the sensitivity of the seismic hazard to those uncertain quantities.

One may also choose to calculate the full epistemic distribution of $\varepsilon_{epistemic}$ and $\varepsilon_{aleatory}$, rather than their first and second moments. These calculations would follow the same nested structure shown above, although the computations would be somewhat more demanding.

5.6 Recommendations

Based on the discussion in Sections 5.2 through 5.5, the following recommendations are presented (recommendations on elicitation are contained in Section 5.7).

Ground Motion Measures

1. We recommend that PGA alone not be used for most applications. A much more useful measure of ground motion is the response spectrum.
2. We recommend that vertical motions, if important for the study, be obtained from independent analyses, in the same manner as for the horizontal motions.

Explanatory Variables

1. All data used to construct the attenuation functions must be in the same magnitude scale and this scale must be the same as the scale used to define seismicity parameters.
2. Seismic hazard studies in the western United States must use the moment magnitude scale. Although seismic hazard studies in CEUS may use either moment magnitude or m_{blg} in the near term, we strongly recommend that an effort should be made to convert the CEUS earthquake catalogs to moment magnitude. At the same time, the collection of macro-seismic data from current earthquakes should not be discontinued, in order to improve our understanding of the relationship between macro-seismic effects and instrumental magnitudes. Because of its potential utility in PSHA, we also recommend a detailed evaluation of the newly-proposed high-frequency magnitude m.

3. **Distance** The definition of distance in the attenuation equations must be consistent with the geometric model of earthquake occurrences. Attenuation functions in terms of distance to a point source (or a projection thereof) are consistent with areal seismic sources and are appropriate for source dimensions less than 5 km. Attenuation functions in terms of distance to the rupture surface (or a projection thereof) are consistent with fault-type seismic sources and are required for source dimensions of 5 km or greater. Consistency is also required for source dimensions of 5 km or greater. Consistency is also required in the treatment of depth, which is important for the host seismic source or for faults located near the site.

4. **Site Response** If the scope of the study does not warrant a site-specific site response analysis, it is necessary to use attenuation equations that are applicable to the conditions at the site or to use appropriate amplification factors. The explanatory variables that characterize site conditions should consider both the depth and dynamical properties of the site; the use of a soil/rock dichotomous explanatory variable is not sufficient.

5. For site-specific analyses, sufficient resources should be made available to adequately characterize local geologic and geotechnical properties.

6. **Additional Explanatory Variables** In most situations, there is no need to introduce additional ground-motion explanatory variables to represent earthquake characteristics or location of the site relative to the earthquake. Additional explanatory variables may be introduced with adequate justification, as discussed in Section 5.3.2. If additional explanatory variables are introduced, their aleatory and epistemic uncertainties must be modeled explicitly.

Methods for Predicting Ground Motion

1. A methodology for obtaining ground motions that adequately capture the uncertainty in the estimates and is defensible in a regulatory arena is recommended in Chapter 5.

2. We recommend that the use of scaled spectral shapes be avoided.

Recommendations on Uncertainty

1. The estimates of total uncertainty in ground motion must be realistic and must include all sources of uncertainty. In particular, one must avoid the following two frequent situations: (1) very narrow estimates of uncertainty as a result of ignoring the existence of other models or the possibility of alternative interpretations of the existing data, or (2) very broad estimates of uncertainty (which would allow for unreasonable ground-motion amplitudes or which predict much more scatter or bias than is observed in the data in (m,r) regions where data are available).

2. The partition of total uncertainty into aleatory and epistemic, though sometimes arbitrary, must be made carefully and in a manner that is consistent with current practice.

3. Ground-motion analysts are encouraged to use quantitative procedures for the development of uncertainty estimates and to follow the framework discussed here. This facilitates the exchange of information and should help resolve some of the differences between experts' estimates of uncertainty. It is recognized, however, that there are limits to the applicability of purely data- and model-driven procedures and that some subjective inputs are always required.

5.7 Specific Expert-Elicitation Guidance for Obtaining Ground-Motion Values

The ground-motion information needed for PSHA is the probability distribution of the ground-motion measure of interest, conditional on earthquakes of magnitude **M** occurring at distance R, for all **M** and R within a specified range. Usually the probability distribution is specified by giving the median value of ground motion and a parameter related to the breadth of the distribution function. In most cases, the ground-motion

measure is assumed to follow a lognormal distribution. The goal of the elicitation, then, is to obtain the median value and the breadth parameter for any M and R within the specified range. The elicitation must consider the uncertainty in the desired parameters.

The procedure for performing the elicitation will depend on the particular project. For projects that do not involve critical facilities whose failure might cause a substantial hazard to the nation and its citizens, the elicitation might involve nothing more than an analyst choosing an equation from the literature. Elicitation at the other end of the spectrum involves an intensive effort that employs a group of experts. We will concentrate here on this latter case. At the end of this section we have a short discussion on the use of the contractor/peer review process outlined in the previous section.

In this section we will recommend a procedure for obtaining ground motions that should be as applicable ten years from now as it is today, even if a new generation of ground-motion models is available by then. The bulk of this section will be devoted to a detailed discussion of how to use multiple experts to obtain ground-motion values. We imagine that such an exercise will be undertaken every 5 to 10 years, and will be focused on ground motions to be used in regional studies. For many projects, the results of such an elicitation can be used with or without modification. For site-specific studies, more detailed knowledge of important parameters such as crustal structure, Q, kappa, and local basin and soil properties might be available, and it would be appropriate to modify the ground-motion values to account for these site-specific properties.

This section begins with a short discussion of the ground-motion elicitation procedures used in the EPRI and LLNL studies. It then presents a brief summary of SSHAC's recommendation for performing ground-motion elicitation. This is followed by a more detailed discussion of the elicitation process. Further details and supporting information are contained in several Appendices.

This section is designed to augment, not substitute for, the general guidance in Chapter 3. Every element of the general guidance applies to ground motion specifically and is an integral part of the ground-motion elicitation process.

5.7.1 Historical Perspective

For ground-motion elicitation, EPRI and LLNL used fundamentally different procedures. EPRI used one analyst (a few individuals in one consulting company), who conducted several information-gathering workshops and then decided on particular models to be used in the analysis. Weights were assigned by the analyst to three specific models, and the hazard calculations were performed for each of these three ground-motion models; the weights were used in aggregating the results.

LLNL used two different procedures. In their initial work (mid 1980's) they asked each member of a group of experts to assign weights to a set of ground-motion models. As in the EPRI work, the hazard analysis was performed for each model in combination with the many different seismicity models. The elicitation procedure involved an information-gathering and dissemination workshop, but, by design, the interaction among experts and the analyst team was minimal. LLNL adopted the role of a "weak" integrator, for they did not want to influence the experts in their choice of models.

In the early 1990's, LLNL again elicited ground-motion information from experts, but in this case what they did with the information—and to some extent how they obtained the information—differed from their first elicitation. After a one-day information dissemination workshop, LLNL asked the experts, in individual interviews, to provide ground-motion estimates and associated uncertainties for a set of magnitudes and distances (what we will refer to hereafter as points in (M, R) space). These estimates were combined to produce a "composite" ground-motion distribution which was used to compute the hazard. LLNL again adopted the role of a "weak" integrator, and interaction among the experts, although intended, was minimal. Lessons learned from LLNL's experience is contained in R. Mensing's paper (Appendix D).

SSHAC's Recommendations

On the basis of past experience with the LLNL and EPRI studies, as well as our experience in two ground-motion workshops convened to test some of our ideas (Appendices A and B), we recommend the following:

Composite ground-motion estimator

SSHAC recommends that ground-motion measures be estimated for a selected set of specific points in (M,R) space (as LLNL did in their second elicitation). The sections below describe a process for eliciting these estimates. Here we discuss the question of how to use the limited set of explicitly elicited (M,R) pairs to produce the information necessary for the hazard calculation, namely a functional form that can be used to estimate the ground motion for all (M,R) pairs.

There are at least three basic ways to generate ground-motion estimates for an arbitrary point in (M,R) space:

1. If the (M,R) pairs were constructed using explicit numerical weights on multiple models, the natural process is to form a composite model equal to a weighted average of the multiple models, and to use this composite model to calculate ground motion (the explicit numerical weighting approach is discussed below; one of its advantages is the attractiveness of this well-defined interpolation process).

   SSHAC strongly discourages the use (without scientific justification) of individual models with the same weights for all points in (M,R) space. Thus, the TFI elicitation process may often result in weights that are different (M,R) pairs. In this case a reasonable approach would be to vary the weights smoothly (e.g., linear interpolation) around the (M,R) space in such a way that the composite model fits through the elicited discrete set of points.

2. Another process is to use one specific model, such as a stochastic model, and adjust the parameters to provide a representation of the median that is a good fit through the elicited (M,R) pairs.

3. A third approach, used by LLNL in 1992, is to perform a regression analysis to fit a response surface empirically (i.e., some convenient parametric mathematical function) to the means of the (M,R) pairs.

   The standard deviations (aleatory and epistemic) can be dealt with similarly; the variation over the (M,R) space is less strong, however.

Use of a TFI

For reasons given elsewhere (see Chapter 3) we recommend for multiple-expert applications that ground-motion elicitation be done by a TFI—one entity responsible for producing a composite, ground-motion estimator based on input and interaction among experts and between the TFI and the experts. In a very real sense, the TFI will have intellectual responsibility for the product. The TFI process is explicitly contrasted with other alternate modes of using models, including using only one model, using multiple models with explicit numerical weights, and using one core model with other models for support. We have found that the TFI process, based explicitly on the principle that there is "no one correct model," reduces the participants' tendencies to view themselves as advocates and emphasize their role as scientists and evaluators with different scientific hypotheses.

We explicitly recommend against the use of a "weak" integrator, who simply mechanically combines the expert's opinions and weights without feedback between the integrator and the expert. Furthermore, we strongly endorse an elicitation process that involves significant feedback, iteration, and group discussion among experts and the TFI. Most of the rest of the chapter contains an extended discussion of the TFI approach to elicitation.

Use of a Technical Integrator (TI) to Develop the Ground-Motion Analysis

It is also feasible to use a Technical Integrator (TI) approach for developing the ground-motion part of the PSHA analysis. We will not develop

detailed guidance here for this option, which is described in more detail elsewhere in this chapter. However, much of the guidance that follows, although directed towards the TFI approach, is useful for the TI approach as well. Moreover, acting as a TI-like evaluator of a range of scientific viewpoints is one of the roles that each expert is asked to play in the TFI process.

5.7.2 The TFI Team

The TFI has two primary roles:

1. Structures and facilitates a high level of interaction among ground-motion experts.
2. Integrates data, models, estimates and expert evaluations to produce a "final" full probabilistic characterization of ground motion as a function of magnitude, distance and frequency.

Figure 3.3, described in Chapter 3, illustrates the different types of disagreement that may occur among a group of ground-motion experts. The figure also illustrates unintended disagreements due to incomplete communication and misunderstandings.

Following the general discussion in Chapter 3, the TFI for ground motion should be a small team that includes at least two essential types of expertise:

- Functional knowledge of ground motion (science, data, models and interpretations)
- Knowledge and expertise in elicitation methods

The functional knowledge is essential in clarifying, facilitating and leading scientific interchange and in summarizing points of agreement and disagreement. The elicitation expertise is essential in designing the interaction process and in structuring and conducting the information elicitation.

It is also extremely useful to have someone on the TFI team with detailed probabilistic seismic hazard expertise. Such expertise can help guide the facilitation process by focusing it on those elements and data that most affect the final hazard calculation. It is rare to find the three types of expertise in one individual; thus, the typical minimal size team would be two or three. In the SSHAC workshops, the TFI team was four to five persons for experimental reasons, but this is on the high side. The TFI team must work together very closely and meet often, so that increasing the size of the team makes logistics difficult. Additionally, the larger the team, the harder and more challenging it will be to achieve TFI consensus.

Another essential piece of the ground-motion TFI team are the resource experts, or "Implementers," described in Chapter 3 who handle logistics, mailings, process expert information, take technical notes, etc. At least one Implementer must be a ground-motion expert. It is worth repeating that it is essential that the Implementers report directly to the TFI because of need to respond quickly to logistical and technical needs.

5.7.3 The TFI Process

Figure 5-5 provides a road map of the ground-motion elicitation process. This process is explicitly based on the elicitation guidance in Section 5.7. There are 6 stages in the process, and in most stages, there are group interactions. Each group interaction is preceded and succeeded by TFI interaction with individual experts. This section is designed to supplement, not replace, Chapter 3, which provides detailed facilitation and integration guidance.

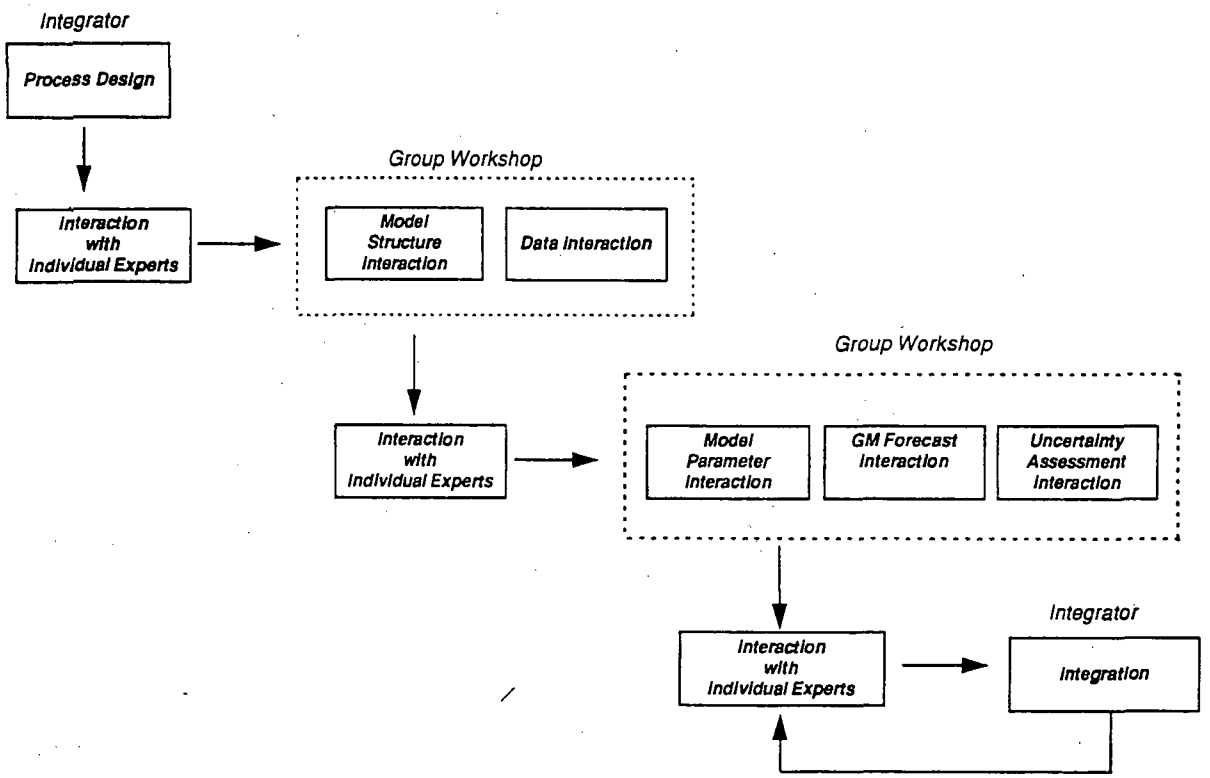

Figure 5-5. Roadmap of GM Elicitation Process

The process begins with a design stage and ends with an integration stage. The group interactions are naturally organized into two group workshops (illustrated by the dotted line boxes in the Figure) but the number of workshops is not as important as ensuring that every type of interaction occurs. TFI interaction with individual experts is also essential at every stage of the process.

The different stages of the TFI process are described below. To help organize the discussion, consideration has been given in each stage of the elicitation process to the purpose and goals of the stage, the process involved in accomplishing the goals, and the products that will result from the stage.

Stage 1: Process Design

In the first stage of the process, the TFI works with the sponsor to lay out the objectives, workplan, and time schedule. It is crucial early on to select and line up the Implementers to help with the logistics of the process.

It is also very important early on to identify potential expert participants and formulate a preliminary schedule of group meetings to ensure that the experts selected will be available roughly when they are needed. Expert selection is described in Chapter 3. The specific types of experts needed are described in the following subsections.

The TFI must fully understand the process laid out in the roadmap (Figure 5-5), as well as the TFI principles in Chapter 3. Moreover, the TFI needs to make sure there are adequate resources in terms of people, time and money to implement the process. Also, the members of the TFI team must be careful to check that they have the necessary expertise; if they do not, the team should be altered or supplemented.

In the design stage, the TFI must work closely with the sponsors of the project. Then, the TFI must work with the Implementers to bring the right set of experts onto the project and to make sure they receive all the necessary information concerning their responsibilities and schedules. The TFI and Implementers must work carefully with the sponsors to make sure that necessary

contracts are set up well ahead of any work that needs to be accomplished.

The time frame for the Process Design will typically be on the order of several months because of the large number of people that need to be contacted and assembled and because of the complications and delays that are often encountered in setting up contracts for a large project. It is SSHAC's experience that a number of TFI team meetings are needed to iron out the goals, details, and procedures for each stage. We believe that the details provided in Appendices A and B that describe the SSHAC ground-motion workshops will reduce the necessary preparation time.

The product of the Process Design should be a carefully laid out workplan and time schedule, in which every type of participant has a documented task list, a set of deliverables, a set of milestones, and a budget. It is particularly important to pre-arrange at least approximate dates for large group meetings so that the participants can block out the time on their calendars.

Stage 2: Review of Data

A key lesson from the SSHAC workshops was the importance of early attention to data issues in preparation for reviewing models and expert positions (refer to Chapter 3 for more details). We suggest that a single reviewer (e.g., the resource expert) prepare a comprehensive white-paper discussing the applicable data well in advance of the first group meeting (which we will hereafter call "Workshop #1"). This is a large job and adequate time and resources should be allowed for its completion. This paper should be distributed to meeting participants in advance, with instructions that the participants carefully review the paper and be prepared to critically discuss the paper at the group meeting.

At the workshop, the reviewer would present the paper, and that presentation would be followed by intensive discussion and interactions among the participants. As in all group interactions, the TFI needs to guide the discussion to make sure that it does not stray from the task at hand.

The product would be one or several sets of data against which to compare ground-motion estimates at Stage 4 of the Elicitation Process. The data would have to be compiled into machine-readable form, but this can be done after Workshop #1.

Stage 3: Review of Methods

The main purpose of this stage is for a relatively large group of experts (from which a smaller group will be chosen for Workshop #2) and the TFI to understand the strengths and weaknesses of the basic classes of methods for predicting ground-motion measures. In addition, other goals of Stage 3 are to make sure that all reasonable methods have been considered and to perform an initial screening of the methods. This is accomplished by the following "required" activities:

- Structuring and facilitating complete information and judgment exchange
- Staging presentations by proponents of different modeling approaches
- Ensuring consistent databases and terminology
- Staging debates in critical areas
- Heavy emphasis on structured discussion regarding basic approaches rather than on individual expert opinions.

Each activity above is an essential part of the TFI process. The centerpiece of Stage 3 is a carefully structured group meeting involving intensive interaction among experts and the TFI. Prior to the group meeting, several people with strong knowledge of specific classes of methods for predicting ground-motion measures should be asked to play the role of reviewers and prepare presentations of the methods. At the group meeting these people present the methods and their strengths and weaknesses (without focusing on a particular model), with various types of group discussions following the presentations (for an example of useful types of discussions, see the agenda for the first SSHAC ground-motion workshop, presented in Appendix A).

The meeting itself requires careful facilitation. It is critical for the TFI to set the right tone for the meeting. In doing so, two elements that bear repeating from the general guidance in Chapter 3 are critical:

- The purpose is not to choose the best 'model.' The experts should be made to understand that the TFI concept is founded on the premise that there is no one correct model, and that the meeting will not be focused on trying to identify a single winner or loser. It is very important psychologically to have the participants feel that they are not there to win or lose, but to identify and clearly understand all important scientific and application issues.
- The purpose is not to achieve consensus. Consensus may occur as a serendipitous outcome, but it is important to state explicitly that the meeting will not be a failure if consensus is not achieved. Rather, it should be communicated that disagreement is not only expected, but acceptable.

It is also important that the experts understand that, other than when they are asked to be proponents (which occurs after the first workshop), they are expected to act as independent, informed evaluators (and later as integrators). An important aspect of the TFI process is that the experts are asked to provide input as to how they would integrate all the models, data and information into a composite representation of the overall expert community. If the experts feel involved as evaluators, they will tend to be constructive, and rather than resisting the process, they will assist it.

The focus in this first interaction is on the logic of different modeling approaches, rather than on variations among similar approaches. Initial focus should be on model logic rather than on numbers.

It is essential for the TFI to isolate and play back points of agreement and disagreement. This is accomplished by playing back a clear summary of the conversation frequently during the meeting. A useful facilitation model is the concept of 'active listening' (elaborated in Chapter 3). The TFI should ask experts who are not communicating to try to state each other's positions clearly.

As part of the group meeting itself, the experts should be asked to provide input on specific points in (M, R) space that are most appropriate for constructing the composite ground-motion estimator. There needs to be a clear common understanding of appropriate assumptions concerning magnitude scale and definitions of distance. The TFI should have already considered these issues, but if the experts are not involved in this initial stage, future analyses are likely to contain conflicting assumptions and errors.

Some suggested, but not required, ideas and tools are:

Pre-meeting Contact with Experts - SSHAC strongly suggests that the TFI meet with at least several of the ground-motion experts individually. This greatly aids in anticipating potential confusions and problems, in understanding the subsequent discussion at the group level, and in helping pre-structure discussion topics and define key agenda items.

Pre-meeting Contact with Reviewers - It is essential that the TFI communicate before the meeting with the reviewers to make sure that they understand their role and to promote a standardized format for their presentations. SSHAC's experience has been that without such structure and guidance, some proponents will give excellent presentations, while others will be either ill-prepared or hard to follow.

Influence diagrams - Influence diagrams are an invaluable graphical communication tool for describing basic relationships in a given modeling approach (see Howard and Matheson 1981, for a general description of influence diagrams). Figure 5-6 illustrates an influence diagram that was elicited from a ground-motion expert to describe how one ground-motion model produces an estimate of uncertainty. Such diagrams provide an excellent context for understanding the reasoning underlying a model or scientific argument.

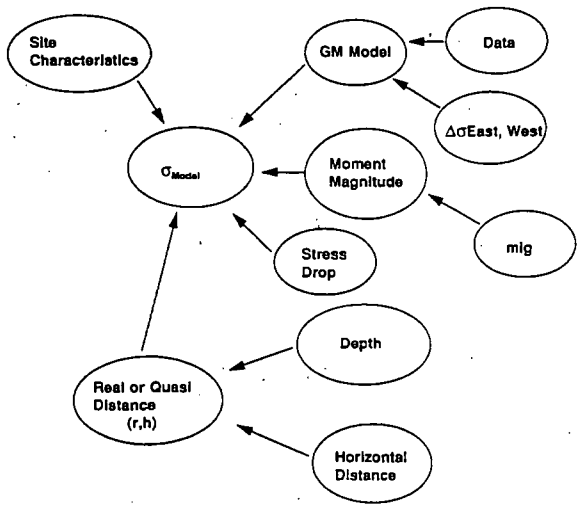

Figure 5-6. Influence Diagram

The key elements in the Stage 3 workshop are an initial session in which the workshop purpose and the various roles of the participants are explained. Second, presentations by experts designated as reviewers (who may or not be members of the expert panel) of representative methods for predicting ground motion form the basis for much of the interchange. Third, the methods should be considered one by one to make sure that all points of confusion and areas of agreement and disagreement are covered in detail. Since the relative efficacy of the different methods depends on magnitude and distance, the discussion needs to be structured (M, R) point by (M, R) point. Fourth, it is important for the experts to document their post-discussion appraisals of the different approaches—this would typically be accomplished through a written survey (the SSHAC Ground-Motion Workshop I survey is described in Appendix A). Finally, it is important that the TFI document, for all participants, a summary of the lessons learned from the meeting, including conclusions about which representative models should be run to provide numerical estimates for the next workshop.

For Workshop #1, it is important to have a large and diverse group of experts, both generalists and specialists who are able to act as reviewers of specific methods. The experts as a group should have a comprehensive understanding of existing data and models and their limitations and should be representative of the overall ground-motion expert community.

The general process of expert selection is described in detail in Chapter 3. Basically, it is important to include enough experts at Workshop #1 such that additional experts would not bring substantially different methods or interpretations to the table. When selecting among specific individuals, it is best to find specialists who are articulate and clear-thinking. It is best to find generalists who are particularly well-respected and who are not perceived to be wedded to one particular approach or interpretation. If possible, it is desirable to include experts who are non - hostile and non-emotional; this contributes to better group dynamics and information exchange. However, if it is necessary to choose between having a diverse set of experts and having a well - behaved group, it is best to go for the diversity. The SSHAC experience, buttressed by extensive decision analysis experience, suggests that if the meeting is structured appropriately and the goals are communicated appropriately, the meeting can proceed without rancor, even if the experts substantially disagree on scientific matters.

The group meeting can be conducted in two or three days. The TFI, however, needs several months to design the meeting and the process, to identify the experts, to solicit participants, and to set up the necessary logistics for the meeting. The reviewers of the methods will require several months to prepare their papers. It is important to take into account the relatively small community of leading ground-motion experts. It is critical to enlist the leading world experts, and this generally necessitates a long lead time.

Basic products of the Review of Methods stage include:

- A set of methods for predicting ground motions clearly understood by the TFI and experts
- A list of specific disagreements, not necessarily resolved, but which are clearly understood and documented

- A set of representative models to be used to forecast ground motion at specific (M, R) points
- The set of (M, R) points to be used in the Stage 4 elicitation
- A set of proponents identified by the TFI to run the models to produce the Stage 4 predictions

Stage 4: Elicitation of Ground Motion at Points in (M, R) Space

Stages 4 and 5 are the heart of the elicitation process. They provide the basic material to be used by the TFI to produce the composite ground-motion estimator. This is done by concentrating ground-motion estimates and discussion on specific (M, R) pairs (determined during and after Workshop #1). The stages are conducted at a group meeting (Workshop #2), smaller than that used for Stages 2 and 3. The workshop must be designed so that information is provided to the TFI in a way that promotes extensive feedback and discussion among experts.

The process starts with a small group of experts in the role of *proponents* who are asked to perform a detailed ground-motion analysis based on a specific model, and then to interpret the results. These proponents should be intimately familiar with particular ground-motion models (generally, these proponents have published these models) providing ground-motion estimates at the (M, R) pairs to the TFI in advance of the meeting, using a specific model. The purpose of the proponent role is not to create advocates, but to create a clear understanding of each model and its results. The proponents also provide a written description of the assumptions and modeling details, as well as an explicit account of the dataset upon which the estimates were based. If possible, proponents should provide numbers and pictures showing what the results would be—based on data only—and compare that to the model estimates. These results may differ. For example, the median ground-motion estimate for one distance may be the result of fitting a curve that applies to a range of distances, whereas the data alone would apply just to that distance.

The TFI needs to make sure that the data used by each proponent are summarized in a form so that easy comparisons can be made. The estimates are displayed by the TFI (and/or resource experts) in a consistent graphical format, along with the data agreed upon in Stage 2. It is useful to include bars representing epistemic uncertainty for each proponent.

The graphs and proponent documentation are distributed, before Workshop 2, to a slightly larger group of experts. This larger group may include the proponents, who would now be asked to wear a different hat, that of *independent evaluator*. The experts-as-evaluators provide estimates for the same (M, R) pairs, using whatever combination of models they wish. Their results are sent to the TFI in advance of Workshop 2. The TFI again prepares graphs showing the various estimates, but they do not have to be distributed before the workshop.

At Workshop 2, the agenda is organized around a discussion of the ground motion estimates. Once again, the TFI attempts to isolate and then focus on areas of strong agreement and disagreement. The purpose is not to achieve consensus (although that is a good outcome if it is a true consensus) but rather a detailed understanding of the rationale for underlying differences so that the experts can each construct an informed composite representation of their own and the overall expert community's state of knowledge. The discussion should illuminate and eliminate any unintended disagreements. Typically, the experts will want to reconsider their estimates after the group discussion. This can be done informally (say overnight) at the workshop, but then needs to be done more carefully immediately after the workshop. Similarly, the TFI may need a round of individual interactions after the group meeting to make sure that the basis for the proponent and expert assessments are fully understand.

Time needs to be allocated for enough iteration so that the TFI can come to a full understanding of the basis for the ground motion estimates. Several months at least are required before Workshop 2 is held for the proponents to (1) perform the model runs, (2) document assumptions and results, (3) receive feedback from the TFI and the other

experts, and then (4) react to the feedback and prepare for the meeting. The meeting itself will typically last two to three days (the SSHAC meeting lasted two days). Roughly a month should be allocated afterwards for individual interactions among the TFI and experts, and for final estimates of the ground motion measures.

The basic product of the model estimate interaction is a well-understood median estimate of ground motion for each specified (M, R) pair, for each model, and for each expert.

Stage 5: Elicitation of Uncertainties

The assessment of uncertainty ranges for both the median and standard deviation of the aleatory distribution on ground motion is naturally, but not necessarily, done in conjunction with the median estimate interaction (Stage 4). Assessments by each proponent and each expert need to be encoded for at least three variables:

- Epistemic uncertainty in median estimate
- Best estimate of the aleatory uncertainty
- Epistemic uncertainty in aleatory uncertainty

If possible, and if there is sufficient time to make sure that all experts are sufficiently well grounded in the concept, it may be appropriate to decompose the assessments of epistemic and aleatory uncertainties into whether they are parametric or modeling uncertainties (see the discussion in Chapter 2). Chapter 2 explains why these different types of uncertainties are needed for a complete specification of the overall uncertainty in ground motion.

The uncertainty-assessment interaction is based on the same paradigm as the median-ground-motion-estimate interaction. At the SSHAC Ground-Motion Workshop 2, the agenda was divided into three major interactions:

- Estimate of median ground motion
- Epistemic uncertainty in the median estimate
- Best estimate and epistemic uncertainty in aleatory uncertainty

Ground-motion experts will not all be familiar with the meanings of these different types of uncertainties, nor will many of them have much experience in or knowledge about probability elicitation. Thus, individual interactions with the experts are required prior to the group meeting to provide education and training in probability elicitation and to elicit probability distributions from the experts (this type of training is described in Chapter 3).

During and after the workshop, the TFI needs to make sure that the experts' probability assessments accurately reflect their true state of information about the uncertainties. At a minimum, two fundamental consistency checks need to be performed:

1. If an expert's uncertainty range (for either the median or the aleatory uncertainty) is narrower than the range of estimates from all experts, the TFI needs to make sure that the expert truly attaches little or no significance to the estimates falling outside the range. In general, it is inconsistent to attach an uncertainty band that is much narrower than the estimates of the set of models and experts that are viewed as credible (this issue is discussed in more detail in Chapter 3). This is especially true when the experts are attempting to represent, not just their own position, but the composite position of the overall community.
2. It is also important to challenge experts whose uncertainty ranges are far greater than the range of model and expert estimates. Such an assessment implies the forecasting error associated with the individual models is quite high—but this would imply that the observed tighter pattern of model estimates is an unlikely coincidence, unless the assessor believes that there is a great deal of correlation among the model forecasts.

The experts need to be comfortable with probability assessment. For this, training in probability assessment and an experienced elicitor is very important. In general, it is important that the variables being elicited are variables with which the experts are intimately familiar.

Generally, experience in other fields suggests that it is far better to assess real observable variables than parameters of complex models or moments of probability distributions (e.g., mean and standard deviation). Due to the way in which data are processed and models are constructed, ground-motion experts seem to find that assessing moments is more natural than specifying a probability distribution directly on ground motion.

The participants and time required for Stage 5 is the same as for Stage 4, since the group meetings for both stages will be held during the same workshop.

The basic product of the uncertainty interaction is a set of probability distributions for each expert on each of the three variables described above. If the elicitation sessions generated influence diagrams and/or conditional distributions, the conditioning and conditional probabilities should be specified explicitly. The TFI should fully understand each expert's rationale underlying the probability assessments. The rationale should be documented by the experts themselves.

Stage 6: Development of Ground-Motion Distributions by the TFI

The basic paradigm for integration is to weight (or weigh) the estimates provided by each model for each (M, R) pair, guided by (1) how the experts as individual evaluators weight the model estimates, and (2) by how the experts integrate all available information into a composite representation of the community. If the experts' estimates as individual evaluators or as integrators are disparate, it is crucial that the TFI understand the sources of the differences before making any final decisions. Once the sources of disagreement are noted, the TFI then has to carefully weigh the strength of the logic, the underlying interpretations, and existing data.

The TFI should carefully consider, step-by-step, each expert-aggregation issue discussed in Chapter 3. It is also useful to apply simplified aggregation models, described in Chapter 3, but these should be viewed as providing rough guidelines only. The value of applying these simple models, especially for TFI team members who are less familiar with probability elicitation principles, is to see how each basic issue can affect the final aggregated probability distribution.

A useful step is for the experts to write down explicitly their judgment about the relative forecasting abilities of the various models and how much overlap or similarity there is between different classes of models. Verbal interaction provides a great deal of information on the rationale for why different experts place different weight on different models, but it is important to quantify these judgments both to ensure that the TFI understands the various positions and to make sure that the experts themselves are thinking consistently about the issues. The survey for the Ground-Motion Workshop 2 provides a starting point for such a quantification (the survey and its results are discussed in Appendix B), although the questions need to be rephrased to be clearer for the experts.

After the TFI is comfortable that the basis for each model and each expert's position is fully understood, it is useful for the TFI to form a preliminary position on the final composite estimates and distributions. (See Chapter 3 on general TFI integration guidance, and Section 5.7.5 below, for a discussion of why equal weights on TI positions is a desirable and likely outcome.) The TFI should document carefully the rationale for the composite representation and present it to the proponents and experts. If resources and time are available, it is best to do this in face-to-face meetings (individually or group); if not, written feedback from the experts is sufficient.

Finally, after receiving feedback from the experts, the TFI team members need to work closely together to construct the final composite representation. Typically, in this step the TFI should continue to interact closely with individual experts to make sure the final representation is based on a complete and accurate state of information.

The final interaction with experts could be done potentially in a several-day meeting, but may require several rounds of individual interaction.

The TFI team members should not rush into a final decision, but should probably iterate with several working meetings. It is essential to make sure that the TFI team completely understands the basis for everything they are integrating.

The product is, for each application: a probability distribution on the median and standard deviation ground motion at each point in (M, R) space. Both the probability distributions and a full and detailed description of the basis for them should be fully documented.

5.7.4 The Technical Integrator (TI) Approach

Several recommendations are appropriate for the case when the Technical Integrator is used to specify ground-motion input to a PSHA. This TI could work as a single entity, using its own expertise (or that of a consultant) to identify ground-motion attenuation equations, or the TI could informally use multiple outside experts to provide input and guidance on the selection and evaluation process. In some cases (for example, in coastal California studies), the equations considered may be entirely taken from the published literature. In other cases, new equations will have to be derived, most likely by modifying similar equations derived from different regions.

Regarding the choice of appropriate ground-motion equations to use for the study, both empirical and analytical equations should be considered. The ultimate choice of equations and how they are used will depend on the region of the study, on available attenuation equations for that region, and on the degree to which attenuation equations from other regions must be adapted to represent characteristics in the study region.

While the TI is not constrained to use explicit numerical weights (i.e., as with the TFI, the TI may choose to "weigh" rather than "weight"), when dealing with multiple models such an approach is encouraged when appropriate. Explicit weights are usually simpler to apply and easier to explain than other aggregation schemes (see the next section for more detail). Compared to the TFI, the TI may have less time and resources, and less control over proponents of different models. Eliciting weights from other experts is usually a simple and straightforward task to perform and the results are easily documented.

In California, it is likely that empirical and analytical equations will be similar for those ranges of magnitude and distance for which numerous data are available with which to calibrate these equations. Thus, the specific weights and credibilities assigned to each equation likely will not be critical. In particular, for distances close to large magnitudes (e.g., distances less than 20 km and magnitudes greater than 7.3), data are lacking and analytical results may differ from empirical results, and different empirical equations may themselves differ because of different extrapolation techniques. In this case, the form of the equation and its consideration of large-magnitude effects (e.g., finite fault rupture) and close-distance effects (e.g., the geometry of the site relative to the fault) must be considered in assessing credibilities of predicted ground motions. For these situations, we recommend that both empirically and analytically based models be considered when selecting the group of attenuation equations used for the PSHA study. Detailed analytical results may provide guidance on appropriate magnitude and distance scaling for large magnitudes and/or short distances, even if the analytical results are not themselves finally used in the hazard calculations.

In many applications, analytical equations have been used with success, but there are differences among available models and among the parameters used as input to those models. An example is the conversion used to relate moment magnitude M to body-wave magnitude mbLg. When such differences exist, they should in general be treated as epistemic uncertainties and both models must be included in the study. Also, the crustal or source parameters for a specific region may be different from generic parameters derived for broader regions. If wave-propagation studies are used to develop attenuation equations, the TI must include all relevant uncertainties in crustal properties. The TI must take care not to

underestimate the epistemic uncertainty in ground-motion prediction for a region with few or no existing ground-motion equations. In such a region, epistemic uncertainty will be high, and the existence of only one or a few (matching) equations is not evidence that epistemic uncertainty is low.

On the other hand, the TI also must not overestimate the uncertainty, just because no empirical observations of strong ground motion are available. Analytical studies conducted in the last decade, calibrated with low-amplitude seismograph records, have gone a long way toward providing an understanding of earthquake ground motions in the central and eastern U.S.

Aleatory uncertainty is relatively easy to estimate for California, where empirical observations are available to quantify scatter about predictions. Here the TI must be careful to incorporate any magnitude dependence of ground-motion scatter into the predictions, as published by the authors of each equation considered.

For other regions of the country, the aleatory uncertainty cannot be estimated from strong-motion observations. The TI may adopt aleatory distributions from California, using similar distributions for the remainder of the country and including, if deemed appropriate, epistemic uncertainty on the magnitude dependence of the aleatory uncertainty. An alternative is to model aleatory uncertainty by estimating aleatory distributions for input variables (such as stress drop) to analytical models, determining the resulting aleatory uncertainty on ground motion as a function of magnitude and distance, and confirming that the derived distribution is not inconsistent with similar distributions from California. There is certainly more epistemic uncertainty in ground motions outside of California, but unless there is a compelling counter-argument, the aleatory uncertainty should be similar to that in California equations.

5.7.5 Step-by-Step Guidance for Ground-Motion Integration

This section contains some summary step-by-step guidance for how ground-motion integration can be performed. The guidance is based on the successful process used to integrate the results of Ground-Motion Workshop 2 (see Appendix B). The guidance is "recommended" rather than "required" because the procedure has been applied in only one workshop.

The process, as performed in GM Workshop 2, works by first comparing model estimates and expert estimates. For simplicity, we will use the word *model* to denote the estimate produced by the model runs of each model proponent and the word *expert* to denote the composite estimate produced by each expert playing the role of integrator. The steps are as follows:

1. TFI posits an intuitive "quick and dirty" median ground-motion estimate.

2. This estimate is compared graphically to the experts' composite median estimates and all the models' median estimates, all overlaid on top of a plot of the available data. This should give the TFI an initial idea as to potential integration problems, if any.

3. The result of equally weighting the experts is then compared to the result of equally weighting the models. This step is for insight only. SSHAC expects equal weights on experts often to be appropriate in forming the final composite distribution. Equal weights on models are almost never appropriate.

4. If unequal weights are still a consideration after steps 1-3 (and after once again interacting with the experts to understand meaningful differences), a range of representative unequal weighting schemes on experts are applied and compared to the equal weighting results. Alternatively, experts are clumped into different subgroups felt to have potentially correlated assessments (Chapter 3), and the subgroups are equally weighted. A sensitivity analysis is performed to see if the different weighting and clumping schemes matter. The point of this step is to determine whether precise unequal weights really matter.

5. If unequal weights on experts are appropriate and the composite estimate is sensitive to the

likely range of unequal weights, then the representativeness of each expert relative to the overall community needs to be evaluated explicitly by the TFI team, again, in consultation with individual experts, as needed, and incorporated into the weights (Chapter 3). Also, although group interaction should have minimized differences in relative interdependence among subgroups of experts and differences in knowledge with respect to the specific application, these issues should be reviewed as well.

6. A final estimate for each (M,R) pair is established.

7. A similar process is used to produce uncertainty ranges.

Recall from Chapter 3 that a well-run facilitation process is expected to result in a defensible and simple equal-weighting process. Thus, SSHAC expects Steps 4 and 5 to be necessary only rarely.

On the more general issue of explicit numerical "weighting" versus non-explicit "weighing" SSHAC's position (discussed also in Chapter 3) is that, while explicit (equal or unequal) numerical weighting is not required, it is a desirable way to arrive at the final TFI estimate for several reasons:

- Explicit weighting provides a decomposition that helps explain how the TFI position was determined
- The TFI position can be explicitly compared to the experts' integrator positions
- Requiring explicit weights on models from experts that they must defend tends to lower the possibility of eliciting extreme and/or non-defensible judgments.
- There are probabilistic expert aggregation models, that, while simplified, provide theoretical underpinnings to the weighting process (these aggregation models can be applied to either experts or ground-motion models).

6. METHODOLOGY FOR CALCULATING SEISMIC HAZARD ESTIMATES AND UNCERTAINTIES

The purpose of a probabilistic seismic hazard assessment (PSHA) is to provide a quantitative assessment of seismic hazard, described by the likelihood that various levels of earthquake-induced ground motions at a site will occur or will be exceeded at a given location in a given future time period. The outputs of a PSHA are estimates of seismic hazard curves, i.e., plots of the estimated probability per unit time of a ground motion variable, e.g., PGA, being equal to or exceeding level a as a function of a. A typical output is a set of curves describing the estimated seismic hazard in terms of curves of the marginal 5th, 50th, and 95th epistemic uncertainty (probability) fractiles of the estimated probability per unit time, P(A>a), as illustrated in Figure 6.1.

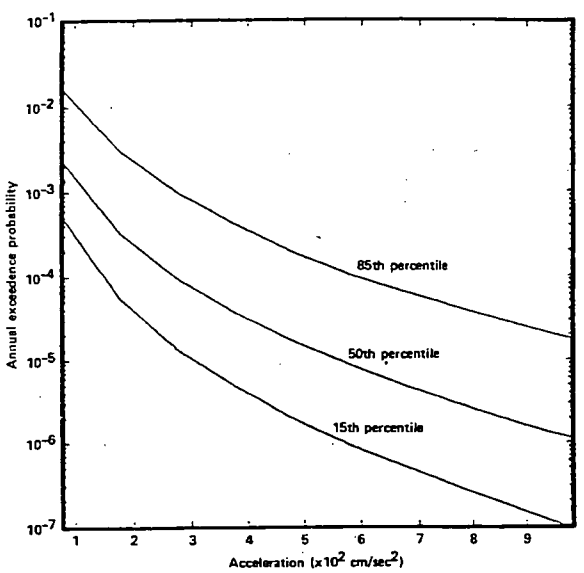

Figure 6-1 Seismic Hazard Curves

Other outputs of a PSHA are described in Chapter 7. Estimation of seismic hazard is based on integrating the seismic source characterizations and ground motion estimates described in Chapters 4 and 5. The mathematical models which form the basis of the seismic hazard calculations are discussed in Chapter 2.

Calculation of the estimated seismic hazard curves involves summing integrals of probability (aleatory uncertainty distributions over multiple seismic areas) is shown in Equation 2.2. The parameters of these distributions are a function of the seismic source characterization and ground motion inputs which are not known exactly (that is, there is epistemic uncertainty); thus, we only have estimates of the distributions. An important part of the calculation involves the quantification of the epistemic uncertainty associated with the estimated seismic hazard due to the epistemic uncertainties in the seismic source and ground motion inputs.

The calculational methodology of assessing the estimated seismic hazard and quantifying its epistemic uncertainty is a nested process. The inner operation is the basic calculation of integrating a specific seismic source characterization with a specific set of ground motion distributions to produce a single estimated seismic hazard curve. This calculation is discussed in Section 6.1.

The outer operation is an uncertainty analysis involving the propagation of the epistemic uncertainties associated with the seismic source characterizations and ground motion distributions to develop the probability (epistemic uncertainty) distribution for the estimated seismic hazard. This epistemic uncertainty is generally assessed in terms of a joint probability distribution of ($PA \geq a$) for a finite number of levels of ground motion, i.e., values of a. The joint probability distribution is sometimes needed for propagating epistemic uncertainty when seismic hazard and fragility are combined in a PRA (ANS/IEEE 1993). One description of epistemic uncertainty is illustrated in Figure 6.1, in which the results of the PSHA are presented as curves of the appropriate fractiles of the marginal (epistemic) probability distributions of the estimated seismic hazard. Calculational methods for the uncertainty analysis are the topic of Section 6.2. Propagation of the epistemic uncertainty in the uncertainty analysis assumes the seismic source characterizations and ground motion inputs are each derived from a

single expert, the TI or TFI. If either or both of these inputs are derived from multiple experts and the multiple inputs are not aggregated prior to doing the calculations, the multiple experts can be thought of as another source of epistemic uncertainty and treated accordingly in the uncertainty analysis. Eliciting and aggregating seismic source and ground motion inputs from multiple experts is discussed in Chapter 3.

6.1 Integration Methods For Producing Seismic Hazard Estimates

The inner loop of the overall seismic hazard estimation process involves the integration of a specific seismic source characterization (SSC) with a specific set of ground motion distributions for all magnitudes and distances to produce a single estimated seismic hazard curve for a given ground motion parameter. Before discussing calculational methods for integrating seismicity and ground motion information to produce an estimate of seismic hazard, it is appropriate to summarize the inputs necessary for seismic hazard evaluation and to reiterate the mathematical identity, discussed in Chapter 2, which is the basis for producing the estimated seismic hazard.

6.1.1 Seismicity and Ground Motion Inputs

6.1.1.1 Seismic Source Characterization

A description of the seismicity throughout the region affecting a site is characterized by

- Seismic source representation of the region, a seismic map

  For purposes of the seismic hazard calculations, the essence of the seismic source representation is that the region be partitioned into areas of homogeneous seismicity, referred to, in this discussion, as "seismic areas." As discussed in Chapter 4, sources are categorized as faults (type 1) or areal (types 2-4) sources. A seismic map is a partition of the region of interest into seismic areas, i.e., into areas of homogenous seismicity.

  Two approaches to developing a seismic map are:

  a. (Bernreuter, D. L., et al. 1989) If the seismic source representation is a partition of the region into "source zones," either faults/fault segments and/or areal sources which are assumed to be areas of homogeneous seismicity, i.e., earthquake expected frequency and magnitude distribution are considered to be homogeneous throughout the zone, a seismic area is equivalent to a source zone. A seismic map is equivalent to a source zonation of the region.

  b. (EPRI 1988) If the seismicity representation is a dual partition of the region into (1) seismic sources to which is associated a maximum magnitude and (2) areas (1°x1° squares in the application by EPRI) in which it is assumed the magnitude-recurrence relation is constant, i.e., earthquake expected frequency and magnitude relative frequency are homogeneous throughout the area—seismic areas are the intersections of seismic sources and the areas in which the magnitude-recurrence relation is constant, i.e., sections of sources of assumed homogeneous seismicity.

- Vector of seismicity information for each seismic area, i.e., area of homogeneous seismicity. The elements of seismicity are:
  - Expected frequency of earthquakes within the area, per time period, of magnitude exceeding a minimum magnitude m_o (e.g., m_{blgo} =5.0); ν
  - Maximum magnitude; m_u

- Magnitude distribution and its parameter(s). Two alternative models are the truncated exponential model and the characteristic earthquake model. Both models involve a parameter β relevant to the exponential portion of the model [$\beta = b\ln 10 = 2.3b$, where b is the slope in the familiar Gutenberg-Richter relation]; the characteristic earthquake model also requires the magnitude/range of magnitudes and frequencies of the characteristic earthquake.

6.1.1.2 Ground Motion Distribution

Assuming that, conditional on magnitude and distance, the distribution of the ground motion parameter is a lognormal distribution, the ground motion is characterized by:

1. The natural logarithm of the median of the ground motion parameter as a function of magnitude and distance, generally given in terms of the value of a ground motion model: g(m, r)
2. The (aleatory) standard deviation of the natural logarithm of the ground motion parameter, possibly a function of magnitude and distance: σ (m, r)

6.1.2 Basic Seismic Hazard Identity

Equation 6.1 shows that, based on the "usual" assumptions of occurrences of earthquakes, seismic hazard $P(A \geq a)$, as a function of ground motion level a, is [see equations 2.2 and 2.3]:

Equation 6.1

$$P(A \geq a \text{ in time } t) = 1 - \exp\left[-\sum_{i=1}^{S} v_i t \iint \Phi'\left(\frac{\ln a - g(m,r)}{\sigma}\right) f_{R_i}(r|m) f_{M_i}(m)\,dr\,dm\right]$$

$$\cong \sum_{i=1}^{S} v_i t \iint \Phi'\left(\frac{\ln a - g(m,r)}{\sigma}\right) f_{R_i}(r|m) f_{M_i}(m)\,dr\,dm \qquad (6.1)$$

where:

- S is the number of seismic areas
- ν is the expected frequency, per time period per seismic area, of earthquakes of magnitude at least m_o.
- $\Phi'(.)$ denotes the standard normal complementary cumulative distribution function (CCDF) which is based on the usual assumption that the ground motion parameter is a lognormal aleatory variable. The ground motion distribution is possibly truncated.
- $f_M(.)$ denotes the probability density function of the magnitude distribution.
- $f_R(.)$ denotes the probability density function of distances, from the site, of the locations of earthquakes, given an earthquake occurs in the seismic area. A commonly accepted model is based on assuming earthquakes occur spatially "at random" within a seismic area, thus, f(r)dr represents the proportion of the seismic area at distance r from the site. For some cases, when the seismic area represent a fault/fault segment, the earthquake rupture is represented as a plane instead of a point and if the rupture length depends on magnitude, the distance also depends on magnitude. Thus, the density function is written as $f_R(r|m)$.

6.1.3 Integration Methodology

As shown in the seismic hazard identity in Equation 6.1, the calculation of the estimated seismic hazard involves a sum of two-dimensional integrals. The standard normal CCDF, $\Phi'(.)$, is also an integral so the calculation could be written as a sum of three-dimensional integrals. However, $\Phi'(.)$ is readily evaluated by packaged subroutines. The standard procedure for integrating functions is numerical integration, also called quadrature. This involves partitioning the magnitude and distance ranges into a finite number of subintervals, evaluating the integrand at a selected point(s) within each interval, and summing weighted products of the integrand and the subinterval width. Several one-dimensional quadrature methods exist, including rectangular, trapezoidal, and Simpson's rules, spline quadrature and Gaussian quadrature, corresponding to various orders of accuracy. For the multidimensional estimated seismic hazard calculation, because of the polygonal geometry of the seismic areas and the frequent numerical input of the ground motion models, simple numerical integration methods are generally used.

Considering the levels of uncertainties associated with the inputs into a PSHA, the choice of numerical integration method does not seem to be critical to the analysis. Two important elements of the calculation are developing and keeping track of the geometry of the seismic areas and evaluating the probability density function, $f_R(r)$, of the distance, which, for the commonly accepted model, involves assessing the proportion of a seismic area corresponding to distance r from the site. The calculation also requires a specification of the ground motion distributions for all (m, r). If the medians of the distributions are expressed in terms of a single ground motion model or a set of weighted models, there is no problem. However, as discussed in Chapter 5, the median ground motion may be based on deriving the medians for a finite subset of the (m, r)s. In that case, it is necessary to interpolate between the inputted values to evaluate the median at the non-inputted (m, r)s. One approach mentioned in Chapter 5 is to fit a model, similar to an accepted ground motion model, to interpolate. This is quite reasonable when interpolating between "most likely" or "best estimate" values of the median ground motion. A more difficult issue is how to represent epistemic uncertainty in the median at the interpolated (m, r)s, given epistemic uncertainty in the medians at a selected subset of (m, r)s. The issue is how to represent epistemic uncertainty which accounts for the epistemic correlation associated with the inputted medians. (Note: this is also an issue if a single model uses uncertainty bands to represent epistemic uncertainty.) This is discussed in Section 6.3.

Details on some of the practical aspects of the integration calculation are included in the reports of past PSHAs (e.g., EPRI 1988; Bernreuter, D. L., et al. 1989).

The output of the integration is a single estimated hazard curve, $P(A \geq a)$ as a function of a[1] which represents the estimate of seismic hazard given the specific values of the uncertain inputs. All other products of the PSHA can be derived from the basic seismic hazard calculations or can be evaluated following the same basic concept. Some of the most important such products are deaggregated hazard results and sensitivities (see Chapter 7). Numerical methods for these products are discussed in EPRI 1988 and Bernreuter, D. L., et al. 1995.

6.2 Propagation of Epistemic Uncertainty

Calculation of the estimated seismic hazard curve, as outlined in Section 6.1, is based on a specific seismic source characterization and set of ground motion inputs, i.e., on a specific seismic map, specific values of the seismic parameters for all seismic areas, and specified ground motion distributions for all magnitudes and distances. Since all these inputs are uncertain, i.e., subject to epistemic uncertainty, it is necessary to reflect this epistemic uncertainty in the estimation of seismic hazard. Quantifying the epistemic uncertainty associated with the estimated seismic hazard due to the epistemic uncertainties associated with the seismic source

[1] Note: computationally, the results are vectors of values of $P(A \geq a)$ for a finite set of values of a.

characterization and ground motion distributions is based on propagating these input uncertainties through the seismic hazard calculations to establish the epistemic uncertainty in the estimated seismic hazard.

6.2.1 Descriptions of the Epistemic Uncertainties of the Inputs

Recommended and/or alternative methods of describing the epistemic uncertainties associated with the inputs into a seismic hazard calculation are discussed in the chapters on seismic source characterization and ground motion estimation, Chapters 4 and 5 respectively. Epistemic uncertainty descriptions, as they relate to the elements of the seismic hazard calculations described in Equation (6.1) are summarized here. It is recognized that the basic input information may not always be expressed in terms of the distributions included in Equation (6.1). For example, magnitude distribution inputs may be derived in terms of the parameters (a, b) of the Gutenberg-Richter relation instead of the expected frequency ν and parameter β in Equation(6.1). This is not a problem since the propagation of uncertainties can be based on the uncertainties of the original parameters or on the uncertainties transformed to uncertainties in the parameters of the distributions given in Equation (6.1). The only requirement is that the epistemic uncertainties be completely quantified and that any potential correlations in epistemic uncertainties be recognized and properly handled in the propagation of the epistemic uncertainty.

6.2.1.1 Seismic Source Characterization

The basic epistemic uncertain inputs are the seismic map and the vectors of seismicity parameters, maximum magnitude, earthquake expected frequency and magnitude distribution parameter(s), for each seismic area in the map.

1. Seismic maps: epistemic uncertainty is described in terms of alternative maps based on alternative representations of faults and/or areal sources, accounting for the probability of activity/existence, and alternative source geometries with weights. The number of alternative seismic maps can be significant, especially for regional studies, and can involve considerable computational effort to develop, maintain, and track depending on the number of seismic sources, alternative source boundaries, and the probabilities of activity/existence provided. Ways to reduce the number of alternatives should be considered, e.g., eliminating alternatives with low weights and combining maps which only differ in areas with an insignificant impact on the hazard value.
2. Seismicity parameters for each seismic area:
   - maximum magnitude, m_u: epistemic uncertainty is described in terms of a discrete or continuous probability distribution for m_u for each seismic area. Epistemic correlations between m_us for different seismic areas must be recognized. Such correlations could arise due to seismological considerations or as a result of the seismic sources and seismicity representation, e.g., in the EPRI representation of seismicity, several seismic areas are sections of the same source, hence have the same maximum magnitude, thus their epistemic uncertainty is perfectly correlated.
   - expected earthquake frequency (of magnitudes at least m_o), ν: epistemic uncertainty is described in terms of a discrete or continuous probability distribution.
   - magnitude distribution parameter(s), β (also the characteristic magnitude and frequency, if appropriate): epistemic uncertainty is described in terms of a discrete or continuous probability distribution.

It should be recognized that, for a given seismic area, the latter two parameters, ν and β, are likely to be epistemically correlated. This correlation has the most significant effect on the estimated seismic hazard since it affects the mean hazard as well as the epistemic uncertainty in the estimated seismic hazard. Thus, it is important that this correlation be recognized and accommodated in the uncertainty analysis. This is discussed further in Section 6.3.

For the exponential model (truncated exponential model or the exponential portion of the characteristic earthquake model), alternative parameters to (ν, β) are (a, b), the parameters of a magnitude-recurrence equation. These pairs of parameters are related and it is possible to transform the epistemic uncertainty in one pair to epistemic uncertainty in the other. Again, the parameters (a, b) are epistemically correlated; this correlation must be propagated to correlation between ν and β.

As with the maximum magnitude, if there is epistemic correlation in the seismicity parameters between seismic areas, this must be recognized and accounted for in the specification of epistemic uncertainty. For example, in the EPRI representation of uncertainty and the introduction of "smoothing" between 1°x1° areas, a potential correlation of ν and β between seismic areas is implied.

6.2.1.2 Ground Motion Distributions

The basic ground motion input parameters are the median ground motion and the aleatory standard deviation of the logarithm of the ground motion for all (m, r).

1. Median: epistemic uncertainty is described in terms of a discrete or continuous probability distribution for g(m, r) for all (m, r). Again, it is likely that the estimated median ground motion for different (m, r)s are correlated. This must be recognized and accommodated in the uncertainty calculations.

2. Standard deviation: epistemic uncertainty is described in terms of a discrete or continuous probability distribution for all (m, r), and, if appropriate, recognition and accommodation of epistemic correlation.

If the ground motion inputs are based on ground motion models containing aleatory variables, the inputs include the aleatory variable distributions and their uncertain parameters. These uncertainties must be properly analyzed to assess uncertainty in terms of uncertainties in the median and aleatory standard deviation.

Epistemic correlation in the median and standard deviation between different (m, r)s is a second order effect with regard to the propagation of epistemic uncertainties in PSHAs since it does not affect the mean seismic hazard. Recognition of epistemic correlation in the median and aleatory standard deviation is important only for quantifying the epistemic standard deviation of the estimated seismic hazard. This is discussed further in Section 6.3.

6.2.2 Epistemic Uncertainty Propagation Methods

Conceptually, estimated seismic hazard, i.e., $P(A \geq a)$, is a function of all of the inputs. Since the inputs are epistemically uncertain, $P(A \geq a)$ is a function of a set of probabilistically distributed parameters. There are several methods for propagating this probability through the seismic hazard calculations to derive the (epistemic) probability distribution of $P(A \geq a)$. Two classes of methods are:

- Analytic methods

  Since $P(A \geq a)$ is a function of probabilistic inputs, conceptually, one method is by "transformation of variables." This is not practical for PSHA because of the complexity of the functional relationship. A second type of analytic approach is based on evaluating the moments of the probability distribution of $P(A \geq a)$ in terms of the moments of the probability distributions of the inputs. The classical procedures include the method of moments, Taylor series expansion and response-surface methods.

- Sampling methods

  1. Complete enumeration: This approach is usable if the probability distributions of all inputs are expressed in the format of discrete distributions. Conceptually, the method involves evaluating $P(A \geq a)$ for all combinations of values of the epistemic uncertain parameters/inputs. The probability associated with the resulting value of $P(A \geq a)$ is the product of the probabilities (properly combined to account for epistemic correlations)

associated with the inputs. The resulting set of values and associated probabilities of $P(A \geq a)$ is the (epistemic) probability distribution of $P(A \geq a)$. The number of combinations may become very large if there are a large number of inputs and/or if there are a large number of alternative values for each input. This is recognized in a version of this approach, referred to in the PRA literature as the Direct Probability Distribution (DPD) method (S. Kaplan 1981). To reduce the number of calculations, this version of the method also involves aggregating values and probabilities of intermediate calculations.

If continuous probability distributions are discretized to apply the complete enumeration method, the proper choice of representative values and probabilities is important to derive an adequate estimate of the probability distribution for seismic hazard.

A convenient graphical tool for enumerating the combinations is a logic tree consisting of nodes identifying the uncertain inputs and branches, representing the alternative "values" of the inputs, emanating from each node. A "limb" or continuous connection of the branches for each of the parameters represents a combination. (See EPRI 1988 for an application of logic trees.)

2. Random sampling: Applicable if the probability distributions of the inputs are either continuous or discrete. Conceptually, the methodology is based on sampling values from the probability distributions for each of the inputs and assessing the corresponding value of $P(A \geq a)$. The most straightforward approach is "Monte Carlo sampling," which is based on simple random sampling of each of the inputs. In order to represent satisfactorily the 5th and 95th fractiles of estimated seismic hazard, a minimum sample size of 200 is recommended. If, however, preliminary results show that the mean hazard lies above the 95th fractile, the sample size must be increased appropriately.

   Alternative approaches, based on restricted random sampling, are designed to be more efficient, i.e., for the same sample size to provide an estimate with a lower sampling variability. One method is "importance sampling." This approach is based on sampling the inputs and values of the inputs which are most important, i.e., the inputs to which the seismic hazard is most sensitive. Thus, it requires some knowledge of the sensitivities of the seismic hazard with respect to the uncertain inputs. Another method is "Latin hypercube sampling" (LHS). The basic concept of this approach is to partition the range of each input into the same finite number of equiprobable subintervals and sampling subintervals at random such that each subinterval (of each parameter) is sampled only once. Within a subinterval the sampled value is selected at random. This approach assures that the entire range of each parameter is represented in the sample (R. L. Iman and M. J. Shortencarier 1984). These alternative approaches have not been used in past PSHAs.

Both the complete enumeration and Monte Carlo sampling methods have been used in past PSHAs. They both can, with proper care, be effective computationally and are acceptable for developing the joint (marginal) probability distribution(s) of $P(A \geq a)$ for a finite number of values of a. This distribution is the basis for the fractile curves for the seismic hazard (Fig. 6.1).

The complete enumeration method and the use of accompanying logic trees provides a more transparent presentation of alternative hypotheses and values as well as displaying sensitivities to alternative inputs. If discrete probabilities are used to represent "continuous" epistemic uncertainties, care must be taken to assure that the discretization, and accompanying loss of information, is not too coarse. Monte Carlo sampling is, in general, more efficient and is most useful for large regional studies.

Uncertainty analysis, as discussed, is based on deriving input information from a single pair (one seismicity and one ground motion) of resources. If the overall methodology involves combining inputs from multiple resources, e.g., multiple SSC experts, using some kind of "weighting" algorithm, the relative weights can be treated as a probability to include the epistemic uncertainty associated with the multiple resources in developing the overall probability distribution associated with the estimated seismic hazard.

6.3 Discussion and Recommendations

PSHAs involve extensive computer calculations requiring considerable bookkeeping to handle the multiple summations associated with numerical integration, the potentially large number of seismic areas, and, in the uncertainty analysis, the alternative SSC characterizations and ground-motion uncertainties. It is important to develop the proper combinations of inputs to assure that the models are correctly represented in the calculations. This is particularly important for the uncertainty analysis.

A potentially difficult issue is the representation of epistemic correlation. One way of measuring the significance of potential epistemic correlations is to evaluate their effects on the estimated mean seismic hazard and the epistemic standard deviation of seismic hazard. Since the mean hazard is an important input into a Probabilistic Risk Analysis (PRA) and in design ground motion criteria, for purposes of this discussion, an epistemic correlation is considered to have (1) a first-order effect if it affects the epistemic expected value (i.e., the estimated mean) as well as the epistemic standard deviation and (2) a second-order effect if it only affects the epistemic standard deviation. Three epistemic correlations are important:

1. The epistemic correlation in the median (and standard deviation) of the ground motion parameter between different (m, r)s.
2. The epistemic correlation between the earthquake occurrence rate and magnitude distribution parameter, i.e., (ν, β), within a seismic area. [Equivalently, the epistemic correlation between (a, b) or between the expected frequencies at two (or more) magnitudes within a seismic area].
3. The epistemic correlation in a seismicity parameter, e.g., m_u , ν, or β, between different seismic areas.

If one considers approximating the integrals in Equation (6.1) by sums, it is clear that the seismic hazard calculation involves summing over seismic areas, magnitudes and distances. Since the expected value of a sum is the sum of the expected values of the summands, the correlation between summands does not affect the mean hazard, whereas correlation affecting the means of the summands does. Therefore, correlations such as the first and third type above do not affect the mean hazard, while the epistemic correlation between (ν, β) within a seismic area (i.e., type 2 above) has a first order (mean) hazard effect, because it affects the expected value of the magnitude density function $f_M(m)$ at each m. The other two epistemic correlations only affect the epistemic standard deviation of the seismic hazard. Thus, it is most important to recognize, model, and propagate the epistemic correlations between ν and β within a seismic area.

If (ν, β) are derived from estimates of (a, b) in the Gutenburg-Richter relation based on historical data, the sampling correlation between (a, b) may provide a basis for epistemic correlation between (ν, β). If other sources of epistemic uncertainty are also considered, these also must be included when determining the epistemic uncertainties in (ν, β). If (ν, β) are derived from elicited values of (a, b) or of the expected frequencies at two (or more) magnitudes, potential epistemic correlations in the elicited parameters must be recognized and accounted for in the seismic hazard calculations. One's ability to describe the epistemic correlation should be considered in selecting the inputs. For example, when using historically based estimates of (a, b) careful redefinition of a to a reference magnitude larger than zero can eliminate the sample correlation between a and b. Similar considerations are also advisable if the (ν, β)s are derived from inputs elicited in terms of other parameters, e.g.,

expected frequencies at selected magnitudes. Several approaches to quantifying correlation have been attempted. No one recommended way of modeling this has been identified.

With regard to epistemic correlation, when modeling the epistemic uncertainty to estimate the median of the ground motion distributions, assigning weights to classes of ground motion models to represent epistemic uncertainty will inherently imply certain epistemic correlations between the median ground motions at multiple (m, r)s depending on the relationships of the values of the several models at the different (m, r)s. If a single ground motion model with uncertainty or the FTI approach of developing uncertainty distributions at a finite number of (m, r)s is used to represent uncertainty, a common practice is to use "ground motion models" based on fitting fractiles of the uncertainty distributions at multiple (m, r)s. It should be recognized that this procedure implies perfect epistemic correlation in the medians between the (m, r)s. Assuming perfect correlation does not affect the mean hazard but will inflate the epistemic variance of the seismic hazard estimates, thus producing reduced median estimates and inflated estimates of higher, e.g., 85th, fractiles.

With regard the epistemic correlation in seismicity parameters between seismic areas, this is an issue primarily when the seismicity is variable between seismic areas within a source. Introducing smoothing of the seismicity parameters in the data analysis induces correlation of the seismicity parameters between seismic areas within a source. This needs to be recognized and properly combined with the epistemic uncertainties in the parameters to assure that the full range of potential values of the epistemically uncertain parameters is represented in the uncertainty analysis. (See Appendix I.)

Quantification of epistemic correlation can be difficult but it should be considered in the propagation of the epistemic uncertainty. Given the difficulty in quantifying correlation, it is recommended that the correlation not be represented by a single value of a correlation coefficient. Rather, it is recommended that the sources of the correlation be investigated, e.g., for ground motion median estimates, investigate magnitude scaling and different classes of ground motion models, etc. as sources of epistemic uncertainties. This information should be used in the context of the sampling procedure to assure that the full ranges of potential values of the epistemic uncertain parameters are represented in the sample.

7. GUIDANCE ON DOCUMENTING THE PSHA PROCESS AND RESULTS

7.1 Introduction

One of the major lessons that the PSHA community has learned in recent years is that documenting the PSHA process and results is as important as carrying out the project in a technically competent way. There are at least three reasons why excellent documentation is crucial:

- Only through adequate documentation can others in the technical community understand or review the analysis and the results.
- Only through adequate documentation can a later analysis team with new information or improved models utilize a PSHA to update it, revise it, or validate that it does not need an update or revision.
- Only through adequate documentation can the sponsoring organization retain an adequate record of the process it supported.

With these issues in mind, the SSHAC has developed guidance for PSHA documentation. A thorough documentation effort is required; however, the specific guidance herein cannot be considered as being required in detail because the specific manner in which a given analysis is documented depends on the objectives of the study, and both the details of the site hazard and the factors that affect it.

Note that much of the guidance below is given using the word must, which is intended to convey that the SSHAC strongly feels this particular aspect is crucial. At the same time, it is recognized that methods of presenting data and results change. With this in mind, guidance with respect to format is recommended, leaving the flexibility for modification to meet specific project needs or permit improved methods of presentation. Other documentation guidance is given using the word should, to convey the intent, although slightly weaker than the first category that SSHAC strongly recommends.

7.2 Process Aspects

The PSHA process is a multi-disciplinary evaluation that requires comprehensive documentation. This chapter provides the PSHA analyst with guidance on:

1. Levels of documentation that must be provided or maintained.
2. Elements of the PSHA process that must be documented.
3. Variations in documentation requirements as they pertain to the applications for which the PSHA was performed.

The following subsections describe these features of the PSHA process documentation.

7.2.1 Documentation—Two Tiers

Documentation of the PSHA should be prepared using a two-tiered approach:

- Tier 1 - consists of the documentation that must be reported, either in the main report or in appendices that are published with the main report, and widely accessible.
- Tier 2 - consists of the much larger body of background material that comprises the analysis documentation. This second-tier material should be maintained by the analysis team in an appropriately accessible, usable, and (if appropriate) auditable form. Of course, readily available documentation or references can be cited were appropriate.

Tier 1 and Tier 2 documentation is provided for each element of the PSHA process. These elements of the process are described in the next subsection.

It is strongly recommended that the authors of the PSHA use the two-tiered approach. If however, an alternative format is adopted, the documentation guidance described here must be satisfied.

7.2.2 Documenting the Elements of the PSHA Process

The following list shows the various elements of the PSHA process for which documentation is required. A summary of each is provided in the subsequent paragraphs.

- Roles and Resposibilities of the Project Participants and Consultants
- Comparisons With Other PSHA Studies
- Internal Quality Control and Review
- PSHA Methodology
- PSHA Results
- External Peer Review
- Documenting Citations

Documenting the Roles and Responsibilities of the Participants and Consultants

Even the simplest PSHA will involve a number of participants, and often a number of consultants. The Tier 1 documentation must identify the participants and provide a thorough discussion of the roles of each with care to differentiate the central roles from the supporting roles. Of particular importance is documenting the names of the author or authors who are professionally responsible for the overall performance of the study, and whose reputations support the findings.

Comparison With Other PSHA Studies

For many parts of the PSHA study, a very useful exercise is the comparison of the methods, data, or results with those from other PSHAs that have examined identical or similar geographical areas. If comparable PSHAs have been widely distributed and extensively reviewed, such comparisons can be valuable in demonstrating how different approaches or different data affect the conclusions. While such comparisons are very helpful, they are not required. However, where feasible the documentation of such comparisons should be done in a way that allows review, especially by the analysts who performed the earlier work or who provided its supporting data or models.

Documenting Internal Quality Control and Review

As part of the PSHA's internal quality-control procedures, it is necessary that there be a review of the ongoing work within the project. The process of such review, including the reviewers and their important findings must be documented in Tier 1 to assist both the sponsors and other users of the results in understanding what internal reviews were performed and what was found. The Tier 2 documentation should retain the detailed records of these reviews, as appropriate.

Documenting the PSHA Methodology

As part of the PSHA, there are a number of methodological aspects of the process that must be described. This includes the choice of the stochastic model to describe earthquake occurrences, the magnitude-frequency model, the elicitation methodology, etc. The Tier 1 documentation of the PSHA must provide a comprehensive description of all phases of the methodology that were used. If new models or approaches are used that differ substantially from the recommendations provided in this document (e.g., Chapters 2, 3, 4, 5, 6), a complete description and supporting basis for the alternative approach must be provided in the Tier 2 documentation. In addition, the Tier 2 documentation should describe the implementation of the methodology, such as identifying/describing the software that was used to compute the hazard, the elicitation processes that were conducted, etc. Section 7.4 discusses in more detail the documentation of the PSHA methodology and process.

Documenting PSHA Results

The results of a PSHA are typically presented in terms of fractile seismic hazard curves that define the probability that levels of ground motion may be exceeded at a site. These hazard curves are the composite aggregation of the epistemic uncertainties in the hazard evaluation. In addition, each hazard curve is computed in a composite aggregation of the aleatory uncertainties modeled in the hazard assessment (e.g., earthquake occurrences, ground motion). Recent experience, the requirements of engineering applications and regulatory processes require that comprehensive

documentation of the hazard results be provided. In addition to providing a broad characterization of the hazard, a comprehensive documentation makes the assessment tractable and transparent. Final results must be provided in the Tier 1 documentation with input to the PSHA and intermediate results and evaluations retained as part of the Tier 2 records.

Documenting External Peer Review

If an external peer review has been undertaken, both the principal review findings and the names of the reviewers must be documented in Tier 1. The details of the peer review should be retained as appropriate in the Tier 2 records.

Documenting Citations

It is important to provide proper citation for all data, methods, etc., that are utilized in the PSHA. To avoid this potential confusion or ambiguity, especially where primary earth-sciences data are used that are not readily available or are published in obscure or poorly circulated journals, the documentation should carefully explain where to find the important citations that may be difficult to obtain. Reliance on unpublished data is, of course, acceptable but such data should be considered part of the project files, to be either documented if necessary in Tier 1 (including Tier 1 appendices) or saved as Tier 2 but in an appropriately accessible and usable form.

7.3 Overview: Objective of the Documentation Process

To satisfy the range of PSHA applications (see Chapter 1), guidance for the presentation of results is provided. The objective is to satisfy:

- needs of those involved in the use of the PSHA results (e.g., provide results that satisfy the applications for which the analysis was performed), and
- requirements that the PSHA be tractable and transparent to the general practitioner, analyst, and technical reviewer.

The requirement to make the PSHA tractable is a critical part of the documentation process and, as experience would suggest, one that can be difficult. With these objectives in mind, this chapter provides guidance for the documentation of PSHA results, including the presentation of sensitivity analyses. Guidance is given so that the documentation:

1. Provides results that are required by the application for which the hazard assessment was performed (e.g., for use in developing a seismic zonation map, input to a seismic probabilistic risk assessment).
2. Provides information that permits the analyst or reviewer to understand the constituent parts of the analysis that dominate the seismic hazard (e.g., dominant seismic source, ground motion attenuation model).
3. Demonstrates the sensitivity/insensitivity of hazard results to the uncertainty in key parameters, and variation in the hazard due to the changes in parameter values considered in the hazard assessment.
4. Includes computer-readable (friendly) data files that facilitate the ability to examine specific parameter assessments or scientific interpretations. These data files would contain information that provides the analyst with the opportunity to understand the sensitivity of the results to specific parameters without the added of effort of recomputing the hazard.

The assessment of the seismic hazard at a site entails extensive computations to generate many thousands to tens of thousands of hazard curves, each corresponding to a specified set of parameters (e.g., seismic source geometries, maximum magnitude values, ground motion model). The role of any one or small group of hazard curves (and therefore the parameters that are their basis) is often difficult to determine.

7.4 Documenting the PSHA Process Methodology, Models, and Data Used

7.4.1 Introduction

The basic methodology for performing a PSHA is discussed earlier in this report. Here we provide

guidance to document the methodology, models, and data used.

The analysis team must document in Tier 1 how the overall PSHA has been structured, including the interrelationships among its several parts. The way in which "results" of one part are coupled to subsequent analyses must be discussed in sufficient detail to allow for review of the logic models, the data, completeness, approximations, and any assumptions. All critical aspects, such as the rationale for the binning of certain types of information, the melding together of different models or data, and the structure of the sensitivity and uncertainty analyses, must be documented in detail in Tier 1 in a form that allows for technical review.

This requirement includes documenting the following aspects (the following list can be considered a check list, but of course it is not nor could it be all-inclusive):

1. The basic formulation of the seismic hazard analysis—specifically, the mathematical formulation that describes how the bottom-line results" are derived from the inputs. This usually takes the form of one or more equations like those cited in Chapters 2 to 6, relating such quantities as the probability of exceedance of certain ground motion quantities to other more basic inputs or derived quantities in the analysis.

2. The definitions of all mathematically defined inputs, process variables, and output "results." This should include both mathematical definitions and word definitions for all quantities.

3. Where such limits exist, definitions of the limits of validity of any mathematical formulas or equations used.

4. Careful definitions of the physical units of all quantities (preferably in SI units, but if other units are used, then an explanation is needed of the relationship to SI units).

5. Careful definition and explanation of any mathematical models used, including their ranges of validity, the approximations used in their derivation or use, and any comparisons with other models, similar or different, that are used elsewhere to describe the same or a similar technical issue. Especially helpful here are discussions of any previous uses of the chosen model, including comparisons to other applications between the model and data, direct observations, or inferred analytical results.

6. A discussion of the sources of all experimental data and field observations, including the methods used to obtain these data and observations, the uncertainties (both aleatory and epistemic) as reported by the experimenters/field observers, and any interpretive discussion necessary to understand the ranges of validity of the data and observations.

7.4.2 Documenting the Methods, Models, and Data Used For Seismic Source Characterization

Tier 1

The PSHA report must provide a complete description of the SSC methodology and its implementation to develop the SSC. The Tier 1 documentation must describe:

1. The steps taken to gather the geologic, seismologic and geophysical data used in the PSHA

2. Data resources available to the earth science experts

3. Methodology and steps taken to elicit expert input, including a description of what was elicited from the experts

4. Methods used to define seismic source geometries, magnitude recurrence relationship and maximum magnitude

The SSC is a critical part of the PSHA. It is a multi-disciplinary effort that requires an integrated scientific evaluation and interpretation of a wide range of earth-sciences data. Documentation of the SSC must provide a comprehensive presentation of the process that

was used to develop a model of the seismicity in the vicinity of a site.

Tier 2

In the Tier 2 documentation, a complete cataloging of the data used by the earth-science experts should be retained. Supporting documents, calculation packages, etc. generated by the earth-science experts, PSHA analysts, TFI, and others involved in SSC process should be catalogued and retained.

7.4.3 Documenting the Methods, Models, and Data Used for Analyzing Ground Motion Attenuation

Tier 1

The PSHA report must provide a complete description of the methodology to determine the ground motion models used in the PSHA and the steps taken to implement it. The Tier 1 documentation should describe:

1. The steps taken to gather strong motion data, attenuation models and geophysical data considered in the analysis.
2. Data resources available to the ground motion experts.
3. Methodology and steps taken to elicit expert input, including a description of what was elicited from the experts.
4. Methods used to define the ground motion models.

Tier 2

In the Tier 2 documentation a complete cataloging of the data used by the ground motion experts should be retained, including models and data that were considered. As noted above, it is important that information used in selecting ground motion models be adequately and completely cited and retained. Similarly, supporting documents, calculation packages, etc. that were generated by the ground motion experts, PSHA analyst, TFI and others involved in the analysis or the selection of ground motion models should be catalogued and retained.

7.4.4 Documenting the Methods Used to Produce the PSHA Results

Tier 1

The Tier 1 report must provide a complete description of the mathematical model used to determine the seismic hazard at a site, the approach used to propagate the epistemic uncertainties and the method used to aggregate expert interpretations. The description of the seismic hazard model should fully describe the method used to compute deaggregated hazard results, including the identification of magnitude distance bins, the calculation of the fraction contribution of seismic sources to the total hazard, and the contribution of parameters to the hazard epistemic variance.

Tier 2

For seismic hazard models that differ from the approach described in Chapters 2 and 6, a detailed description of the basis for the alternative model must be presented. In cases where a conventional approach is used, no Tier 2 documentation of the seismic hazard methodology is required.

A description of the software used to compute the seismic hazard should be provided. As a minimum, the software routines, the flow of information, and the software output must be described.

7.5 Documenting the Seismic Hazard Results—Scope

This section provides guidance for documenting the results of the PSHA, including the set of numeric results that quantify the hazard at a site(s), the seismic source characterizations developed to model the active tectonic features in a region (e.g., identification of active seismic sources, the estimate of earthquake rates and maximum magnitudes), and the ground motion attenuation models that are used (or possibly developed in site-specific studies). Guidance is provided for Tier 1 and Tier 2 documentation.

Documentation of the seismic hazard results for a site(s) is divided into three parts:

1. Basic PSHA Results
2. PSHA Deaggregation
3. Sensitivity Analysis

These parts define a hierarchy of results that proceed from basic user-required results to increasing levels of detail that provide insights into the dominant contributors to the site hazard and the sensitivity of the results to parameter variations.

Basic PSHA Results

These are the results that must be generated by the PSHA to satisfy the needs of the specific applications for which the study was performed. Examples of results that document the hazard at a site are the fractile and mean hazard curves for each ground motion measure and the uniform hazard response spectra (UHS). Table 7-1 presents a list and description of Basic PSHA Results.

PSHA Deaggregation

The assessment of the seismic hazard at a site is the result of an aggregation of the aleatory and epistemic uncertainties in the analysis. A deaggregated presentation of the seismic hazard provides a measure of the relative contribution of the constituent parts of the seismic hazard model to the total hazard and an indication of the sensitivity to different parameter assumptions. Table 7-2 provides a list and description of deaggregated seismic hazard results. Note, in some applications deaggregated hazard results may be required as input to certain applications (e.g., studies that require an estimate of the mean magnitude and distance).

Deaggregated seismic hazard results present the hazard in terms of a number of the basic building blocks of the analysis (e.g., the characterization of seismic sources, the prediction of ground motion). By themselves, these results provide a measure of the sensitivity of the hazard to specific inputs and the impact of potential changes to the hazard. For example, a deaggregation of the hazard in terms of seismic sources provides insight to the source(s) that dominate the site hazard. At the same time, this result also demonstrates the insensitivity of the hazard results to parameter variations for sources that make a small contribution. Consequently, deaggregation of seismic hazard results provides valuable insights to the PSHA and the inputs that contribute to the results.

Sensitivity Evaluations

At different stages of the PSHA, sensitivity evaluations are performed. For example, early in the study, sensitivity evaluations may be conducted to identify the dominant factors in the analysis to guide the collection of data, focus the SSC, etc. Similarly, at the conclusion of the study, sensitivity analyses are performed to demonstrate the role of different parameters or their contribution to the epistemic uncertainty. Due to the often complex relationship that may exist between parameters in the analysis (e.g., correlations), sensitivity analyses are a useful means to provide specific insights into their role in the analysis.

7.6 Documentation Guidance: Reporting the Seismic Hazard Results

7.6.1 General Guidance

Table 7-3 provides a summary of general guidance for documenting Basic PSHA Results. The table addresses required fractile levels, use of the mean hazard and presentation of results for rock and soil site conditions. Documentation of the seismic hazard results must include graphic and tabular presentation. In addition, all graphic displays of like results should be provided to a consistent scale for comparison.

Table 7-1 List and Description of Standard PSHA Results

Standard PSHA Result	Required or Optional	Description	Format
Fractile and Mean Hazard Curves	Required	For each ground motion parameter considered in the PSHA, the seismic hazard is expressed in terms of fractile and mean hazard curves. A fractile hazard curve quantifies the probability, p, that the frequency of exceeding each ground motion level is not greater than the value defined by the hazard curve.	The following fractile hazard results are reported: 0.05, 0.15, 0.50, 0.85, and 0.95. In addition, the mean hazard curve is presented.
Uniform Hazard Response Spectra	Required	Response spectrum shapes corresponding to a specified probability of exceedance level. Fractile UHS, and the mean response spectra are determined from the corresponding hazard curves.	The UHS are presented in at least two formats: 1) fractile and mean UHS for a specified probability of exceedance, and 2) the mean or selected fractile level UHS for different probability levels displayed together.
Aggregated Hazard Curves	Optional	Hazard curves that have been generated from an analysis in which a large number of hazard curves have been aggregated to produce a smaller, more manageable set. the combination process should preserve the diversity in hazard curve shapes as well as essential properties of the original set of hazard curves (e.g., mean hazard). This format is used as input to seismic probabilistic risk assessments.	A group of discrete hazard curves is generated, each with a probability weight assigned to it. The hazard curve weights sum to one (see Fig. 7-8).
Ground Motion Contour Map	Optional	To display the hazard in a region, the results can be presented in terms of a ground motion contour map. The ground motion contours define ground shaking levels that have the same probability of exceedance in a specified time period.	A map is produced for each ground motion measure, time period and probability of exceedance (see Fig. 7-9).

Table 7-2 Deaggregated PSHA Results[1]

Deaggregated Result	Description
Magnitude and Distance	A magnitude-distance (M-D) deaggregation entails a presentation of the hazard for selected ranges of magnitude and distances. A M-D aggregation can be presented in terms of the hazard for each M-D pair or in terms of the relative contribution of each M-D pair to the total hazard.
Seismic Sources Individual Sources	Seismic hazard results are presented on a source-by-source basis. The epistemic uncertainty in the activity of the source is not considered. These results can be used to determine the contribution of individual seismic sources to the total hazard. The presentation of source specific results can follow the format for presenting the total hazard (see above).
Magnitude and Distance	For each seismic source, the hazard is deaggregated in terms of magnitude and distance in the same manner as the total hazard (see above). The M-D deaggregation by seismic source provides a breakdown of the difference size earthquakes for the sources that contribute to the site hazard (e.g., importance of the estimate of maximum magnitude).
Ground Motion Attenuation Model	The hazard results are readily deaggregated with respect to the ground motion models that are used in the PSHA. For each attenuation model fractile and mean, hazard results can be presented in a format similar to that used for the total hazard. Each set of fractile results is conditional on the attenuation model considered.
SSC and Ground Motion Experts	If multiple SSC and Ground Motion Experts are used, fractile and mean hazard results can be displayed. The format is similar to the results presented for the total hazard. If a TFI approach is used, results can be presented in terms of particular alternatives or hypotheses that are selected.

Table 7-3 General Guidelines for Documenting PSHAs

PSHA Result/Parameter	Guidance
Fractile Hazard Curves	Results should be presented for the 0.05, 0.15, 0.50, 0.85, and 0.95 fractile levels.
Mean Hazard	The mean seismic hazard curve should be reported for all Basic PSHA Results.
Soil Sites	Basic PSHA results should be presented for both rock and soil site conditions.
Deaggregated Hazard Results	For estimating the relative contribution of a parameter (e.g., seismic source, ground motion model) to the hazard, this should be done using the mean.

[1]Note: Depending on the methods recommended by the SSHAC, there may be other types of deaggregation that could be considered.

7.6.2 Basic PSHA Results

Tier 1 Documentation

Table 7-1 listed the Basic PSHA Results that should be reported. As noted in the table, certain of the results are "Required." whereas others are "Optional." The analyst should note the distinction. The "Required" results are those that must be presented for all applications, whereas results that are listed as "Optional" are those that must be provided for the purpose of satisfying the application for which the PSHA was conducted (see Table 7-1).

For example, most PSHAs are performed for a single site; therefore, a contour map of ground motion is not computed/required. However, in a regional study in which a contour map must be produced, fractile hazard results should also be reported for selected sites.

Fractile and Mean Hazard Curves

The seismic hazard at a site is presented in terms of the annual probability of exceedance of selected ground motion parameters such as PGA (peak ground acceleration), S_a (absolute spectral acceleration), or PSV (pseudo spectral velocity). The latter two are presented as a function of frequency. In some cases, results for displacement are also presented.

Figures 7-1 and 7-2 show the fractile and mean hazard curves for PGA and PSV (1 Hz) for a rock outcrop. Figures 7-2 and 7-3 show the same information for the same site but for soil site conditions (the site in this case is a deep soil site). This information is also presented in tabular form as shown in Table 7-4 for peak ground acceleration. Graphic and tabular results similar to Figures 7-1 to 7-4 and Table 7-4 must be presented for all the ground motion parameters considered in the PSHA.

Note that in presenting the final results, it is necessary to specify certain key parameters, including whether the hazard is for a rock outcrop or for a soil site, and the damping value used when the hazard is presented in terms of response spectrum ordinates.

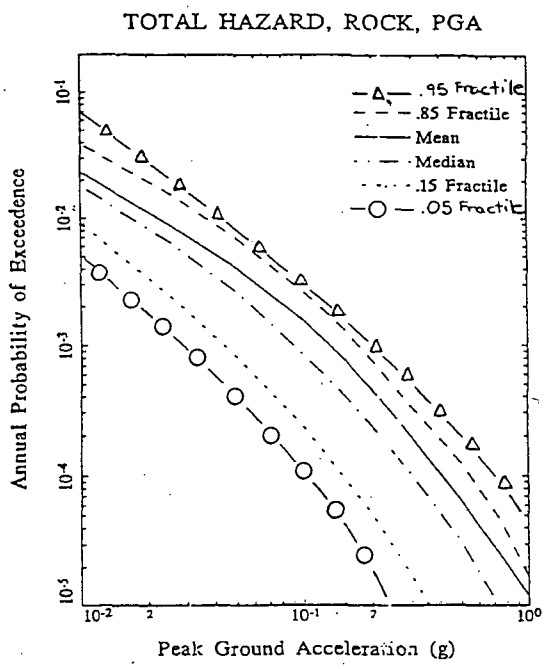

Figure 7-1 Total seismic hazard curves for PGA and rock site conditions.

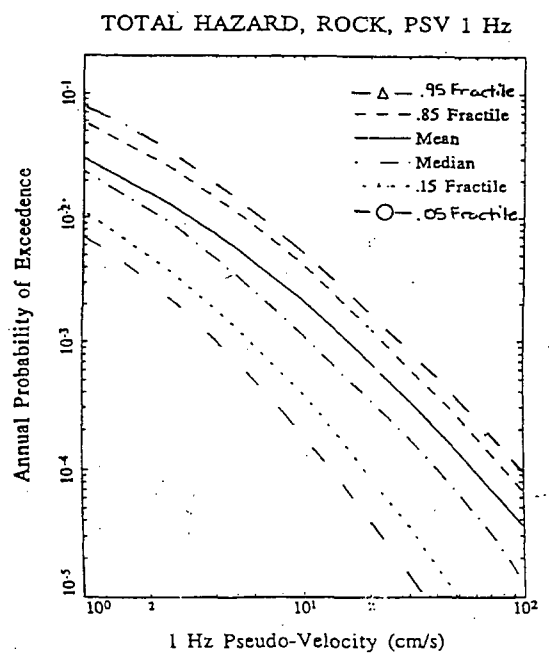

Figure 7-2 Total seismic hazard curves for PSV (1 Hz) and rock site conditions.

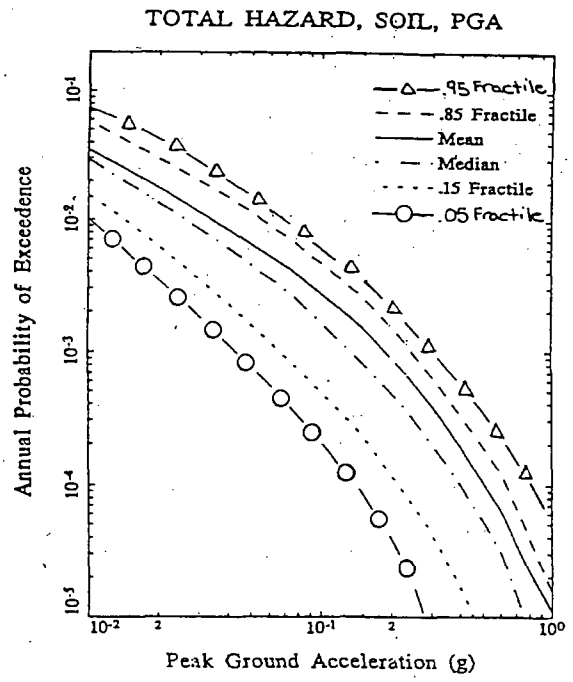

Figure 7-3 Total seismic hazard curves for PGA and soil site conditions.

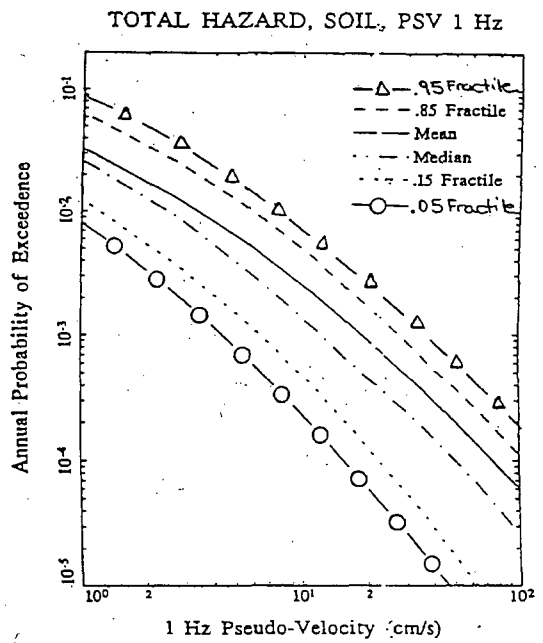

Figure 7-4 Total seismic hazard curves for PSV (1 Hz) and soil site conditions.

Table 7-4 Seismic Hazard Results for Peak Ground Acceleration—Rock (The fractile values were not available.)

Level	Mean	Fractile Levels				
		0.05	0.15	0.50	0.85	0.89
1	2.34E-2					
2.5	8.88E-3					
5	4.07E-3					
10	1.55E-3					
15	7.76E-4					
20	4.49E-4					
30	1.96E-4					
50	6.52E-5					
75	2.48E-5					
100	1.18E-5					

Uniform Hazard Spectra

If the hazard assessment is performed for multiple ground-motion parameters over a range of frequencies, uniform hazard response spectra must be reported. When presenting the UHS results in graphical and tabular format, the following information must be presented:

- annual probability of exceedance level
- frequencies and spectral values
- damping level
- fractile and mean response spectrum values

A number of alternative formats are available to graphically present UHS results. They are:

1. Fractile and mean UHS for a specified annual probability of exceedance and damping level.
2. UHS for a specified damping, multiple annual probability of exceedance levels using the mean or a specified fractile (e.g., 0.50 fractile).
3. UHS for a specified annual probability of exceedance, multiple damping levels using the mean or a specified fractile (e.g., 0.50 fractile) level.

UHS can be displayed in terms of acceleration or velocity. Log-log plots are often used, but other formats can be selected. In the PSHA report, a consistent format should be followed.

When determining the ground motion levels corresponding to a specified annual probability of exceedance, a log-log interpolation scheme is recommended. If extrapolations beyond the computed hazard curve must be made, this should be noted as part of the tabular and graphical presentation.

The UHS should be determined for annual probability levels that satisfy the application for which the study was performed. Typically, a number of probability levels are used, ranging from 10^{-2} to 10^{-5}.

Figure 7-5 shows an example of a UHS for a specified damping level and annual probability of exceedance. For the damping and probability levels shown, the 0.05, 0.15, 0.50, 0.85 and 0.95 fractiles and mean UHS are shown. Figure 7-6 shows the mean UHS for a specified annual probability of exceedance (10^{-3}) and different damping levels. Figure 7-7 shows the mean UHS for a single damping level and different annual probabilities of exceedance.

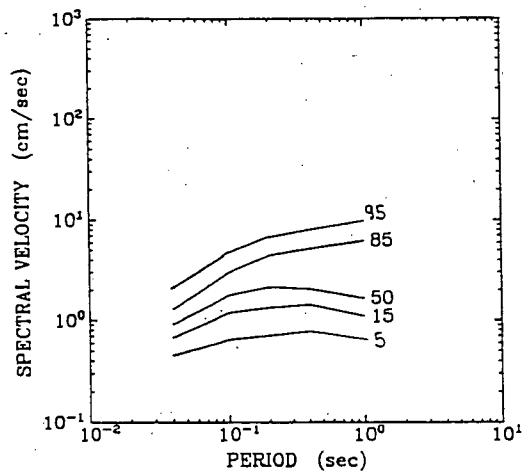

Figure 7-5 Uniform hazard response spectra for soil site conditions for an annual probability of exceedance of 10^{-3} and damping level 5% of critical.

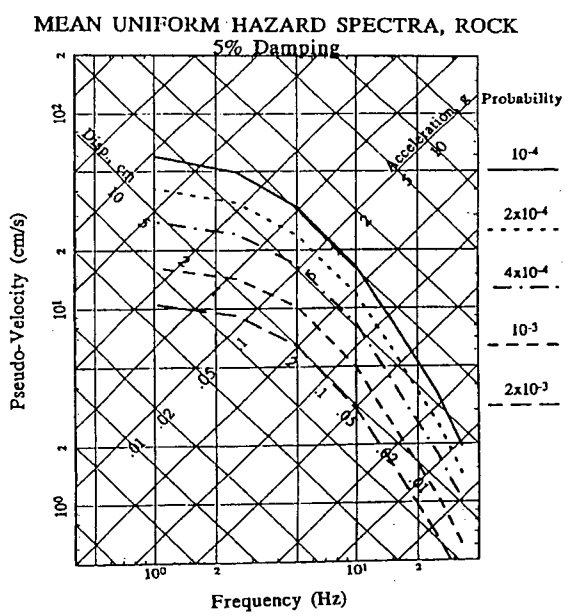

Figure 7-6 Mean uniform hazard response spectra for soil site conditions and annual probabilities of exceedance of $2x10^{-3}$, 10^{-3}, $4x10^{-4}$, $2x10^{-4}$, and 10^{-3} and a damping level 5%of critical.

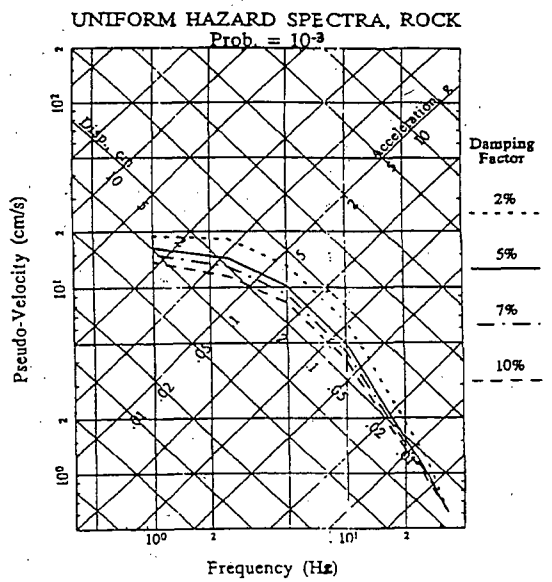

Figure 7-7 Mean uniform hazard response spectra for soil site conditions at four damping levels. Annual probability of exceedance = 10^{-3}.

Table 7-5 Tabulation of Uniform Hazard Response Spectra Results Rock Site Conditions

Frequency	Probability Level	Mean	Fractiles				
			0.05	0.15	0.50	0.85	0.95
1.0	$2x10^{-3}$	0.067					
	10^{-3}	0.104					
	$2x10^{-4}$	0.262					
	10^{-4}	0.379					
2.5	$2x10^{-3}$	0.147					
	10^{-3}	0.230					
	$2x10^{-4}$	0.558					
	10^{-4}	0.791					
5.0	$2x10^{-3}$	0.204					
	10^{-3}	0.326					
	$2x10^{-4}$	0.763					
	10^{-4}	1.06					
10.0	$2x10^{-3}$	0.197					
	10^{-3}	0.319					
	$2x10^{-4}$	1.00					
	10^{-4}	1.06					
25.0	$2x10^{-3}$	0.106					
	10^{-3}	0.171					
	$2x10^{-4}$	0.414					
	10^{-4}	0.582					
PGA	$2x10^{-3}$	0.083					
	10^{-3}	0.129					
	$2x10^{-4}$	0.297					
	10^{-4}	0.410					

For soil sites, UHS results for a rock outcrop and soil-site conditions should be presented (no such examples are provided here). The graphical presentation of the rock and soil UHS should be provided to the same scale.

Table 7-5 shows a typical tabular presentation of UHS results, which lists the mean UHS for different damping values (2%, 5%, 7%, 10%), and presents PSA (pseudo-acceleration) at five frequencies (1, 2.5, 5, 10, and 25 Hz). A table similar to Table 7-5 is presented to accompany each graphical UHS presentation.

When presenting these bottom-line hazard results, it is not usually possible to present "too much information." To the informed reader, the different formats, including both figures and tables, are of great benefit in understanding the results from different perspectives.

Aggregated Seismic Hazard Curves

For input to a probabilistic seismic risk assessment in which an uncertainty assessment is performed, a discrete family of seismic hazard curves must be provided by the PSHA. A discrete family of hazard curves is a group of individual hazard curves with weights assigned to each curve that quantify the epistemic uncertainty in the hazard. The weights sum to one for the group of hazard curves. As noted in Chapter 6, many thousands to many tens-of-thousands of discrete hazard curves may be computed in the hazard assessment. For purposes of performing a seismic risk assessment, it is possible to aggregate this large set of hazard curves into a much smaller, more manageable set for use in a risk assessment.

Cluster analysis techniques (Veneziano, Cornell, and O'Hara 1984) are available to combine hazard curves while retaining the basic probabilistic properties of the original set (i.e., mean and variance). Figure 7-8 presents a schematic illustration of a set of aggregated hazard curves. In most applications, an aggregate set of 10 to 20 hazard curves is adequate for input to a seismic risk assessment. For completeness, the set of aggregated hazard values should also be tabulated. The tabulation lists the hazard curves and their respective weights.

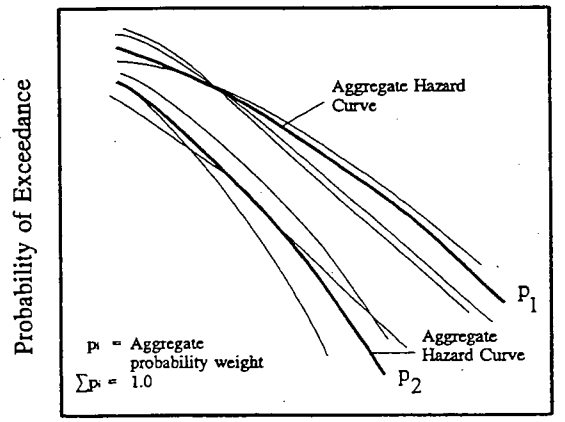

Figure 7-8 Illustration of an aggregate set of seismic hazard curves for PGA for soil site conditions. Each curve has an assigned weight to it.

Ground Motion Contour Maps

For certain applications, contour maps are generated that define the ground motion levels that have the same probability of exceedance for a specified period of time. One such application is in the development of a national seismic design code. Figure 7-9 shows an example of such a map. In defining a ground-motion contour map, the analyst must decide on the following:

- future time period(s) to be considered
- probability of exceedance levels
- ground motion parameters to be mapped (including damping levels)
- fractile levels or mean hazard to be mapped

In addition, the analyst must select a group of sites in a region in order to provide adequate spatial sampling of the ground motion.

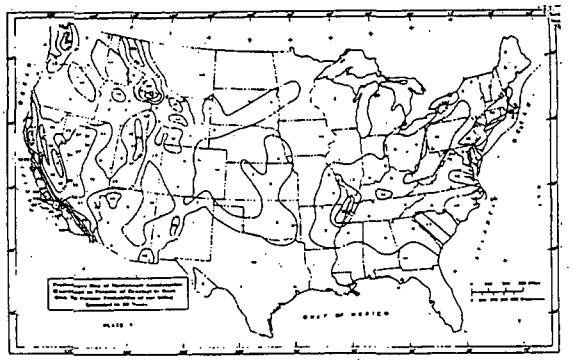

Figure 7-9 Illustration of a ground motion contour map corresponding to specified time period and probability of exceedance level.

Tier 2 Documentation

The Tier 2 documentation of the Basic PSHA Results is contained in the seismic hazard information base maintained in computer-readable data files. The information contained in these files is described in Section 7.12.

7.7 Documenting Deaggregated PSHA Results

7.7.1 Overview

The seismic hazard at a site is an aggregation of:

- the hazard associated with individual seismic sources, and
- earthquakes of different magnitude that occur over a range of distances form the site

In addition, the quantification of the epistemic uncertainty in the hazard is an aggregation of the epistemic uncertainty in individual parameters in the analysis. The form of aggregation is different in each of these examples. In the former case, aggregation is carried out to account for the randomness of earthquake occurrences by location (seismic source to seismic source, and within a seismic source) and earthquake magnitude. In the later case, a very different form of aggregation is performed. Here the epistemic uncertainty in parameter assessments is propagated through the analysis to determine the total epistemic uncertainty in the seismic hazard. To facilitate the understanding of the PSHA, deaggregated results must be presented.

7.7.2 General Guidance

For all PSHA studies, deaggregation results for seismic sources and magnitude and distance must be provided. In addition, if the seismic hazard is estimated for a range of ground-motion parameters, the deaggregation should be performed for at least two spectral frequencies. It is recommended that the deaggregation be performed, as a minimum, for two ground-motion parameters (PSV or S_a) at 1 and 10 Hz. The analyst may consider other frequencies based on the application for which the results will be used. For example, if a hazard assessment is being performed for a long-period structure such as a suspension bridge, results at longer periods (e.g., lower frequencies) will be of interest.

The deaggregation should be performed using mean seismic hazard results. (Note, some applications may require the use of the median hazard.)

7.7.3 Presenting Deaggregated Results

This section describes the deaggregated results that must be provided.

Tier 1 Documentation

Source Deaggregation —The seismic hazard at a site is attributed to the likelihood of ground motions that are generated by multiple sources of seismic activity. An informative PSHA result is to display the mean hazard curve for each seismic source. Figures 7-10 and 7-11 show such a presentation for PGA and PSV at 1 Hz. This is the same site and analysis as for Figures 7-1 and 7-2, except here the mean seismic hazard associated with nine seismic sources is presented. When this information is compared to that in Figures 7-1 and 7-2, one can assimilate clearly the fact that one seismic source dominates the mid-range exceedance probabilities, but a second source dominates at the high end while a third source dominates at the low end of the plot. Table 7-6 presents the results for PGA in tabular form.

A clear picture of the relative contribution of each seismic source to the total mean hazard can be displayed as shown in Figure 7-12. The figure displays, for a selected ground motion parameter, the relative contribution of each seismic source to the total mean hazard at specified ground motion levels. Similar plots can be displayed for each ground-motion parameter. These results are tabulated in Table 7-7.

Magnitude-Distance Deaggregation—Hazard results deaggregated in terms of magnitude and distance must be presented for the total hazard. In addition, magnitude-distance deaggregation should also be presented for the seismic sources that dominate the site hazard. The deaggregation is presented for selected M and D bins that cover the range of magnitudes and distances considered in the analysis and provide adequate representation of the M-D density. The following magnitude and distance have been useful in PSHA applications.

Parameter	Bin
Magnitude	5-5.5, 5.5-6, 6-6.5, 6.5-7, 7-7.5, 7.5-8, >8
Distance (km)	0-10, 10-25, 25-50, 50-100, 100-150, 150-200, >200

Table 7-6 Mean Seismic Hazard Curves for Each Seismic Source Peak Ground Acceleration and Rock Site Conditions

Level (g)	Total	Seismic Source								
		1	2	3	4	5	6	7	8	9

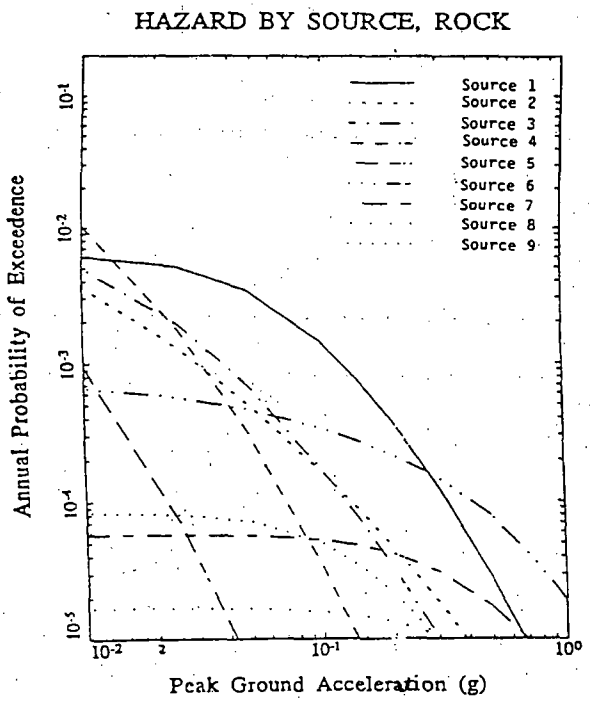

Figure 7-10 Mean seismic hazard curves for individual seismic sources. Results are for PGA and rock site conditions.

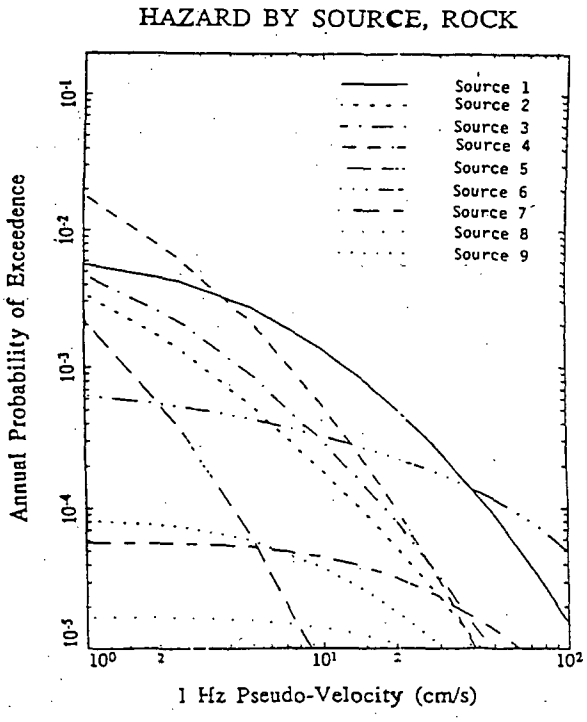

Figure 7-11 Mean seismic hazard curves for individual seismic sources. Results are for PSV(1 Hz) and rock site conditions.

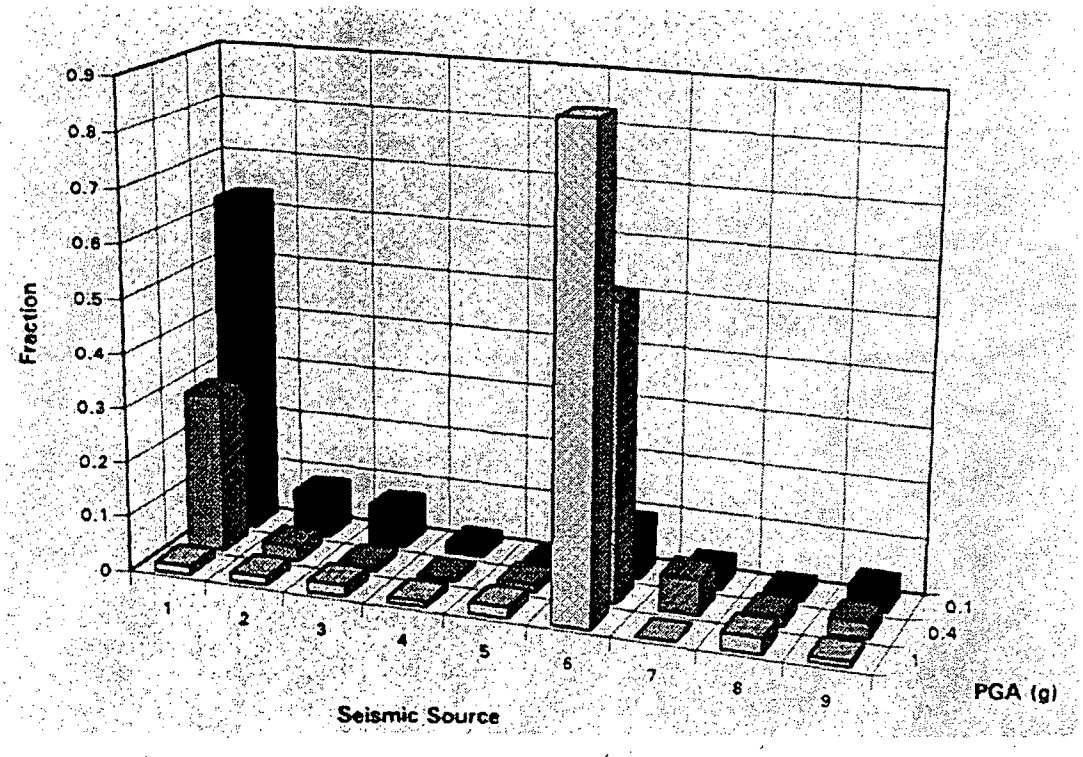

Figure 7-12 Illustration of the relative contribution of individual seismic sources to the total mean hazard. The results are presented for PGA and rock site conditions and three ground motion levels.

Table 7-7 Relative Contribution of Each Seismic Source to the Total Mean Hazard for Peak Ground Acceleration and Rock Site Conditions

Seismic Source	PGA (g)		
	0.10	**0.40**	**1.0**
1	0.63	0.29	0.00
2	0.07	0.00	0.00
3	0.07	0.00	0.00
4	0.02	0.00	0.00
5	0.00	0.00	0.00
6	0.16	0.29	1.00
7	0.03	0.12	0.00
8	0.01	0.00	0.00
9	0.03	0.00	0.00

The PSHA analyst should select the M-D bins appropriate for a given application.

Figure 7-13 shows an example of the M-D deaggregation for the total seismic hazard for PGA at a selected ground motion level. In this case, it is apparent that the hazard is dominated by seismic events with magnitude less than 6.0 that occur within 50 km of the site.

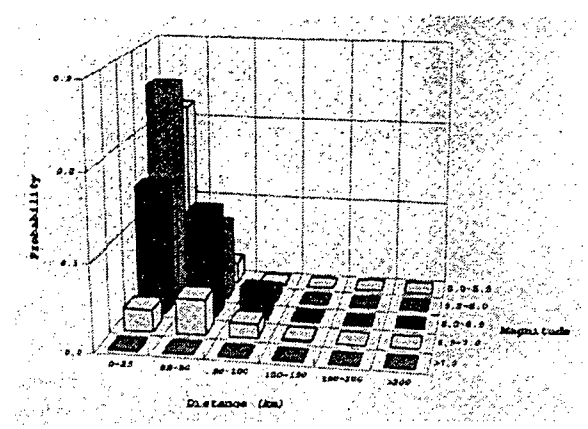

Figure 7-13 Magnitude-distance deaggregation for the total hazard. Results are provided for PGA at 0.25g and rock site conditions.

Table 7-8 tabulates the results presented in Figure 7-13. Similar results should be presented for the seismic sources that dominate the hazard.

Tier 2 Documentation

The Tier 2 documentation of the Deaggregated PSHA Results is contained in the seismic hazard information base that is maintained in computer-readable data files. The information contained in these files is described in Section 7.12.

7.8 Documenting PSHA Sensitivity Analyses

As part of a PSHA, sensitivity analyses are performed to move the study forward and to demonstrate the role of parameters in the analysis. For example, during the course of the study, sensitivity calculations may be performed to provide insights to the factors that will be important/unimportant to the assessment of the hazard at a site. The results of these calculations often become a guide for the PSHA.

At the conclusion of the PSHA, the results of sensitivity analyses provide a means to demonstrate the role that the variation in

individual parameters has on the results. For example, sensitivity calculations can be used to show the variation in the mean hazard due to the different estimates of the maximum magnitude for the seismic source that dominates the hazard. Sensitivity calculations can also be used to determine the contribution of different parameters in the analysis to the total epistemic uncertainty (e.g., total variance).

A number of alternative methods are available to perform sensitivity evaluations. Experimental design and response surface techniques (to name just a few) are examples of sophisticated methods that can be used. In PSHA, relatively simple methods can be used to show the sensitivity of the hazard to parameter variations. As noted above, a deaggregation of the hazard on the basis of seismic sources, magnitude and distance and ground motion attenuation models provides valuable insights to the factors that do/do not contribute to the hazard.

As part of the PSHA documentation, the results of sensitivity calculations should:

1. provide insights to the site hazard that guided the scope and depth of the analysis that was performed
2. demonstrate the sensitivity of the hazard results to the variation in critical parameters in the PSHA (e.g., parameters for the dominant seismic source)

Two types of sensitivity evaluations are recommended. In the first approach, a base case is assumed and the parameter of interest is varied. The results are displayed to demonstrate the variation in the hazard. As an example, consider a site where the hazard is, dominanted by a single seismic source. For this source, three estimates of the maximum magnitude (m_{max}) are defined by the experts. A series of hazard calculations are performed in which the maximum magnitude is set to each of the three m_{max} values.

Table 7-8 Magnitude-Distance Contribution to the Total PGA Hazard at 0.25g—Rock Site Conditions

Distance (km)	Magnitude				
	5.0-5.5	5.5-6.0	6.0-6.5	6.5-7.0	>7.0
0-25	.011	0.26	0.15	0.03	0
25-50	0.02	0.10	0.11	0.05	0.01
50-100	0	0.02	0.06	0.04	0.01
100-150	0	0	0	0.02	0
150-200	0	0	0	0.01	0
>200	0	0	0	0	0

Table 7-9 Contributions to the Epistemic Variance in the Hazard

S_a (g)	Attenuation Model	Hayward Tran.	Recurrence Model	Fault Segmentation	Total Length	Magnitude Distribution	San Andreas Depth	M_{max}	L.P. Assc.	Activity Rate	b-Value
Peak Acceleration											
0.050	0.255	0.008	0.306	0.010	0.018	0.087	0.001	0.106	0.001	0.155	0.054
0.100	0.249	0.005	0.394	0.005	0.014	0.050	0.000	0.077	0.001	0.142	0.064
0.200	0.232	0.001	0.488	0.008	0.013	0.014	0.000	0.066	0.002	0.110	0.066
0.300	0.315	0.000	0.428	0.014	0.013	0.006	0.000	0.060	0.002	0.104	0.057
0.400	0.427	0.000	0.314	0.020	0.013	0.004	0.000	0.057	0.001	0.113	0.051
0.500	0.509	0.000	0.205	0.027	0.011	0.004	0.000	0.057	0.001	0.135	0.052
0.600	0.538	0.000	0.117	0.036	0.009	0.003	0.000	0.063	0.000	0.170	0.062
0.650	0.531	0.000	0.083	0.043	0.008	0.003	0.000	0.069	0.000	0.192	0.070
0.700	0.511	0.000	0.056	0.051	0.006	0.003	0.000	0.077	0.000	0.217	0.080
0.800	0.436	0.000	0.021	0.069	0.004	0.002	0.000	0.098	0.000	0.268	0.103
1.000	0.255	0.000	0.004	0.104	0.001	0.001	0.000	0.145	0.000	0.344	0.144
1.250	0.183	0.000	0.004	0.117	0.000	0.001	0.000	0.183	0.000	0.352	0.161

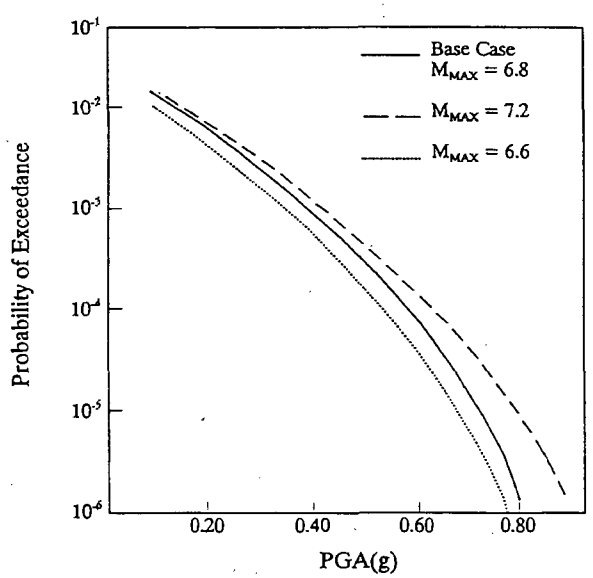

Figure 7-14 Illustration of the sensitivity of hazard results to the variation in maximum magnitude.

Figure 7-14 shows an example of this type of result. A comparison of the mean hazard curves for the three sets of calculations demonstrates the variation in the results based on each of the three maximum magnitude values. Similar sets of hazard calculations can be used to demonstrate the sensitivity of the PSHA results to other parameters. The advantage of this type of sensitivity evaluation is that it provides the analyst, reviewer or user of the PSHA with an understanding of the specific variation in the hazard that is attributed to the change in a particular parameter. At the same time however, these types of sensitivity results may not provide a complete picture of the relative contribution of one or multiple parameters to the hazard.

An alternative format for presenting the sensitivity of the hazard to different parameters is to compute the contribution of the epistemic uncertainty in individual parameters to the total epistemic uncertainty. Table 7-9 presents an example of this type result. This type of sensitivity analysis corresponds to an analysis of the epistemic variance.

Because there are so many different types of sensitivity analyses that could be performed, it is not feasible to present examples here of how to display the results from them. The following is a partial list of the types of analyses for which it may be desirable to present graphical or tabular information:

- sensitivity of hazard to M_{max}
- sensitivity of hazard to various b-values
- sensitivity of hazard to various a-values
- sensitivity of hazard to attenuation parameters, of which there are various that one could display
- sensitivity of hazard to geometry of the dominant fault(s) or other seismic sources
- sensitivity of hazard to slip rate for the dominant fault(s)
- sensitivity to M_L conversion
- sensitivity to local site conditions, such as soil-amplification factors

Tier 2 Documentation

For the sensitivity calculations that are reported in the Tier 1 documentation, backup computer data files similar to those that document the Basic PSHA Results should be provided in the Tier 2 documentation.

7.9 Comparisons with Other Studies

As part of the PSHA documentation, it is useful to the study sponsor to provide a comparison with the results of prior studies. Often, questions about how the current study results compare to previous analyses will arise. It is therefore beneficial to provide in the Tier 1 documentation the results of a comparative evaluation.

If detailed comparative assessments are performed, the supporting documentation should be retained in Tier 2 records.

7.10 Documentation Guidance: Results of the Seismic Source Characterization

The basic purpose of the SSC is to estimate the rate of future earthquake occurrences in the vicinity of a site. This rate has a spatial as well as a temporal component. The spatial variation of earthquake occurrences is modeled through the determination of the temporal component of earthquake occurrence rates within individual seismic sources. The earth science expert's model of earthquake occurrences near a site is defined by the map of seismic sources that are defined and the individual source earthquake recurrence models. Combined, the source map and source recurrence models fully define the spatial and temporal rate of earthquake occurrences in the vicinity of a site.

Tier 1

In the Tier 1 documentation of the SSC, the following must be presented:

1. Seismic source maps that present the earth science expert model for a region. Multiple maps or figures may be required to provide adequate detail legible to the reader. For example, alternative maps and figures may be required to present faults that are modeled as three-dimensional structures in the hazard analysis. Figure 7-15 shows an example for an expert seismic source map. If multiple experts provide input to the PSHA, the seismic source maps for each must be presented.

2. For the seismic sources that dominate the site hazard, the magnitude recurrence model, including the epistemic uncertainty, must be presented. The epistemic uncertainty must be presented in terms of the fractile recurrence curves at the 0.05, 0.15, 0.50, 0.85 and 0.95 fractile levels. The mean recurrence is also presented. Figure 7-16 shows this type of result.

3. The PSHA model for seismicity in the vicinity of the site is presented for the rate of earthquake occurrences at several (at least 3) magnitudes. Figure 7-17 shows an example of a map that displays the mean rate of earthquake occurrences above magnitude 5.

4. For the region around a site (approximately 200 km), a comparison of the historic rate of earthquake occurrences and the PSHA estimate must be presented. Figure 7-18 shows this type of comparison.

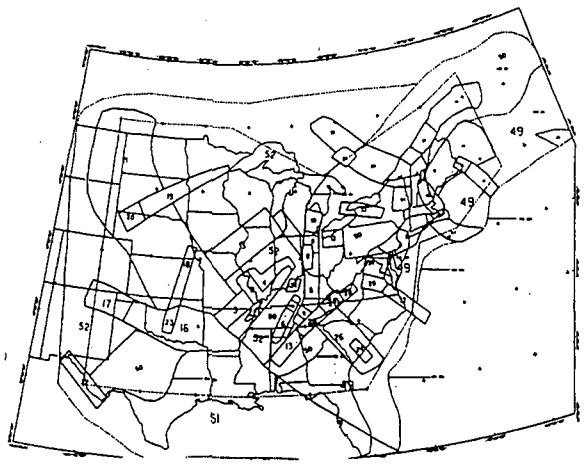

Figure 7-15 Example of an expert seismic source map.

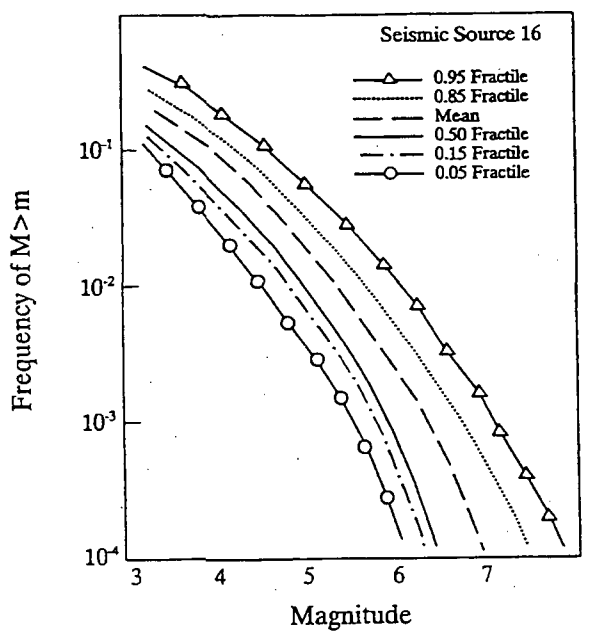

Figure 7-16 Illustration of magnitude recurrence for a seismic source.

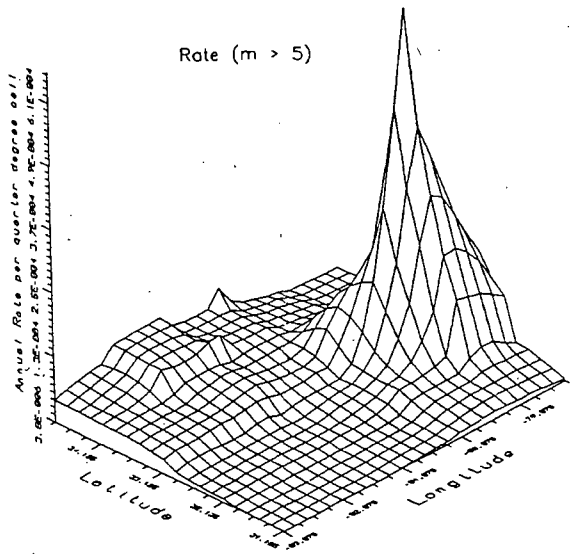

Figure 7-17 Map showing the mean rate of earthquake occurrences above magnitude 5.0.

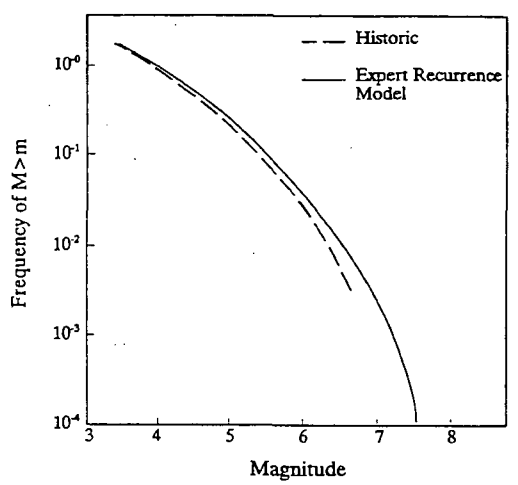

Figure 7-18 Comparison of historic seismicity and the expert recurrence model for a region.

Tier 2

The Tier 2 documentation of the SSC results should contain supporting documentation of the seismic source maps and calculation results of seismic source recurrence models.

7.11 Documentation Guidance: Results of Characterization of Ground Motion Attenuation

The graphical presentation of ground-motion-attenuation results can be done in a number of different ways. Perhaps the most difficult challenge in presenting this type of information is when the results from several different models are being displayed on the same figure. The problem here is to differentiate among many different types of curves, or types of results, on the same figure. The guidance, although obvious, is well worth repeating:

- keep everything legible
- use similar scales for graphs that the reader might want to compare

7.12 Computer-Readable Data Files

Tier 1 Documentation

As part of the PSHA documentation, it is recommended that computer-readable (friendly) data files be generated and retained by the analyst and the study sponsor, if desired. This section provides the guidance for documentation of these data files.

As part of the Tier 1 documentation of the PSHA, the analyst should describe the information that is retained in computer readable data files. The description should include:

1. The content of each type of data file that is retained
2. Potential uses of these data files
3. How the files can be used/accessed (i.e., Can a spreadsheet be used to read them?)

The purpose is to make the sponsor of the study and the technical reviewer aware of the content of the data files and their potential applications. This write-up need not contain a detailed description of each computer data file; rather, it should briefly describe their content and availability.

Tier 2 Documentation

As part of the PSHA Tier 2 documentation computer data files should be created that contain all of the intermediate and final calculations that form the basis for the Basic PSHA Results, the PSHA Deaggregated Results and the Sensitivity Analyses reported in the Tier 1 documentation. These guidelines identify the information that should be contained in these files; however, specific file formats, etc. are not specified.

The information contained in the Tier 2 documentation of the PSHA results should be comprehensive enough to permit the analyst or technical reviewer to conduct sensitivity evaluations, examine the impact of individual parameters to the results without having to rerun the hazard analysis, which may not be an option for the sponsor or the technical reviewer. Table 7-10 contains a summary of the information that should be provided in the Tier 2 documentation of the PSHA results. Figure 7-19 shows a tabular summary of a computer data file.

Table 7-10 PSHA Computer Data Files—Tier 2 Documentation

Item/Data File	Description
Computer Data File Documentation	Complete documentation of the computer data files generated as part of a PSHA project should be created and maintained. This should include a description of the file content and format.
Seismic Hazard Input Files	Computer data files that are the input to the PSHA calculation software. There may be one or multiple files that contain information for each seismic source (e.g., geometry data, seismicity parameters, fault rupture models, etc.) and the rules for combining seismic sources.
Seismic Source Hazard File	For each seismic source, data files should be provided that contain the hazard results for the alternative parameter values used to quantify the hazard and the probability values assigned to each parameter. Examples of alternative parameters include different estimates of the maximum magnitude, seismic activity rate, b-value, ground motion attenuation models, source geometry, etc. For each hazard curve, information should be provided that makes it possible to identify exactly the parameters used to produce that particular hazard result.
Total Hazard File	In a format similar to the hazard results for individual seismic sources, a data file should be provided that contains each of the individual hazard curves generated in the analysis. In addition to the information provided for each seismic source, this data file must identify the seismic sources that were included in the hazard curve determination and the probability weight assigned to the hazard result.
Deaggregated Hazard File	Data files should be provided for the deaggregated hazard results in the same way that the total hazard is documented. This should be done on a source-by-source basis and for all sources combined (see above).
Sensitivity Analyses	Data files should be provided for sensitivity analyses that are performed in the same way that the total hazard is documented (see above).

```
SAMPLE PROBLEM  TEAM 1, SITE 1                  89.80     35.81
A     1 1.00 1 6.5 0.85 1 0.50  3.120 3.723 4.768 5.770 7.049
A     1 1.00 2 6.8 0.15 1 0.50  3.087 3.658 4.628 5.531 6.659
A     1 1.00 1 6.5 0.85 2 0.50  2.617 3.128 4.090 5.042 6.251
A     1 1.00 2 6.8 0.15 2 0.50  2.602 3.093 3.998 4.872 5.961
B     3 0.75 1 6.0 0.33 1 0.50* 3.347 3.710 4.317 4.967 5.877
B     3 0.75 2 6.5 0.34 1 0.50* 3.285 3.638 4.226 4.820 5.598
B     3 0.75 3 6.9 0.33 1 0.50* 3.266 3.612 4.190 4.764 5.483
B     3 0.75 1 6.0 0.33 2 0.50* 3.028 3.391 4.031 4.679 5.575
B     3 0.75 2 6.5 0.34 2 0.50* 2.982 3.325 3.939 4.548 5.345
B     3 0.75 3 6.9 0.33 2 0.50* 2.971 3.304 3.902 4.494 5.245
B     4 0.25 1 6.0 0.33 1 0.50* 4.193 4.555 5.154 5.792 6.689
B     4 0.25 2 6.5 0.34 1 0.50* 4.121 4.472 5.045 5.619 6.373
B     4 0.25 3 6.9 0.33 1 0.50* 4.097 4.440 5.000 5.548 6.234
B     4 0.25 1 6.0 0.33 2 0.50* 3.852 4.232 4.871 5.509 6.393
B     4 0.25 2 6.5 0.34 2 0.50* 3.798 4.154 4.764 5.356 6.128
B     4 0.25 3 6.9 0.33 2 0.50* 3.783 4.129 4.719 5.289 6.008
C     4 1.00 1 5.5 0.85 1 0.50* 3.975 4.464 5.262 6.072 7.201
C     4 1.00 2 6.2 0.15 1 0.50* 3.702 4.161 4.886 5.567 6.442
C     4 1.00 1 5.5 0.85 2 0.50* 3.498 4.020 4.869 5.688 6.789
C     4 1.00 2 6.2 0.15 2 0.50* 3.250 3.724 4.503 5.223 6.129
```

Problem title and the site coordinates
Results for Source A

For each line the following is given:
- *Source name*
- *Seismicity option and its probability*
- *Maximum magnitude value and its probability*
- *Attenuation function and its probability*
- *Flag; '*' if this is a host source, else blank*
- *-log (base 10) probability of exceedance for each ground motion level*

Figure 7-19 Schematic illustration of the content of a Source Data File.

8. SEISMIC HAZARD GLOSSARY

TERM	DEFINITION
Acceleration (ground)	Acceleration at the ground surface produced by seismic waves. Typically expressed in g, the vertical acceleration of gravity at the earth's surface (9.80665 m/s^2).
Acceleration, Spectral	Pseudo-absolute response spectral acceleration, given as a function of period or frequency and damping ratio (typically 5%). It is equal to the peak relative displacement of a linear oscillator of frequency f attached to the ground, times the quantity $(2\pi f)^2$. It is expressed in g or cm/s^2.
Active Fault, Active Source	A fault or area source that on the basis of historical, seismological, or geological evidence is considered to have a non-zero probability of producing an earthquake in the present tectonic environment.
Activity Rate	See "Recurrence."
Aleatory Uncertainty	The uncertainty inherent in a non-deterministic (stochastic, random) phenomenon. Aleatory uncertainty is reflected by modeling the phenomenon in terms of a probability model. In principle, aleatory uncertainty cannot be reduced by the accumulation of more data or additional information. Sometimes called randomness.
Area Source	A region of the earth's crust that is assumed for PSHA to have relatively uniform seismic source characteristics. (See also "Seismic Source Zone").
Attenuation, Ground Motion	Decrease in severity (or amplitude) of ground shaking with increasing distance from the earthquake source.
Background Source	A regional scale area source. (Type IV source in text).
b-value	A parameter describing the decrease in the relative frequency of occurrence of earthquakes of increasing sizes. It is the slope of a straight line relating absolute or relative frequency (plotted logarithmically) to earthquake magnitude or intensity, the Gutenberg-Richter recurrence relationship.
Bandwidth	A range of frequencies or periods.

Complementary Zone	See "Background Zone."
Control Point	The location in the soil profile where the control motion is specified.
Control Motion	The input time history to a seismic site response analysis.
Convolution	Complex multiplication in the frequency domain. Used in site response analysis to take the ground motion at a given depth and "propagate" it upward through the soil column and in probability calculations.
Design Earthquake	The magnitude, distance, and other parameters representing the design ground motion.
Design Ground Motion	A specification of the seismic ground motion at a site used for the earthquake-resistant design of a structure.
Design Spectrum	A set of curves for design purposes that gives spectral acceleration, velocity, or displacement (usually absolute acceleration, pseudo-relative velocity, and relative displacement) of a single degree of freedom oscillator as a function of natural period of vibration and damping. (Alternate: The spectral representation of design ground motion).
Distance, Epicentral	Distance from the epicenter to a specific location (site).
Distance, Fault	Shortest distance from the fault to a specific location (site).
Distance, Hypocentral	Distance from the hypocenter to a specific location (site).
Distance, JB	Shortest distance from a point immediately above the ruptured portion of the fault to a specific location (site) (after Joyner and Boore, 1981).
Duration (of ground motion or earthquake rupture)	The length of time during which ground motion at a site shows certain characteristics (e.g., perceptibility, large amplitudes). (See "Corner Frequency").
Earthquake	A sudden motion or trembling of the earth caused by the abrupt release of slowly accumulated strain. The ground motion may range from violent at some locations to imperceptible at others. (Alternate: Naturally occurring shear failure of rock masses within the earth that gives rise to propagating seismic waves).

Epistemic Uncertainty	Uncertainty attributable to incomplete knowledge about a phenomenon which affects our ability to model it. Epistemic uncertainty is reflected in a range of viable models, multiple expert interpretations, and statistical confidence. In principle, epistemic uncertainty can be reduced by the accumulation of additional information. (See "Modeling Uncertainty").
Exceedance Probability	The probability that a specified level of ground motion for at least one earthquake will be exceeded at a site or in a region during a specified exposure time.
Expected Value	The average value, taken with respect to its probability distribution, of an aleatory (random) variable.
Expected Occurrence Rate	The expected value of the number of occurrences of an event (e.g., earthquakes) per unit area per unit time; generally denoted as ν.
Family of Hazard Curves	A set of hazard curves used to reflect the epistemic uncertainties associated with estimating seismic hazard. A common family of hazard curves used in describing the results of a PSHA are curves of fractiles of the probability distributions of estimated seismic hazard as a function of the level of ground motion parameter.
Fault	A planar or gently curved fracture surface or zone in the earth across which there has been relative displacement.
Fault, Dip-Slip	A fault in which the relative displacement is along the direction of the dip of the fault plane; either down-dip (normal fault) or up-dip (reverse fault).
Fault, Normal	A dip-slip fault in which the block above the fault has moved downward relative to the block below. This type of fault represents crustal extension.
Fault, Reverse	A dip-slip fault in which the block above the fault has moved upward relative to the block below, and the fault dip > 45°.
Fault, Strike-Slip	A fault in which the relative displacement is along the strike of the fault plane, either right- or left-lateral.
Fault, Thrust	A dip-slip fault in which the block above the fault has moved upward relative to the block below, and the fault dip < 45°. This type of fault represents crustal compression.

Fault Zone	The zone of deformation comprising a fault.
Focal Mechanism	The combination of the dip angle of the fault and the direction of slip across the fault; faults are classified as strike-slip, normal or reverse. (See "Fault"). (Alternate: Geometrical representation of earthquake faulting expressed in terms of the strike and dip of the fault plane and the rake angle of the slip vector with respect to the fault plane).
Frequency, Corner	Frequency at which the amplitude spectrum of an earthquake transitions from a low-frequency level controlled by the seismic moment, to a high-frequency level controlled by the stress drop. $1/f_c$ is approximately the duration of the earthquake rupture.
Ground Motion Attenuation Model	An analytic model used to relate some measure of ground motion (peak ground acceleration, spectral acceleration, etc.) to distance, magnitude, source and path parameters. A variety of such models exist. A simple, commonly used form is $g(m,r) = C_1 + C_2 M + C_3 \log R + C_4 R$. The ground motion model is part of a model for observed ground motion measures, e.g., $\log A = g(m,r) + E$ where E denotes aleatory uncertainty. Inherent in the model of the observed ground motion measure is a model of the aleatory uncertainty, often taken to be a normal (Gaussian) probability distribution, i.e., $E \sim \text{Normal}(0,\sigma)$ where σ, the standard deviation of E, quantifies the aleatory variability of the ground motion measure. If more complex models are considered, including source and path parameters, e.g., stress drop, and if any of these parameters are aleatory uncertain parameters, the model should include their (aleatory) probability distribution similar to that given for E above.
Gutenberg-Richter Relation	A model of the relationship between frequency and magnitude of earthquakes (in some specified region) expressed as $\log N = a - bM$ where N is the number of earthquakes with magnitude greater than M.
Hypocenter, focus	The point in the earth at which an earthquake is initiated.
Intensity	A measure of the effects of an earthquake at a particular place. Commonly used scales to specify intensity are the Rossi-Forel, Mercalli, and Modified Mercalli.

Lower Bound Magnitude	The lowest earthquake magnitude considered in deriving the seismic hazard curve for a site. (The choice of the lower bound magnitude is based on arguments that smaller earthquakes will not structurally damage well-engineered structures).
Magnitude	A measure of earthquake size, determined by taking the common logarithm (base 10) of the largest ground motion observed during the arrival of the P-wave or seismic surface wave and applying a standard correction for distance to the epicenter. (Alternatively: A measure of earthquake size).
Magnitude, Body-Wave	Magnitude derived from the largest displacement amplitude of body waves (P or S).
Magnitude, Coda-Wave	Magnitude derived from the amplitude and duration of the seismic coda.
Magnitude Distribution	The (conditional) aleatory probability distribution of earthquake magnitude, given the occurrence of an earthquake, assumed to be homogeneous at all locations throughout a source/subsource/seismic area.The probability distribution (given a sufficient number of earthquake events) is estimated as $f_M(m)\Delta m = \frac{\text{number of earthquakes with magnitude in } \Delta m}{\text{total number of observed earthquakes}}$ where $f_M(m)$ is the probability density function. Due to lack of sufficient historical data, this distribution is often taken to be the Gutenberg-Richter relation.
Magnitude, Lg	Magnitude derived from the displacement amplitude of Lg waves; often used in Eastern North America because it can be accurately measured from typical low-gain seismographs at long distances from the source.
Magnitude, Moment	Earthquake magnitude derived from the seismic moment. Approximately equal to local magnitude for moderate earthquakes, and to surface-wave magnitude for large earthquakes.
Magnitude, Richter or Local (1935)	Common logarithm of the trace amplitude (in microns) of a standard Wood-Anderson seismograph located on firm ground 100 km from the epicenter. Correction tables are used to account for other distances and ground conditions.

Magnitude, Surface-Wave	Earthquake magnitude determined from the maximum amplitude of 20 s period surface waves.
Maximum Magnitude	The largest earthquake that a seismic source is capable of generating. The maximum magnitude is the upper-bound to recurrence curves.
Maximum Credible	The phrase used to specify the largest value of a variable, e.g., the magnitude of an earthquake, which might reasonably be expected to occur. A confusing term with no quantifiable definition. Not recommended for use in PSHA.
Mean	Average value of a set of data.
Mean Occurrence Rate Estimate	An estimate of the expected occurrence rate, usually taken as the total number of occurrences of an event (e.g., earthquakes) observed in a specified area and time interval divided by the area times length of time. (See "Rate of Seismicity").
Median (sample median)	Fiftieth fractile of the probability distribution of a variable. (Middle value of an ordered list of a set of data).
Modeling Uncertainty	The variability of a model predicted value from the value of the quantity being predicted. In principle, it can be reduced or eliminated by further testing, data accumulation, or more detailed modeling. It is one source of epistemic uncertainty. (Often called systematic uncertainty).
Outcrop Motion	Motion specified at the free surface of either a real or hypothetical bedrock outcrop at the ground surface. This motion thus represents the earthquake motion unaltered by surface soft soil layers.
Peak Acceleration	Maximum value of acceleration displayed on an accelerogram.
Peak Displacement	Maximum value of displacement obtained or calculated from a record of ground motion.
Peak Velocity	Maximum value of velocity obtained or calculated from a record of ground motion.
Randomness	See "Aleatory Uncertainty."

Rate of Seismicity	Rate of occurrence of earthquakes above some specified magnitude for a specified region.
Recurrence, Recurrence Rate, Recurrence Curve	The frequency of earthquake occurrence of various magnitudes often expressed by the Gutenberg-Richter relation.
Recurrence Interval	The mean time period between earthquakes of a given magnitude.
Recurrence Model	A model to express the relative number or frequency of earthquakes having different magnitudes. A common recurrence model is the exponential magnitude distribution.
Repeat Time	See "Recurrence Interval."
Response Spectrum	A set of curves that gives spectral acceleration, velocity, or displacement as a function of period of vibration and damping.
Return period	Commonly used to express the mean time period between ground motions of a particular amplitude (increase of annual frequency).
Seismic Hazard Curve	A plot of an estimate of the expected frequency of exceedence (over some specified time interval) of various levels of some characteristic measure of an earthquake (often peak ground acceleration). The time period of interest is often taken as one year, in which case the curve is called the annual frequency of exceedence.
Seismic Moment	A measure of the size of an earthquake based on interpretations of how much stress was relieved over the area of the fault or rupture surface. It is defined by the product of the rupture area, the average slip, and the crustal shear modulus.
Seismicity	Denotes the propensity for earthquakes to occur in a region and the possible magnitudes, locations and depths of these earthquakes.
Seismic Source	General term to define faults or area sources. (Types 1-4 in text).

Seismic Source Characteristics	The parameters that characterize a seismic source for PSHA, including source geometry, probability of activity, maximum magnitude, and earthquake recurrence.
Seismic Source Zone	See "Area Source."
Seismic Zone	A region showing relatively elevated levels of observed seismicity.
Seismogenic	Capable of generating tectonically significant earthquakes.
Seismotectonic Province	A region of the earth's crust having similar seismicity and tectonic characteristics.
Site Response (amplification)	The amplification (increase or decrease) of earthquake ground motion by rock and soil near the earth's surface in the vicinity of the site of interest. Topographic effects, the effect of the water table, and basin edge wave-propagation effects are sometimes included under site response.
Source Zone	See "Area Source."
Spatial Clustering	Observed or inferred proximity of earthquake occurrences.
Stationary Poisson Process	A probabilistic model of the occurrence of an event over time (space) characterized by the following properties: (1) the occurrence of the event in a small interval is constant over time (space), (2) the occurrence of two (or more) events in a small interval is "negligible," and (3) the occurrence of the event in non-overlapping intervals is independent. This model is often used to model the temporal and spatial occurrence of earthquakes within a source zone/seismic area.
Stress Drop	The average shear stress released across a rupture surface during an earthquake. (1 bar = 1.013×10^6 dyne/cm^2).
Tectonic Province	See "Seismotectonic Province."
Temporal Clustering	Occurrences of multiple closely timed earthquakes separated by longer periods of quiescence. Events that tend to cluster represent a deviation from a stationary Poisson process.

Upper Bound Magnitude	See "Maximum Magnitude."
Uncertainty	See "Epistemic Uncertainty" and "Aleatory Uncertainty."
Variance	The expected value, taken with respect to its probability distribution, of the squared deviation of an aleatory variable from its expected value.
Zonation	The process of developing seismic source maps (or a set of seismic zones).

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Appendix: Review Report by the National Academy of Sciences/ National Research Council

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Review of

Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts

Panel on Seismic Hazard Evaluation
Committee on Seismology
Board on Earth Sciences and Resources
Commission on Geosciences, Environment, and Resources
National Research Council

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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Preface

In the 1980s two studies produced probabilistic seismic hazard estimates for nuclear power plant sites in the central and eastern United States. The first, sponsored by the U.S. Nuclear Regulatory Commission (USNRC), was conducted by Lawrence Livermore National Laboratory. The second, sponsored by utilities in the Seismicity Owners Group, was conducted by the Electric Power Research Institute (EPRI). The studies produced similar hazard curves and generally similar estimates of relative hazard. But for several sites absolute hazard levels differed by two or more orders of magnitude.

Because absolute hazard levels are important for nuclear power plant design, a new study, sponsored jointly by the USNRC, EPRI, and the U.S. Department of Energy, was undertaken by the newly formed Senior Seismic Hazard Analysis Committee (SSHAC) to determine the source of the major discrepancies in the two hazard estimates and to derive a robust probabilistic seismic hazards analysis methodology that could be used for future estimates.

At the same time, the USNRC asked the National Research Council (NRC) to review the work of the SSHAC study and evaluate the proposed methodology. This review was undertaken by the Panel on Seismic Hazard Evaluation of the NRC's Committee on Seismology which followed the work of the SSHAC study and produced the present critique of the SSHAC report.

Carl Kisslinger
Chairman

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Executive Summary

This review and commentary by the National Research Council's Panel on Seismic Hazard Evaluation presents the panel's evaluation and critique of the report titled *Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts* (U.S. Nuclear Regulatory Commission, NUREG/CR-6372, Washington, DC, 1997). The reviewed report was prepared by the Senior Seismic Hazard Analysis Committee (SSHAC), a committee created and sponsored by the U.S. Nuclear Regulatory Commission (USNRC), the U.S. Department of Energy, and the Electric Power Research Institute. The panel was appointed at the request of the USNRC to provide an independent interactive review of the results of SSHAC's efforts.

SSHAC's charge from its sponsors' perspective was to provide an up-to-date procedure for obtaining reproducible results from the application of probabilistic seismic hazard analysis (PSHA) principles established in past practice, not to advance the foundations of PSHA or develop a new methodology. This focus led to an emphasis on procedures for eliciting and aggregating data and models for performing a hazard analysis, rather than an examination of the earth science foundations of PSHA. SSHAC focused on process because previous PSHA studies have shown that different groups of experts can produce highly discrepant results. A second major theme in the SSHAC report is the treatment of uncertainties in data and models in arriving at stable estimates of seismic hazard at a selected site.

With this in mind, the panel found that the SSHAC report offers substantial contributions to the foundations and practice of PSHA. In particular, the panel commends SSHAC for emphasizing the need for critical evaluation of expert opinion. But the panel also identified some limitations in both the report and the recommended procedures, of which

potential users should be aware. Only certain key points are highlighted here in the summary; the rest are included in later chapters.

MAIN FEATURES OF THE SSHAC REPORT

As stated above, the SSHAC report focuses on procedures for using experts in probabilistic seismic hazard analysis and for determining uncertainties at key stages of the analysis process. In its treatment of the use of expert opinion, SSHAC outlines four possible levels of effort and complexity. But the SSHAC report is strongly flavored by emphasis on hazard analysis for nuclear and other critical facilities, and SSHAC therefore discusses at great length its highest-level (level 4) procedure for evaluating expert opinion. And although SSHAC includes proper disclaimers the unwary reader could gain the incorrect impression that the high-level (level 4) PSHA procedure is needed for every hazard analysis.

The panel agrees that all PSHA projects should share the same basic principles and goals, but that the elaborate level 4 methodology is not required for every PSHA study. SSHAC does indeed recognize that alternate simpler methods are probably adequate for less critical facilities, but the simpler methods are not discussed in detail and the reader is not fully advised about other sources of information. Adequate disclaimers in the SSHAC report should protect the analyst who chooses to use procedures other than those recommended by SSHAC from the need to defend that decision in a regulatory setting.

THE SSHAC METHODOLOGY

SSHAC's contributions to PSHA methodology include the testing and full explication of the technical facilitator/integrator (TFI) entity, which is the essential ingredient in implementing SSHAC's high-level (level 4) analysis.[1] The TFI approach was found to be very effective in two workshops on ground motion estimation and led to an unexpected degree of agreement among the experts consulted, who began with many diverse viewpoints. The panel notes that TFI elicitation procedure is not

[1]For a description of the TFI entity, see Chapter 2.

synonymous with PSHA methodology. Nor is the TFI approach recommended by SSHAC for every PSHA study.

In outlining its four levels of complexity, SSHAC visualizes three distinct roles that experts should play at various stages of the process. First, an expert may start out as the proponent of a particular position (data or model). Then the expert is asked to become an objective evaluator of the positions of the other experts in the group. Finally, the expert becomes an integrator and aggregates all the positions to arrive at a putative position of the whole informed scientific community. This estimation of the position of the whole informed community by integration of the positions of a sample of well-qualified experts is the primary goal of the more complex SSHAC procedure. **The panel questions whether any group of experts can truly assess the view of the whole informed scientific community on the entire range of relevant issues.**

BACKGROUND WORKSHOPS

SSHAC sponsored workshops on seismic source characterization, ground motion estimation, and earthquake magnitudes. These workshops are documented in detail in Appendixes A, B, C, and H of the SSHAC report. The workshops contributed both to the development of the procedures SSHAC recommends and to advancement of our knowledge of the earth science elements of PSHA for the eastern United States. Because SSHAC focused on procedures for PSHA rather than technical issues, some of these valuable results are presented but not highlighted. They deserve more attention.

THE TREATMENT OF UNCERTAINTY

The SSHAC report emphasizes the importance of how uncertainty is treated because the results of a PSHA can be influenced heavily by uncertainties in the data, the models, or both. SSHAC's treatment distinguishes and emphasizes the difference between two types of uncertainty: aleatory (i.e., uncertainty due to variability inherent in the phenomenon under consideration) and epistemic (uncertainty due to our limited knowledge of the phenomenon). After separation, these two

components must be quantified for the model or parameter under consideration. The panel has more trouble with this element than any other in the SSHAC report.

Recognition of the two kinds of uncertainty is useful initially when eliciting and combining expert inputs. Experts need to be aware of the sources of uncertainties (e.g., limitations of available data) so that they can make informed assessments of the validity of alternative hypotheses, the accuracy of alternative models, and the value of data and then transmit those uncertainties to the TFI. However, as detailed in Chapter 3 of this report, the panel believes that the statistical analysis and uncertainty separation procedures recommended by SSHAC may in some cases be more sophisticated than is warranted by the data or the purposes for which the results are to be used.

During the planning of a PSHA, a detailed analysis of uncertainty would be helpful but typically is not available. It may be sufficient for planning purposes to conduct limited sensitivity analyses, using bounding hypotheses, and to consider the level of effort that would be required to reduce the associated uncertainty.

In addition, the value of an epistemic/aleatory separation to the ultimate user of a PSHA is doubtful. In particular, it is not clear that such a separation would be more helpful than the display of expert-to-expert variability of a mean hazard at the time of an analysis, with an explanation of the source of the differences.

The panel also notes that the SSHAC report's discussions and recommendations on uncertainty and the use of experts are quite independent of PSHA and can be applied to other types of risk analysis. The panel believes that the SSHAC report makes a solid contribution to the methodology of hazard analysis, especially in the use of expert opinion.

1
Introduction

> "The future utility of PSHA in decision making depends to a large degree on our ability to implement the process in a meaningful and cost-effective way. Development of the SSHAC guidelines was planned with this goal in mind."
> —*from Sponsors' Perspective, SSHAC Report*

This review and commentary by the National Research Council's Panel on Seismic Hazard Evaluation presents the panel's evaluation of the report *Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts* (U.S. Nuclear Regulatory Commission, NUREG/CR-6372, Washington, DC, 1997). That report was prepared by the Senior Seismic Hazard Analysis Committee (SSHAC) (not a committee of the National Research Council) with sponsorship and oversight by the U.S. Nuclear Regulatory Commission (USNRC), the U.S. Department of Energy (DOE), and the Electric Power Research Institute (EPRI).

WHAT IS SEISMIC HAZARD ANALYSIS?

Earthquakes present a threat to people and the facilities they design and build. Seismic hazard analysis (SHA) is the evaluation of potentially damaging earthquake-related phenomena to which a facility may be subjected during its useful lifetime. An SHA is done for some practical purpose, typically seismic-resistant design or retrofitting. Although strong vibratory ground motion is not the only hazardous effect of earthquakes (landslides, fault offsets, and liquefaction are others), it is the cause of much widespread damage and is the measure of earthquake hazard that has been accepted as most significant for hazard resistance planning.

The level of effort put into an SHA depends on the investment in the facility that might be lost and the consequences to society should it fail. Critical facilities are those that are deemed so important to the functioning of society or whose catastrophic failure will have such disastrous consequences that a maximum (and necessarily costly) effort to assess seismic and all other natural hazards is justified. The SSHAC project was born in the context of SHA for such critical facilities, nuclear power plants in particular. Even though SSHAC broadened its concept of the applicability of its recommended approach to SHA, its report is strongly influenced by this orientation toward very large, costly facilities for which the end goal is to prevent catastrophic failure, even at great expense.

Two general approaches to SHA have been developed and applied. The first approach uses discrete, single-valued events to arrive at scenario-like descriptions of the hazard. Typically, a seismic source location, a maximum earthquake associated with that source, and a ground motion attenuation relationship are specified. The ground motion at the site of interest implied by the chosen inputs is then calculated. The frequency of earthquake occurrence is usually not taken into account, and there is no formal and open way of treating uncertainties. This approach has been labeled deterministic seismic hazard analysis (DSHA) and has been used for many years in the design of power plants, large dams, and other critical facilities.

The other approach is probabilistic seismic hazard analysis (PSHA) and is the subject of the SSHAC effort. PSHA allows the use of multivalued or continuous events and models incorporating the effects and frequencies of all earthquakes that could impact a site. PSHA can easily incorporate model and parameter uncertainties. The results of a PSHA, including the uncertainties, can be represented as a series of curves (mean, median, or selected fractiles), showing the annual frequency of exceeding different levels of the chosen measure of ground motion. The intent of high-level PSHA is to capture and display as much as possible of the knowledge provided by existing data, theory, and computational simulations.

It should be noted that the procedures recommended by SSHAC for the elicitation and aggregation of expert opinion as input to PSHA are equally applicable for compiling the input for DSHA. The only essential difference between DSHA and PSHA is that the latter carries units of time while the former usually does not (Hanks and Cornell, 1994). In the case of a specific design situation, both DSHA and PSHA result in estimates of

ground motion values or time histories that provide the basis for earthquake-resistant design. PSHA yields, in addition, the annual frequency of exceedance of that ground motion level together with attendant uncertainties. SSHAC's responsibilities did not extend to a discussion of the steps by which project engineers and sponsors use the output of a hazard assessment. One approach to this issue is presented in a recent paper by McGuire (1995).

Projection of the location, severity, and frequency of occurrence of future extreme natural events inherently involves a variety of uncertainties. Yet decisions on the siting and design of needed facilities must be made in the face of these uncertainties. No amount of statistical analysis, no matter how rigorously based and carefully done, can totally compensate for the incompleteness of available data and the defects of our evolving scientific knowledge. **A primary objective of SSHAC was to acknowledge and document uncertainties explicitly so that users of PSHA will be able to make better-informed decisions.**

BACKGROUND AND CONTEXT OF THIS REPORT

The Panel on Seismic Hazard Evaluation was created under the Committee on Seismology of the National Research Council in October 1992. The panel was formed in response to a request from the USNRC to provide an independent review and evaluation of a report on PSHA to be produced by SSHAC.

The work of the panel was influenced by several factors. First, the USNRC asked the panel to provide an "interactive review," that is, to submit feedback to SSHAC as it worked in order to avoid the production by SSHAC of a report in which the panel might find serious flaws after it was completed. This request raised serious questions as to how the panel could meet its requirement and not become so involved in the production of the SSHAC report that the objectivity of the panel's own review would be compromised. The panel agreed with the USNRC to provide "arms-length" interaction with SSHAC and developed methods of operation to achieve that goal.

Another factor affecting the work of the panel was a change in the charge to SSHAC after it began its work. The original task assigned by the sponsors concentrated on the reconciliation of two studies done in the mid-1980s by Lawrence Livermore National Laboratory (LLNL) and EPRI of the earthquake hazard at nuclear power plant sites in the United

States east of the Rocky Mountains. These studies were prompted by advice to the USNRC from the U.S. Geological Survey, based on its reconsideration of the likelihood that a major earthquake, such as the Charleston, S.C. earthquake of 1886, could occur again in Charleston or elsewhere along the eastern seaboard. The possibility of such an earthquake could have implications for the safety of nuclear power plants in the eastern United States. A brief history of the LLNL and EPRI studies is given in the SSHAC report.

Although the two studies ranked the many sites approximately the same (from most hazardous to least hazardous in terms of the mean hazard estimates), the absolute hazard values for specific sites, in terms of the mean value of the annual probability of exceeding a specified level of ground motion, differed greatly, with the LLNL results consistently greater.

The problem is illustrated in Figure 1.1, which displays the hazard at three widely separated sites as the annual frequency of occurrence of peak ground acceleration (PGA), the ground motion parameter chosen for this evaluation. The median hazard curve from each study is shown, as well as the 85th and 15th percentile curves. In two of the three cases shown, the median hazard calculated by LLNL is well above that derived by EPRI, and the "uncertainty," measured by the spread of the 15th and 85th percentile curves, is much greater for LLNL than EPRI. Also, the uncertainty is large, a factor of 5 or more at potentially damaging levels of ground motion (PGA greater than 200 cm/sec^2).

The mean hazard curves, not shown in the figure, differ by even greater factors in many cases. This is because the LLNL median and 85th percentile curves are above the EPRI results, and arithmetic averages spanning several orders of magnitude give greatest weight to the largest numbers. This explains the relatively high values of the mean hazard derived by LLNL but it does not get at the fundamental cause for the differences in the estimates.

The desirability of discovering the cause(s) of the discrepancies was obvious, not only for intellectual reasons (why did competent scientists working from the same or similar knowledge and data bases get vastly different answers?), but also for the practical reason that the quantitative estimate of seismic hazard is important in judging whether earthquakes represent a substantial threat, as well as the weight of earthquakes relative to other natural hazards in making design and retrofitting decisions. The USNRC funded LLNL to investigate the

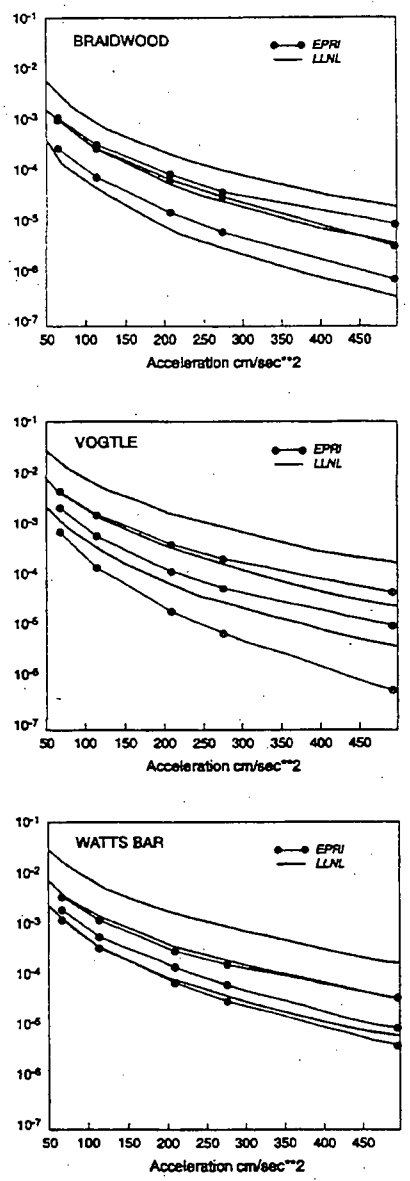

FIGURE 1.1 Median, 15th, and 85th percentile hazard curves for three representative separated sites in the eastern United States, illustrating the differences in results of the LLNL and EPRI studies. The ordinate is the estimated annual frequency of exceedance of the peak ground acceleration shown as the abscissae (adapted from Figures 2.3.1, 2.3.7, 2.3.8 in Bernreuter et al., 1987).

problem. LLNL's study (Bernreuter et al., 1987) concluded that the factors involved in the discrepancy were: (1) different values were chosen for the lower-bound earthquake when the groups were integrated over seismicity to calculate the hazard, (2) different ground motion models were used, and (3) LLNL included a correction for local site effects and EPRI did not. This explained why the two studies obtained different answers but does not explain why competent analysts arrived at significantly different inputs to the hazard calculations.

As SSHAC was being assembled, the underlying cause of the discrepancies between the two studies was identified by further study at LLNL. Researchers there concluded that the differences were due to the ways in which the inputs provided by experts had been elicited. Once this was recognized and taken into account, the differences in the outputs (mean hazard curves) were reduced from orders of magnitude to small factors that represented satisfactory agreement, given the many uncertainties in every step of the analysis. This resolution of the original problem led to changes in the SSHAC charter (1994), from which the following items are selectively cited to provide the context within which the SSHAC report was developed:

> *Objective:* To develop implementation guidelines, including recommended methodology, suitable for the performance of PSHA for seismic regulation of nuclear power plants and other critical facilities.
>
> *Requirements and Guidelines* (for the implementation guidelines and methodology):
>
> - Be able to provide probabilistic seismic hazard results in the form of fractile probabilities and mean values over a range of ground motion levels suitable for use in probabilistic seismic risk assessments for nuclear facilities.
> - Be defined in sufficient detail that, when independently applied by different organizations, no ambiguity exists on how the PSHA is to be performed and comparable results are obtained.
> - It is specifically not the objective of this program to advance PSHA methodology or to develop a new PSHA methodology. Rather, an important step in reaching the

objective of this program is expected to be the completion of evaluations of independent PSHA applications by LLNL and EPRI as well as other relevant applications.

- The outcome of this process will be the recommended methodology and implementation guidelines for PSHA in nuclear power plant licensing.

The emphasis on methodology for doing PSHA as the central theme is reflected in the title of the SSHAC report. The focus on siting nuclear facilities, though not emphasized explicitly in the report, strongly influenced its concentration on high-level PSHA.

It should be recognized that the charges to SSHAC and to the panel did not call for the defense or promotion of PSHA as a method for evaluating earthquake hazards. **SSHAC has produced a document that sets forth its conclusions and recommendations on the proper way to do a PSHA if that is the approach chosen by project developers and their analysts.** Neither the SSHAC report nor the panel evaluates the efficacy of PSHA relative to other methods, DSHA in particular. The SSHAC report does provide criteria that can be used to decide the appropriate level of effort for a specific study. Some of the issues related to alternatives to a full-blown PSHA and alternatives to SSHAC's recommended procedures are discussed elsewhere in this report.

The panel offers its appraisal of the SSHAC report, with primary emphasis on the scientific validity of the work and its conclusions, with appropriate attention to the clarity of the presentation, possible sources of misinterpretation, and the report's contributions to PSHA.

INTERACTIONS OF THE PANEL WITH SSHAC

The panel met with SSHAC three times (June 28-29, 1993; May 27-28, 1994; and December 9-10, 1994). Members of SSHAC, representatives of the three sponsoring organizations, and scientific and technical consultants to SSHAC attended the meetings. In addition, Thomas Hanks, a member of the panel, attended a number of SSHAC meetings as liaison observer.

By the nature of its charge, the panel was not able to begin its work until it received a draft product from SSHAC and could not finish its work until it had received the complete final SSHAC report. The June

1993 meeting was devoted primarily to briefings by agency representatives, SSHAC members, and scientific consultants, designed to educate the panel about the goals of SSHAC, the background of the problems being addressed, and the procedures SSHAC would follow. A spokesman for the USNRC explained that the agency wanted two products from SSHAC: (1) a set of guidelines for the process of seismic hazard assessment, and (2) a set of guidelines for the agency, using current data sets and computer codes, to reevaluate the hazards at existing sites. A SSHAC spokesman concluded that the central thrust of the project was to develop, justify, and illustrate methods for capturing both the inherent uncertainties in the parameters that go into an analysis and the disagreement among experts about the values of these parameters. At this time, the panel decided that it needed two additional members, one who could provide expertise in expert opinion analysis and decision science and one with extensive knowledge of both the deterministic and probabilistic approaches to seismic hazard assessment.

By May 1994 the focus of the SSHAC effort had changed, as noted above, from the reconciliation task to the more substantial and significant task of building on the lessons learned from prior experience in hazard assessment to develop scientifically sound procedures for doing PSHA. The SSHAC chairman explained that his committee's goal had been broadened to the development of a methodology that would be applicable not only to nuclear power plants but to other critical facilities as well. SSHAC members presented detailed technical briefings in their areas of expertise, so that the panel gained insight into the flavor of the report that SSHAC would produce. Vigorous discussions of both earth science and decision science issues provided a forum for the panel to explore details of the proposed SSHAC approaches and to convey in broad terms some concerns of the panel. Points raised in these discussions and the panel's evaluation of how SSHAC treated each are addressed elsewhere in this report.

The December 9-10, 1994, panel meeting was based on a detailed review of a draft report submitted by SSHAC. The draft was incomplete; in particular, the extensive appendixes, which on later examination proved to be essential and very valuable contributions of the SSHAC effort, were not available. But, the panel did conduct a detailed review of the main report. SSHAC members, as well as the agency representatives, were present for this review. The results of the review were submitted in the form of a formal letter report to the USNRC on March 16, 1995 (reproduced here as Appendix B). The USNRC forwarded this letter

report to SSHAC as part of its oversight of the final version of the SSHAC report.

The March 1995 letter report was the principal formal feedback from the panel to SSHAC. The letter report offered the panel's general comments on the SSHAC draft, a statement of concerns and problems, with suggestions for improvement, and a summary of specific scientific and technical concerns that the panel thought should be addressed. A draft of the final SSHAC report was sent to the panel on October 6, 1995. The present report is based on the panel's review of the October 6 draft, supplemented by several figures and parts of the appendixes that were submitted later. (Although the October 6 draft needed editing the panel was informed that the work of SSHAC was completed and that no further substantive changes in the SSHAC report would be made.)

The expectations of the sponsoring organizations are expressed succinctly in the last sentence of the *Sponsors' Perspective* that opens the SSHAC report, which is quoted at the beginning of this chapter. The panel has reviewed and evaluated the SSHAC report in light of these expectations and how well the goal has been achieved.

ORGANIZATION OF THE PANEL'S REPORT

The panel determined that the SSHAC report could be reviewed under four main headings: (1) process (elicitation and aggregation) and documentation, (2) the treatment of uncertainty, (3) seismic source characterization, and (4) ground motion estimation. The first two concentrate on the decision science components of PSHA, the latter two on the earth science inputs. Following a chapter on each of these, the panel offers a summary of its findings and recommendations.

2
Process and Documentation for a Probabilistic Seismic Hazard Analysis

By its own definition, the main emphasis of the Senior Seismic Hazard Analysis Committee's (SSHAC) report is on the procedural rather than the technical aspects of probabilistic seismic hazard analysis (PSHA). SSHAC argues that many of the major potential pitfalls of PSHA are procedural and therefore goes to great efforts to outline what it views as an appropriate process. In SSHAC's view the important aspects of "process" have to do primarily with experts, their interaction, and methods for translating their views into useful input for a PSHA. Of particular significance is the role assigned to the facilitation/integration team that organizes and directs a PSHA project and its use of experts. SSHAC lays out two basic principles underlying the PSHA process and its results:

1. Regardless of the scale of a PSHA study, the goal (as stated by SSHAC) is *"to represent the center, the body, and the range of technical interpretations that the larger technical community would have if they were to conduct the study."*
2. *"It is absolutely necessary that there be a clear definition of ownership of the inputs into the PSHA, and hence ownership of the results of the PSHA."*

The panel supports these principles as ideological guidelines for planning and executing a PSHA study, at least in the case of critical facilities. The first is, or should be, the goal of a sponsor in initiating a PSHA, the assumption being that using the collective input of the *informed* technical community would be the best, and most defensible, way of defining seismic hazard. That principle also has an enabling effect because, as discussed later, it allows experts to transcend the role of being proponents of models (the usual mode in scientific discourse) into the

roles of objective evaluators and integrators. **The extent to which this goal can reasonably be pursued in a particular case should depend on the scope and importance of the project and the resources available to support the study.**

The second principle is important because it assigns to an identified entity, the "owner," clear intellectual or scientific responsibility for the conduct and results of a PSHA. This does not necessarily mean that the "owner" agrees with every particular input or result but that the owner feels confident that the PSHA has fulfilled the purpose of representing the larger technical community and can be defended in scientific and regulatory arenas, as necessary. These principles underlie the primary recommendations of the SSHAC report that deal with the PSHA process.

LEVEL OF EFFORT IN A PSHA

SSHAC recognizes that a PSHA can be carried out at different levels of effort and emphasizes that the effort expended should match the importance of the facility, the degree of controversy, uncertainty, and complexity associated with the relevant scientific issues, and external decision factors, such as regulatory concerns and the resources available. This is shown in Table 2.1, taken from Chapter 3 of the SSHAC report.

Four levels of study are defined, the first three of which rely on a single entity called the technical integrator (TI), who is responsible for all aspects of the PSHA, including specifying the input. Although experts may be involved on a consulting basis, there is no formal elicitation of their views. The highest level of study (level 4) makes use of formally elicited expert judgment. As such, a new entity called the technical facilitator/integrator (TFI) is needed. The role of the TFI is discussed below. A large part of the SSHAC report is devoted to defining what is necessary to carry out a level 4 study and explaining the function of the TFI because the ideas are new, not because this level of effort is required for every seismic hazard assessment. **It would be inappropriate to infer that all PSHAs require the considerable resources needed to carry out the level 4 PSHA described by SSHAC.**[2]

[2]Nor does SSHAC make such a claim or inference. This statement is more a caveat to users than a criticism of SSHAC.

The Panel endorses the conceptual framework embodied in Table 2.1, recognizing that the application of PSHA to engineering and regulatory problems is varied and that the level of effort needed should also vary.

SSHAC points out that most site-specific studies make use of some type of TI approach. The TI performs analyses, accumulates information relevant to each issue, and develops a representation of the technical community's views on the relevant input models, parameters, and their uncertainties. At the lowest level of effort (level 1) the technical community's views are determined primarily by a literature search. At higher levels the TI makes use of outside technical researchers and proponents to gain insight into different data sets and models.

The panel emphasizes that a TI must still be guided by the principles of representation and ownership described above.

The importance of peer review is discussed below, but the panel stresses its particular significance when the TI mode is used. Reliance on a single entity (TI) to characterize the input of the whole technical community may be a very efficient mode of operation, but additional assurance is needed to provide confidence that the results are a reasonable representation of the community's views.

THE MULTIPLE ROLES OF EXPERTS

The TFI process views experts as acting in different roles—proponents, evaluators, and integrators. The proponent role is one in which the expert explains, and argues for, the choice of a particular model or set of parameters. The aim is to make sure that the different views in the technical community are presented and discussed by the expert panel. If necessary, individuals outside the expert panel may be brought in to argue points of view with which panel members may not be comfortable. The next role the experts are asked to assume is that of independent evaluators representing their own views of the information presented. Mean estimates of model, component, or parameter values are elicited, along with their uncertainties as appropriate. The result should be the group's composite views of the issues at hand. The experts are encouraged to evaluate their own and other models according to their own technical judgment, without regard to who originally proposed the models. In the past, most PSHAs that have relied on formally elicited expert judgment have strived to get experts to think in this manner. The hope was that the experts' composite view also represented the composite view of the technical community as a whole.

TABLE 2.1 Degrees of PSHA Issues and Levels of Study (Table 3-1 of the SSHAC Report)

Issue Degree	Decision Factors	Study Level
A **Non-controversial; and/or insignificant to hazard**	• **Regulatory concern** • **Resources available** • **Public perception**	**1** **TI evaluates/weights models based on literature review and experience; estimates community distribution**
B **Significant uncertainty and diversity; controversial; and complex**		**2** **TI interacts with proponents & resource experts to identify issues and interpretations; estimates community distribution**
C **Highly contentious; significant to hazard; and highly complex**		**3** **TI brings together proponents & resource experts for debate and interaction; TI focuses debate and evaluates alternative interpretations; estimates community distribution**
		4 **TFI organizes panel of experts to interpret and evaluate; focuses discussions; avoids inappropriate behavior on part of evaluators; draws picture of evaluators' estimate of the community's composite distribution; has ultimate responsibility for project**

To more truly represent the technical community's view, the SSHAC report recommends that the experts be specifically asked to assume the role of integrators and to characterize their perception of how the *technical community as a whole* would view the issues at hand. Thus, although the expert may view his/her assessment as being the most correct, he/she is explicitly thrust into the role of trying to fulfill the first principle of PSHA as outlined above and must be willing to do so. This mode of expert behavior may not be achievable in all issues. Also, **the**

panel is not aware of any objective way to test the assumption that a whole technical community's views can be accurately determined from the interactions of a small group of experts.

SSHAC introduces some useful concepts in its discussion of the interaction among experts. One is that in the process of eliciting, aggregating, evaluating, and integrating the opinions of experts the TFI (discussed in the next section) should create an atmosphere in which there will not be "winners" and "losers." Another useful idea is the avoidance of unintended dissent or consensus. Apparent disagreement may arise because of lack of communication and understanding among those disagreeing; the process of "active listening," in which a listener is asked to give back what he/she has just heard, is a step toward eliminating disagreement where it really does not exist. At the other extreme is the development of an apparent but false consensus; the TFI should strive for consensus among the experts only if it is really agreed on.

The panel views the role of expert as integrator as important and worthwhile. However, successful implementation of the integrator role of the experts should be viewed more as a goal to strive for than a uniformly and demonstrably achieved measure of success.

The SSHAC report implies four basic criteria for the identification and selection of experts: (1) technical expertise, (2) strong communication skills, (3) willingness to assume the role of independent evaluator, and (4) willingness to commit the time and effort to participate actively in the study. The choice of disciplines to be represented and the breadth of knowledge of each expert depend on the issues to be addressed and whether or not interdisciplinary subgroups of experts will be formed to provide input. SSHAC also strongly recommends a formal nomination process based on consulting the literature and asking technical societies, government organizations, and knowledgeable individuals to submit the names of potential experts. **Whatever the issue or structure of elicitation, the panel believes that the credibility and quality of an elicitation-based PSHA depend very much on the choice of experts. The panel supports the need for careful attention to the selection process and finds the criteria suggested by SSHAC to be reasonable and likely to be effective.**

TECHNICAL FACILITATOR/INTEGRATOR

One of SSHAC's main contributions to PSHA methodology is the introduction of the technical facilitator/integrator (TFI) concept. The SSHAC report describes this new function in Section 3.3.1 as follows:

> The TFI is a single entity who has the responsibility and is empowered to represent the composite state of information regarding a technical issue of the scientific community.... The TFI process is centered on the precept of thorough and well-documented expert interaction as the principal mechanism for integration.

As SSHAC acknowledges, a major stimulus for its charge was the need to resolve the differences in hazard estimates between the Lawrence Livermore National Laboratory and the Electric Power Research Institute studies. SSHAC's investigation revealed that the process of elicitation and the procedures for integration allowed room for considerable misunderstanding and potential misinterpretation. Six areas in which improvements could lead to a better outcome are detailed in Section 3.3.2.2 of the SSHAC report:

1. Overly diffused responsibility
2. Insufficient face-to-face expert interaction
3. Inflexible aggregation schemes
4. Imprecise or overly narrow objectives
5. Outlier experts
6. Insufficient feedback

The TFI concept was designed to resolve these procedural issues. This approach is described in detail in Chapters 3 through 5 and Appendix J of the SSHAC report. **The panel concurs that, in cases in which decisions about a critical facility of major complexity depend on controversial and uncertain inputs, the TFI approach offers an effective mechanism for capturing the best of what is known about the particular issues.**

The Proposed TFI Process

The seven steps proposed by SSHAC for the TFI approach (Section 3.3.4) were first suggested by Keeney and von Winterfeldt (1991), based on their experience in eliciting expert judgment for probabilistic risk assessment of nuclear power plants. The steps are:

1. Identification and selection of technical issues
2. Identification and selection of experts
3. Discussion and refinement of technical issues
4. Training for elicitation
5. Group interaction and individual elicitation
6. Analysis, aggregation, and resolution of disagreements
7. Documentation and communication

A flow chart of the process as applied to ground motion elicitation by SSHAC is reproduced here as Figure 2.1. Appendix J of the SSHAC report spells out the background, evolution, and details of the TFI process as developed by SSHAC. Appendix J must be read carefully; readers may need to consult additional references in order to fully understand some of the issues discussed, such as the weighting of individual expert inputs.

The TFI process requires careful and time-consuming setup procedures to ensure that all participants are clear on the objectives of the study, their roles in the study, and the intended results. The TFI (an individual or, perhaps, a team of two or three people) must be highly competent in the relevant subject areas, adept at elicitation and group process, and thorough. Because a strong TFI will have a major influence on the outcome of the elicitation/aggregation process, **it is essential that, if more than one TFI is assigned to work on a particular analysis project, they all be equally well qualified.**

The panel concludes that for appropriate issues the TFI process holds significant promise for PSHA. This process was developed by SSHAC as part of its effort to overcome limitations of previous PSHA studies. The panel cautions, however, that this process is expensive, time consuming, and demanding of all participants. SSHAC's criteria for identifying the issues for which the full TFI process is justified (Table 2.1) must be understood by project sponsors and their analysts.

As discussed in the next chapter, each element of a seismic hazard analysis may involve high degrees of uncertainty. Many situations arise in

which competent experts may legitimately disagree in their interpretation of extant data and theory. In view of the complexity of the issues and models involved in PSHA, SSHAC concluded that an improvement in the process of elicitation would help focus attention on the technical issues by reducing previously observed problems in "consensus," unintended agreement, and unintended disagreement.

At each step of the elicitation process, the TFI strives for complete understanding by each expert of all technical issues. The goal is that all experts are "on the same page." The results of two ground motion workshops conducted by SSHAC and documented in Appendixes A and B of its report indicate that investment in the TFI process bore substantial results.

The panel is aware that the TFI process, as implemented in these workshops, has rarely been used in the earth sciences. An example of the application of the process in a related subject field is provided by a probabilistic volcanic hazards analysis (Coppersmith et al., 1995).

TREATMENT OF EXPERT INPUT

Integration of Expert Opinion

SSHAC correctly points out that in theory it is always possible to formulate the expert integration problem as a Bayesian inference problem in which the opinions rendered by the experts are viewed as "noisy observations" of the quantities of interest (e.g., parameter values, distributions). Difficulties lie in the formulation of an "observation model" tailored to each expert combination task and sometimes in implementing the Bayesian analysis to produce *a posteriori* uncertainties. A discussion of combination problems and models is given in Appendix J of the SSHAC report. SSHAC repeatedly warns against blindly using any specific model and stresses that the models described in Appendix J are only examples for illustration. The panel agrees with these warnings and adds the following comments:

- In essence, Appendix J presents two very different types of models: (1) the so-called classical models, which emphasize the "noisy observation" interpretation of expert opinion, and (2) the TFI model, which regards each expert as being potentially correct, with a probability

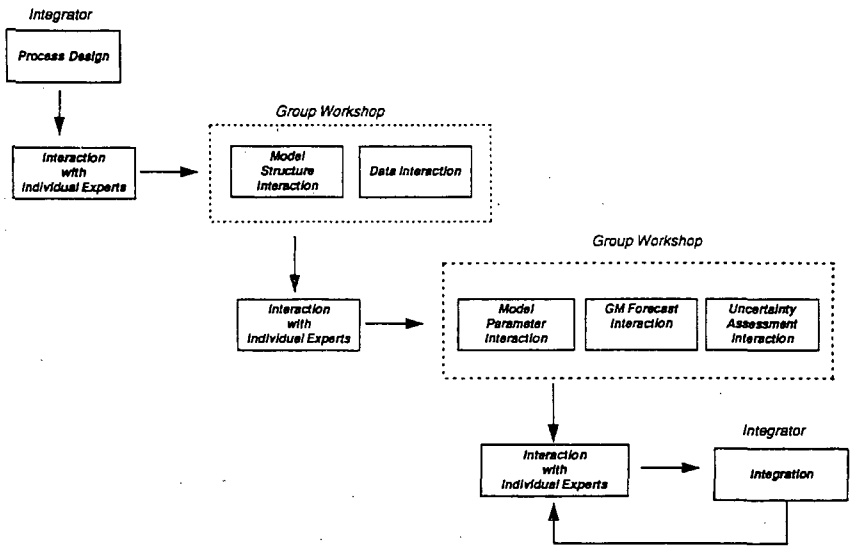

FIGURE 2.1 Roadmap of ground motion elicitation process (Figure 5-5 of the SSHAC report).

proportional to an assigned weight. Although this interpretation of the TFI model is not given in the SSHAC report, the fact that the community distribution is defined as a weighted sum of the expert distributions is equivalent to saying that each expert is correct with a probability equal to his/her assigned weight. At the end of Appendix J, the two approaches are compared numerically and shown to produce very different results. Without an in-depth discussion of when each type of model (or neither) is applicable, Appendix J may leave the reader confused. The classical models combine distribution functions with the meaning of uncertainty on the value of an unknown parameter. Hence, in this case the object of estimation is an unknown *scalar quantity* and the distributions express uncertainty on that quantity according to different experts. The TFI model, on the other hand, combines distribution functions that express the state of uncertainty of the scientific community according to different experts. In this second case the object of estimation is the *distribution function* itself. Therefore, while the inputs to, and results from, both

models are in the form of probability distributions, such distributions have different meanings in the two cases and should not be compared.

- The community distribution, which the TFI model estimates, is defined in Appendix J, Section 5, of the SSHAC report as "the mixture of the distributions of the individual experts if [the decision maker] believed that the experts . . . in this 'perfect community' were effectively equally informed on the issue of interest and equally interdependent. . . ." **As the entire SSHAC procedure revolves around this distribution, the panel believes that its definition should have been given in the main report, with a detailed explanation and justification.**
- SSHAC gives expressions for the mean and variance of the community distribution after stages 1 and 2 of the TFI process. Given the approximate nature of the results for the variance and the fact that distributions, not just mean values and variances, are needed, a much simpler and basically as accurate combination rule would be to take the weighted average of the distributions provided by the experts. The statement in Appendix J that "determination of the predictive (i.e., *a posteriori*) distribution follows a straightforward but cumbersome Bayesian statistical analysis" indicates that SSHAC knows how to perform a fully nonparametric Bayesian estimation of the community distribution function. This panel could think of no straightforward procedure to do so (one would need to consider the expert distribution estimates as random processes given the true community distribution function, with serious practical and conceptual implications). Because determination of community distribution and its uncertainty is at the core of the SSHAC approach, the report should have been more explicit about such a procedure.
- SSHAC favors an equal weighting integration scheme, unless there are clear indications that different weights should be used, for example, to reduce the influence of outliers. Linear combination rules with equal (unequal if necessary) weights are applied to parameter estimates (classical models) as well as to the probability distributions that, according to the panel of experts, quantify uncertainty in the scientific community (TFI model). Conditions for "equal weights" are set forth in the report. The panel believes that there may be some confusion about linear combination with equal weights and symmetrical (but possibly nonlinear) treatment of the expert assessments. The conditions quoted in the SSHAC report apparently lead to symmetrical treatment, not necessarily to averaging. There is a brief reference to nonlinear

combination rules in the section on nonequal weights in Appendix J, with little discussion. Analysts are advised to verify whether the conditions of linearity and normality of the observation model apply before using a linear combination rule. Contrary to what SSHAC states (e.g., Figure J-6), in some cases it would be better to combine the parameters of the distributions provided by the experts rather than the distributions themselves (combining the parameters results in a *nonlinear* combination of the distributions.) For example, if the experts agree on all distribution characteristics except for a location parameter, combining the estimated locations would be the right thing to do.

In view of these limitations and the objective difficulties in properly combining expert opinions, the panel recommends the following:

1. Use the models in Appendix J of the SSHAC report for reference, not as prescriptive or even recommended combination procedures.

2. Do not accept the results of a mechanical combination rule unless they are consistent with judgment.

3. If a mechanical combination rule is used, a general way by which to derive that rule is to view experts as noisy observers of the quantity being estimated. This approach is always the correct one from a Bayesian viewpoint, irrespective of the problem at hand. What differs in different cases is the nature of the observation errors, which need not necessarily be normal, additive, or independent.

4. When combining expert opinions on distribution functions, the correct Bayesian approach requires the use of a random process formalism, unless the problem can be reduced to a discrete one through appropriate parameterization. In all but the simplest cases a formal analysis becomes prohibitive, and the panel recommends primary reliance on judgmental combination procedures.

Weighting

One of the more problematic aspects of PSHA has always been the aggregation of input from different experts, especially when one or more expert opinions are outliers relative to the views of the rest of the

participants. This problem has led to consideration of weighting of different experts' opinions based on quantitative or qualitative assessments of the degree of expertise (typically a highly subjective exercise). The extensive interactive education and elicitation process proposed by SSHAC is intended to bring all expert participants to parity. This process should make it more reasonable to use equal weighting of all the experts. Appendix B of the SSHAC report states that equal weights were used for the combination of expert opinions and concludes that the TFI "integration process is robust."

The panel concurs that equal weighting of experts should be the clearly preferred target in a multiple-expert PSHA. To achieve this, proper choice of experts and group interactions should be emphasized, as outlined in Chapter 4 and Appendix H of the SSHAC report. In the case in which a different weighting scheme is applied, the burden of proof rests with the TFI; nevertheless, every effort should be made to obtain expert concurrence on the weights used or modification applied.

Dependency Among Experts

A related aggregation problem, dependency among experts, is, on the surface, exacerbated by the TFI process. The overall community is composed of a finite number of experts who rely on a finite number of models and methodologies. While one or more of the participating experts may not be thoroughly familiar with the entire range of such models and methodologies at the beginning of the exercise, such familiarity is an objective of the TFI process. As shown in the second SSHAC ground motion workshop, this interactive process narrowed the range of estimates as the experts increased their knowledge and understanding of issues and methods. One goal of a well-executed TFI process is that all participating experts are better able to make informed independent judgments.

Peer Review

SSHAC requires that peer review be an integral part of the PSHA process. The panel concurs. SSHAC defines two types of review: (1) participatory and (2) late stage. Participatory peer review involves "full

and frequent access throughout the entire project" by the reviewers. The advantage of a participatory review is the opportunity to subject interim results and deliberations to independent feedback. This provides the PSHA team with an opportunity for adjustment and limits the possibility that a lengthy and costly effort might be found to have serious flaws in the end. SSHAC recognizes that a limitation of participatory peer review is that "peer reviewers might lose their objectivity as they interact with the project over time." The panel views a participatory peer review as equivalent to a backup group of experts who provide oversight of the work of the primary team. **Safeguards must be established to preserve the objectivity of the review process.** As explained in the introduction to this report, this panel was asked to provide participatory peer review to SSHAC, and the panel insisted on a process by which it would not become so deeply involved in the preparation of its report that its objectivity would be compromised. The panel believes that this is also a necessary precaution for peer review of any PSHA study.

The late-stage review is closer to the traditional academic review in that it occurs near the end of a project. SSHAC strongly recommends participatory peer review on the grounds that a late-stage review can be risky, especially with regard to the process aspects of a PSHA study. Table 3-2 in the SSHAC report summarizes its recommendations on how to structure the peer review process.

The panel concludes that participatory review, as part of a PSHA process, would serve to improve the quality of a study insofar as it is another step toward incorporating the views of the broad informed scientific community. Other considerations—for example, the requirements of regulatory bodies—might call for a late-stage review also.

Documentation

Chapter 7 of the SSHAC report puts much emphasis on the importance of fully documenting every PSHA study. The guidelines on documentation are intended to ensure that each step of the PSHA process is not only completely recorded but also that the records are stored in accessible formats that permit the technical community to review all operations and decisions. This documentation also greatly facilitates later reanalysis and update as new information becomes available, perhaps eliminating the necessity of redoing the entire PSHA.

The panel believes that the calculated seismic hazard derived from each individual expert's input needs to be presented. It is not clear whether this is included in SSHAC's recommendations. Regardless of how the aggregation is carried out, it is important to be able to compare results caused by each expert's input with those of the composite produced by aggregating the individual inputs. This comparison provides users with a good indicator of the diversity of input and its impact on the final calculations, as discussed in Chapter 3.

SSHAC proposes that this documentation follow a two-tiered approach that is to be applied to every element of a PSHA. Tier 1 documentation is defined as all documentation that must be published as part of the main report or its appendixes, so that it is widely accessible. Simply stated, tier 2 is everything else that constitutes background material for the analysis. SSHAC's prescription for what materials should go into the two tiers is spelled out for each of the elements of a PSHA (i.e., seismic source characterization, ground motion attenuation, and the methods used to produce the PSHA results).

The SSHAC report specifically states that the computer software used should be identified and archived. This would include any relevant programs and code that would be necessary for an independent analyst to replicate the study. Should problems be identified later with either the computer code or the input data, reanalysis is greatly facilitated. **The panel recommends that specialized computer programs needed to implement the SSHAC procedures be readily accessible to any group that wants to engage in seismic hazard evaluation as part of a research program or business venture.** The availability of these programs becomes especially important if the procedures recommended by SSHAC are so successful that they become the standard adopted by governmental regulatory bodies and the major engineering concerns of the nation.

To facilitate the accurate and timely documentation of PSHA projects, **the panel recommends that an individual or small team be designated as the Project Archivist and that a documentation plan be in place at the beginning of each project.** The thoroughness and complexity of the SSHAC approach, especially when the TFI is used, require that all participants have ready access at any time to materials generated previously. This implies a documentation process that keeps current with the rest of the project.

The panel concludes that the discussion of the documentation process in Chapter 7 of the SSHAC report provides thorough and useful guidance for numerous other applications in addition to seismic hazard assessment. **Documentation is not one of the more glamorous aspects of the scientific enterprise, but it is essential to the full realization of the benefits of the large investment in data acquisition, analysis, and interpretation that are characteristic of large projects.**

3
Treatment of Uncertainty

A fundamental aspect of the Senior Seismic Hazard Analysis Committee's (SSHAC) methodology is the distinct and separate treatment of aleatory and epistemic uncertainty. Throughout its report, SSHAC emphasizes the need to distinguish between these two types of uncertainty, the quantifications of their contributing sources, and the propagation and full display of the epistemic component to users (see, e.g., Sections 1.8 and 1.9). SSHAC deals with techniques to assess, elicit, combine, propagate, document, and display epistemic uncertainty, and it is clear that much if not most of the effort in any probabilistic seismic hazard analysis (PSHA) conducted according to SSHAC's recommendations would have to be expended in activities related to the handling of uncertainty.

The two fundamental types of uncertainty are defined by SSHAC as:

- Epistemic: the uncertainty attributable to incomplete knowledge about a phenomenon that affects our ability to model it.
- Aleatory: the uncertainty inherent in a nondeterministic (stochastic, random) phenomenon.

Epistemic uncertainty may be reduced with time as more data are collected and more research is completed. Aleatory uncertainty, on the other hand, cannot be reduced by further study, as it expresses the inherent variability of a phenomenon.

Making a rigorous separation between aleatory and epistemic uncertainty, as advocated by SSHAC, requires a level of effort and expertise much greater than that for most PSHA efforts. Therefore, the panel thinks it is appropriate to elaborate as to when and why such classification may be needed and indeed whether it is appropriate (these

issues are not addressed directly by SSHAC). In this regard, it is useful to consider separately two questions:

1. Is the aleatory/epistemic classification unique and clear?
2. Why is a separate treatment of epistemic and aleatory uncertainty needed and to what degree should it be pursued in a PSHA analysis?

Embedded in the second question are issues of utilization of results in which epistemic uncertainty and aleatory uncertainty are separated (i.e., of results stated in a "probability of frequency" format), either in the process of conducting the PSHA study or in the process of decision making by the ultimate user. In this chapter the panel briefly reviews SSHAC's position on these issues and makes some recommendations.

IS THE ALEATORY/EPISTEMIC DISTINCTION UNIQUE AND CLEAR?

SSHAC correctly points out that the classification of uncertainty as epistemic or aleatory depends on the model used to represent seismicity and ground motion. For example, epistemic uncertainty would be much greater if, in the assessment of seismic hazard at an eastern U.S. site, instead of representing random seismicity through homogeneous Poisson sources one used a model with an uncertain number of faults, each with an uncertain location, orientation, extent, state of stress, distribution of asperities, and so forth. As little is known about such faults, the total uncertainty about future seismicity and the calculated mean hazard curves would be about the same, irrespective of which model is used. However, the amount of epistemic uncertainty would be markedly different; it would be much greater for the more detailed, fault-based model. Consequently, the fractile hazard curves that represent epistemic uncertainty would also differ greatly.

A reasonable interpretation of the probabilistic models used in seismic hazard analysis is that they represent not intrinsic randomness but uncertainty on the part of the analyst about the actual states and laws of nature—for example, about the number of earthquakes of magnitude 6 to 7 that will occur in the next 50 years in a given crust volume. According

to this interpretation, all or most of the uncertainty in PSHA is due to ignorance. In certain cases, uncertainty due to ignorance may be expressed numerically by long-term relative frequencies. For example, with a very long record of seismicity, one could extract the long-term relative frequency with which earthquakes of magnitude 6 to 7 occur in a generic 50-year period. In the absence of other relevant information, it is reasonable to use this long-term relative frequency as a measure of epistemic uncertainty about the occurrence of the event in the next 50 years. Note that as interest in PSHA is typically in the occurrence of rare events in the near future and because the occurrence of such events depends to a large extent on the current physical conditions of the earth's crust near the site, ignorance or epistemic interpretation of the occurrence probability is more appropriate than the long-term relative frequency or aleatory interpretation. In certain parts of its report, SSHAC concedes that in reality there may be just one type of uncertainty. For example, Section 2.2.3 reads, in part:

> . . . Even though we have discussed probabilities appearing in the model of the world and the epistemic model, and we have given them different names, leading philosophers of science and uncertainty (e.g. de Finetti 1974; de Groot 1988) believe that, conceptually, there is only one kind of uncertainty; namely, that which stems from lack of knowledge.

Other statements support this position. For example, Section 2.2.6 states that ". . . the different terminology [aleatory versus epistemic] is not intended to imply that these uncertainties are of fundamentally different nature." Similarly, Section 1.8 points out that in the context of seismic hazard analysis, "the division between the two different types of uncertainty, epistemic and aleatory, is somewhat arbitrary." **The panel concludes that, unless one accepts that all uncertainty is fundamentally epistemic, the classification of PSHA uncertainty as aleatory or epistemic is ambiguous.**

Reference to a particular class of seismicity models (e.g., the models described in Sections 2.1 and Chapter 4 of the SSHAC report) produces some stability in the epistemic/aleatory distinction. However, if such distinction is to have any impact on the decisions, the basis for choosing any particular model type should be made clear, as alternative

and equally valid choices would lead to different decisions. In view of this undesirable dependence of epistemic uncertainty on the models selected for PSHA, one may question whether the epistemic/aleatory uncertainty decomposition is actually called for in a PSHA study and the extent to which it is needed for decision making by the users. These questions are addressed in the following section.

IS THE EPISTEMIC/ALEATORY SEPARATION NEEDED?

SSHAC does not provide a clear rationale for the need to separate aleatory uncertainty from epistemic uncertainty, although the report refers to several uses of this separation. Sections 2.2.5 and 2.2.6 of the report cite facilitated communication of results, discipline on the part of the analyst, and completeness of results. A "theoretical foundation" for the aleatory/epistemic distinction is offered in Section 2.2.6 by quoting a result by de Finetti in probability theory that shows how to combine epistemic and aleatory uncertainty to quantify total uncertainty for a particular (the binomial) model. However, the same result indicates neither how to separate the two uncertainties in practice (this is acknowledged by SSHAC) nor how to make decisions considering epistemic uncertainty. Therefore, the panel finds reference to de Finetti's result not relevant to whether or why the aleatory/epistemic distinction is necessary.

Reference to the decision-making implications of the epistemic/aleatory character of the uncertainty is made at the end of SSHAC's Appendix F, where it is stated that: "because epistemic and aleatory uncertainties are treated differently in making design and retrofit decisions, and because the median hazard is sometimes the preferred central measure of hazard due to its stability, it is also important to allocate uncertainties in the proper category." While it is true that the median curve is often preferred to the mean curve, a clear rationale for this practice or, more generally, a procedure for dealing with epistemic uncertainty in decision making is not presented in the SSHAC report. Finally, in Section 7.6 reference is made to the need for multiple hazard curves in the context of probabilistic risk assessment studies.

It is not the purpose of this discussion to analyze in detail each of the reasons for quantifying epistemic uncertainty. However, the panel observes that different uncertainty representations are appropriate for

different applications. To add focus to this discussion, we consider and contrast three main uses of quantified epistemic uncertainty in PSHA:

1. In the *elicitation and experts/model combination process*, quantitative estimates of epistemic uncertainty are used to characterize the credibility of alternative hypotheses and models, to assess the statistical variability of parameters, and to communicate this information among the experts and between the experts and the TFI.
2. In the course of a properly conducted analysis, the effect of epistemic uncertainty on the final hazard is used to *assess the relative importance of different models* (e.g., of the seismicity model versus the ground motion model) *and parameters* and to guide the analyst in seeking further information (data, expert opinion, etc.) to reduce uncertainty in the most cost-effective way.
3. A project's sponsor typically accounts for uncertainty in a hazard when *making decisions* (e.g., about the design of a new facility or the retrofitting of an existing one).

For ease of reference, we label these three phases of uncertainty consideration as the elicitation/combination phase, the PSHA planning phase, and the final utilization phase. Different needs for uncertainty representation characterize these phases.

In the *elicitation/combination phase*, experts need to be aware of all pertinent sources of uncertainty, including parameter and model uncertainties and their correlations, and the limitations and errors of the available data, so that they can make an informed assessment of the validity of alternative hypotheses, the accuracy of alternative models, and the value of data and can convey such uncertainties to the TI/TFI. **The panel finds the type of epistemic uncertainty analysis recommended by SSHAC to be most useful at this stage of a PSHA study.**

In the *PSHA planning phase* (which refers to resource allocation for the purpose of maximizing the reduction of uncertainty on the final hazard results), there is no need for a detailed analysis of uncertainty. In fact, such analysis is usually not available when the PSHA effort is structured. **For this purpose it may be sufficient to conduct limited sensitivity analyses, using bounding hypotheses, and to consider the level of effort that would be required to substantially reduce each component of uncertainty.**

The final *utilization phase* is critically important and arguably the one phase that should drive the level of uncertainty analysis and mode of uncertainty representation in a properly conducted PSHA. SSHAC's position is that the final results of a study should represent the epistemic uncertainty of the informed scientific community. This is roughly defined by SSHAC as the average of the uncertainties of the experts that make up the community (possibly weighted according to their degree of expertise, their outlier status, etc.).

A fundamental problem with this way of presenting the final results is that, as previously noted, the epistemic uncertainty in the hazard depends on which among many legitimate models one uses—for example, a deterministic or stochastic model of earthquake occurrence. What changes with the model is not the mean hazard but the amount of epistemic uncertainty and, therefore, all the fractile hazard curves—including the median. Therefore, any decision that is based on the fractile curves rather than the mean curve depends on the essentially arbitrary choice of how much epistemic uncertainty is included in the seismicity and ground motion models. This well-known fact has often been taken to mean that the only admissible decision rules are those based on the mean hazard and that other decision rules are wrong and should be excluded. In fact, this is not quite correct. As the study by Veneziano (1995) quoted in the SSHAC report shows:

1. If the mean hazard can be assumed to remain constant over the lifetime of the project (e.g., because only a small amount of relevant new information is expected to become available in the near future), decisions should be based exclusively on the present mean hazard.
2. On the other hand, if the mean hazard cannot be assumed to remain constant over the lifetime of the project, decisions should depend on possible future fluctuations of the mean hazard (Veneziano, 1995, p. 121).

These results show why the common practice of using mean probabilities is appropriate in certain cases but also explain why in other cases one should act conservatively. Notice that **the distinction does not depend on the total amount of current epistemic uncertainty but on the amount of total uncertainty that might be explained in the future and thus might cause the mean hazard to fluctuate.**

This is consistent with intuition. As a classic example of the irrelevance to decision making of the aleatory/epistemic classification, the betting attitude of a rational individual on the outcome of a coin flip should not change from before flipping, when all the uncertainty is aleatory, to after flipping (but before the outcome is revealed), when the same total amount of uncertainty is epistemic. On the other hand, the importance of temporal fluctuations of a mean hazard may be illustrated by considering the retrofitting problem, which occurs when, at some time after completion of a project, the estimated mean hazard changes and exceeds a regulatory limit. The reason why future volatility of the mean hazard should in this case affect present decisions is that the utility of each decision depends in an asymmetric way on future positive and negative changes in the mean hazard: large penalties are associated with retrofitting if the mean hazard increases, whereas only modest gains may result from future reductions in the mean hazard. The decision maker should consider the potential future volatility of the mean hazard and include it in his/her deliberations.

In the future, fundamental advances in PSHA may come from adopting this time-dependent view of earthquake safety decisions. However, explicit quantification of future volatility of a mean hazard would require a level of analysis even more sophisticated than that proposed by SSHAC, and the panel does not advocate such an extension at the present time, even for critical facilities.

Short of explicitly quantifying the future variability of the mean hazard, what could be done to provide the decision maker with a useful representation of epistemic uncertainty? One possibility, but certainly not the only one, is to calculate the mean hazard according to the uncertainty of each participating expert, when that expert acts as an evaluator (not integrator) of alternative models, data sets, etc. **To the degree that the beliefs held now by different members of the scientific community reflect possible future fluctuations in the overall community mean hazard, this should be useful input to the decision maker.** For example, this information would allow the decision maker to see how the decision he/she must make would vary if different experts in the informed scientific community had to make that same decision. Notice that the hazard curves derived from each expert do not suffer from the limitations of the fractile curves observed earlier; each of them is a mean hazard curve and therefore is insensitive to the choice of model type used by the expert.

Some observations should be made on presenting the final hazard results through the community mean hazard and the interexpert variability in the mean hazard, as just described:

1. One might argue that full epistemic uncertainty quantification is needed anyway, to calculate the mean hazard of the community and the mean hazard of the individual experts. However, this is true only in theory, as it is clear that different amounts of information are needed to estimate with confidence the mean value of a random variable, as opposed to its complete distribution. For example, the use of best estimates for recurrence and ground motion models often leads to hazard values that are close to the mean hazards obtained by considering a large number of alternative models. Moreover, there is no need when calculating the mean hazard to label accurately each component of uncertainty as epistemic or aleatory, provided that the total uncertainty is accounted for. Therefore, the elaborate machinery needed to carefully separate uncertainties of different types is no longer needed.
2. Much emphasis is given in the SSHAC report to intensive interaction among experts, discussion of alternative models, and exclusion or downweighting of outliers. These are all appropriate and remain valid under the format proposed here. **In essence, what changes is that the TFI quantifies not the total uncertainty of the scientific community, as done in the SSHAC approach, but the variability of the mean hazard according to the experts that make up that community.** In so doing, weights can be applied and outliers can be removed for the same reasons and in the same way as discussed by SSHAC.
3. The multiple interpretations, models, and model parameters at the basis of the elicitation process are not "lost." They remain part of the documentation of the PSHA study and should be made available to interested users. The panel anticipates that users will primarily be technical experts—for example, in the context of a regulatory review or an update of a PSHA study. However, that information should, for the most part, be irrelevant to the decision maker.

As observed previously, the correct way to represent epistemic uncertainty for decision making would be through the uncertain fluctuations of the mean hazard in future assessments. The expert-to-expert variability of the mean hazard at the time of the analysis is only a surrogate for this variability and is not entirely satisfactory because using

it this way implies that, during the time interval of interest, new evidence and knowledge may end up "proving right" one member of the present group of experts. While this may not be a valid assumption, documentation of the expert-to-expert variability in the mean hazard may be preferable to the full display of epistemic uncertainty proposed by SSHAC.

4
Seismic Source Characterization

Chapter 4 of the Senior Seismic Hazard Analysis Committee's (SSHAC) report, entitled "Methodology for Characterizing Seismic Sources," describes the key elements of a seismic source characterization (SSC): the seismic source requirements for a probabilistic seismic hazard analysis (PSHA), the uncertainties in seismic source characterization, and guidance on expert elicitation for seismic source description. The chapter presents a good description of the state of practice for SSC in a PSHA, as shaped chiefly by guidance on methodology from the seismic hazard programs of the Lawrence Livermore National Laboratory and the Electric Power Research Institute (EPRI), as well as from other PSHA exercises modeled on those programs, for many other critical facilities. In the panel's judgment, **practitioners of PSHA should be aware of and free to use other valid approaches to SSC.**

SCIENTIFIC VALIDITY AND CLARITY OF PRESENTATION

A primary concern of the panel is the overall scientific validity of the procedures recommended by SSHAC. The basic methodology for SSC described in the SSHAC report has been validated by extensive peer review of prior projects in which such a methodology was used. The SSHAC report correctly states that a seismic source is a construct developed for seismic hazard analysis as a means of approximating the locations of earthquake occurrences. Insofar as SSC involves a simplified representation of real-world complexity, the validity of the simplifications is always an issue. Such validity is generally tested as part of sensitivity analyses, which are an essential part of a PSHA, as correctly advocated in SSHAC's report. With regard to modeling real-world complexity, the

classification of seismic source types (Section 4.2) is nonunique, and the categories described in the report are admitted to be arbitrary. Nevertheless, they provide a useful framework for discussion and guidance on methodology.

The practitioner experienced in PSHA will have no trouble understanding SSHAC's Chapter 4. However, the nonpractioner scientist may be confused by the subtleties between differing concepts of a "seismic source" presented in chapters 4 and 5. Chapter 4 describes a seismic source as a geologic structure or as a domain within which the spatial and temporal occurrences of earthquakes are approximately uniformly distributed. Chapter 5, on ground motion, describes seismic source basically as a dynamic excitation in the earth that causes ground motion at the surface.

Readers of the SSHAC report should be aware that two different terms, upper-bound and maximum magnitude, and two symbols, m_u and M_{max}, are used Section 2.1 and in Chapter 4 to denote the largest-magnitude earthquake that a particular seismic source is capable of producing. This magnitude is the upper bound of the frequency of occurrence magnitude curve used in the analysis. A value for this parameter must be specified in order to carry out the integration over all relevant magnitudes when calculating seismic hazard. The problems encountered and conventional procedures used in the selection of M_{max} (m_u) and the specification of the substantial epistemic uncertainty often associated with it are discussed in Sections 4.2.2 and 4.3.2 of the SSHAC report.

If one accepts the basic formalism of uncertainty analysis presented in Section 2.2 of the SSHAC report, the approaches for characterizing uncertainties in SSC (Section 4.3) will seem logically consistent and well established in practice. Similarly, the guidance described in Section 4.4 for the expert elicitation process follows one's acceptance of the decision science methodology laid out in Chapter 3.

A notable gap in Chapter 4 of the SSHAC report is the absence of discussion on and guidance for earthquake catalogs. In Section 4.4 the technical facilitator/integrator (TFI) or the technical integrator (TI) is given responsibility for providing a comprehensive and uniform data base to the experts for use in the PSHA. The only guidance given, under the subheading "Area Sources" in Section 4.2.3, is the recommendation that "seismicity catalogs should be reviewed for uniformity in designation of magnitudes and for completeness as a function of magnitude, location,

and time. The association of older historical events with particular seismic sources should be assessed bearing in mind the location uncertainties."

Earthquake catalogs can play a major, even dominating, role in determining the outcome of a PSHA, particularly in the central and eastern United States, where information on active faults and other geologic structures is generally lacking. There are many problems hidden in earthquake catalogs that need be sought out and identified. There may be improper or mistaken entries, particularly for historic earthquakes. In many cases, locations and sizes were assigned to historic earthquakes based on inadequate or incomplete information. Unfortunately, modern earthquake catalogs often do not indicate which events have been critically reexamined and which have been carried forward without question from original catalog compilations.

Uniformity of the data with time is also variable even in times of instrumental monitoring. Changes in network configurations and sensitivity and changes in the procedures for computing event magnitudes reported in earthquake catalogs (often not documented in an easily available form) should be sought out and carefully considered in a PSHA. Tests are available for identifying time-varying systematic shifts in reported magnitudes. Declustering or decomposing earthquake catalogs into main and secondary events (foreshocks, aftershocks, swarm events) is a nontrivial procedure that also requires careful attention.

Recognizing that earthquake recurrence relationships based on seismicity depend critically on factors such as those described above, EPRI undertook major efforts to address these and other earthquake data base issues, which are still of great importance in PSHA—both in principle and in continuing practice. **Those who utilize the SSHAC procedures should be aware of these requirements for preparation of their earthquake catalog for PSHA. To the panel's knowledge, a comprehensive study of the effects of systematic changes in earthquake catalogs on the results of a PSHA has not been done.**

Most of Chapter 4 of the SSHAC report is well organized and well written, and the presentation should be easy for general readers to follow. The text refers to Appendixes H and I, each of which provides some ancillary pertinent material. Appendix H describes the results of a workshop on expert elicitation of seismic source (zone) information, while Appendix I describes effects of a nonuniform spatial distribution of seismicity in a seismic source (zone). Both of these appendixes are informative.

The table in Section 4.2.1 is important for guidance, but it is confusing. The lines beginning with "Faults" and "No faults" should be understood to be "if" statements, recognizing "fault" to mean a "Type 1 seismic source" (i.e., "If no Type 1 fault source within 50 km of a site, then . . .").

Because the SSHAC report is intended for general PSHA guidance, the following question arises: Is the EQPARAM code (which is introduced as an important element of the methodology in Section 4.3.5) readily available or is it proprietary to EPRI? If the latter, it should have been described as such. This question illustrates the concerns of the panel about software availability expressed in the previous discussion of documentation.

CONTRIBUTIONS TO THE DEVELOPMENT OF PSHA

Because SSC is such a major component of a PSHA, the comprehensive methodology for expert elicitation presented in Section 4.4 of the SSHAC report is an important contribution. On first reading, the material in Chapter 4 may appear to be just a restatement of Chapter 3. However, SSHAC is correct in noting in Section 4.4 that the elicitation procedures and methods for SSC differ from those for ground motion characterization. Further, "lessons learned" from past SSC exercises are incorporated into major PSHA projects (Appendix H).

Another important contribution of Chapter 4 and its accompanying appendixes is the practical guidance provided for carrying out sensitivity analyses to determine "what drives the seismic hazard" and "what contributes significantly to uncertainties in hazard." Basic discussion relevant to SSC is presented in Section 4.3.6, but important details are given in Appendix G and Section 7.8.

A third major contribution of Chapter 4 is the exposition in Section 4.3.5 (bolstered by Appendix I) of the effects of spatial variations in seismicity within a seismic source vis-à-vis the assumption of homogeneous seismicity. The analysis techniques date from the EPRI program (EPRI, 1989, as cited in the SSHAC report), but the detailed discussion and examples presented there forcefully demonstrate how the usual assumption of homogeneous seismicity for seismic sources can, under certain predictable cases, significantly affect both the mean seismic hazard and its statistical uncertainty.

THE OUTLOOK FOR EVOLUTION OF SSC

While affirming the scientific validity and practical effectiveness of the SSC methodology set forth in the SSHAC report, the panel recognizes that the scientific community will naturally strain against the confines of SSHAC's prescriptions for SSC. The panel applauds SSHAC's perspective that "[its] formulation should not be viewed as an attempt to 'standardize' PSHA in the sense of freezing the science and technology that underlies a competent PSHA, thereby stifling innovation" (Section 1.2 of the SSHAC report). A few brief examples suffice to illustrate current trends in the scientific community that may influence the evolution of SSC. Diverse trends lead to advocacy for both greater simplification and greater complexity.

Frankel (1995) proposes a method for PSHA that uses spatially smoothed representations of historic seismicity instead of seismic source zones to directly calculate probabilistic seismic hazard. Insofar as he demonstrates the capability to produce values of mean seismic hazard similar to those from the more complicated EPRI methodology, his simple methodology offers understandable attraction. The applicability obviously pertains to cases where seismicity "drives the hazard"—either for specific regions or for definable exposure periods.

In terms of modeling earthquake occurrence with greater complexity, one example is the multidisciplinary approach (e.g., Ward, 1994), in which data from space geodesy and synthetic seismicity are added to the traditional information from geology, paleoseismology, and observational seismology. Main (1995) examines the implications if earthquake populations are really an example of a self-organized critical phenomenon. If this is correct, the *a priori* assumption of the Gutenberg-Richter frequency-magnitude distribution is no longer valid in some cases, and Main provides evidence for questioning the use of only the Poisson distribution in seismic hazard analyses, based on the accumulating evidence of local or long-range interactions of earthquakes. It should be pointed out that PSHA is not limited to the use of the Gutenberg-Richter relationship. Alternate estimates of the frequency-magnitude distribution are, and have been, used in probabilistic analyses.

Main (1995) also discusses an independent approach to the vexing problem of estimating the maximum-magnitude earthquake that is "credible" for a seismic source zone, based on his suggested distribution of moment release and the long-term slip rate on the causative fault

system. Geophysicists are becoming increasingly aware of the nonstationarity of earthquake occurrence, particularly in light of observations of fault interactions leading to "triggered" or "encouraged" earthquakes. As earth scientists improve their ability to assess time-varying earthquake potential on active faults, SSC will evolve correspondingly. Indeed, "time-variable seismic hazard" is already a topic of special sessions at geophysical society meetings.

5
The Estimation of Earthquake-Generated Ground Motion

Chapter 5 of the Senior Seismic Hazard Analysis Committee's (SSHAC) report, entitled "Methodology for Estimating Ground Motions on Rock," addresses the basic building block of a well-executed probabilistic seismic hazard analysis (PSHA) that has the surest observational and theoretical foundation. The past two decades have brought significant theoretical advances in ground motion models, as well as significant new data sets with which to test the new models. Fundamental to the stability of state-of-the-art high-frequency (f= 1 Hz) ground motion estimates is the essential constancy of earthquake stress drops. This allows the substantial experience developed from California and elsewhere to be transferred to the eastern United States (EUS) with little modification.

There are, to be sure, real variations in earthquake stress drops, and recent data for the EUS point to some anomalous magnitude-dependent high-frequency excitation (Atkinson, 1993). The EUS data set on the excitation and propagation of earthquake ground motion for the purposes of PSHA is still very sparse. Model predictions of EUS earthquake ground motion, whether empirical or theoretical, can vary significantly across the magnitude, distance, and frequency range of interest.

SCIENTIFIC VALIDITY AND CLARITY OF PRESENTATION

SSHAC's Chapter 5, together with the supporting Appendixes A and B (Ground Motion Workshops I and II), is an impressive synthesis of current knowledge about estimating high-frequency ground motions and their uncertainties in the EUS. The reader experienced in SHA will note

that site-response issues, including nonlinear effects, are not addressed, on the grounds that they can only be incorporated on a site-specific basis.

Chapter 5 is itself a well-written primer on the essentials of ground motion estimation, valid for any region in which earthquakes occur. It begins with basic ground motion measures; provides the fundamentals of magnitude, distance, and site response; and describes the essentials of empirical and theoretical predictions of earthquake ground motion. It explicitly warns against the use of fixed spectral shapes anchored by peak ground acceleration (PGA) alone, and then progresses to a discussion of uncertainty in ground motion predictions. A fourfold decomposition of uncertainty for the Hanks and McGuire (1981) point-source, stochastic model, the simplest physical model used in these predictive exercises, is demonstrated in this discussion. Readers should study this decomposition carefully (Table 5-1, Section 5.5.1). It is difficult, and, if this example is not well understood, similar attempts at uncertainty decomposition for more sophisticated and parametrically complicated models will be frustrating.

Section 5.7, "Specific Expert-Elicitation Guidance for Obtaining Ground Motion Values," is based on the results of Workshops I and II, reported in detail in Appendixes A and B. Figure 5-5, reproduced as Figure 2.1 in this report, is intended to guide readers through the process. Regrettably, it is not well keyed to the description in the text.

CONTRIBUTIONS TO THE DEVELOPMENT OF PSHA: SUMMARY OF THE GROUND MOTION WORKSHOP RESULTS

The comprehensive treatment of ground motion estimation in Appendixes A and B is an important contribution to the SSHAC effort. Workshop I provided for the presentation of four basic ground motion estimation models: (1) intensity-based models presented by M. D. Trifunac, (2) empirical models presented by K. W. Campbell, (3) stochastic or random-vibration models presented by G. M. Atkinson, and (4) the empirical source-function method presented by C. Saikia. These proponents of the models were asked to evaluate the models in the company of 10 additional experts, the "invited participants" listed in Table A-1 of the SSHAC report. The principal result of Workshop I was rejection of intensity-based models for estimating ground motion in the EUS (SSHAC Table A-2). Additional information was collected on the

applicability or validity of all models as a function of frequency, magnitude, and distance (SSHAC Tables A-3 and A-4). These polls of the assembled experts also show a distinct preference for the stochastic models.

Workshop II proceeded to actual ground motion numbers and their uncertainties on the basis of the "selected models" resulting from Workshop I. The threefold elicitation exercise that constituted Workshop II, described below, provided for pre-, co-, and postworkshop estimates. Prior to the workshop, the four proponents were asked to provide estimates of peak acceleration and spectral accelerations based on the ground motion models they actually use, along with the corresponding estimates of epistemic and aleatory uncertainties. The distances, frequencies, and magnitudes for which estimates were requested are listed in an unnumbered table in "Instructions for Proponents," Appendix B. In keeping with the Workshop I preference for stochastic models, two of the four Workshop II proponents supported stochastic models (Atkinson and Silva), although there are significant differences between their models.

In advance of Workshop II these ground motion estimates were sent to three additional experts. These experts were asked to provide their own estimates of ground motion and uncertainties for the same distances, frequencies, and magnitudes, on the basis of what the proponents had provided, as well as any other information they considered relevant. Significantly, the four proponents were also asked to perform as experts; as such, their ground motion estimates were generally not the same as those they provided as proponents. These pre-Workshop II ground motion estimates and uncertainties are labeled as Expert 1 results, examples of which are shown in SSHAC Figure B-3, reproduced here as Figure 5.1a.

The second stage of the elicitation process occurred at the workshop, attended by all proponents and experts, the integration team, and several observers (SSHAC Table B-1). The principle of "active listening" was put to work, the idea being that all proponents and experts were to understand what every other proponent and expert was doing, whether or not he/she agreed with it. The panel concludes that this worked very well, revealing significantly different interpretations of key terms and procedures. It is noteworthy that Workshop II deliberations also revealed considerable misunderstandings about the differences between epistemic and aleatory uncertainties.

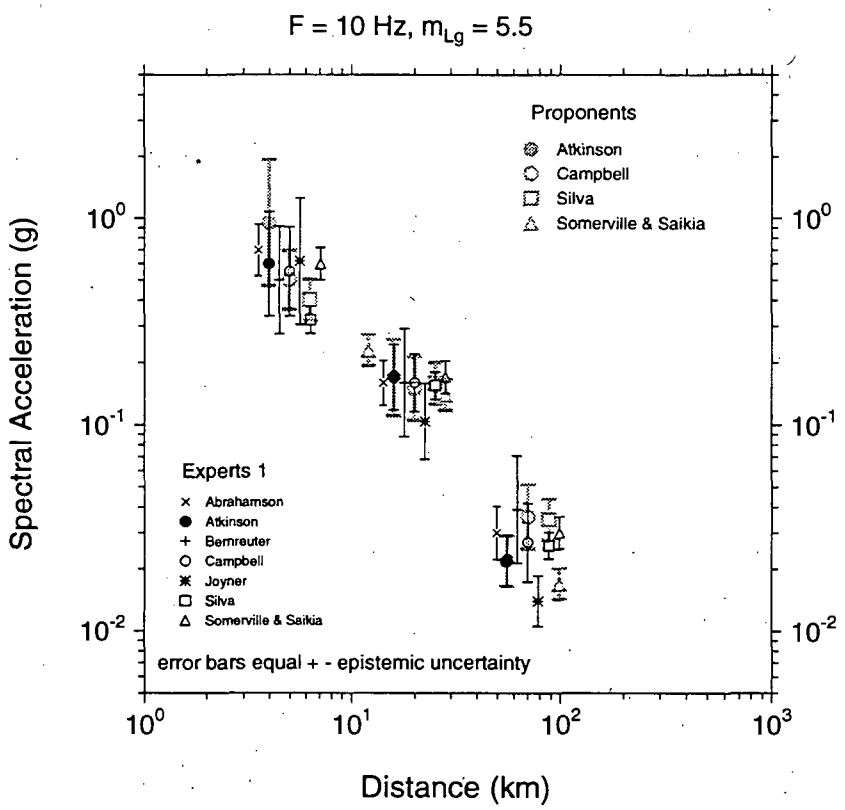

FIGURE 5.1a Comparison of proponents' estimates (gray) to Experts 1 estimates (black) of 10-Hz spectral acceleration for $m_{bLg} = 5.5$. The error bars represent $\pm\,\sigma_{epistemic}$ range.

Next, experts (at this stage all proponents were now experts) were asked to reconsider overnight their estimates of ground motion and uncertainties. This led to the Expert 2 results, which are compared to the Expert 1 results. An example (SSHAC Figure B-7) is reproduced here as Figure 5.1b. The differences are modest to zero at $f =$ 10 Hz and somewhat greater at $f =$ 1 Hz.

Two activities followed the workshop. First, all experts were invited to change their estimates one more time. Only a few did, and no one offered significant changes. An example of the integrated Expert 3 (postworkshop) results is shown here in Figure 5.1c (SSHAC Figure B-21). The second postworkshop activity was the manipulation of the Expert 3 results by the Integration Team. The results of the seven experts were weighted equally (SSHAC Table B-8, shown here as Table 5.1), and the results of the four proponents were weighted unequally (SSHAC Table B-9). The former are the preferred results, but the differences in median values and epistemic and aleatory uncertainties are slight.

IMPLICATIONS FOR FUTURE GROUND MOTION ESTIMATION

The many successes and few limitations of the Workshop II elicitation/integration process are summarized in Section B.5, "Concluding Observations and Discussion," of the SSHAC report. The panel is impressed with the success of this process in two principal ways, one of which SSHAC recognized and the other it did not.

SSHAC recognized explicitly that "the Proponents and Experts exhibited a striking amount of agreement. . . ." **Once freed from the thicket of unintentional disagreements, mutual misunderstandings, and individual egos, the group of specialists who participated found that what it knows about ground motion estimation is impressively consistent. The panel doubts that this degree of consistency and agreement could have been achieved without this highly interactive elicitation/integration process.**

There may be some who will believe that this agreement is illusory, that in some unspecified way it was cajoled or coerced. The panel finds no evidence of this. Doubters should note the workshop finding that "the estimated values of aleatory uncertainty for 10 Hz

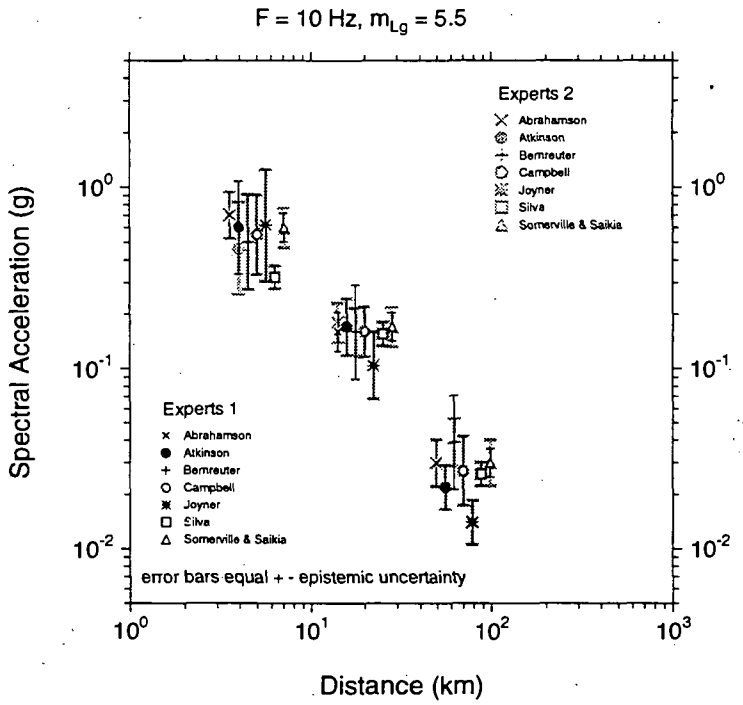

FIGURE 5.1b Comparison of Experts 2 results (gray) to Experts 1 results (black) for 10-Hz spectral acceleration at m_{bLg} = 5.5 as a function of distance.

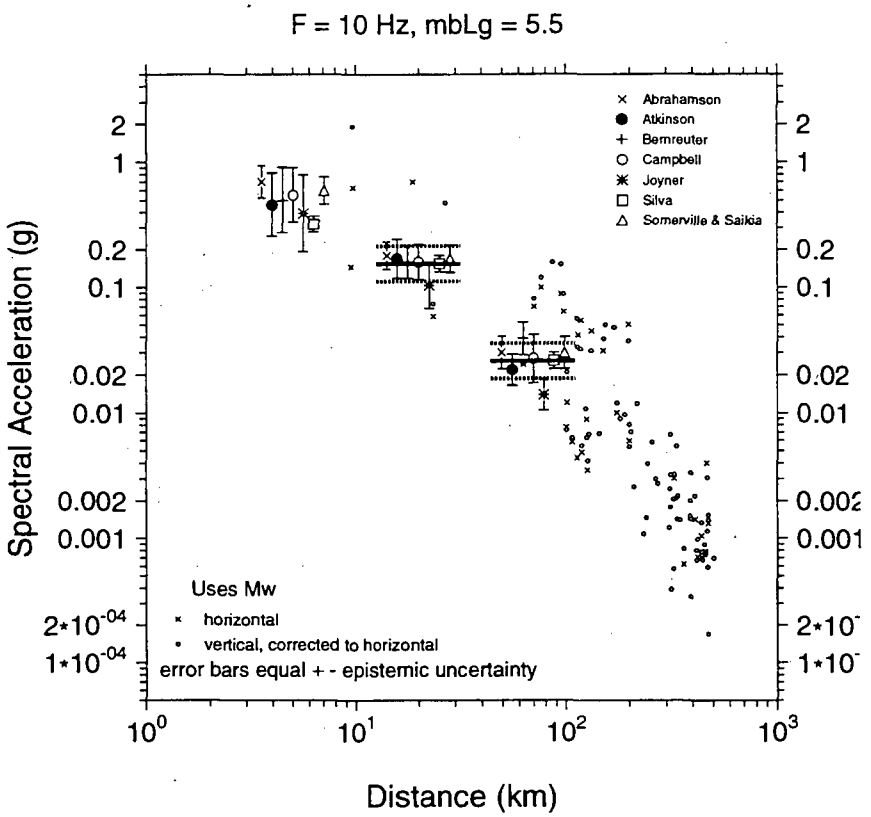

FIGURE 5.1c Experts 3 results, together with mean values and variances obtained from equally weighting the Experts 3 results for 10-Hz spectral acceleration at $m_{bLg} = 5.5$ as a function of distance. Small circles and crosses represent instrumental data.

TABLE 5.1 Results of Integrating Experts' Estimates with Equal Weights (Table B-8, Appendix B, SSHAC Report)

f(Hz)	m_{bLg}	R (km)	Median Amplitude (g)	Epistemic Std. Dev.	Aleatory Std. Dev.
1	5.5	20	1.09E-02	0.48	0.80
	5.5	70	2.27E-03	0.46	0.80
	5.5	200	9.36E-04	0.37	0.80
	7.0	20	1.67E-01	0.66	0.78
	7.0	70	4.50E-02	0.71	0.78
	7.0	200	1.82E-02	0.73	0.79
2.5	5.5	20	4.17E-02	0.34	0.77
	7.0	20	3.67E-01	0.53	0.73
10	5.5	20	1.55E-01	0.32	0.73
	5.5	70	2.58E-02	0.32	0.75
	7.0	20	8.45E-01	0.52	0.70
	7.0	70	1.88E-01	0.53	0.72
25	5.5	20	2.13E-01	0.34	0.73
	7.0	20	1.07E+00	0.51	0.70
PGA	5.5	70	1.28E-02	0.41	0.75
	7.0	70	9.36E-02	0.51	0.70

and PGA are, however, significantly higher than [the] values obtained using western North America strong-motion data, especially for large magnitudes."

SSHAC did not comment on the extent to which the workshop ground motion estimates and uncertainties can actually be used in future PSHA studies, at any level. The panel recognizes that there is a certain incompleteness about Table 5.1. Considerable interpolation and some extrapolation of the results in that table will be required to cover the many distances, frequencies, and magnitudes that must be considered in even the lowest-level PSHA. Unfortunately, the elicited results for R = 5 km, where R is the distance between the seismic source and the affected area, are not presented by SSHAC, presumably because of problems with the interpretations of "closest distance."

Even if the SSHAC ground motion results are not suitable for further use in their present form, the panel wonders how many times this information will be reelicited in the future. **The panel believes that community consensus on PSHA-type ground motion issues, at any level of PSHA, may well be close at hand, at least within the limits of the ground motion models and data sets available in 1994.** The broad agreement resulting from the two SSHAC ground motion workshops led to this opinion of the panel. With further consideration of some additional distances, frequencies, and magnitudes, together with appropriate interpolation schemes, ground motion matters of concern to PSHA could well be resolved at least for the next few years.

6
Summary and Conclusions

GENERAL APPRAISAL OF THE SSHAC REPORT

The Senior Seismic Hazard Analysis Committee's (SSHAC) report offers substantial contributions to the foundations and practice of probabilistic seismic hazard analysis. But the primary focus of the report is not on how to create an assessment from the inputs; only in Chapter 2, in an introductory fashion in Chapter 6, and in Appendix J is a methodology for calculating the hazard estimates and their uncertainties addressed.

Instead, the central theme of SSHAC is guidance on the process of eliciting and aggregating expert opinion on seismic sources, seismicity within these sources, and ground motion attenuation, as well as the associated uncertainties and final estimates of the hazard. SSHAC focused on this theme based on its conclusion that the reason for some serious discrepancies in the results of prior studies is differences in ways in which these inputs were derived, even though the work was done by competent specialists working from the same or similar data bases. **In the panel's view, SSHAC's most important message is that the quality of a PSHA using multiple experts can be enhanced by careful and wise choice of experts and skillful facilitation of expert discussion and interaction through workshops and other meetings.**

The panel believes it very important to emphasize what the SSHAC report is and what it is not. The report presents a procedure for using experts in seismic hazard evaluation and for determining the uncertainties at key stages of the hazard analysis process. Its primary domain of application is to nuclear and other critical facilities. According to SSHAC, if a project sponsor and the analysts choose to do a probabilistic hazard analysis, its procedures will yield stable results. The SSHAC report is not a defense of the probabilistic approach to hazard assessment. In particular, SSHAC explicitly excludes any discussion of the nonprobabilistic methods of seismic hazard assessment. The panel

accepts this decision of SSHAC on the grounds that an evaluation of the relative effectiveness of the two approaches, or their relationship, was not in the committee's charge. The full-blown version of the SSHAC procedure, utilizing the technical facilitator/integrator (TFI) technique where needed, is costly and will almost certainly be used only for major critical facilities. The SSHAC report offers useful guidelines as to the level of effort required for various kinds of problems and for various levels of information already available to analysts. In the view of the panel, simpler methods of probabilistic hazard analysis are appropriate for application to noncritical facilities.

GENERAL SHORTCOMINGS AND LIMITATIONS OF THE SSHAC REPORT

The SSHAC report, with its appendixes, is a lengthy and complex document that requires careful reading. Many important ideas, including clarification of the limitations of the SSHAC procedures, are distributed throughout the text. A casual scanning of the document may leave readers with incorrect impressions as to what SSHAC has recommended, especially with regard to nonnuclear facilities. Most importantly, the report appears to have been written for those already quite familiar with PSHA methods, offering guidance on a preferred way to get stable results from a PSHA.

SSHAC's Executive Summary will be useful to administrators and project sponsors who are not specialists in hazard analysis methodology, but it includes nothing about the excellent earth science materials that are in the report and its appendixes.

SSHAC provides an up-to-date procedure for obtaining stable results from the application of PSHA principles that have been established in past practice. It does provide a consistent and systematic approach to elicitation and aggregation of diverse expert opinion and the uncertainties that arise therefrom, but this is not the same as the calculation of seismic hazard from the information elicited.

The SSHAC report does not make reference to nuclear reactors or other nuclear facilities, thereby lending an air of generality to its final report and the applicability of its recommended procedures. The panel believes, nevertheless, that the flavor of the report is strongly influenced by concern for applications to nuclear facilities and this generality is more

apparent than real. In response to recommendations in the panel's March 1995 letter report (Appendix B) to the U.S. Nuclear Regulatory Commission, SSHAC did attempt to narrow the scope of the applications for which its recommended procedure is intended. Disclaimers are included in several places that are technically adequate to protect a practitioner who chooses not to use the SSHAC prescription against the need to defend that decision in a regulatory situation. Nevertheless, it seems clear that the report was written to support the highest, most sophisticated level of PSHA practice. Because the concept of the TFI is held by SSHAC to be one of its most important contributions to PSHA practice, a great deal of space is devoted to this topic, even though there are repeated comments that it is not needed for many of the issues that arise. The impression is given that this highest level of operation is really the key to success in general.

The panel concludes that the SSHAC contention—namely, that all PSHA projects should share the same basic principles and goals—should be taken as an overarching postulate for project design. But this contention should not be taken as implying or imposing the full elaborate and demanding methodology for application to every PSHA study. That alternate simpler methods may well be adequate for noncritical facilities is acknowledged by SSHAC, but they are not discussed nor is guidance offered as to where readers can learn about them.

In meetings and in its letter report of March 1995 (Appendix B), the panel urged SSHAC to document in adequate detail the manner in which lessons leading to the recommended SSHAC procedures were learned from the study of prior PSHA studies. Although the SSHAC report states that its conclusions are based on a thorough review of a number of such studies, the requested details are not offered and no previous PSHA analyses other than the Lawrence Livermore National Laboratory and Electric Power Research Institute studies are referenced.

The panel's evaluation of SSHAC's treatment of uncertainty is presented in detail in Chapter 3 of this report. The panel acknowledges that recognition of the two kinds of uncertainty is useful in elicitating expert opinion and in making decisions about where additional data gathering and research are likely to lead to reduced uncertainty about hazard estimates. However, as discussed in Chapter 3, the panel has reservations about how this distinction is ultimately helpful to final users, especially because the distinction between uncertainty types is sometimes

ambiguous and the amount of epistemic uncertainty regarding a hazard depends on the type of models used in the analysis.

Moreover, it is the impression of the panel that the statistical analysis and uncertainty separation procedures recommended in the SSHAC report are, at times, more sophisticated than is warranted by the data on which such analysis is based or the purposes for which the results are used.

The problem of integrating the opinions of a group of experts is difficult. It is treated in greatest detail in Appendix J of the SSHAC report. The panel found that this treatment is not easy to follow and that specific aggregation models described are not exhaustive. **Therefore, the panel recommends that the quantitative methods of Appendix J be used as examples and not be regarded as prescriptive procedures.** Given the current state of the art in formal expert aggregation and the difficulties specific to the earthquake hazard problem, the panel suggests that judgmental combination rules may be at least as valid as quantitative procedures.

SOME CONTRIBUTIONS OF SSHAC TO HAZARD ASSESSMENT

The contributions that the SSHAC report makes to the hazard assessment process are discussed in detail in the preceding sections of this report. A few key items are highlighted here.

The TFI Methodology

SSHAC considers the TFI methodology to be the centerpiece of its work and developed it from lessons it learned from prior hazard analysis studies and from workshops conducted as part of its study. The panel is favorably impressed with the concept and its implementation in the two ground motion workshops (SSHAC's Appendixes A and B). Readers of the SSHAC report should keep in mind that use of a TFI is not recommended or needed for all hazard assessments and should not even be viewed as a rigid prescription for a high-level PSHA. The TFI elicitation procedure is not synonymous with PSHA methodology.

Clear Definition of Experts' Distinct Roles as Proponents, Evaluators, and Integrators

It is important that experts be educated to the significance of their distinct role as proponents of a particular position or as evaluators. The panel is not sure that experts can truly assess the view of the whole informed community on the entire range of relevant issues.

Results of SSHAC-Sponsored Workshops

SSHAC held workshops on seismic source characterization, ground motion estimation, and earthquake magnitudes. The outputs of these workshops (Appendixes A, B, C, H), especially those on ground motion, are a valuable contribution of the SSHAC effort and led to the formulation of many of the recommended procedures in the committee's report.

Considering the broad consensus on ground motion modeling that was reached at the end of Workshop II, the panel believes that a real opportunity exists now to formulate, with further work to fill in necessary details, a ground motion model that can be used as a standard in the eastern United States for PSHA until new data or future theoretical developments warrant a reevaluation. The results of this effort would eliminate the need to elicit again ground motion input for each hazard analysis and could be used as a baseline for more detailed studies as needed for specific problems.

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Appendix A

ACRONYMS

DOE	Department of Energy
DSHA	deterministic seismic hazard analysis
EPRI	Electric Power Research Institute
EUS	eastern United States
LLNL	Lawrence Livermore National Laboratory
NRC	National Research Council
PGA	peak ground acceleration
PSHA	probabilistic seismic hazard analysis
SHA	seismic hazard analysis
SSHAC	senior seismic hazard analysis committee
SSC	seismic source characterization
TI	technical integrator
TFI	technical facilitator/integrator
USNRC	United States Nuclear Regulatory Commission

Appendix B

LETTER REPORT OF THE PANEL ON SEISMIC HAZARD EVALUATION, MARCH 1995

Committee on Seismology, National Research Council
Comments on SSHAC Draft Report of 11 November 1994
Based on the Panel Meeting of December 9-10, 1994

The Panel on Seismic Hazard Evaluation of the Committee on Seismology, National Research Council (NRC), is charged with reviewing the report to be produced by the Senior Seismic Hazard Analysis Committee (SSHAC) under the sponsorship of the U.S. Nuclear Regulatory Commission (USNRC), the Department of Energy (DoE), and the Electric Power Research Institute (EPRI). The USNRC prescribed that the Panel provide feedback to SSHAC as they prepare their report, but in such a way as not to compromise the objectivity of the Panel in providing its review of the final product. SSHAC submitted for review a draft of their report in mid-November, 1994, and the Panel met, with all SSHAC members present, on December 9, 1994, for discussion of the draft.

Unfortunately the draft was not complete, missing some key appendices, some sections of text, and an executive summary. It should be understood that the Panel may have comments with regard to the missing material when it is available for the final review. The discussions of December 9 were carried out in the presence of representatives of the sponsoring organizations. The Panel met in executive session on December 10 to continue its review. The resulting comments and recommendations are submitted to the USNRC.

The suggestions made are offered as guidance to SSHAC on the issues at this stage of their work, in accord with the request of the USNRC. They should not be interpreted as a substitute for the final report to be developed by the Panel.

GENERAL COMMENTS

The Panel believes that the draft report is a basis for a useful final product that has the potential to advance the process of Probabilistic Seismic Hazard Analysis (PSHA). However, the Panel feels that the introduction to the report must be expanded to make clear the purpose and scope of the report, and specifically to state what the report is not. As it stands, the report implies that the methodology is applicable to a broader range of facilities than can be justified. The full range of alternative approaches is not discussed, let alone taken into account.

From the discussions, it appears that there may be a conflict between the expressed needs of the USNRC for a single unified, fully prescribed regulatory method of seismic hazard analysis (SHA) and the attempt by SSHAC to produce a general consensus methodology. The USNRC wants a prescribed procedure that is based on what has been learned from past PSHA experiences. The USNRC recognizes that the way in which input from experts was obtained is a main reason for the discrepencies between the analyses made by Lawrence Livermore and EPRI.

The Panel recognizes the strengths of the report and the significant contributions it offers to PSHA. As applied to nuclear regulations the SSHAC report breaks new ground in its discussion of the Technical Integrator (TI)/Technical Facilitator Integrator (TFI) approaches. However, as discussed in detail below, the presentation of these ideas needs to be made more clear to eliminate some apparent contradictions and advise the users of the report when the full TFI treatment is called for. The TI/TFI approach has the potential to overcome some aspects of past PSHA applications that have led to objections by critics of the whole process.

Because the focus of the report is on process for PSHA, rather than on the underlying earth science, the detailed attention to the treatment of uncertainty is appropriate. However, as discussed below, the motivation for this careful treatment of uncertainty and the way in which the results will be applied are not made clear to the potential user.

Again without yet having the benefit of full discussion of the subject, the Panel feels that the recommendation that behavioral aggregation of expert input be employed is sound, because mechanical aggregation algorithms, if used as "black boxes," may lead to poor results.

CONCERNS AND PROBLEMS

Recommendations for Improvement

Some suggestions for revision and restructuring of the report were given orally to SSHAC during the Panel meeting. The most essential of these, which the Panel feels cannot be neglected during revision of the report, are repeated here for completeness of the record.

The word "Consensus" should be removed from the title, perhaps replaced by a more appropriate adjective.

An excellent executive summary is essential for the success of this report. The report is lengthy and detailed. The key findings and recommendations of SSHAC must be assembled in concise, easily understandable form if they are to be accessible to others than the experienced practioneer of PSHA.

The draft as submitted is overly repetitious. Unnecessary redundancy should be eliminated, to reduce the length substantially without loss of content.

The specific criticisms to follow all can be categorized as due to one or more of the following: inadequate *focus* of the report, absence of the *history* of evolution of the key concepts and recommendations, or lack of a presentation of the *context* within which the report was developed and is to be understood and applied.

Motivation. The reader should be offered better motivation for adopting the procedures required or recommended in the report. In addition, the context for the procedures should be framed in such a way that the PSHA analyst who follows other procedures for any of a number of valid reasons is not put in a position of having to defend in a regulatory situation the failure to carry out the SSHAC prescription in every detail.

PSHA methodologists often have sound reasons for introducing new concepts and approaches, but have not always included in their reports the background reasoning that has led to these innovations. Where it exists in this report, this shortcoming must be overcome if the final SSHAC product is to be widely accepted and applied. In particular, the report should say how the results are to be used as motivation for the great emphasis on the distinction between aleatory and epistemic uncertainty and the need to separate the two in SHA.

Space and emphasis devoted to the TFI approach. Scattered through the text, and asserted by SSHAC members at the December 9 meeting, is the key idea that the full TFI approach is required only for some complex issues for which a review of the published literature cannot produce satisfactory input to the PSHA process. However, the great detail in which the recommended TFI approach is depicted tends to obscure this principle. The reader is left with the impression that the use of the TFI is dominant in a properly executed PSHA.

- SSHAC must carefully set out the criteria for deciding if an issue requires a TFI. What are the operational criteria for deciding if an issue is of type A, B, C?
- SSHAC must state its perception of the qualifications required of the TFI. The recommendation for use of a *strong* TFI for prescribed issues, without clearly expressed qualifications, contradicts one of the stated criteria for success: that the recommended methodology, when applied independently by different groups, should always yield comparable results.
- The Panel is concerned that the TFI is empowered to act as a "super expert," able to overrule the diverse views of the experts from whom input is elicited. It is not prudent to generate an apparent consensus unless consensus among the experts is really achieved. It is not necessary that the TFI agree with the outcome of the process; the TFI can stand behind that outcome as the result of thorough interaction among experts.

The issue of breadth. The statement on breadth of application on page 1-7 of the draft report and other statements related to the intended breadth of application of the recommended methodology are the cause of much uneasiness among the Panel. *A clear statement of the purpose and scope of the report should be included early in the introduction.*

- It should be made clear that the recommended methodology is based on a study of the experiences with LLNL and EPRI procedures. This should be brought out in the history-context material called for above. In the appropriate places, specific references to the lessons learned by examination of previous PSHA projects should be cited. The studies from which the recommended methodology was derived should be clearly described, even though the intent of the report is not to address the reconciliation of the LLNL/EPRI studies. The reader should be made

aware of the lessons learned from the evaluation of those (and other?) studies that have gone into the formulation of this report. The reader should be told explicitly that alternate PSHA approaches were not assimilated and that this report is not based on a consensus of a broad sample of practioneers.

- Some statement of costs would be in order. What a hazard evaluation can deliver is often a matter of how many dollars are available. Cost estimates may be beyond SSHAC's scope, but even this could be mentioned.
- The Panel anticipates that the full procedure recommended in this report will not be applied to the seismic regulation of all critical facilities. It is not a general methodology that will be applied step-by-step in all situations. Therefore, criteria or guidelines are needed in the report, to aid the project sponsor and the PSHA analysts in deciding when the full procedure is justified. A statement is needed about what can be delivered with different levels of PSHA, so the buyer can make an informed decision as to what will and will not be produced. As stated above, the analyst who chooses for sufficient reasons to use other procedures should not be put by this report in a position of having to defend that decision in a regulatory setting. He or she, of course, must be prepared to defend the procedures that were adopted.

SCIENTIFIC AND TECHNICAL CONCERNS

The Panel questions whether the links between SSHAC's recommended methodology and its applications are spelled out in sufficient clarity. Although SSHAC is not charged with specifying the use of hazard numbers in engineering design, a brief treatment is needed pointing to how the results can be used, and, in particular, what the knowledge of highly refined uncertainty estimates contributes to applications. A clear and unequivocal definition of aleatory and epistemic uncertainty is needed, as well as a clear and readily applied prescription

for separating the two. This is needed because of the emphasis on this subject in the report.

Although not as yet the subject of full panel evaluation, the following example illustrates the need for SSHAC to be very clear on the value and the method of application of their categorization of uncertainty. "What should count for decision is not the aleatory/epistemic distinction, but the temporal variation in the total uncertainty (in the total or predictive distribution of A_T, maximum peak ground acceleration and spectral values at the site in the next T years) during the lifetime of the project." According to this viewpoint:

- There is no need to label uncertainty as epistemic or aleatory.
- If one sees total uncertainty as being contributed by different sources (e.g., by uncertainty on model type or on various parameters), then it is reasonable to expect that the uncertainty associated with each source will evolve in its own way in time. Making a binary distinction between epistemic and aleatory uncertainty corresponds to assuming that each source will be either explained totally (epistemic components) or will remain constant over the lifetime of the system (aleatory components.)
- One can formulate rational ways to make decisions accounting for the possible temporal evolution of uncertainty. The Panel member responsible for these comments is not, on the other hand, aware of any convincing method to make decisions based on the aleatory/epistemic decomposition. The amount of conservatism displayed by decisions under time-varying uncertainty depends on the nature of the problem (essentially on the degrees of asymmetry in the rewards and penalties associated, respectively, with future possible decreases and increases in the calculated risks).

The SSHAC report will be strengthened by addressing these concerns in a straightforward way.

Intensity data from historic strong earthquakes in the central and eastern United States is not incorporated in the ground motion models. The relation between m_{bLg} and intensity in the eastern United States, first established by Nuttli, should not be ignored.

"Seismic source zones", a key concept in the prescribed source characterization procedure, should be explicitly recognized as an artificial construct introduced to make hazard calculations tractable. They are not real physical entities.

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R.J. Budnitz(Chairman, G. Apostolakis, D.M. Boore, L.S. Cluff, K.J. Coppersmith, C.A. Cornell, P.A. Morris

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Probabilistic Seismic Hazard Analysis (PSHA) is a methodology that estimates the likelihood that various levels of earthquake-caused ground motion will be exceeded at a given location in a given future time period. Due to large uncertainties in all the geosciences data and in their modeling, multiple model interpretations are often possible. This leads to disagreement among experts, which in the past has led to disagreement on the selection of ground motion for design at a given site. The Senior Seismic Hazards Analysis Committee (SSHAC) reviewed past studies, including the Lawrence Livermore National Laboratory and the EPRI landmark PSHA studies of the 1980's and examined ways to improve on the present state-of-the-art. The Committee's most important conclusion is that differences in PSHA results are due to procedural rather than technical differences. Thus, in addition to providing a detailed documentation on state-of-the-art elements of a PSHA, this report provides a series of procedural recommendations. The role of experts is analyzed in detail Two entities are formally defined – the Technical Integrator (TI) and the Technical Facilitator Integrator (FI) – to account for the various levels of complexity in the technical issues and different levels of efforts needed in a given study.

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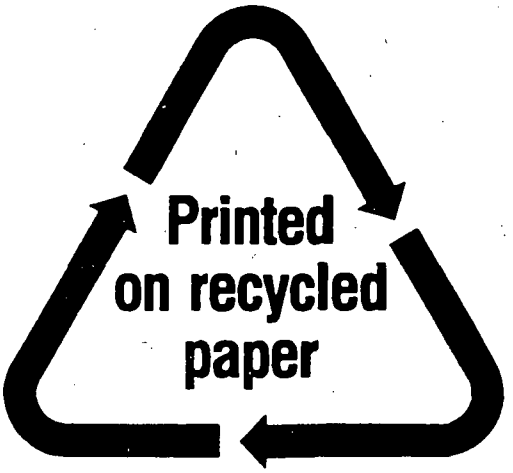

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Appendices

Prepared by
Senior Seismic Hazard Analysis Committee (SSHAC)
R. J. Budnitz (Chairman), G. Apostolakis, D. M. Boore, L. S. Cluff, K. J. Coppersmith, C. A. Cornell, P. A. Morris

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R. J. Budnitz (Chairman), G. Apostolakis, D. M. Boore, L. S. Cluff, K. J. Coppersmith, C. A. Cornell, P. A. Morris

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ABSTRACT

Probabilistic Seismic Hazard Analysis (PSHA) is a methodology that estimates the likelihood that various levels of earthquake-caused ground motion will be exceeded at a given location in a given future time period. Due to large uncertainties in all the geosciences data and in their modeling, multiple model interpretations are often possible. This leads to disagreement among experts, which in the past has led to disagreement on the selection of ground motion for design at a given site.

In order to review the present state-of-the-art and improve on the overall stability of the PSHA process, the U.S. Nuclear Regulatory Commission (NRC), the U.S. Department of Energy (DOE), and the Electric Power Research Institute (EPRI) co-sponsored a project to provide methodological guidance on how to perform a PSHA.

The project has been carried out by a seven-member Senior Seismic Hazard Analysis Committee (SSHAC) supported by a large number other experts.

The SSHAC reviewed past studies, including the Lawrence Livermore National Laboratory and the EPRI landmark PSHA studies of the 1980's and examined ways to improve on the present state-of-the-art.

The Committee's most important conclusion is that differences in PSHA results are due to procedural rather than technical differences. Thus, in addition to providing a detailed documentation on state-of-the-art elements of a PSHA, this report provides a series of procedural recommendations.

The role of experts is analyzed in detail. Two entities are formally defined—the Technical Integrator (TI) and the Technical Facilitator Integrator (TFI)—to account for the various levels of complexity in the technical issues and different levels of efforts needed in a given study.

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SPONSOR'S PERSPECTIVE

Probabilistic Seismic Hazard Analysis (PSHA) has become an increasingly important tool for aiding design and decision making at all levels in both the private sector and government. The level of sophistication applied to PSHA has increased dramatically over the past 27 years since the technique was first introduced in the literature. As more and more people and groups implemented and used PSHA in different forms, it became clear to the sponsors of the Senior Seismic Hazard Analysis Committee (SSHAC) report that the time had arrived to establish more uniform and up-to-date guidelines for future PSHA studies.

The need for such guidelines is threefold:

1. As the situation stands today, it is often the case that multiple PSHA studies are available for the same geographic region. However, due to differences in implementation, results of these studies often differ by substantial amounts for the same physical location. Further, because of the amount of technical information and complex combination of techniques utilized, it is not always simple to determine the source of these differences and which answer should be used.

2. Potential sponsors of a PSHA study are faced with the difficulty of determining the appropriate level of a proposed PSHA to ensure stable results that meet the sponsor's needs.

3. The cost to perform a PSHA study can be quite large. The sponsors of this report expected that a suitable set of guidelines could be developed to assist the potential user in choosing the appropriate level of analysis consistent with the overall goals and resources available. Given the need to conserve resources, issuing such guidelines to optimize future PSHA studies in accordance with the sponsor's need takes on added importance.

Overall, the sponsors saw a need for more stability in the PSHA process, both for nuclear and non-nuclear applications, in dealing with future needs for using PSHA to establish seismic hazard levels throughout the United States.

Comparative evaluations have shown that the differences between PSHA studies are often not technical, but due to the information gathering and assembly process used in the study. The integration of the different types of information required in a PSHA (geologic, seismotectonic, probability and statistics, information theory, and decision making) presents significant inter-disciplinary challenges and requires a project structure and process that assure proper integration. The skills required to be a good integrator and evaluator are not necessarily the same skills needed to be a good scientist. Our observation is that although many PSHA practitioners are trained experts in one or more fields, the PSHA divergence issue can partly be explained by a lack of integration and evaluation skills so important to the PSHA product. We believe this is true at all levels of PSHA, and these skill requirements may be most acute at the simpler levels of seismic hazard analysis not associated with critical facility assessments where typically the PSHA analysts must complete their work.

This report addresses the integration and evaluation issues that should be considered and focuses on the process of integration required in a PSHA. The SSHAC's investigations have led to the conclusion that technical facilitation and integration is a necessary component for the proper implementation of a PSHA in some instances. In most of these cases, it is anticipated that following the approaches outlined in the report will bring about more consistent interpretations that are supported by the data or bulk of scientific thought. However, if an outlier interpretation persists, it is our firm belief—in agreement with the SSHAC —that the approaches outlined will allow for essential downweighting of that interpretation. This is

preferable to the stiff adherence to an equal weighting scheme, which can result in the final seismic hazard being driven by a single outlier input.

The issues that are raised and discussed in the SSHAC report, especially but not exclusively the process issues, apply in varying degrees to any PSHA project, and should be at least considered by sponsors and analysts before undertaking a PSHA. While the primary focus of SSHAC was on siting critical facilities, it is believed that all PSHA projects should attempt to achieve several primary objectives: 1) proper and full incorporation of uncertainties, 2) inclusion of the range of diverse technical interpretations that are supported by available data, 3) consideration of site- specific knowledge and data sets, 4) complete documentation of the process and results, 5) clear responsibility for the conduct of the study, and 6) proper peer review. Regardless of the level of the study, the goal in the various approaches is the same: to provide a representation of the informed scientific community's view of the important components and issues and, finally, the seismic hazard.

For these reasons, the sponsors believe that the SSHAC report is complete in terms of outlining the process a principal investigator should follow to complete a PSHA. Indeed, the report provides for technical flexibility where such flexibility is needed and, at the same time, encourages standardization of technical approaches and procedures as much as is feasible.

The future utility of PSHA in decision making depends to a large degree on our ability to implement the process in a meaningful and cost-effective way. Development of the SSHAC guidelines was planned with this goal in mind.

EXECUTIVE SUMMARY

Probabilistic seismic hazard analysis (PSHA) is a methodology that estimates the likelihood that various levels of earthquake-caused ground motions will be exceeded at a given location in a given future time period. The results of such an analysis are expressed as estimated probabilities per year or estimated annual frequencies. The objective of this project has been to provide methodological guidance on how to perform a PSHA. The project, co-sponsored by the U.S. Nuclear Regulatory Commission, the U.S. Department of Energy, and the Electric Power Research Institute, has been carried out by a seven-member Senior Seismic Hazard Analysis Committee (SSHAC), supported by a large number of other experts working under the Committee's guidance, who are named in the following "Acknowledgments" section.

The members of the Senior Seismic Hazard Analysis Committee (SSHAC) are:

Dr. Robert J. Budnitz (Chairman)	President Future Resources Associates, Inc.
Professor George Apostolakis	Massachusetts Institute of Technology previously at University of California, Los Angeles
Dr. David M. Boore	Seismologist U.S. Geological Survey
Dr. Lloyd S. Cluff	Manager, Geosciences Department Pacific Gas & Electric Company
Dr. Kevin J. Coppersmith	Vice President Geomatrix
Professor C. Allin Cornell	C. A. Cornell Company
Dr. Peter A. Morris	Applied Decision Analysis, Inc.

The scope of the SSHAC guidance is intended to cover both site-specific and regional applications of PSHA (more broadly, applications in both low-seismicity and high-seismicity regions) in both the eastern U.S. and western U.S. Although the sponsors' primary objective is guidance for applications at nuclear power plants and other critical facilities, the methodological guidance applies in whole or in part, on a case-by-case basis, to a broad range of applications.

The SSHAC guidance involves both technical guidance and procedural guidance, with a strong emphasis on the latter for reasons explained below. Therefore, the audience for the report includes not only analysts who will implement the methodology and earth scientists whose expertise will support the analysts, but also PSHA project sponsors—those decision-makers in organizations such as private firms or government agencies who have a need for PSHA information and are in a position to sponsor a PSHA study.

Note that our guidance is not intended to be "the only" or "the standard" methodology for PSHA to the exclusion of other approaches; there are other valid ways to perform a PSHA study. Likewise, our formulation should not be viewed as an attempt to "standardize" PSHA in the sense of freezing the science and technology that underlies a competent PSHA, thereby stifling innovation. Rather, our guidance is intended to represent SSHAC's opinion on the best current thinking on performing a valid PSHA.

The most important and fundamental fact that must be understood about a PSHA is that the objective of estimating annual frequencies of exceedance of earthquake-caused ground motions can be attained only with significant uncertainty. Despite much recent research, major gaps exist in our understanding of the mechanisms that cause earthquakes and of the processes that govern how an earthquake's energy

propagates from its origin beneath the earth's surface to various points near and far on the surface. The limited information that does exist can be—and often is—legitimately interpreted quite differently by different experts, and these differences of interpretation translate into important uncertainties in the numerical results from a PSHA.

The existence of these differences of interpretation translates into an operational challenge for the PSHA analyst who is faced with (1) how to use these different interpretations properly, and (2) how to incorporate the diversity of expert judgments into an analytical result that appropriately captures the current state-of-knowledge of the expert community, including its uncertainty.

The SSHAC studied a large number of past PSHAs, including two landmark studies from the late 1980s known as the "Lawrence Livermore (LLNL)" study and the "Electric Power Research Institute (EPRI)" study, both of which broke important new methodological ground in attempting to characterize earthquake-caused ground motion in the broad region of the U.S. east of the Rocky Mountains. Most important, the mean seismic hazard curves presented in the reports for most sites in the eastern U.S. differed significantly. However, the median hazard results did not differ by nearly as much. We now understand that differences in both the inputs and the procedures by which the two studies dealt with the inputs were among the key reasons for the differences in the mean curves. At the time this was not understood, and the differences between the mean curves caused not only considerable consternation, but launched several efforts to understand what might underlie the differences and attempts to update the older work.

Ultimately, the inability to understand all of the differences between the LLNL and EPRI hazard results—and the concomitant need for an improved methodology going beyond the late-1980s state-of-the-art—led directly to the formation of the SSHAC to perform this project. However, although the Committee studied both the LLNL and EPRI projects carefully to obtain methodological insights (both positive and negative), it did not undertake a forensic-type review to identify past "errors." Rather, it attempted to draw more broadly upon the entire body of PSHA literature and experience, including of course the LLNL and EPRI projects along with many others, to formulate the guidance herein.

In the course of our review, we concluded that many of the major potential pitfalls in executing a successful PSHA are procedural rather than technical in character. One of the most difficult challenges for the PSHA analyst is properly representing the wide diversity of expert judgments about the technical issues in PSHA in an acceptable analytical result, including addressing the large uncertainties. This conclusion, in turn, explains our heavy emphasis on *procedural* guidance.

This also explains why we believe that *how a PSHA is structured* is as critical to its success as the technical aspects—perhaps more critical because the procedural pitfalls can sometimes be harder to avoid and harder to uncover in an independent review than the pitfalls in the technical aspects. Finally, this also explains why *one of the key audiences for this report is the project sponsor*, who needs to understand the procedural/structural aspects in order to initiate and support the desired PSHA project appropriately.

This Executive Summary will conclude with a brief overview of what the SSHAC believes are its most important findings, conclusions, and recommendations in the procedural area. Because we recognize that several very important pieces of technical guidance concerning the earth-sciences aspects of PSHA will not be discussed in this Executive Summary, the SSHAC requests that readers turn to the full report to review the technical guidance. The key procedural points follow:

1) SSHAC identifies and describes several different *roles for experts* based on its conclusion that confusion about the various roles is a common source of difficulty in executing the aspect of PSHA involving the use of experts. The roles for which SSHAC provides the most extensive guidance

include the expert as *proponent* of a specific technical position, as an *evaluator* of the various positions in the technical community, and as a *technical integrator* (see the next paragraph).

2) SSHAC identifies four different types of consensus, and then concludes that one key source of difficulty is failure to recognize that 1) there is not likely to be "consensus" (as the word is commonly understood) among the various experts and 2) no single interpretation concerning a complex earth-sciences issue is the "correct" one. Rather, SSHAC believes that the following should be sought in a properly executed PSHA project for a given difficult technical issue: (1) a representation of the legitimate range of technically supportable interpretations among the entire informed technical community, and (2) the relative importance or credibility that should be given to the differing hypotheses across that range. As SSHAC has framed the methodology, this information is what the PSHA practitioner is charged to seek out, and seeking it out and evaluating it is what SSHAC defines as *technical integration*.

3) SSHAC identifies a hierarchy of complexity for technical issues, consisting of four *levels* (representing increasing levels of participation by technical experts in the development of the desired results), and then concentrates much of its guidance on the most complex level (level 4) in which a panel of experts is formally constituted and the panel's interpretations of the technical information relevant to the issues are formally elicited. To deal with such complex issues, SSHAC defines an entity that it calls the Technical Facilitator/Integrator (TFI), which is differentiated from a similar entity for dealing with issues at the other three less-complex levels, which SSHAC calls the Technical Integrator (TI). Much of SSHAC's procedural guidance involves how the TI and TFI functions should be structured and implemented. (Both the TI and TFI are envisioned as roles that may be filled by one person or, in the TFI case, perhaps by a small team).

4) The role of *technical integration* is common to the TI and TFI roles. What is special about the TFI role, in SSHAC's formulation, is the *facilitation* aspect, when an issue is judged to be complex enough that the views of a panel of several experts must be elicited. SSHAC's guidance dwells on that aspect extensively, in part because SSHAC believes that this is where some of the most difficult procedural pitfalls are encountered. In fact, the main report identifies a number of problems that have arisen in past PSHAs and discusses how the TFI function explicitly overcomes each of them.

5) For most technical issues that arise in a typical PSHA, the issue's complexity does not warrant a panel of experts and hence the establishment of a TFI role. Technical integration for these issues can be accomplished—indeed, is usually best accomplished—by a TI. In fact, SSHAC has structured its recommended methodology so that even the most complex issues *can* be dealt with using the less expensive TI mode, although with some sacrifice in the confidence obtained in the results on both the technical and the procedural sides.

6) One special element of the TFI process is SSHAC's guidance on sequentially using the panel of experts in different roles. Heavy emphasis is placed on assuring constructive give-and-take interactions among the panelists throughout the process. Each expert is first asked, based on his/her own knowledge (yet cognizant of the views of others as explored through the information-exchange process), to act as an *evaluator*; that is, to evaluate the range of technically legitimate viewpoints concerning the issue at hand. Then, each expert is asked to play the role of *technical integrator*, providing advice to the TFI on the appropriate representation of the composite position of the community as a whole.

   Contrasting the classical role of experts on a panel acting as individuals and providing inputs to a separate aggregation process, the TFI approach views the panel as a team, with the TFI as the team leader, working together to arrive at (i) a composite representation of the knowledge of the group, and then (ii) a composite representation of the knowledge of the technical community at large. (Neither of

these representations necessarily reflects panel consensus—they may or may not, and their validity does *not* depend on whether a panel consensus is reached.)

The SSHAC guidance to the TFI emphasizes that a variety of techniques are available for achieving this composite representation. SSHAC recommends a blending of behavioral or judgmental methods with mathematical methods, and in the body of the report several techniques along these lines are described in detail. A key objective for the TFI is to develop an aggregate result that can be endorsed by the expert panel both technically and in terms of the process used.

7) The TFI's integrator role should be viewed not as that of a "super-expert" who has the final say on the weighting of the relative merits of either specific technical interpretations or the various experts' interpretations of them; rather, the TFI role should be seen as charged with characterizing both the commonality and the diversity in a set of panel estimates, each representing a weighted combination of different expert positions. SSHAC thus sees the TFI as performing an integration assisted by a group of experts who provide integration advice.

8) Thus, the TFI as facilitator structures interaction among the experts to create conditions under which the TFI's job as integrator will be simplified (e.g., either a consensus representation is formed or it is appropriate to weight equally the experts' evaluations of the knowledge of the technical community at large). In the rare case in which such simple integration is not appropriate, additional guidance is provided. In the main report, guidance is presented on two possible approaches involving (i) explicit quantitative but unequal weights (when it becomes obvious that using equal weighting misrepresents the community-as-a-whole); and (ii) "weighing" rather than "weighting", in cases when the experts themselves, acting as evaluators and integrators, find fixed numerical weights to be artificial, and when it is appropriate to represent the community's overall distribution in a less rigid way.

9) The SSHAC guidance gives special emphasis to the importance of an independent peer review. We distinguish between a participatory peer review and a late-stage peer review, and we also distinguish between a peer review of the process aspects and of the technical aspects for the more complex issues. We strongly recommend a participatory peer review, especially for the process aspects for the more complex issues. This paper details the pitfalls of an inadequate peer review.

ACKNOWLEDGMENTS

This project has been jointly supported by the U. S. Department of Energy (DOE), the U. S. Nuclear Regulatory Commission (NRC), and the Electric Power Research Institute (EPRI). The project managers for the three sponsors, whose participation went far beyond managerial support to include technical input as well, and without whom the project could not have been successfully completed, were Jeffrey Kimball and Ann Bieniawski (DOE), Andrew J. Murphy and Ernst G. Zurflueh (NRC), and J. Carl Stepp and John Schneider (EPRI). They were ably supported administratively by Michael P. Bohn of Sandia National Laboratories (DOE) and Jean B. Savy of Lawrence Livermore National Laboratory (NRC), both of whom made technical contributions as well.

Although the intellectual responsibility for the report rests solely with the seven SSHAC members, the task could not have been accomplished without the diligent and very capable contributions of a large number of others who worked in a collaborative mode under the SSHAC Committee's overall direction. These other experts, some of whom ghost-wrote entire subsections or appendices of the report, were:

Don L. Bernreuter, Lawrence Livermore National Laboratory

Michael P. Bohn, Sandia National Laboratories (DOE Project Manager; lead author for the Glossary)

Auguste C. Boissonnade, Lawrence Livermore National Laboratory

Martin W. McCann, Jack Benjamin & Associates Inc. (lead author for Chapter 7)

Robin K. McGuire, Risk Engineering Inc. (author of Appendix G)

Richard W. Mensing, Logicon-RDA (lead author for Chapter 6; author of Appendix D; contributor to Chapter 4 and Appendix A)

Jean B. Savy, Lawrence Livermore National Laboratory (NRC Project Manager)

Gabriel R. Toro, Risk Engineering Inc. (major contributor to Chapter 5; author of Appendices F and I; contributor to Chapter 4 and Appendices A and B)

The SSHAC project organized four different workshops that were attended by a large number of experts representing a variety of disciplines. The participants, who are all listed in the workshop descriptions (see Appendices A, B, C, and H), deserve our thanks for contributing so significantly to the project.

We would also like to thank Norman Abrahamson for contributing an excellent piece of guidance that we have taken the liberty to incorporate herein as Appendix E.

The National Academy of Sciences/National Research Council (NAS/NRC) organized a special "Panel on Seismic Hazard Evaluation" under its Committee on Seismology with the charter to review our report. This review was supported by the U.S. Nuclear Regulatory Commission. The Panel's review comments on our draft report of November 11, 1994 were especially helpful in focusing the SSHAC on key issues that needed extra attention. Besides the NAS/NRC Panel's review, we had the benefit of informal review comments on the November draft from about a dozen other specialists and organizations for which we are very grateful. The comments of the NAS/NRC Review Panel, which were published separately by the National Academy Press, are included in this report as an Appendix to Volume 1.

Finally, the logistical work of pulling the report together, based on input from many different authors typing on many different word processors, was accomplished in an outstanding manner by Rosa I. Yamamoto of LLNL, whose skill and dedication the SSHAC gratefully acknowledges.

GROUND MOTION WORKSHOPS I & II

Appendices A & B

APPENDIX A

GROUND-MOTION WORKSHOP I
MARCH 17-18, 1994
BOULDER, COLORADO

A.1 INTRODUCTION

As the SSHAC deliberations progressed, it became clear that expert elicitation would be one of the main topics of the final report. SSHAC decided to hold several workshops dealing with ground-motion issues to test some of the ideas regarding elicitation that emerged from the deliberations. The primary purpose of the workshops was to test the concept of integration and facilitation by an Integrator, one entity responsible for representing the composite state of information of the community of ground-motion experts (later, we renamed this entity "Technical Facilitator/Integrator," or TFI). The Integrator process to be tested was explicitly contrasted with the alternative approaches of using models (including using one and only one model), using multiple models with explicit numerical weights, and using one core model with other models for support. One of the hypotheses we wished to test was that the Integrator process, based explicitly on the principle that there is "no one correct model," would reduce the participants' tendencies to view themselves as advocates or "proponents" and would accentuate their role as scientists with different scientific hypotheses (this, in fact, is just what happened in the second workshop). In addition, we believed that the process of structured interaction among the experts could be improved beyond what was done in previous ground-motion elicitation efforts. The workshop also helped test and strengthen the distinction between the "proponent" and "evaluator" roles of the experts (see Chapter 3).

A second purpose of the workshop was to capture the current state of thinking regarding the issues in predicting ground motions in central and Eastern North America (CENA) for use in PSHA, and hopefully in providing specific guidance about these issues.

We originally planned two workshops, each of which focussed on a different ground-motion issue: the first on uncertainty and the second on central estimates of ground-motion amplitudes. As planning for the first workshop progressed, we came to the realization that uncertainty is intimately tied to the underlying ground-motion model, and therefore we should concentrate on these models rather than on the uncertainty in the elicitation. We planned two workshops. Workshop I examined the general methods for ground-motion prediction and presented SSHAC's views about uncertainty. This first workshop set the stage for the second workshop, which was focussed on elicitation of central estimates and uncertainties in ground-motion amplitude for specific magnitudes and distances. This appendix discusses Workshop I; Workshop II is covered in Appendix B.

A.2 DESIGN AND ORGANIZATION

The design of Workshop I evolved from seven planning meetings that involved a core planning group composed of D. Boore, C.A. Cornell, R. Mensing, P. Morris, and G. Toro. This unusually large number of meetings is explained by the evolution of the focus of the workshop described above. The first meeting was held about five months before the workshop.

After careful deliberation, a list of invited attendees was prepared by the planning committee. As usual, the committee had to grapple with the competing factors of too large a group stifling discussion and too small a group not encompassing the range of views about the subject. The final list represents a compromise that we feel struck a good balance between the two conflicting requirements. The list of attendees is given in Table A-1. The attendees included the integrators (discussed below), invited participants, and observers.

In this workshop, the Integration Team was comprised of four individuals with a combination of ground-motion and elicitation expertise. The group interaction was led by two facilitators, one with ground-motion expertise (D. Boore) and one with elicitation expertise (P. Morris). Two other Integrators (C.A. Cornell and R. Mensing) aided in questioning and interpreting the

TABLE A-1
ATTENDEES AT SSHAC
GROUND-MOTION WORKSHOP I

Integrators:

David M. Boore, SSHAC
C. Allin Cornell, SSHAC
Peter Morris, SSHAC
Richard Mensing, Logicon-RDA

Invited Participants:

Norman A. Abrahamson, Consultant
Gail M. Atkinson, Consultant
Don Bernreuter, Lawrence Livermore National Laboratory
Kenneth W. Campbell, EQE
Robert B. Herrmann, Saint Louis University
Klaus Jacob, Lamont-Doherty Earth Observatory
William Joyner, U.S. Geological Survey
Chandan Saikia, Woodward-Clyde Consultants
Walter J. Silva, Pacific Engineering and Analysis
Paul Somerville, Woodward-Clyde Consultants (via telephone)
Gabriel R. Toro, Risk Engineering, Inc.
Mihailo Trifunac, University of Southern California
Daniele Veneziano, Massachusetts Institute of Technology
Robert Youngs, Geomatrix Consultants

Observers:

George Apostolakis, SSHAC
Ann Bieniaswski, U.S. Department of Energy
Mike Bohn, Sandia National Laboratory
Auguste Boissonnade, Lawrence Livermore National Laboratory
Nilesh Chokshi, U.S. Nuclear Regulatory Commission
Tom Hanks, National Academy of Sciences
Jean B. Savy, Lawrence Livermore National Laboratory
John F. Schneider, Electric Power Research Institute

experts and in performing the final integration. The Integrator team was responsible for the following functions:

- Structuring and facilitating complete information and judgment exchange among the experts
- Ensuring consistent databases and terminology
- Staging interactive debates among experts in critical areas
- Eliciting from the experts the strengths and weaknesses of different methods for ground-motion prediction
- Obtaining agreement on a representative set of state of the art methods.
- Deciding on which methods to consider explicitly in Workshop II.

Specific questions the workshop was designed to address regarding the Integrator process included:

- Would it be possible to have a useful structured discussion focused on basic ground-motion prediction methods rather than on individual expert opinions?
- Would the "active listening" process work in the ground-motion expert community?
- Would the explicit de-emphasis on choosing the "best" model and not numerically weighting different models promote an enhanced, less emotional information exchange?
- Would the meeting, with its heavy emphasis on information exchange and structured interaction, provide useful information to the Integrators; i.e., how hard wi it be for the Integrators to integrate?

The meeting was held in the Hotel Boulderado in Boulder, Colorado on March 17 and 18, 1994. The participants were sent a short set of instructions (Attachment A-1) as well as a paper on uncertainty prepared by G. Toro (a revised version of which is given in Appendix F) to help them prepare for the meeting. Five of the participants were asked to give oral

presentations on ground-motion prediction methods. The methods and presenters were identified by the planning committee. The presenter for each method had been closely involved in the development and application of that method. These presenters were sent an additional set of instructions (Attachment A-2). The intent was for a broad overview rather than a detailed exposition of the method. Unfortunately, some of the presenters apparently did not understand the charge to them, and therefore not all presentations fulfilled the goal of the planning committee. The lesson is that more verbal communication with each presenter is required, to make sure they understand what is being asked of them.

The Agenda (Attachment A-3) contained three SSHAC presentations (introduction, discussion of elicitation, and characterization of uncertainty), followed by the five reviews of methods for obtaining ground-motion values for use in PSHA. The Integrators then led several discussions of the methods. On the second day, the participants were asked to complete a survey (Attachment A-4). While the survey was being completed, the Integrators met to discuss what had taken place in the workshop; their conclusions were presented to the participants in the closing session, which also allowed for feedback from the participants. After the workshop, a detailed analysis of the survey was completed by one of the Integrators (P. Morris).

A.3 SUMMARY OF PRESENTATIONS

The following is a summary of the formal presentations by SSHAC members and invited presenters. In addition, this summary contains two brief presentations by D. Veneziano.

A.3.1. Introduction (D.Boore)

This presentation outlined the purposes of Workshop I, which were as follows:

- (Main) Examine and compare various methods (classes of models) available for prediction of ground motion in the central and eastern United States for use in seismic hazard analysis.

- (Second) Describe and elicit feedback about a different procedure for eliciting information from ground-motion experts.

- (Third) Present and discuss a proposed framework for the characterization of uncertainty in ground-motion predictions.

A.3.2. Elicitation: Past, Present, Future (P. Morris)

This presentation provided a summary of the approaches used in past efforts at ground-motion elicitation and integration, and described the approach proposed by SSHAC.

The two most significant past elicitation efforts were those of EPRI and LLNL in the late 1980's and LLNL in 1992. In the EPRI study, a limited number of ground motion models were selected for use in seismic hazard analysis. This approach included extensive discussions and interactions between members of a working group and with outside experts, but the ultimate selection of ground-motion models was made by a small group of analysts/experts. The advantage of this approach is that there is significant interaction within the working group. The drawback of this approach is that there is a negative perception because the final choice of models was not made directly by multiple experts.

In the latest LLNL study, a group of approximately six experts were asked to provide estimates of ground-motion amplitudes and associated aleatory and epistemic uncertainties, at selected magnitudes and distances. These estimates were in the form of joint probability

distributions, not necessarily lognormal or independent, for the aleatory and epistemic uncertainties. The advantage of this approach is that the final ground-motion estimate (in this case, expressed in non-parametric form) is derived directly from the experts. The drawbacks of this approach are that relatively little effort was made to have the experts "defend" their estimates, and there was relatively little interaction between experts about their interpretations and estimates.

The elicitation and integration approach proposed by SSHAC will take place in two phases, and will be led by a small group of Integrators who will take an active role in guiding and focusing discussions, eliciting information, and integrating the information. Morris described the two phases as follows:

1. **Initial Elicitation: Estimation Approaches (Workshop 1).** This phase contains extensive discussion and interaction about ground-motion estimation methods by experts representing the principal classes of models, e.g., intensity models, empirical models, stochastic models, and semi-empirical models. Discussion, as guided by the Integrators, is intended to focus on the methods, not the work/inputs of individual experts or on model-specific parameter values or details; its goals are to isolate sources of disagreements between methods and the attributes of the various methods and to identify areas of agreements between experts. Discussions are designed to be based on active listening and to foster constructive feedback by participants.

   Integrators formulate, based on the discussions from the first workshops and their collective judgement, a position on which classes of models are to be pursued in the second phase, based on their given state of development.

2. **Final Elicitation: Ground-Motion Predictions (Workshop 2).** Using the results of the first workshop, Integrators develop a process for eliciting the appropriate ground-motion information based on the methods selected. Inputs to be elicited include

estimates of median amplitudes at specified magnitude-distance pairs, aleatory uncertainty, and epistemic uncertainty.

Finally, the Integrators aggregate information derived from the elicitations into a composite model. Details of the aggregation procedure are to be presented at the second workshop.

Several panelists expressed strong opinions about the need to be informed about how their inputs are to be used. They would like to know what difficulties are encountered with their inputs, and what are the results of their inputs. They stated that such feedback was absent from past ground-motion elicitation efforts.

A.3.3. Proposed Framework for Characterizing Ground-motion Uncertainties (G.Toro)

This presentation provided a framework for the treatment of uncertainty. This framework partitions uncertainty using a two-way classification: epistemic versus aleatory and parametric versus modeling. This partition is particularly useful in the context of models having physical parameters, because it helps in capturing all sources of uncertainty. An expanded version of this presentation is contained in Appendix F.

A.3.4. Reflections in the Nature of Uncertainty in PSHA (D. Veneziano)

This presentation discussed the partition of uncertainty and presented a series of examples to illustrate the arguments presented. The following is a short list of the key arguments.

1. With respect to a specific model, one may separate epistemic and aleatory uncertainty. With respect to nature, all uncertainty in PSHA is epistemic because the underlying physical processes are deterministic, albeit complex.

2. Although there is no need to differentiate among components of uncertainty, it may be useful to differentiate during the intermediate steps of PSHA in order to ensure that all components of uncertainty are captured.

3. A finer differentiation of components of uncertainty and the separate propagation of these components may lead to additional complexity and lack of transparency in PSHA results. This additional complexity should be avoided. Moreover, there should be an effort to streamline PSHA.

A.3.5. Intensity Methods (M. Trifunac)

The main reason for using Intensity-based methods for predicting ground motions is that most of the earthquake-size data in seismicity catalogs is in the form of (or is based on) epicentral-intensity (I_0) measurements. This was true in the past and it is still true in many parts of the world. Another reason is that site intensity (I_S) is directly related to damage.

The most serious difficulty in using intensity-based methods is that there are few data for the development of relations to predict instrumental ground-motion amplitudes (e.g., peak acceleration, spectral acceleration) from site intensity and site conditions. Although it is recognized that these relationships should also include magnitude and distance for theoretical reasons (i.e., they should be of the form $\ln A=f[I_S$, site conditions, m, r]), magnitude and distance terms are not included for lack of data and because those terms would make the relationships non-transportable from one region to another.

Another difficulty is that there are many intensity scales in use throughout the world and that the assignment of intensities contains a subjective element.

Examples were presented showing graphs and equations for peak acceleration, peak velocity, peak displacement, and Fourier amplitude, given I_S and site category.

Another application was presented using intensity data from eastern Europe, showing the data used, the relationship among the various intensity scales used, and the procedure to compute the distribution of distance to isoseismals. Results from the intensity-attenuation analysis are in the form of probability distributions of distance to the isoseismal for I_S, given I_0; they should be applied in this form in seismic-hazard analysis.

Another application compares two seismic-hazard maps for 0.9-sec spectral velocity and 100-year return period in the Los Angeles area. One map was obtained working directly with attenuation equations for spectral velocity; the other was obtained using intensity attenuation relations and relationships between intensity and spectral velocity. The two hazard maps are similar but not identical, with the latter map showing slightly higher amplitudes at some locations.

A.3.6. Notes on Intensity Methods and on the Joint use of Intensity Methods, Instrumental Data, and Physical Models (D. Veneziano)

This presentation illustrated the proper mechanics of deriving attenuation equations for instrumental ground motions in CENA (or any region where there is intensity data and there is little or no instrumental data) as a function of magnitude and distance, using intensity-attenuation relationships. This process requires knowledge of three probabilistic relationships for the region of interest. These three relationships may be written as conditional probability distributions; i.e., $(I_S|I_0,R)_E$, $(I_0|M)_E$, and $(Y|I_S,M,R)_E$, where subscript E (East) refers to CENA and Y denotes instrumental ground-motion amplitude. Difficulties arise because the relationship $(Y|I_S,M,R)_E$ is not available. The conventional practice has been to assume that $(Y|I_S,M,R)_E=(Y|I_S,M,R)_W$, where subscript W (West) denotes western North America, thereby assuming that differences between east and west are limited to the first two relationships.

Two approaches were proposed to alleviate this difficulty. The first approach would derive $(Y|I_S,M,R)_E$ using physical models. The second approach would transform an empirically derived $(Y|I_S,M,R)_W$ into $(Y|I_S,M,R)_E$ using physical models. Finally, a unified approach was sketched, which combines the above two approaches and also makes use of instrumental data from eastern North America.

A.3.7. Empirical Methods (K. Campbell)

Two approaches are possible for the empirical prediction of ground motion for CENA (or for any region where there is limited instrumental data). The first one is direct empirical regression using data from CENA. This approach is not satisfactory at present because the data are limited, particularly in the magnitude-distance region of interest. Several graphs were used to illustrate this point.

The second approach consists of modifying attenuation equations obtained using data from western North America (WNA), to account for known differences between CENA and WNA. This approach rests on the assumption that ground motions at short distances are the same in both regions. This second approach was the focus of the presentation.

The modifications must take into account the following factors:

1. Magnitude. Depending on which magnitude scale is used to characterize seismicity, it may be required to convert the attenuation equations from moment magnitude to m_{bLg}. Magnitude modification was not required in the application presented as an example.

2. Stress Drop. Based on the current thinking that stress-drop differences are not large, no modification for stress drop is applied.

3. Differences in geometric and anelastic attenuation. These differences are important, except at short distances and require the use of modification factors.

4. Differences in distance measure. Most WNA attenuation equations use some form of minimum distance to the rupture or projection of the fault. Because magnitudes are typically lower in CENA and because most PSHA studies in CENA use area sources, hypocentral or epicentral distance is often used. Differences in the distance measure affect the attenuation equation and the residual standard deviation.

5. Differences in site conditions. Most strong-motion data in WNA come from soil sites and the more robust WNA attenuation equations are those for soil. Most CENA attenuation equations are derived for rock site conditions, because most CENA data come from seismograph stations founded on rock.

The modification for site conditions uses the amplification factors recently proposed by Roger Borcherdt (USGS) for use in building codes. These factors are used to convert the WNA soil predictions to rock.

The modification for geometric and anelastic attenuation effects is obtained by applying a stochastic ground-motion model, making predictions for rock site conditions in both CENA and WNA and then computing their ratio as a function of frequency, magnitude, distance. This ratio is then used as a modification factor that multiplies the WNA empirical attenuation equations.

The modification for differences in distance measures assumes that both the attenuation equations in terms of rupture and hypocentral distance predict the same amplitudes for some pre-specified magnitude-distance combination. This resulting modification may be different for different WNA attenuation equations.

Epistemic uncertainty is introduced by considering multiple WNA attenuation equations, thereby obtaining multiple CENA attenuation equations. Epistemic uncertainty in the modification factors is not considered.

One advantage of this approach is that extended-source effects and other effects that may cause saturation are automatically captured.

Examples were presented showing the attenuation equations obtained for a particular site and comparing the predicted response spectra to those obtained using a stochastic method.

A.3.8. Stochastic Methods (G.Atkinson)

The basic assumptions of most stochastic models are that ground motions may be represented as a finite-duration segment of a stationary gaussian random process and that we know enough about earthquakes (particularly in CENA, where these methods are used the most) to be able to predict the expected Fourier power spectrum and duration of the ground motion for any magnitude-distance combination of interest.

The Fourier amplitude spectrum is generally written in the form $A(M,R,f)=E(M,f)\times D(R,f)$, where E represents the source spectrum, D represents attenuation effects, **M** is moment magnitude, R is hypocentral distance, and f is frequency. Specification of duration T(**M**,R) is also required in order to calculate root-mean-square (rms) and peak time-domain amplitudes.

The most controversial piece of the model is the source spectrum E(M,f) and its dependence on M. Information on the source spectrum of CENA earthquakes comes from various sources as follows:

1. At low frequencies (<< 1 Hz): from estimates of seismic moment.

2. Near 1 Hz: from Street and Turcotte's compilation of regional recordings, from Boatwright and Choy's analyses of teleseismic recordings of the larger intraplate events, and from records obtained using strong-motion instruments at distances within 200 km.

3. At higher frequencies (above the event's corner frequency): Eastern Canada Telemetered Network (ECTN) records, records obtained using strong-motion instruments at distances within 200 km, and from intensity data (felt area exhibits high correlation with the high-frequency Fourier amplitude).

The ECTN data set, which is the largest of these data sets, is composed in large part of earthquakes with M≤5 and R>100 km.

Traditionally, E(M,f) has been characterized by a Brune spectrum with stress drop of approximately 100 bars. As more data have been collected, it has become apparent that the spectral shapes predicted by the Brune model deviate systematically from the observed spectral shapes. Figures were shown indicating that 1-Hz Fourier amplitudes are consistent with a 50-bar Brune model, whereas 10-Hz amplitudes are consistent with a 200-bar Brune model. Another example is provided by the Fourier spectra of the station S-16 recordings from the 1988 Saguenay earthquake.

Based on these observations, a model with two corner frequencies was proposed by Atkinson. The dependence of the two corner frequencies on M was derived empirically from the data listed above. This model is not too different from the Brune model for M≅5. For larger

earthquakes and for frequencies lower than 0.5 Hz, this model predicts significantly lower Fourier amplitudes than the Brune model.

The attenuation effects D(R,f) are generally divided into three physical mechanisms, as follows:

1. Geometric attenuation, representing elastic wave-propagation effects, the simplest form of which is R^{-1}.

2. Crustal anelastic attenuation, represented by the quality factor Q, which may be frequency-dependent.

3. Phenomena controlling the shape of the Fourier spectra at frequencies of 10 Hz and higher, generally explained as near-site anelastic attenuation and characterized by the cutoff frequency f_{max} and the attenuation parameter κ.

The available data are sufficient to determine the combined effect of geometric attenuation and Q, with little uncertainty at all distances greater than 15 km. These data are not sufficient to resolve between the two mechanisms.

Fewer data are available for determining the spectral shape at high frequencies (represented by f_{max} or κ), due to bandwidth limitations of the instruments and to lack of records at R<100 km. In addition, there is considerable site-to site variability: some records suggest κ<0.003 sec, others suggest κ=0.03 sec (typical of WNA).

Duration increases with distance due to wave-propagation effects. This tendency is seen even at distances shorter than the distance of the first Moho reflection. The following expression has been used to represent duration as a function of magnitude and distance:

$T(M,R)=T_{src}(M)+0.05R$, where T has units of sec, R has units of km, and T_{src} is the source duration.

In summary, the strengths of the stochastic method are its conceptual simplicity and its versatility (e.g., can accommodate a variety of model assumptions, is amenable to a formal treatment of uncertainty). The limitations of the method relate to the uncertainty in model parameters, due to limitations in the data. In particular, there are no data to verify the predictions for large M. These limitations are common to any methods that are used to predict ground motions in CENA.

A.3.9. Empirical Source Function Method (C. Saikia and P. Somerville)

In the current form of this method, empirical source functions (ESF's) are used to simulate the portion of the ground motion above 1 Hz and a deterministic method is used to simulate the portion below 1 Hz. In the discussion that follows, the term "ESF method" will refer to this hybrid approach.

For both portions of the simulation, the rupture plane is divided into a number of rectangular sub-faults. The slip in each sub-fault is given by a pre-specified slip distribution. The total ground motion is generated as the sum of the ground motions from the various sub-faults.

In the ESF portion of the simulation, the effects of source radiation and scatter are captured empirically by using recorded ground motions from small earthquakes, corrected for path effects. Path effects are quantified using generalized ray theory or frequency-wavenumber integration. Site effects are introduced in the form of a frequency-domain correction to account for differences in parameter kappa.

In the deterministic portion of the simulation, source effects are represented by means of theoretical source functions, using a pre-specified spatial and temporal distribution of slip. Path effects are quantified using frequency-wavenumber integration.

In the final step, the ESF and deterministic time histories are combined by using matched filters.

The validity of this method has been demonstrated by comparisons to data in California and in CENA. Some comparisons are in terms of amplitudes as a function of distance for a given event, other comparisons are in terms of observed and modeled time histories for a given record.

The ESF method requires specification of the following parameters:

1. Rupture dimensions for a given seismic moment. Typically, the Somerville et al. (1987) relationship is used.
2. Rupture geometry (strike angle, dip angle, depth range) and location of the site.
3. Spatial distribution of slip along the rupture (or an algorithm to generate artificial slip distributions) and rake angle.
4. Layered crustal structure (layer thicknesses, seismic velocities, densities, and Q values). The EPRI (1993) crustal regionalization of CENA may be used to obtain these data.
5. Site kappa value.

The ESF method has been extensively validated by comparing predicted to observed amplitudes. Results shown using the ESF-deterministic method for 16 near-fault Loma Prieta

stations show no significant bias over the 0.2-30 Hz frequency range (bias arises below 1 Hz if only time histories simulated using empirical source functions are used for the entire frequency range). The standard deviation of the residuals (representing modeling uncertainty) is approximately 0.45 (natural-log units) over the entire frequency range. Predictions made by Saikia (1993) for a **M** 7 thrust earthquake in the Elysian thrust system are consistent with observed peak accelerations from the 1994 Northridge earthquake. The ESF method is applicable to all magnitudes, distances, and frequencies of engineering interest.

The strengths of the ESF method are as follows:

1. It uses the same wave-propagation methods that are used by seismologists to invert for the source characteristics of past earthquakes.
2. It can make use of data to be obtained by the new broadband stations of the National Seismic Network.
3. It has been extensively validated against strong-motion data from California and against some CENA data.
4. It predicts CENA motions with slightly lower bias and standard error than the stochastic method.
5. It is especially useful for CENA locations where crustal-structure and source data are available but no ground-motion data are available.

The weaknesses of the ESF methods are as follows:

1. Green's functions do not include the effects of scattering and of non-planar structures. These effects may be important at high frequencies. Scattering effects are included implicitly in the empirical source functions. This does not allow adjustments for regional differences in scattering or for the effect of distance.
2. Requires knowledge of the crustal structure and substantial computational effort.

A.4. OBSERVATIONS AND LESSONS

Workshop I had two positive outcomes. First, we were able to test each of our hypotheses about ground-motion elicitation to some degree. Second, the Integrator process appeared to be very successful. Its credibility was strengthened as a candidate for the SSHAC-recommended elicitation process, at least in the ground-motion arena. Here are some of the more pertinent results:

- Workshop I brought together many experts, helping to draw in, for broad consideration, very diverse points of view. This format proved useful for identifying methods and issues that should receive further consideration. A workshop of this type is not sufficient, in and of itself, and it must be followed by a more focused workshop.

- The approach of conditioning the conversation on different fundamental methods for ground-motion prediction proved to be extremely successful. From a facilitation perspective, the discussions naturally focused on technical debates rather than on personal disagreements.

- There was remarkable agreement on the relative strengths and weaknesses of the various models. Dave Boore summarized observations about the strengths and weaknesses of the models, and the group accepted the summaries without apparent reservation, even those who supported the less popular models.

- There was also remarkable agreement among the experts regarding the following issues: 1) <u>unequal</u> weights for the various methods are appropriate, 2) these weights may vary as a function of magnitude and distance, and 3) the values of the weights for the different approaches. It was clear in the group interaction that most of the experts preferred certain models over others, and that this preference depended on the application (characterized by magnitude, distance, and spectral

frequency). The survey results presented below quantify this observation, but it was also a clear qualitative signal from the structured interaction.

- A consensus developed on the set of ground-motion models that define the current state of the art. While there are many flavors of each basic model form, the Integrators proposed an initial list, and the group refined the list into five ground-motion models (direct empirical, hybrid empirical, empirical source function, intensity-based, stochastic [single corner], and stochastic [two corner]). The group agreed that these five methods define a representative set.

- There was apparent clear group understanding about the details of each method except for the Empirical Source Function method. (The Integrators were briefed by N. Abrahamson at a later meeting in order to help them understand the details of this method. Abrahamson also prepared Appendix E.)

- While there was clear group understanding at a conceptual level about the models, it was also clear that the group format is not appropriate for complete and detailed information exchange. To obtain a more complete understanding of the implications of the models, one must assemble a much smaller group of experts and one must stage discussions focused on specific model estimates and on the effects of model assumptions and parameter values. This was the motivation for Workshop II.

- The information provided was indeed useful for the Integrators. The structured discussion and the survey were directly useful in designing the next, more detailed, elicitation stage (Workshop II and the mail exchanges that preceded it). Even if there had been no follow-on workshop, the information developed would have been useful in helping the Integrators make a final numerical ground-motion assessment at this stage.

- The experts did not appear to have problems assigning weights to the various methods (as opposed to assigning weights to other experts). All experts but one assigned explicit weights in the survey, and the expert who did not provide weights refused on general principles, not because he regarded the weights as a stigma in any sense. This is a very positive result, because, in general, there is a great deal of empirical evidence that experts are very reluctant to assign weights to one another.

- The workshop also validated the notion that the Integrator should be minimally a team that consists of someone with functional knowledge of the subject matter (in this case, ground motion) and someone with experience and knowledge in elicitation methods. The functional knowledge was especially valuable in clarifying the scientific interchange and in summarizing points on which there appeared to be clear points of group agreement or disagreement. The elicitation expertise was useful in designing the structure for expert interchange, formulating the expert survey, and setting the "tone" and format for the interaction.

- Discussions during the workshop highlighted the practical and philosophical difficulties in defining and quantifying uncertainty, particularly epistemic uncertainty. Generally, experts are most comfortable at specifying their "best-shot" models. Aleatory uncertainty is easily grasped if it can be related to scatter in observations, but it becomes more difficult if it involves propagation of parameter uncertainties. The partition of uncertainty into four categories is helpful for some experts but not for others.

Because of time and resource limitations, the workshop explicitly did not include some elements that are likely to be part of any final elicitation process. We did not conduct individual interviews, which would have helped to make sure that the methods were described in a common format and language. The presentations were not as focused and pre-structured as they could have been -- e.g., a common format would have been useful, graphical communication schemes such as influence diagrams would have streamlined communication,

and prescribing common terminology would also have helped. Finally, there was not much time for the experts to reflect and iterate. Some of these aspects that were left out were the motivation for holding a later follow-up workshop (described in Appendix B).

A.5 RESULTS OF THE INTEGRATOR SURVEY

The survey that was handed out to the thirteen ground-motion experts is included as Attachment A-4[1]. This section summarizes the overall results of the survey, focusing on the summary data provided in Tables A-2, A-3 and A-4. A great deal of additional interesting and useful information is provided in Attachments A-5 through A-8, whose contents are briefly described here:

Attachment A-5: Expert Inputs on Comparison of Methods. These tables summarize the experts' ratings on method logic, use of data, parameter estimation, and credibility of the various methods. These tables help explain the overall ratings in Table A-2.

Attachment A-6: Experts' Written Comments on Comparison of Methods. The experts provided a great deal of supporting information in the form of written comments that explain their inputs. This information is crucial for a detailed understanding of the relative credibility each expert assigned to each method.

Attachment A-7: Detailed Expert Inputs on Using the Various Methods for Forecasting. This is the raw input, expert-by-expert, application-by-application, that formed the basis for the aggregated data shown in Table A-3.

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[1]In attachments A-4 through A-8, the Empirical Source Function (ESF) method is referred to as the "Advanced Numerical" method.

Attachment A-8: Detailed Expert Inputs on Preferences of the Overall Expert Community.

This is the raw input, expert-by-expert, application-by-application, that formed the basis for the aggregated data shown in Table A-4.

The basic results of the survey are most easily understood by reviewing Tables A-2, A-3 and A-4, which are discussed below.

Overall Rating (Table A-2). Table A-2 shows rather dramatically that the experts do not regard the five methods as equally attractive. The numbers in the figure were derived by assigning a 0-10 scale (0 = "poor, low" and 10 = "excellent, high") to the expert ratings on the first page of the survey. While the numbers are somewhat arbitrary, nevertheless there is a striking, remarkably consistent pattern of preference towards the stochastic and empirical source function methods and a lack of preference for the intensity-based method. This is also demonstrated by the two rows at the bottom of the table, which indicate--for each method--the number of experts that rated that method the highest among the five methods and the number of experts that rated that method the lowest among the five methods. For example, nine out of the thirteen experts rated the stochastic model at least as highly as any of the others, and none of the experts rated the stochastic model the lowest. In contrast, only one expert rated the intensity-based method highest, while nine out of the thirteen experts rated it lowest.

It is important to note from other parts of the survey that the relative attractiveness of the five methods depends in some cases heavily on the magnitude, distance, and structural frequency. Further, it is very clear that the approach of assigning equal weights to the various methods would not capture the sense of the ground-motion community, as represented by these thirteen experts.

Using the Methods for Forecasting (Table A-3). Probably the most interesting results of the survey are presented in Table A-3. This table averages the weights for each of the models over the thirteen experts in each application (the expert-by-expert weights are presented in Attachment A-7). Once again, the most striking observation is that *the weights are definitely unequal.* In fact, a close examination of the detailed expert inputs in Attachment A-5 reveals a good amount of consistency among the bulk of experts in how they weight the methods for each application (although there are clearly a few outlier opinions).

A number of interesting observations can be made about the weights in Table A-3, including:

- Consistent with Table 1, the stochastic and empirical source function methods tend to get the highest weights, while the intensity-based and hybrid empirical tend to get the lowest weights.

- The weights are, in some cases, heavily a function of the application. For example, the direct empirical method gets much more weight at 5.5 magnitude than at 7.0 magnitude, clearly because this is where data are available. The empirical source function method gets relatively higher weight for the higher magnitude, as does the hybrid empirical method.

- It is important to note that the weights, as well as the overall ratings in Table A-2, are consistent with the expert discussion.

Preferences of the Overall Expert Community (Table A-4). Table A-4 shows the average weights, averaged over thirteen experts, indicating how the experts feel the overall expert community would rate the five methods. The most relevant observation about this table is that, in aggregate, the percentages in this table are roughly consistent with the weights in Table A-3, which indicates that the thirteen experts generally feel that they are representative of the overall ground-motion expert community. However, there are at least a couple of interesting differences between the two tables:

- The experts apparently feel that the overall ground-motion expert community would be even less positive about the intensity-based method than themselves.

- For some reason, the thirteen experts felt that the overall ground-motion community would rate the direct empirical method higher for frequency 1 Hz and magnitude 7.0 than the thirteen experts rated it (18, 16, 10 versus 4, 4, 3). This is true to a lesser extent for the 10 Hz frequency applications.

TABLE A-2

INTEGRATOR SURVEY: OVERALL RATINGS

(Scale: 0=poor, low; 10=excellent, high)

Expert	Stochastic	Empirical Src. Funct.	Direct Empirical	Hybrid Empirical	Intensity Based
1	8	8	10	8	0
2	8	10	10	5	5
3	8	8	0	5	2
4	10	×	×	×	×
5	10	8	0	5	0
6	8	8	5	2	0
7	8	8	5	8	0
8	10	8	10	5	0
9	8	6	5	5	0
10	8	8	0	2	2
11	10	8	5	2	0
12	5	2	×	×	8
13	8	8	10	2	0
Average	**8.4**	**7.5**	**5.5**	**4.5**	**1.4**
High Rank[1]	**9**	**5**	**4**	**1**	**1**
Low Rank[1]	**0**	**1**	**3**	**1**	**9**

[1] High Rank (Low Rank) indicates the number of experts that gave this method the highest (lowest) score. If two methods are tied for the highest (lowest) score, both methods are counted as highest (lowest).

TABLE A-3

INTEGRATOR SURVEY: USING THE APPROACHES FOR FORECASTING

How would you expect to weight the results if all five approaches were applied to a specific site application? (weights averaged over 13 experts)

Frequency	1	1	1	1	1	1	10	10	10	10	10	10
Magnitude	5.5	5.5	5.5	7.0	7.0	7.0	5.5	5.5	5.5	7.0	7.0	7.0
Distance	5	70	200	5	70	200	5	70	200	5	70	200
	WEIGHTS											
Stochastic	38	38	38	41	42	45	38	41	42	45	47	50
Empirical Src. Funct.	22	20	22	28	29	32	18	18	19	27	25	29
Direct Empirical	26	29	28	4	4	3	27	29	28	4	4	3
Intensity Based	10	8	9	13	12	11	9	8	8	13	12	10
Hybrid Empirical	4	4	3	13	13	9	9	4	3	12	12	8

TABLE A-4

INTEGRATOR SURVEY: PREFERENCES OF THE OVERALL EXPERT COMMUNITY

What percentage of the ground-motion community would you expect to favor each method if they could only choose one? (percentages averaged over 13 experts)

Frequency	1	1	1	1	1	1	10	10	10	10	10	10
Magnitude	5.5	5.5	5.5	7.0	7.0	7.0	5.5	5.5	5.5	7.0	7.0	7.0
Distance	5	70	200	5	70	200	5	70	200	5	70	200
	PERCENTAGE											
Stochastic	41	41	43	44	42	48	39	43	46	47	49	51
Empirical Src. Funct.	21	21	23	26	29	31	20	19	20	29	29	29
Direct Empirical	28	28	27	18	16	10	27	28	26	11	9	9
Intensity Based	6	5	4	6	5	5	6	5	4	6	6	5
Hybrid Empirical	4	6	3	8	8	7	9	5	3	7	8	6

ATTACHMENT A-1

GROUND-MOTION WORKSHOP I

WRITTEN INSTRUCTIONS MAILED TO INVITED EXPERTS

SSHAC FIRST GROUND-MOTION ELICITATION WORKSHOP
March 17 and 18, 1994

INSTRUCTIONS FOR EXPERTS

You have been asked to attend the first SSHAC Ground Motion Elicitation Workshop, in the capacity of Ground Motion Expert.

SSHAC (Senior Seismic Hazard Analysis Committee) is a panel of engineers, seismologists, and geologists with experience in seismic-hazard analysis and in risk analysis in general. Its task is to develop a new, more stable, methodology for seismic hazard analysis, drawing on the experience from the EPRI and LLNL seismic-hazard studies and from other major seismic-hazard studies performed in the last five years. The SSHAC effort is sponsored by DOE, EPRI, and NRC.

The main objective of this workshop is to examine and compare the various approaches available for the prediction of ground-motions in the central and eastern United States for the purposes of seismic hazard analysis. The term "approach" is used here in a broad sense, representing a whole class of methods and including variants proposed by other authors. The following approaches will be presented and examined:

- Advanced numerical modeling (empirical Green's functions)
- Empirical regressions
- Intensity based approach
- Stochastic (source-spectrum based) approach

The second objective of the workshop is to test a different procedure for the elicitation of information from ground-motion experts. The proposed procedure will differ from past elicitations in three main aspects, as follows: (1) there will be more interaction, in order to clarify--and hopefully resolve--differences among experts, (2) a small group of integrators will take an active role in guiding and focusing the discussion, and (3) the integrators will formulate, based on the discussions and on their collective judgment, a position on which approaches are to be pursued, given their current state of development.

The third objective of the workshop is to present and discuss SSHAC's proposed framework for the characterization of uncertainty in ground-motion predictions. To meet this objective it is important that you read and study the paper entitled "Characterization of Uncertainty in Ground-Motion Predictions," which will be mailed to you in the next few days. You should be prepared to critique and discuss the paper at the workshop.

You will be asked to discuss the technical and practical merits of the four approaches. The discussion should focus on the scientific bases for the various approaches and on their ability to predict ground motions for future earthquakes of engineering interest. More specifically, the parameters of interest are as follows:

Geographic area:	Central and eastern United States (east of the Rockies)
Ground-motion measures:	PGA and spectral accelerations in the 0.5 to 35-Hz range.
Magnitudes:	**M** 5 to 8, or m_{Lg} 5 to 7.5
Distances:	0 to 500 km, with emphasis on the following: a) 0 to 100 km, all magnitudes and frequencies b) 100 to 500 km, f<2.5 Hz, M>6
Site conditions:	Hard rock

After the presentations and discussions, you will be asked to provide brief written comments on your opinions about the various approaches. These comments, together with the discussions, will be used by the integrators to formulate their conclusions.

Your contributions to the discussions and your written comments should be aimed at giving the SSHAC members[2] who will act as integrators--and other ground-motion experts--a clear picture of the strengths and limitations of various approaches. Detailed discussions on parameter values, minor differences among variants of the various approaches, implementation details, and predictions for specific magnitude-distance values will be the subject of a second workshop.

[2]Most of these SSHAC members are not experts in ground-motion estimation but have considerable expertise in seismic-hazard analysis, general probabilistic methods, and expert elicitation.

ATTACHMENT A-2

GROUND-MOTION WORKSHOP I

WRITTEN INSTRUCTIONS MAILED TO PRESENTERS

SSHAC FIRST GROUND-MOTION ELICITATION WORKSHOP

March 17 and 18, 1994

INSTRUCTIONS FOR PRESENTERS

You have been asked to make a presentation on one of the approaches for ground-motion prediction listed below, before the SSHAC Ground-Motion Subcommittee and other ground-motion experts like yourself, during the first SSHAC Ground Motion Elicitation Workshop.

SSHAC (Senior Seismic Hazard Analysis Committee) is a panel of engineers, seismologists, and geologists with experience in seismic-hazard analysis and in risk analysis in general. Its task is to develop a new, more stable, methodology for seismic hazard analysis, drawing on the experience from the EPRI and LLNL seismic-hazard studies and from other major seismic-hazard studies performed in the last five years. The SSHAC effort is sponsored by DOE, EPRI, and NRC.

The main objective of this workshop is to examine and compare the various approaches available for the prediction of ground-motions in the central and eastern United States for the purposes of seismic hazard analysis. The term "approach" is used here in a broad sense, representing a whole class of methods and including variants proposed by other authors. The following approaches will be presented and examined:

- Advanced numerical modeling (empirical Green's functions) - Chandan Saikia
- Empirical regressions - Ken Campbell
- Intensity based - Mihailo Trifunac
- Stochastic (source-spectrum based) - Gail Atkinson

The second objective of the workshop is to test a different procedure for the elicitation of information from ground-motion experts. The proposed procedure will differ from past elicitations in three main aspects, as follows: (1) there will be more interaction, in order to clarify--and hopefully resolve--differences among experts, (2) a small group of integrators will take an active role in guiding and focusing the discussion, and (3) the integrators will formulate, based on the discussions and on their collective judgment, a position on which approaches are to be pursued, given their current state of development.

The third objective of the workshop is to present and discuss SSHAC's proposed framework for the characterization of uncertainty in ground-motion predictions. To meet this objective it is important that you read and study the paper entitled "Characterization of Uncertainty in Ground-Motion Predictions," which will be mailed to you in the next few days. You should be prepared to critique and discuss the paper at the workshop.

The presentation should focus on the ability of the approach you are presenting to predict ground motions for future earthquakes of engineering interest. More specifically, the parameters of interest are as follows:

Geographic area:	Central and eastern United States (east of the Rockies)
Ground-motion measures:	PGA and spectral accelerations in the 0.5 to 35-Hz range.
Magnitudes:	M 5 to 8, or m_{Lg} 5 to 7.5
Distances:	0 to 500 km, with emphasis on the following: a) 0 to 100 km, all magnitudes and frequencies b) 100 to 500 km, f<2.5 Hz, M>6
Site conditions:	Hard rock

Your presentation should be aimed at giving the SSHAC members[3] who will act as integrators--and other ground-motion experts--a clear picture of the basic assumptions, strengths, and limitations of the approach. The presentation should be broad enough to include other authors' variants of the approach you are presenting. The following is a list of topics that you should cover in your presentation (this is intended as guidance, not as a prescribed outline):

1. Brief description of the approach, emphasizing its basic elements. This exposition should cover only the basic elements that define the approach you are presenting and differentiate it from the other three approaches being presented by others. The exposition should also include a brief description of the main differences among investigators using the approach you are presenting.

2. Scientific/technical basis for the approach. This exposition should cover the basic assumptions of the approach you are presenting.

3. Required Data and Parameters. Describe the types of data or parameters required for

[3]Most of these SSHAC members are not experts in ground-motion estimation but have considerable expertise in seismic-hazard analysis, general probabilistic methods, and expert elicitation.

application of the approach you are presenting to the region, magnitudes, distances, and frequencies of interest. This discussion should focus on the types of data and parameters, including the availability and quality of the data, confidence in the parameter values, and the impact of the various and parameters on the final predictions.

4. Summary of Validation Studies. This exposition should summarize studies that serve to give confidence in the approach you are presenting. Studies that validate the approach as a whole (rather than its parts), and studies relevant to central and eastern North America and to ground-motions of engineering interest, should be emphasized (if feasible).

5. Applicability to the Various Magnitude-Distance-Frequency Ranges of Engineering Interest. For this discussion, we ask you to put yourself in the role of a seismic-hazard analyst who is trying to select attenuation equations to predict ground-motions for the various frequencies of interest. Discuss the parameter combinations for which the predictions obtained using the approach you are presenting are most reliable, and those for which they are less reliable. To help focus your discussion, we ask you to consider the following specific combinations of magnitude, distance (to the rupture), and frequency:

m_{Lg} 5.5	m_{Lg} 7.0
5 km (1 Hz, 10 Hz, and PGA)	5 km (1 Hz, 10 Hz, and PGA)
70 km (1 Hz, 10 Hz, and PGA)	70 km (1 Hz, 10 Hz, and PGA)
200 km (1 Hz and 10 Hz)	200 km (1 H, 10 Hz, and PGA)

You are not being asked to provide ground-motion predictions for these magnitude-distance combinations, only to comment on the adequacy of the approach for these combinations.

6. Areas of Strength and Weakness. Discuss the strengths and weaknesses of the approach you are presenting for the magnitude-distance-frequency combinations of interest. This should not be a critique of other approaches (there will be time for this elsewhere in the agenda).

Your presentation should focus on the basic scientific and technical issues relating to the approach you are presenting and its applicability to the problem of interest. Detailed discussions on parameter values, minor differences among variants of the approach, implementation details, and predictions for specific magnitude-distance values will be the subject of a second workshop.

You will be given 45 minutes for your presentation. You should allow some time for clarifications.

You are also asked to participate in all other discussions planned for the workshop. See the enclosed agenda and "Instructions to Participants" for more details.

ATTACHMENT A-3

GROUND-MOTION WORKSHOP I

AGENDA

SSHAC FIRST GROUND-MOTION ELICITATION WORKSHOP
March 17 and 18, 1994

AGENDA

Thursday, March 17

9:00-9:30	Introduction	David Boore
9:30-10:00	Elicitation: Past, Present and Future	Peter Morris
10:30-11:00	Break	
11:00-1:00	Characterization of Uncertainty in Ground Motions (presentation & discussion)	Gabriel Toro
1:00-2:00	Lunch	
2:00-3:30	Approaches to Ground-Motion Prediction	
	Intensity-based approach (2:00-2:45)	Mihailo Trifunac
	Empirical regression approach (2:45-3:30)	Ken Campbell
3:30-4:00	Break	
4:00-5:30	Approaches to Ground-Motion Prediction (continued)	
	Stochastic approach (4:00-4:45)	Gail Atkinson
	Advanced numerical modeling (4:45-5:30)	Chandan Saikia
5:30-6:00	Do we span the space of models with this set of basis vectors? (Is the shopping list complete?)	Discussion led by David Boore

Friday, March 18

8:30-10:30	Pros and Cons of Each Method	Discussion led by Integrators
10:30-11:00	Break	
11:00-12:30	Applicability of the various approaches to the (magnitude, distance, frequency) values of engineering interest	Discussion led by Integrators
12:30-1:00	Preparation of written comments to Integrators	Experts (individually)
1:00-2:00	Lunch	
2:00-3:00	Preliminary Integration	
	Presentation	Integrators
	Feedback	Experts
	Wrap-up	Integrators

ATTACHMENT A-4

GROUND MOTION WORKSHOP 1

INTEGRATOR SURVEY

PURPOSE OF SURVEY

- GUIDANCE FOR INTEGATORS
- FOR COMPARING APPROACHES, NOT EXPERTS
- ANONYMOUS

CONTEXT OF SURVEY

ALL QUESTIONS SHOULD BE ADDRESSED FOR:

- CENTRAL AND EASTERN UNITED STATES ONLY
- 1 TO 10 HERTZ FREQUENCY RANGE ONLY
- HARD ROCK SITE ONLY

COMPARISON OF APPROACHES

Use the key below to rate the various approaches in terms of how it deals with each issue. All four approaches should be rated for each issue:

A	=	**ADVANCED NUMERICAL**	**I**	=	**INTENSITY BASED**
E	=	**EMPIRICAL**	**S**	=	**STOCHASTIC**

	Poor Low				**Excellent High**
Example: **APPROACHE'S NAME**	**A**		**I S**		**E**
- Characterizes approach accurately					
MODEL LOGIC					
- Theoretically sound - Based on solid science - Reasonable underlying assumptions					
USE OF DATA					
- Based on relevant data - Does not use questionable data					
PARAMETER ESTIMATION					
- Sound estimation methods - Adequate sample size					
CREDIBILITY OF APPROACH					
- Well-established, non-controversial - Time-tested, well-understood by expert community					
OVERALL RATING					

Please list the key assumptions that make each approach attractive or unattractive. Which assumptions or hypotheses are especially essential or undesirable? (use back of page if necessary):

Advanced numerical:

Empirical:

Intensity Based:

Stochastic:

USING THE APPROACHES FOR FORECASTING

Assign a weight (0 to 100) to each approach based on how you would expect to weight the results of all your approaches were applied to a specific site application characterized by frequency, magnitude, and distance. The weights should sum to 100.

Frequency: 1 Hz

Magnitude: / Distance:	m_{Lg} 5.5 / 5 km	m_{Lg} 5.5 / 70 km	m_{Lg} 5.5 / 200 km	m_{Lg} 7.0 / 5 km	m_{Lg} 7.0 / 70 km	m_{Lg} 7.0 / 200 km
Advanced Numerical	_____	_____	_____	_____	_____	_____
Empirical	_____	_____	_____	_____	_____	_____
Intensity Based	_____	_____	_____	_____	_____	_____
Stochastic	_____	_____	_____	_____	_____	_____
Total	100%	100%	100%	100%	100%	100%

Frequency: 10 Hz

Magnitude: / Distance:	m_{Lg} 5.5 / 5 km	m_{Lg} 5.5 / 70 km	m_{Lg} 5.5 / 200 km	m_{Lg} 7.0 / 5 km	m_{Lg} 7.0 / 70 km	m_{Lg} 7.0 / 200 km
Advanced Numerical	_____	_____	_____	_____	_____	_____
Empirical	_____	_____	_____	_____	_____	_____
Intensity Based	_____	_____	_____	_____	_____	_____
Stochastic	_____	_____	_____	_____	_____	_____
Total	100%	100%	100%	100%	100%	100%

Please summarize your reasons for the judgments by approach (use back of page if necessary):

Advanced numerical:

Empirical:

Intensity Based:

Stochastic:

PREFERENCES OF THE OVERALL EXPERT COMMUNITY

Consider the entire community of ground motion experts. What percentage would you expect to favor each approach of they could only choose one for each application. The percentages should add to 100 in each column.

Note: This should *not* reflect your own rating, only what you believe about the preferences of the overall group of experts.

Frequency: 1 Hz

Magnitude: / Distance:	m_{Lg} 5.5 / 5 km	m_{Lg} 5.5 / 70 km	m_{Lg} 5.5 / 200 km	m_{Lg} 7.0 / 5 km	m_{Lg} 7.0 / 70 km	m_{Lg} 7.0 / 200 km
Prefer Adv. Numerical	_____	_____	_____	_____	_____	_____
Prefer Empirical	_____	_____	_____	_____	_____	_____
Prefer Intensity Based	_____	_____	_____	_____	_____	_____
Prefer Stochastic	_____	_____	_____	_____	_____	_____
Total	100%	100%	100%	100%	100%	100%

Frequency: 10 Hz

Magnitude: / Distance:	m_{Lg} 5.5 / 5 km	m_{Lg} 5.5 / 70 km	m_{Lg} 5.5 / 200 km	m_{Lg} 7.0 / 5 km	m_{Lg} 7.0 / 70 km	m_{Lg} 7.0 / 200 km
Prefer Adv. Numerical	_____	_____	_____	_____	_____	_____
Prefer Empirical	_____	_____	_____	_____	_____	_____
Prefer Intensity Based	_____	_____	_____	_____	_____	_____
Prefer Stochastic	_____	_____	_____	_____	_____	_____
Total	100%	100%	100%	100%	100%	100%

Please summarize your reasons for the judgments (use back of page if necessary):

ATTACHMENT A-5

GROUND MOTION WORKSHOP 1

EXPERT INPUTS ON DIFFERENT ASPECTS OF THE GROUND MOTION MODELS

GROUND MOTION WORKSHOP I

MODEL LOGIC

INTEGRATOR SURVEY

Expert	Stochastic	Advanced Numerical	Direct Empirical	Hybrid Empirical	Intensity Based
1	8	10	10	5	0
2	10	10	8	8	5
3	8	10	8	5	2
4	10	x	x	x	x
5	10	10	8	8	5
6	8	10	5	2	2
7	8	8	10	8	2
8	10	8	10	5	2
9	10	10	5	5	0
10	5	8	8	2	2
11	10	8	10	2	0
12	2	2	x	x	8
13	x	x	x	x	x
Average	8.3	8.5	8.2	5.0	2.5
Hi Rank	6	7	5	0	1
Lo Rank	1	1	0	2	9

GROUND MOTION WORKSHOP I

USE OF DATA — *INTEGRATOR SURVEY*

Expert	Stochastic	Advanced Numerical	Direct Empirical	Hybrid Empirical	Intensity Based
1	8	10	10	10	5
2	8	10	10	8	5
3	10	10	10	8	2
4	10	x	x	x	x
5	10	10	5	5	0
6	10	8	5	5	2
7	8	8	5	5	2
8	10	10	10	5	8
9	8	8	5	5	2
10	x	8	10	5	2
11	8	5	10	2	5
12	x	x	x	x	8
13	8	8	10	2	0
Average	8.9	8.6	8.2	5.5	3.4
Hi Rank	7	7	6	1	1
Lo Rank	0	1	0	1	9

GROUND MOTION WORKSHOP I

CREDIBILITY OF APPROACH

INTEGRATOR SURVEY

Expert	Stochastic	Advanced Numerical	Direct Empirical	Hybrid Empirical	Intensity Based
1	8	8	10	8	0
2	10	10	10	8	0
3	8	8	10	2	2
4	10	x	x	x	x
5	5	5	10	5	0
6	8	5	5	2	0
7	8	8	8	8	0
8	8	5	10	2	5
9	8	2	2	2	0
10	8	8	8	2	2
11	10	5	10	2	0
12	5	2	x	x	8
13	10	8	8	2	0
Average	8.2	6.2	8.3	3.9	1.4
Hi Rank	8	3	8	1	1
Lo Rank	0	1	0	4	10

GROUND MOTION WORKSHOP I

PARAMETRIC ESTIMATION

INTEGRATOR SURVEY

Expert	Stochastic	Advanced Numerical	Direct Empirical	Hybrid Empirical	Intensity Based
1	8	8	x	8	2
2	10	10	10	10	10
3	5	5	0	8	2
4	10	x	x	x	x
5	x	x	x	x	x
6	10	5	5	2	8
7	8	8	2	5	0
8	8	5	10	x	0
9	8	5	5	5	0
10	5	5	0	2	2
11	8	5	2	2	0
12	5	5	x	x	5
13	8	8	10	2	0
Average	7.8	6.3	4.9	4.9	2.6
Hi Rank	9	4	3	3	2
Lo Rank	1	1	2	0	7

ATTACHMENT A-6

GROUND MOTION WORKSHOP 1

EXPERTS' WRITTEN COMMENTS

GROUND MOTION WORKSHOP I — INTEGRATORS SURVEY
COMPARISON OF APPROACHES

Experts who signed their surveys:
Expert 4 — Bill Joyner
Expert 12 — Mike Trifunac
Expert 13 — Bob Hermann

ADVANCED NUMERICAL:

Expert 1: Can include details in source and propagation (A); Difficult to implement (D).

Expert 2: I rate A as exceptional, because it handles everything.

Expert 3: Best captures physical process/requires too many parameters.

Expert 4: Too complex — Too many parameters.

Expert 5: Advantages: rigorous treatment of wave propagation, captures elements of natural variability in source functions, favorably compares to extant data; Disadvantages: too many poorly determined parameters, computationally cumbersome.

Expert 6: No comments

Expert 7: Requires that fairly detailed knowledge of source and earth structure are known. This makes this method attractive for very specific applications but less attractive for generalizing to regional attenuations.

Expert 8: Requires many (source) parameters. Correlations between source parameters not well known. Distributions of additional source parameters are uncertain.

Expert 9: Clarification: Refers to an application of A where one has randomized over all epistemic (as of the present) and aleatory uncertainties.
Unattractive: complexity, need for very detailed data, empirical modeling of seismic source is cumbersome.
It is not clear how much is gained by using a very detailed physical model when parameters are not well known and have to be integrated over. One has to integrate over some parameters (e.g., crustal structure) because they have epistemic uncertainty and over others because they have aleatory uncertainty (fault dip, azimuth/distance, rake angle, slip distribution, etc.). This is where I see the stochastic model <u>as a useful compromise</u>.
Attractive: most complete physical model; especially useful for 1Hz at 500 km.

Expert 10: Allows for good physical modeling etc. Main problems: do not have good source functions. Must extrapolate from small earthquakes and/or WUS data for small earthquakes. Also iffy on how to distribute over fault.

Expert 11: Useful for understanding past earthquakes and extrapolating to crustal structures without empirical data.

Expert 12: Cannot go beyond 1-3Hz.

Expert 13: Attractive: Permits theoretically based extrapolation of data set
Unattractive: time-consuming to consider all possible source time functions.

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EMPIRICAL:

Expert 1: Direct: Based on data (A); Not dependent on models (A); No large M data (D)

Hybrid: Based on data (A); Less dependent on Models (A); Large uncertainty (D); Cannot be used at long distances (D)

Expert 2: They are good methods, probably the best, provided we have data. In east and central United States this may be a limitation.

Expert 3: Least number of assumptions/too few data (D); Makes good use of UCUS data/calibration to EVS problematic (H)

Expert 4: Direct: Inadequate data above M_{eq} =5

Hybrid: No advantage over stochastic if scaling is the same E and W and inadequate if the scaling is not the same

Expert 5: Direct: Limited data

Hybrid: Advantage: uses WNA data; Disadvantage: uncertainty in shifting to ENA

Expert 6: No comments

Expert 7: Direct: General form of relationships is well known from studies of empirical data and modeling — problem is lack of data to refine estimate

Hybrid empirical: Key assumption is that one can identify the key differences between EUS & WUS and adjust for them. To the extent that this can be done with the stochastic model, then the HE method may not bring much information on the mean, but it can bring a lot of information on sigma.

Expert 8: Direct: When data is available, this is the best method

Hybrid: No comments

Expert 9: Direct:
Advantages: Conceptually simple (straightforward), would be preferred if there were more data (S. Calif.)
Disadvantage: Not sufficient data (M dependence is very poorly constrained).

Hybrid:
Advantage: Brings some of the WUS information to bear (e.g., M scaling, extended source, short-distribution attenuation)
Disadvantages: Does not use CEUS data as much as it should. It is not a clean procedure, affected by uncertainties about parameters in both east and west. Except for extended source effects, the structure of the stochastic model may be a better way to transfer knowledge from west to east (except for extended-source effects).

Expert 10: Direct: Excellent but no data: not useful except at M≅5.

Hybrid: Have to make assumption that M scales the same in WUS as in EUS. Corrections a bit iffy but then no more so than the results from the stochastic model.

EMPIRICAL (cont'd):

Expert 11: Direct: Useful for ≈M5 earthquakes. Can't be extrapolated to M≥6.

Hybrid: Not useful due to uncertainty in "adjustments" except possibly as a consistency check.

Expert 12: No adequate data for EUS

Expert 13: Attractive: Data cannot be denied, but extrapolation to larger distances, magnitudes must be model-based.

INTENSITY-BASED:

Expert 1: Tied to intensity data (A); Poor relationship with ground motion (D)

Expert 2: We do not have much data except for the data in the old BSSA papers. An evaluation of these data by the experts is relevant.

Expert 3: Uses data from large ENA earthquakes/poor quality, non-engineering data

Expert 4: Intensity data can be better used in the stochastic model. Intensity data should be used in the form of isoseismal areas.

Expert 5: Limited data; High uncertainty in translating to engineering parameter

Expert 6: No comments

Expert 7: Key assumption is translation from I_S to ground motion parameter — this is a weak correlation and implies large uncertainties.

Expert 8: Poor reliability going from site intensity to ground motion. Useful for M_{eq} estimation.

Expert 9: Clarification: Refers to the LLNL Expert-5 approach, as documented by LLNL and by Trifunac-Lee NRC reports (ca. 1988) (this characterization may be out of date). Trifunac presentation did not help at all.
[Footnote #1 to I under Parameter Estimation:] Parameter estimation method is very poor. Sample size is large.

Expert 10: Generally not useful because we lack the key information of GM=f(I_S, size, d) for region of interest. However, it is actual data from the large EUS earthquakes that reflect the ground motion and actual source. Therefore useful in M~7-8 range out to about 150 Km.

Expert 11: Useful for limited purposes only: Use felt area to determine high-frequency level.

Expert 12: Good, simple and direct.

Expert 13: Unattractive: Should compare Fourier amplitude spectra estimates in WUS to EUS data.

STOCHASTIC:

Expert 1: Can include basic source and propagation parameters (A); May not adequately predict long periods (D)

Expert 2: I like this and apply this myself. I know its inherent limitation. We may say those limitations do not matter, but they are limitations. Parameters that properly [sic] depth-related and crustal structure-related attenuation are quite average. In east, this is our chance to include them correctly so that we do not have to come back later and spin the wheel again. I see a strong interaction between stochastic and Advanced numerical method because I am a believer and doer of both.

Expert 3: Good physical basis, computational expedient/in part still under development

Expert 4: No comments

Expert 5: Advantages: simple with easy-to-measure parameters therefore robust, predictions compare favorably with extant data; Disadvantage: highly sensitive to one parameter, delta sigma.

Expert 6: No comments

Expert 7: Gross properties of earthquakes can be represented in "simple" physical models (validated in WUS) and that these can be estimated for the east

Expert 8: Simple enough to keep the number of source parameters small. Better known source parameter distributions.

Expert 9: Advantages: Contains (or mimics) most significant physical processes affecting ground motions, yet simple enough, moderate number of parameters.

Disadvantages: There is still significant uncertainty about source spectrum of large CEUS quakes (given Mo or MLg). Handling of extended-source effects is not well established. Wave propagation: geometric attenuation and duration modeling need some improvement.

Expert 10: Generally most useful in M range of most interest. Can be calibrated with existing data. Has problems with large earthquakes close-in. Some uses exist. Overall the most useful method as it requires the fewest empirical parameters and yet keeps some physics

Expert 11: Useful for these predictions. Emphasis on model validation with data is required.

Expert 12: No comments

Expert 13: Attractive: Permits theoretically based extrapolation of data set.

ATTACHMENT A-7

GROUND MOTION WORKSHOP 1

DETAILED EXPERT INPUTS ON USING THE APPROACHES FOR FORECASTING

GROUND MOTION WORKSHOP I — INTEGRATORS SURVEY USING THE APPROACHES FOR FORECASTING

ADVANCED NUMERICAL:

Expert 1: [refers to list of advantages/disadvantages under "Comparison of Approaches"]

Expert 2: Advanced numerical modeling helps to include the source complexity, path effects including scattering and site. It is stable and also helps us to understand the variation of ground motions due to known parameters at least in east and central United States.

Addendum:

- It has super predictive power
- To integrate the parameter effects, you have to know first these effects in real situations.
- Note: it could predict the ground motion of Northridge event. You cannot rule out this kind of power of this method in the ground motion prediction.
- Please do not [sic] do the exercise and see how stochastic prediction did against the Northridge data just as an exercise, at least to evaluate the method.

  Events that cannot be modeled should not be discarded. They may give inputs to real hazard estimation.

Expert 3: The above [i.e., the numbers on same sheet] reflect rough a priori estimates. I am sure I would revise the weights based on the results and uncertainties of the various methods.

Expert 4: I would use the stochastic method in all cases for reasons given on the back page [transcribed here]:

I am not very good at checking boxes. I believe that the stochastic point source model is the best approach for all of the magnitudes and distances except possibly for the M_{eq} =5.0, where the direct empirical might be preferred. M_{eq} =5.0 earthquakes are not, however, a significant part of the hazard and the advantages of using one method across the magnitude range favor the use of the stochastic point source model even for M_{eq} =5.0. There is simply not enough data to use the direct empirical methods for magnitudes higher than M_{eq} =5.0. As for the hybrid empirical method, there is no advantage over the point-source stochastic method if the magnitude scaling is the same in the east as the west, except that the hybrid method might represent finite source effects better. Walt Silva's comparisons of point-source stochastic models with data in the west suggest that the deficiencies of the point-source models for representing extended sources are small and would not have much effect on eastern US hazard. If the ground-motion scaling is different in the east, then the point-source stochastic model is superior.

I believe that intensity data should be incorporated as suggested by Gail Atkinson, that is by using felt areas (or isoseismal areas) to determine the high-frequency spectral levels. Isoseismal areas could also be used in methods such as proposed by Art Frankel to check the parameters (e.g., Q) of the point-source stochastic model. The direct use of intensity requires the use of ground-motion vs. intensity relationships

which I don't understand very well, but which make me very uneasy. As I understand it, their use results in large increases in uncertainty. In any case, if they are used they should be scrutinized very carefully.

There are a number of different advanced methods (which I interpret as finite-source methods). Some of them I don't like very much; one of them I am the author of. I believe they all are too complex and involve too many parameters for the eastern US problem. The only possible advantage I see is in taking account of finite source effects for the M_{eq} =7.0 earthquake at 5.0 km. As I stated earlier, however, it does not seem to me that the deficiencies of the point-source stochastic model in accounting for finite-source effects would have much impact on eastern US hazard.

Expert 5: Both Stochastic and Advanced Numerical match extant data about equally well. Because stochastic requires fewer parameters, it is more robust and therefore warrants slightly higher weight.

Expert 6: Logic, complete, when used together with "empirical" scattering functions it is globally applicable. Difficulty lies in constraining "geophysical" parameter space for input. Easy to use sensitivity studies to explore dependence of sigma on various input parameters. Difficulty how to test output against observable data.

Expert 7: The model requires too much additional information that is not known to give it an advantage over the S method in the east.

Expert 8: In its current form, I would not use the advanced numerical results. I've assumed that a sufficient number of parameter variations have been run with a simplified presentation of results (e.g., attenuation relation has been removed or table of mean and standard error of ground motions for each magnitude and distance is given). Requires a lot of runs before I'm confident that the results are robust.

Expert 9: No comments

Expert 10: For small earthquakes (M=5.5) I don't see much difference between A and S, so I put weight on S. For other cases I have down-weighted A because of complexity in use and in the need for source function. I'm not sure about the percentage between A and S here. I need to look a bit more closely at A to see where it has significant (if any) advantages over S. In this case I'm assuming that S includes extended source model "S". If not, then my weights would change accordingly.

Expert 11: Approach is good, especially at low frequencies, but needlessly complex. Parameters hard to determine.

Expert 12: Cannot be used beyond 1-3 Hz

Expert 13: [see General Comments below]

EMPIRICAL:

Expert 1: [refers to list of advantages/disadvantages under "Comparison of Approaches"]

Expert 2: Useful when data is available, also even when we use hybrid method in a less expensive manner

Expert 3: The above [i.e., the numbers on same sheet] reflect rough a priori estimates. I am sure I would revise the weights based on the results and uncertainties of the various methods.

EMPIRICAL (cont'd):

Expert 4: I would use the stochastic method in all cases for reasons given on the back page [transcribed above, under "Advanced Numerical"]

Expert 5: Direct: Limited data.
Hybrid: Useful approach, but uncertainty in shifting to ENA

Expert 6: Direct: Limited data sets make uncertainties high at short distances and for large magnitudes.

Expert 7: Direct: Data available for small magnitudes by magnitude scaling not known well enough provides a basis for estimating uncertainties

Expert 8: Direct: Only have data for M < 5.
Hybrid: No comments

Expert 9: No comments

Expert 10: Direct: Good for M=5.5 but no good elsewhere other than a check — too little data.
Hybrid: No point using at M=5.5 — of some value for larger events as you get the source function in.

Expert 11: Direct: Method good but data lacking at large M.
Hybrid: I don't think the method is useful due to unknown source differences between east and west.

Expert 12: OK. but no adequate data

Expert 13: Direct: Direct empirical is limited by distance/magnitude range of data sets and the extent to which observations are extrapolated.
Hybrid: Hybrid empirical is affected by lack of knowledge of variability (regional) of controlling factors. However, this may provide a plausible constraint for large-magnitude, short-distance motions.

INTENSITY-BASED:

Expert 1: [refers to list of advantages/disadvantages under "Comparison of Approaches"]

Expert 2: Should use it as a check. Many times you have intensity information at a site where you do not have ground motion. For such a scenario, it can be tool (supportive at least)

Expert 3: The above [i.e., the numbers on same sheet] reflect rough a priori estimates. I am sure I would revise the weights based on the results and uncertainties of the various methods.

Expert 4: I would use the stochastic method in all cases for reasons given on the back page [transcribed above, under "Advanced Numerical"]

Expert 5: Useful approach, large uncertainty

Expert 6: Poor quality of "original" data (site geology-dependent, construction-dependence make these data uncertain, but should be used at high M and at short distances to check results on other methods where these are highly uncertain because of poor or non-existent instrumental data

INTENSITY-BASED (cont'd):

Expert 7: Too much uncertainty in the translation to ground motion parameters of interest

Expert 8: I have no confidence in this method to predict ground motions.

Expert 9: No comments

Expert 10: Good for checking — of value for very large events out to 70km as only actual data from such events which is the actual source effects

Expert 11: Intensity data generally unreliable for making direct ground motion predictions; no credible methods.

Expert 12: OK

Expert 13: No comments

STOCHASTIC:

Expert 1: [refers to list of advantages/disadvantages under "Comparison of Approaches"]

Expert 2: It is sound process and as good as numerical modeling. I have not seen their time-series and fit at long period. So at present, I am critical (I am open to change my opinion when I see it).

Expert 3: The above [i.e., the numbers on same sheet] reflect rough a priori estimates. I am sure I would revise the weights based on the results and uncertainties of the various methods.

Expert 4: I would use the stochastic method in all cases for reasons given on the back page [transcribed above, under "Advanced Numerical"]

Expert 5: Both Stochastic and Advanced Numerical match extant data about equally well. Because stochastic requires fewer parameters, it is more robust and therefore warrants slightly higher weight.

Expert 6: Probably the most versatile, particularly when combined in an upgraded hybrid form together with advanced numerical methods. There are some problems with duration i.e., beyond 100 km. At short distances the source randomness (and finite source size) may cause difficulties. The source model (Brume, 1-corner, 2-corner, multicorner spectral shape) may cause epistemic uncertainties, but whose σ can be readily determined by applying alternative source models.

Expert 7: Does a good job of matching observations in the WUS with a simple set of parameters that can be estimated for the east.

Expert 8: Well developed model. I have confidence that results are robust. Maybe (but I don't think so) troubles at 1 Hz.

Expert 9: No comments

Expert 10: Generally the best, except around M=7 or greater close in there are problems.

Expert 11: Applicable to predictions, requiring a minimum of parameters, and well-accepted.

Expert 12: Problem at ≤ 1 Hz.

Expert 13: No comments

ATTACHMENT A-8

GROUND MOTION WORKSHOP 1

DETAILED EXPERT INPUTS ON PREFERENCES OF THE OVERALL EXPERT COMMUNITY

GROUND MOTION WORKSHOP I — INTEGRATORS SURVEY
PREFERENCES OF OVERALL EXPERT COMMUNITY

SUMMARY OF "YOUR REASONS FOR THE JUDGMENTS":

Expert 1: Above estimates are highly speculative and will depend on the makeup of the experts. Seismologists will prefer the numerical methods (S-bias), engineers will prefer the empirical methods (E-bias), and a small minority of primarily engineers and other disciplines will prefer the intensity methods (I-bias). Assigning values in above table has a very large uncertainty, but since the community of ground motion experts in the east is biased towards seismologists, the numerical methods (Advanced and Stochastic) will be the preferred models as a percentage of total.

Expert 2:
1. Stochastic and Advanced Numerical methods are useful and have predictive powers, except at long period where Advanced Numeric wins.
2. Empirical and Hybrid may be useful at 5.5 by extrapolating 5.0.
3. Intensity data may not be transportable because it depends on the site condition.

Expert 3: Some of the techniques are newer and less well established than others (e.g., Hybrid Empirical may be hardly known and Advanced Numerical is, I believe, fast gaining popularity). I cannot break the percentages down by M_{Lg}, R, or f.

Expert 4: I don't really think I have a good sense of the views of the entire community.

Expert 5: Stochastic and Advanced Numerical have track record in WNA and are perceived as reliable models. Intensity is still favored by some. Indirect Empirical has attractive elements.

Expert 6: No comments

Expert 7: Community still likes to consider intensity because of presence of data. Community likes Advanced Numerical modeling because of its conceptual advantages.

Community beginning to recognize that much of what AN offers can be captured in S.

Expert 8: No comments

Expert 9: No comments

Expert 10: No comments

Expert 11: I think most people are comfortable with the stochastic approach and appreciate its simplicity. Numerical models are also favored, but I think to a lesser degree due to complexity. But for large events at low frequencies, numerical models are often preferred. I sense no support for intensity-based ground motion predictions because no credible method has been presented. Empirical methods are favored by data are lacking.

Expert 12: No comments, except quotes were added around the word "expert"

Expert 13: I presume that the experts know the inherent difficulties of prediction for Eastern North America. I would also assume that they are optimistic about data sets, and hence inclined or prejudiced toward empirical data of any time and that they distrust complicated numerical techniques.

GROUND MOTION WORKSHOP I — INTEGRATORS SURVEY
GENERAL COMMENTS

Expert 13:

- One general comment is that prediction models must agree with observations, where those observations exist. If there is no agreement, then model parameters for advanced numerical, stochastic must be carefully modified.
- Given my extensions to stochastic, Silva's work for finite fault stochastic, stochastic is really a hybrid, advanced numerical technique. A difference between the two is that one is tied to a specific waveform and the other to a specific spectrum and duration. Stochastic encompasses time domain modeling ensembles.
- Because of uncertainty about large earthquakes, a distribution of source models must be considered for large magnitudes, primarily to incorporate reasonable fault length/width aspect ratio, and high-frequency asperities typically seem in large (M >6) earthquakes.
- Advanced numerical has practical, computational limits at high frequency. At lower frequency it is a good extrapolator.
- In general, empirical data are required for calibration of all models, especially stochastic/advance numerical. The real advantage of these two latter techniques is that sensitivity analysis can be performed to:

a) Estimate the effect of "epistemic" error on motion estimates. For example, for a given M_{Lg}, measured at large distance, the effect will be to increase uncertainty at short distance.

b) The second aspect is that such a sensitivity analysis would define the most crucial source parameters and thus drive research to reduce the "epistemic" uncertainty for future analysis.

Estimation of uncertainty may be as important as estimating the mean ground motion value.

GROUND MOTION WORKSHOP I

INTEGRATOR SURVEY: EXPERT INPUTS

USING THE APPROACHES FOR FORECASTING

		Freq.		1				Freq.		1				Freq.		1				Freq.		1		
		Mag.		5.5				Mag.		5.5				Mag.		5.5				Mag.		7		
		Dist.		5				Dist.		70				Dist.		200				Dist.		5		
Exp	AN	DE	IB	S	HE		AN	DE	IB	S	HE		AN	DE	IB	S	HE		AN	DE	IB	S	HE	
1	5	85	0	5	5	100	5	85	0	5	5	100	5	85	0	5	5	100	50	0	20	15	15	100
2	50	20	20	10	0	100	35	30	0	35	0	100	50	0	0	50	0	100	40	15	0	25	20	100
3	35	15	5	35	10	100	35	15	5	35	10	100	35	15	5	35	10	100	30	5	15	30	20	100
4	0	0	0	100	0	100	0	0	0	100	0	100	0	0	0	100	0	100	0	0	0	100	0	100
5	40	0	0	50	10	100	40	0	0	50	10	100	40	0	0	50	10	100	40	0	0	50	10	100
6	30	15	5	50	0	100	35	15	5	45	0	100	40	15	5	40	0	100	20	10	10	40	20	100
7	10	20	0	50	20	100	10	20	0	50	20	100	10	35	0	50	5	100	10	0	0	60	30	100
8	35	25	0	40	0	100	20	50	0	30	0	100	25	50	0	25	0	100	35	0	0	50	15	100
9	20	20	0	60	0	100	20	30	0	50	0	100	20	30	0	50	0	100	10	20	0	50	20	100
10	0	70	0	25	5	100	0	70	0	25	5	100	0	70	0	30	0	100	40	0	25	20	15	100
11	30	30	0	40	0	100	30	30	0	40	0	100	30	30	0	40	0	100	50	0	0	50	0	100
12	5	3	90	2	0	100	5	3	90	2	0	100	0	0	100	0	0	100	5	3	90	2	0	100
13	30	30	5	30	5	100	30	30	5	30	5	100	25	40	5	25	5	100	40	5	5	40	10	100
Avg	22	26	10	38	4	100	20	29	8	38	4	100	22	28	9	38	3	100	28	4	13	41	13	100

GROUND MOTION WORKSHOP I

INTEGRATOR SURVEY: EXPERT INPUTS

USING THE APPROACHES FOR FORECASTING

		Freq.		1				Freq.		1				Freq.		10				Freq.		10			
		Mag.		7				Mag.		7				Mag.		5.5				Mag.		5.5			
		Dist.		70				Dist.		200				Dist.		5				Dist.		70			
Exp	AN	DE	IB	S	HE		AN	DE	IB	S	HE		AN	DE	IB	S	HE		AN	DE	IB	S	HE	
1	50	0	10	20	20	100	50	0	10	20	20	100	5	85	0	5	5	100	5	85	0	5	5	100
2	35	10	0	35	20	100	50	0	0	50	0	100	25	40	10	25	0	100	35	30	0	35	0	100
3	30	5	15	30	20	100	30	5	15	30	20	100	35	15	5	35	10	100	35	15	5	35	10	100
4	0	0	0	100	0	100	0	0	0	100	0	100	0	0	0	100	0	100	0	0	0	100	0	100
5	40	0	0	50	10	100	40	0	0	50	10	100	40	0	0	50	10	100	40	0	0	50	10	100
6	30	10	10	35	15	100	40	10	10	30	10	100	20	10	10	60	0	100	25	15	10	50	0	100
7	10	0	0	60	30	100	20	0	0	60	20	100	10	20	0	50	20	100	10	20	0	50	20	100
8	35	0	0	60	5	100	40	0	0	60	0	100	25	25	0	50	0	100	15	50	0	35	0	100
9	10	20	0	50	20	100	10	20	0	50	20	100	15	15	0	8	70	108	15	25	0	60	0	100
10	40	0	25	20	15	100	50	0	0	40	10	100	0	70	0	30	0	100	0	70	0	30	0	100
11	50	0	0	50	0	100	50	0	0	50	0	100	25	30	0	45	0	100	25	30	0	45	0	100
12	5	3	90	2	0	100	0	0	100	0	0	100	0	5	90	5	0	100	0	5	90	5	0	100
13	40	5	5	40	10	100	40	10	5	40	5	100	30	30	0	35	5	100	30	30	5	30	5	100
Avg	29	4	12	42	13	100	32	3	11	45	9	100	18	27	9	38	9	101	18	29	8	41	4	100

GROUND MOTION WORKSHOP I

INTEGRATOR SURVEY: EXPERT INPUTS

USING THE APPROACHES FOR FORECASTING

		Freq.		10				Freq.		10				Freq.		10				Freq.		10		
		Mag.		5.5				Mag.		7				Mag.		7				Mag.		7		
		Dist.		200				Dist.		5				Dist.		70				Dist.		200		
Exp	AN	DE	IB	S	HE		AN	DE	IB	S	HE	0	AN	DE	IB	S	HE		AN	DE	IB	S	HE	
1	5	85	0	5	5	100	25	0	25	25	25	100	30	0	10	30	30	100	30	0	10	30	30	100
2	50	0	0	50	0	100	60	15	0	20	15	110	35	10	0	35	20	100	50	0	0	50	0	100
3	35	15	5	35	10	100	30	5	15	30	20	100	30	5	15	30	20	100	30	5	15	30	20	100
4	0	0	0	100	0	100	0	0	0	100	0	100	0	0	0	100	0	100	0	0	0	100	0	100
5	40	0	0	50	10	100	40	0	0	50	10	100	40	0	0	50	10	100	40	0	0	50	10	100
6	30	10	10	50	0	100	40	5	15	40	0	100	35	10	15	40	0	100	40	5	15	40	0	100
7	10	35	0	50	5	100	10	0	0	60	30	100	10	0	0	60	30	100	20	0	0	60	20	100
8	15	50	0	35	0	100	35	0	0	50	15	100	35	0	0	60	5	100	30	0	0	70	0	100
9	15	25	0	60	0	100	10	15	0	70	5	100	10	15	0	70	5	100	10	15	0	70	5	100
10	0	70	0	30	0	100	25	0	25	25	25	100	25	0	25	25	25	100	50	0	0	40	10	100
11	25	30	0	45	0	100	40	0	0	60	0	100	40	0	0	60	0	100	40	0	0	60	0	100
12	0	0	90	10	0	100	0	5	90	5	0	100	0	5	90	5	0	100	0	0	90	10	0	100
13	25	40	5	25	5	100	30	5	5	45	15	100	35	5	5	45	10	100	40	10	5	40	5	100
Avg	19	28	8	42	3	100	27	4	13	45	12	101	25	4	12	47	12	100	29	3	10	50	8	100

GROUND MOTION WORKSHOP I

INTEGRATOR SURVEY: EXPERT INPUTS

PREFERENCES OF THE OVERALL EXPERT COMMUNITY

		Freq.		1				Freq.		1				Freq.		1				Freq.		1		
		Mag.		5.5				Mag.		5.5				Mag.		5.5				Mag.		7		
		Dist.		5				Dist.		70				Dist.		200				Dist.		5		
Exp	AN	DE	IB	S	HE		AN	DE	IB	S	HE		AN	DE	IB	S	HE		AN	DE	IB	S	HE	
1	22	50	1	22	5	100	22	50	1	22	5	100	22	50	1	22	5	100	22	50	1	22	5	100
2	30	30	10	30	0	100	30	20	0	30	20	100	50	0	0	50	0	100	60	0	0	30	10	100
3	25	5	10	50	10	100	25	5	10	50	10	100	25	5	10	50	10	100	25	5	10	50	10	100
4	x	x	x	x	x	0	x	x	x	x	x	0	x	x	x	x	x	0	x	x	x	x	x	0
5	30	0	10	50	10	100	30	0	10	50	10	100	30	0	10	50	10	100	30	0	10	50	10	100
6	20	10	0	70	0	100	20	10	0	70	0	100	20	10	0	70	0	100	20	10	0	70	0	100
7	40	10	10	40	0	100	40	10	10	40	0	100	40	10	10	40	0	100	40	5	10	40	5	100
8	30	30	5	30	5	100	30	30	5	30	5	100	30	30	5	35	0	100	10	0	10	75	5	100
9	20	20	0	60	0	100	20	30	0	50	0	100	20	30	0	50	0	100	10	20	0	50	20	100
10	0	70	0	25	5	100	0	70	0	25	5	100	10	80	0	10	0	100	10	80	0	10	0	100
11	20	20	0	55	5	100	20	20	0	55	5	100	20	20	0	55	5	100	50	0	0	45	5	100
12	10	5	20	60	5	100	10	5	20	60	5	100	0	5	10	80	5	100	10	5	20	60	5	100
13	5	80	5	5	5	100	5	80	5	5	5	100	5	80	5	5	5	100	20	40	5	20	15	100
Avg	21	28	6	41	4	100	21	28	5	41	6	100	23	27	4	43	3	100	26	18	6	44	8	100

GROUND MOTION WORKSHOP I

INTEGRATOR SURVEY: EXPERT INPUTS

PREFERENCES OF THE OVERALL EXPERT COMMUNITY

		Freq.		1				Freq.		1				Freq.		10				Freq.		10		
		Mag.		7				Mag.		7				Mag.		5.5				Mag.		5.5		
		Dist.		70				Dist.		200				Dist.		5				Dist.		70		
Exp	AN	DE	IB	S	HE		AN	DE	IB	S	HE		AN	DE	IB	S	HE		AN	DE	IB	S	HE	
1	22	50	1	22	5	100	22	50	1	22	5	100	22	50	1	22	5	100	22	50	1	22	5	100
2	50	0	0	35	15	100	50	0	0	50	0	100	35	20	10	35	0	100	30	20	0	30	20	100
3	25	5	10	50	10	100	25	5	10	50	10	100	25	5	10	50	10	100	25	5	10	50	10	100
4	x	x	x	x	x	0	x	x	x	x	x	0	x	x	x	x	x	0	x	x	x	x	x	0
5	30	0	10	50	10	100	30	0	10	50	10	100	30	0	10	50	10	100	30	0	10	50	10	100
6	20	10	0	70	0	100	20	10	0	70	0	100	20	10	0	70	0	100	20	10	0	70	0	100
7	40	5	10	40	5	100	40	5	10	40	5	100	40	10	10	40	0	100	40	10	10	40	0	100
8	50	0	5	45	0	100	40	0	0	60	0	100	10	25	5	60	0	100	10	25	5	60	0	100
9	10	20	0	50	20	100	10	20	0	50	20	100	15	15	0	8	70	108	15	25	0	60	0	100
10	10	80	0	10	0	100	50	0	10	30	10	100	10	80	0	10	0	100	10	80	0	10	0	100
11	50	0	0	45	5	100	50	0	0	45	5	100	15	20	0	60	5	100	15	20	0	60	5	100
12	10	5	20	60	5	100	0	5	10	80	5	100	10	5	20	60	5	100	10	5	20	60	5	100
13	30	20	5	30	15	100	30	20	5	30	15	100	5	80	5	5	5	100	5	80	5	5	5	100
Avg	29	16	5	42	8	100	31	10	5	48	7	100	20	27	6	39	9	101	19	28	5	43	5	100

GROUND MOTION WORKSHOP I

INTEGRATOR SURVEY: EXPERT INPUTS

PREFERENCES OF THE OVERALL EXPERT COMMUNITY

		Freq.		10				Freq.		10				Freq.		10				Freq.		10		
		Mag.		5.5				Mag.		7				Mag.		7				Mag.		7		
		Dist.		200				Dist.		5				Dist.		70				Dist.		200		
Exp	AN	DE	IB	S	HE		AN	DE	IB	S	HE		AN	DE	IB	S	HE		AN	DE	IB	S	HE	
1	22	50	1	22	5	100	22	50	1	22	5	100	22	50	1	22	5	100	22	50	1	22	5	100
2	50	0	0	50	0	100	60	0	0	30	10	100	50	0	0	35	15	100	50	0	0	50	0	100
3	25	5	10	50	10	100	25	5	10	50	10	100	25	5	10	50	10	100	25	5	10	50	10	100
4	x	x	x	x	x	0	x	x	x	x	x	0	x	x	x	x	x	0	x	x	x	x	x	0
5	30	0	10	50	10	100	30	0	10	50	10	100	30	0	10	50	10	100	30	0	10	50	10	100
6	20	10	0	70	0	100	20	10	0	70	0	100	20	10	0	70	0	100	20	10	0	70	0	100
7	40	10	10	40	0	100	40	5	10	40	5	100	40	5	10	40	5	100	40	5	10	40	5	100
8	10	25	5	60	0	100	10	0	10	75	5	100	10	0	10	75	5	100	20	0	5	75	0	100
9	15	25	0	60	0	100	10	15	0	70	5	100	10	15	0	70	5	100	10	15	0	70	5	100
10	10	80	0	10	0	100	50	0	10	30	10	100	50	0	10	30	10	100	50	0	10	30	10	100
11	15	20	0	60	5	100	45	0	0	50	5	100	45	0	0	50	5	100	45	0	0	50	5	100
12	0	5	10	80	5	100	10	5	20	60	5	100	10	5	20	60	5	100	0	5	10	80	5	100
13	5	80	5	5	5	100	20	40	5	20	15	100	30	20	5	30	15	100	30	20	5	30	15	100
Avg	20	26	4	46	3	100	29	11	6	47	7	100	29	9	6	49	8	100	29	9	5	51	6	100

APPENDIX B

GROUND MOTION WORKSHOP II

JULY 28-29, 1994

MENLO PARK, CALIFORNIA

B.1 INTRODUCTION

As discussed in the introduction to Appendix A, two ground-motion workshops were held to test a way of eliciting information that SSHAC felt was an improvement over previous elicitation methods. The first workshop, discussed in Appendix A, dealt with the broad issues of what methods should be considered in ground-motion estimation for ENA and was attended by 26 individuals. The second workshop, discussed in this Appendix, was smaller and more intense. In it, specific values of ground motion were elicited and specific differences in data, assumptions and estimates were addressed.

The experts were asked to provide ground-motion estimates at three different times; namely, before, during, and after the workshop. Intensive information exchange and directed interaction took place before and between these times. This Appendix starts with a discussion of the workshop planning and organization, and then proceeds to discuss the Pre-, Co-, and Post-workshop results in sequence. Following this, we discuss the integration performed by the Integrators. Because of time and budget limitations, this integration is not yet complete. In spite of that, however, we feel that the integration process was adequate to allow useful recommendations for future integrations, and that the ground-motion estimates themselves will prove to be useful to the scientific and engineering community.

Many attachments accompany this Appendix. All of the questionnaires and documentation from the experts are included, as well as various graphical presentations of the ground-motion

values. In addition, a description of the database prepared for comparison with the ground-motion estimates is included (one lesson from Workshop I was that this database should have been prepared prior to the first workshop; as it happened, the database discussed here was prepared after the second workshop, for use in the integration process).

B.2 DESIGN AND STRUCTURE

The planning for Workshop II was carried out by the core integrator team, composed of D. Boore, A. Cornell, R. Mensing, P. Morris, and G. Toro, during 6 meetings. The first meeting took place 4 months prior to the workshop.

The participants included the integrator team, proponents, experts, and observers (see Table B-1 for a list of the attendees). Each proponent was specifically asked to provide estimates using only one model. The experts were asked to provide estimates of ground motions using any or all methods and information that they considered appropriate, including the estimates provided by the proponents. The role of the experts in this workshop was typical of what SSHAC calls the "evaluator" role, in contrast to the role of the "proponent" (see Chapter 3). The proponents assumed the role of experts after fulfilling their proponent role. This was done for reasons of economy and efficiency. One open question was whether the same person could successfully change from a role of proponent to one of expert. The nature of Workshop I was such that a large number of participants were welcomed and desired. For Workshop II, however, this was not the case. In order not to dampen the discussions at the workshop, the Integrator team made a substantial effort to keep the number of participants to a minimum (among other things, by limiting the number of observers). The number that attended was just about right, with enough different realms of expertise represented to have fruitful technical discussions and not so many as to discourage open discussion by all experts present.

The Integrator team first chose the methods of estimating ground motion that would be represented by proponents, and then identified proponents who would apply a specific model to the selected prediction problems. The choice of methods was largely based on the results

TABLE B-1
ATTENDEES AT SSHAC
GROUND-MOTION WORKSHOP II

Integrators:

David M. Boore, SSHAC
C. Allin Cornell, SSHAC
Peter Morris, SSHAC
Richard Mensing, Logicon-RDA
Gabriel R. Toro, Risk Engineering, Inc.

Invited Participants:

Norman A. Abrahamson, Consultant
Gail M. Atkinson, Consultant
Don Bernreuter, Lawrence Livermore National Laboratory
Kenneth W. Campbell, EQE
William Joyner, U.S. Geological Survey
Walter Silva, Pacific Engineering and Analysis
Paul Somerville, Woodward-Clyde Consultants

Observers:

Tom Hanks, National Academy of Sciences
Robert Rothman, U.S. Nuclear Regulatory Commission
Jean B. Savy, Lawrence Livermore National Laboratory
John F. Schneider, Electric Power Research Institute
Ernst Zuerflueh, U.S. Nuclear Regulatory Commission

of the first workshop. Included were the stochastic method, the hybrid-empirical method, and the empirical source function method. Because of its widespread use and because of some fundamental differences in the model parameters, two proponents were used for the stochastic method. Based on the strong guidance from Workshop I, no intensity-based methods were included (this does not preclude experts from using such information, of course). The

proponents were chosen because of their intimate familiarity with a particular model for predicting ground motion, and they were asked to base their estimates solely on that model. An important advantage to having the proponents provide estimates rather than relying on an analyst to do so is that the chance of an erroneous application of a model was eliminated and furthermore, the proponents could provide reliable sensitivity studies. The experts were made up of the proponents and several generalists who have a broad knowledge of ground-motion estimation. Although all the proponents assumed the role of experts, this is not necessary.

The Integrator team was responsible for the following tasks:

- Setting up cases on which model runs by proponents were to be based.
- Providing detailed instructions to both proponents and experts.
- Disseminating results of initial model runs and expert assessments to all participants prior to the workshop.
- Guiding the interchange among experts at the workshop.
- Focusing debates on key points of disagreements.
- Summarizing the key points of agreement or disagreement and the key quantitative results, at various times during the workshop.
- Assessing the strengths and weaknesses of different modeling approaches and expert positions.
- Integrating the results, i.e., forming an integrated position regarding the median and the standard deviation of ground motion for each application.

Specific questions the workshop was designed to address regarding the Integrator process included the following:

- Would it be possible to maintain the effective interchange observed in Workshop I, even when the discussion is focused on specific model details or ground-motion estimates? In particular, would it be possible for the Integrators to focus debate on the key issues and have all the experts participate actively in this debate?

- Would it be feasible and meaningful for proponents and experts to develop, not only median ground-motion estimates, but also probabilistic descriptions of the epistemic and aleatory uncertainties?
- Would the distinction between the proponent and expert roles promote information exchange among experts and focus the experts on the task of evaluating the merits of the various models and then arriving at estimates that are representative of the expert community? Is this distinction useful to the integration process?
- Would experts' estimates and uncertainty bands display more or less agreement than the estimates and uncertainty bands provided by the proponents?
- Would the workshop develop sufficient information for the Integrator team to formulate specific Integrator estimates?
- Would the Integrator estimates be defensible and reasonably easy to articulate, and how would the experts respond to the Integrator estimates?

The most important consideration in designing the workshop was that there be ample opportunity and time for interaction amongst the experts and that adequate opportunity was given the experts to study intermediate results and to alter their ground-motion estimates. The Integration team felt that previous ground-motion elicitation exercises did not have sufficient interaction and feedback. To accomplish this, the elicitation was divided into three stages -- Pre-, Co-, and Post-Workshop. The content and results from each stage are discussed below.

B.3 CONTENT AND RESULTS

B.3.1 Pre-Workshop Stage

In the Pre-Workshop stage, four proponents provided ground-motion estimates, obtained using four separate models, for a specified set of magnitudes and distances, for specified measures of ground motion at a very-hard rock site in eastern North America. The distances and magnitudes were chosen so that data was available for some magnitude-distance combinations

and not for others. Also, the magnitude was specified in terms of m_{bLg}, because this is the current standard for the specification of seismicity in PSHA and we wanted to include the conversion of m_{bLg} to **M** in the elicitation. In particular, we specified $m_{bLg} = 7.0$ because the lack of data for earthquakes this large introduces some uncertainty in the relation between the two magnitudes. The proponents were also asked to document the model used to obtain their estimates, to provide sensitivity results for the most important model parameters (so that an experts could easily modifiy a proponent's results if he or she felt that a different parameter value was more appropriate), to discuss the pros and cons of the model used, and to discuss the required modifications for use of the model in other geographic regions. The actual magnitudes, distances, and ground-motion measures are included in the Instructions to Proponents. These instructions and the responses from the proponents, including their written documentation explaining the processes used in arriving at their estimates, are given in Attachment B-1. In addition, Attachment B-1 contains plots of the ground motions made by the Integrator team.

The proponent results were sent to the experts well before the workshop. The experts then estimated the ground motions at the same set of magnitudes and distances for which the proponents provided values. The experts were asked to act as "mini-Integrators", basing their estimates on the proponents results as well as any other models, methods, or information that they considered appropriate (and were willing to defend during the workshop). The instructions to the experts, their results (referred to as "Experts 1"), and plots of their results are contained in Attachment B-2.

The Experts 1 results were collated and plots comparing the estimates were made before the workshop; the estimates and the plots were sent to the experts before the workshop. The cover letter for the transmission of the results is contained in Attachment B-3; for the sake of comparison between the various stages of ground motion, these initial results will be discussed later.

B.3.2 Co-Workshop Stage

The meeting for Workshop II was held from July 28--29, 1994, in Menlo Park, California, at the headquarters of Applied Decision Analysis, Inc.

The workshop was divided into the consideration of median ground-motion estimates, the consideration of uncertainties in ground motion (both epistemic and aleatory), and the completion of an Integrator's survey. The working agenda, made up before the workshop, is given in Attachment B-4. As expected, the agenda was changed somewhat as the workshop proceeded. Overall, however, the deviations from the agenda were minor. Each topic was introduced by a member of the Integrator team, who summarized the results of the proponents and experts and then conducted an informal--but guided--discussion of the results, with an emphasis on interaction amongst the participants. The experts were encouraged to challenge the bases for the ground-motion estimates of the other experts, and were also expected to be prepared to explain the reasoning behind their own choices. The Integrators made sure that the discussion moved from topic to topic, made oral summaries of what they heard before moving to the next topic, and kept the experts from dwelling on issues not important to the end result. These discussions were very fruitful and were carried out at a high intellectual level. The Integrator team believe that the experts were truly trying to do the best job possible of estimating ground motions and were not just trying to defend their territories.

After the first day, the experts were asked to reconsider their ground-motion estimates and to provide new estimates by the start of the second day, if they desired to do so. New plots comparing the ground-motion estimates were made while the meeting was in progress, and these new plots were then discussed by the participants. The new results are termed "Expert 2", and the responses are collected in Attachment B-5.

B.3.2.1 Ground-Motion Estimates. To facilitate discussion, plots were made of the various results, with care given to using common scales, symbols, and so on. Overhead transparencies were used so that comparisons between results and editing of results could easily be made. Not having the means to include transparencies in this appendix, we have shown the comparisons by using two levels of a gray scale to differentiate between results.

(Also, the various estimates at a particular distance were offset horizontally around the specified distance in order to reduce overlap.)

A comparison of selected Proponents, Experts 1, and Experts 2 results are given in Figures B-1 through B-8. Please note that the ordering of the figures follows the order of the workshop, with all the Proponent-Expert 1 comparisons before the Experts 1-Experts 2 comparisons. The results are for 1 and 10 Hz oscillator frequencies. To save space, comparison plots are not given for the 2.5 Hz, 25 Hz, and PGA estimates.

It should also be noted that the meaning of the shortest distance (5 km) was interpreted differently by the different participants, and therefore the ground-motion estimates for 5 km should be treated with caution or ignored. (Somerville and Saikia provided numbers at 12 km as proponents rather than 5 km; the other participants variously interpreted the distance of 5 km as closest distance to the fault and as horizontal distance to the surface projection of the fault). In hindsight, the distance should have been stated as being directly over the earthquake source. In this way the experts would have to grapple with the way to handle the depth extent of faulting and the associated uncertainty that the depth parameter introduces into the estimates. The lesson learned by the Integrators is that greater care must be given in the specification of the elicitation to avoid ambiguity.

The experts utilized a variety of procedures to arrive at their estimates. For instance, several experts used weighted combinations of the proponents' results. Some experts used weights that are magnitude- and distance-dependent. Some experts used these weights in a formal (quantitative) manner, others used them to guide their reasoning for obtaining ground-motion estimates. One expert identified correlation between models as a factor in assigning weights to the proponents' models. Another expert used a subjective combination of modified proponent results and data. A third expert used a single model, which was a modification of a proponent's model. The experts' Pre-Workshop documentation (Attachment B-2, part b) and Co- and Post-Workshop comments (Attachment B-5, part a, and B-7, part b) provides further insights into the experts' reasoning.

The first thing to note in the median amplitudes is that the spread in the 1 Hz estimates is greater than in the 10 Hz estimates. For that reason, the following discussion concerns the 1 Hz estimates. The trend in going from the Proponents to the Experts 1 results was for the range of estimates to be reduced. This is easily seen in Figures B-1 and B-2. In the written documentation (Attachment B-2), the experts who had also acted as proponents clearly stated that they attempted to be "mini-Integrators" (this is consistent with the ideas in Chapter 3 and Appendix J). In particular, note that Atkinson's and Somerville and Saikia's low proponent values increased when they acted as experts, and Campbell's and Silva's high proponent values decreased when they acted as experts.

Reasons for proponent differences were discussed at the workshop. In particular, the low results of Atkinson are due to her source spectral model and to her increase of duration with distance. In view of her low estimates relative to those of the other proponents, as an expert she increased her values. At the workshop, however, there were no challenges to her parameters. (In fact, Joyner considered all the proponent results and decided that the scientific evidence favored the Atkinson model, with a modification to her source spectra. As a result, Joyner did not provide an assessment of the community's best estimate [e.g., see Chapter 3], nor was he asked to[1]. His estimates were derived after careful consideration of all the proponent results). As a result of the discussion during day 1 of the workshop, Atkinson altered her estimates downward (Figures B-5 and B-6). Somerville and Saikia were persuaded by the discussion to give more weight to the Atkinson proponent model and as a result, lowered their estimates for m_{bLg} 5.5 at 1 Hz. In addition, the discussion of Somerville and Saikia's estimates revealed that the moment magnitude associated with their conversion of m_{bLg} 7 was much lower (6.4) than those of the other experts (7.0 to 7.2). The difference lies in the weight given to model extrapolations vs. empirical extrapolations in a region for which few data exist (and this problem is precisely why the Integrators chose m_{bLg} 7 and why they did not specify moment magnitudes). Appendix C contains some plots illustrating

[1]At the time of Workshop II, the elicitation scheme of Chapter 3 and Appendix J had not fully crystallized. Hence, the Integrators did not emphasize the distinction between an expert's own opinions and an expert as a mini-Integrator representing the whole community of experts. In fact, many of the ideas in Chapter 3 grew out of the experience from Workshop II.

the problem. As a result of the discussion, Somerville and Saikia modified their m_{bLg} 7 values upward in their Expert 2 estimates (Figures B-6 and B-8).

B.3.2.2 Uncertainty Estimates. The uncertainty estimates did not vary as much from Proponent to Experts 1 or between Experts 1 and Experts 2, as did the median ground motion values (the same is true between the Experts 2 and Experts 3 estimates; the latter will be discussed in Section B.3.3 and shown in Figures B-14 through B-17). In other words, the experts did not feel as much of a need to resolve differences in the uncertainty estimates. Discussions revealed misunderstandings about what the epistemic uncertainty represents, about the difference between epistemic and aleatory uncertainty, and about how to compute epistemic uncertainty. There was also a misunderstanding about how the experts were asked to report epistemic uncertainty in the input forms (initially, some experts reported the quantity ln[Amplitude, 90-percentile] – ln[Amplitude, median], rather than the epistemic standard deviation). Some experts relied on formal procedures for the quantification of epistemic uncertainty, while others used a subjective approach.

B.3.2.3 Integrator's Survey. The survey that was handed out to the seven ground-motion experts is included as Attachment B-6, part a. This section summarizes the overall results of the survey, focusing on the summary data provided in Tables B-2 through B-5. Additional interesting and useful information also is provided in Attachment B-6, whose contents are briefly described here:

Attachment B-6, part b: Experts' Written Comments. The experts provided supporting information in the form of written comments that explain their Experts 1 inputs. This information is important in understanding how each expert evaluated each model.

Attachment B-6, part c: Detailed Expert Inputs on Weighting the Forecasts. This is the raw data, expert-by-expert, application-by-application, that formed the basis for the aggregated data shown in Table B-3.

Attachment B-6, part d: Detailed Expert Inputs on Relative Forecasting Uncertainty. This is the raw input, expert-by-expert, application-by-application, that formed the basis for the aggregated data shown in Table B-4.

The basic results of the survey are most easily understood by reviewing Tables B-2 through B-5, which are described below.

Basis for Experts' Estimates (Table B-2). Table B-2 illustrates that all seven experts used weights either implicitly or explicitly as the basis for determining their own Experts 2 estimate based on the model results. This supports both an expert interaction process and an Integrator process that uses model weights, at least for guidance, if not for formal mathematical combination.

No expert did <u>not</u> weight informally or formally. In the ground-motion arena, weighting appears to be a natural mode in which experts think. This lends more credence to the model-based elicitation process in which Integrators focus on the models like the experts do and use the experts for guidance as to how to weight the models.

Weighting the Forecasts (Table B-3). Each expert was asked to assign numerical weights to the Proponent models, even if the expert had used informal weighting to derive his estimates. Table B-3 shows, for six different applications,[2] the weights for the four Proponent models averaged over seven experts (the expert-by-expert weights are presented in Attachment B-6, part c). Several observations are pertinent:

- The weights are definitely **not** equal. While the relative weights assigned by the experts are reasonably diverse, the experts very clearly do not equally weight each modeling approach. This is true despite the initial association between models and specific proponents prior to and during the early stages of the workshop (recall that, in the past, experts have shown reluctance to weight

[2]We refer to one frequency-magnitude-distance combination as one "application".

other experts). This suggests that, in the later stages of the workshop, experts (even those who had acted as proponents) are able to de-couple models from individuals for the purpose of assigning numerical weights. This confirms the same observation of the more general survey of Workshop I.

- The average weights are remarkably consistent across the different applications–more consistent than they were in Workshop I. The stochastic model with empirical attenuation consistently gets the greatest weight, while the hybrid empirical model consistently gets the lowest weight. The stochastic model with ray theory attenuation and the empirical-source-function methods fall in between.

Relative Forecasting Uncertainty (Table B-4). This table needs to be interpreted only roughly because a number of experts stated that they were somewhat confused over the meaning of the question. One of the homework assignments for the Integrator team from the workshop is to construct a more meaningful measure for assessing forecasting error. The table shows:

- The relative forecasting of each model is seen to vary, sometimes rather dramatically, with application. For example, the hybrid empirical model is judged to be almost 50% less accurate for magnitude 5.5 applications than for a frequency 1 Hz, 7.0 magnitude application.

- The stochastic model with empirical attenuation tended to be judged as having the least forecasting error, and the hybrid empirical judged as having the most forecasting error. In general, however, there is a fairly high degree of similarity among all the numbers. This indicates, again, that the experts see the models as all providing useful information.

Correlation Among Model Forecasts (Table B-5). This table is perhaps most easily understood by looking at the average correlation among model pairs, shown on the left

portion of the table. This indicates that for the six experts who responded, there is a correlation or overlap of 22% to 56%, for an average of 39%, among pairs of models. This supports the observation made by the Integrator team during the group interaction that there is clearly a reasonable amount of overlap among all four of these models. Some specific observations are:

- The empirical-source-function method is seen to have the least overlap with the other models, as evidenced by the lowest average percent correlation demonstrated in the small table to the right, and as evidenced by the generally smaller correlations with the other models shown in the larger table to the left.

- The experts show significant diversity in their assessments of the correlation among the different model forecasts. This indicates that, prior to integration, these disagreements need to be explored to find out whether they are unintentional or based on true differences.

- The survey also revealed that there is substantial disagreement about the relative correlation among the different model forecasts. Part of this disagreement may be unintended, due to confusion about the interpretation of the question and about the correlation measure, but part of this disagreeement may be due to actual substantive differences. Prior to final integration, it would be useful to explore the source of the diversity and opinion in this area.

B.3.2.4 List of Contributors to Uncertainty. The experts were asked to discuss and catalog the different factors that contribute to total uncertainty in ground-motion prediction, whether they contribute to aleatory or epistemic uncertainty, and which factors are the most important. The result of this exercise is Table B-6. It would have been useful to devote more time to these issues, in order to elicit each expert's quantitative estimates of the various contributors to aleatory and epistemic uncertainty.

B.3.3 Post-Workshop Stage

Following the workshop, the experts were given another chance to change their estimates. Most of the experts responded (the instructions and response are contained in Attachment B-7; the results are referred to as "Experts 3"). Because of time and budget constraints only a few experts modified their estimates, although more would have liked to do so. Those who did not provide revised estimates, however, indicated that the changes would probably not be major. The Expert 3 estimates of median ground-motion amplitude for all magnitudes, distances, and oscillator frequencies are contained in Figures B-9 through B-13.

The Expert 3 estimates of epistemic and aleatory uncertainty are contained in Figures B-14 through B-17. The epistemic uncertainties are greater for m_{bLg} 7 than for m_{bLg} 5.5 (Figures B-14 and B-15) , which makes sense in terms of the data available to constrain the estimates and calibrate the models. On the other hand, there is a large spread among the experts' estimates. This spread may be due, in part, to the following causes: the misunderstandings described in Section B.3.2.2 (which may have remained after the Workshop), and differences in the way the experts estimated epistemic uncertainty (formally vs. subjectively). In contrast, the aleatory uncertainty showed surprisingly little variation among experts (Figures B-16 and B-17). The lesson is that it is much harder to elicit and estimate epistemic uncertainty than it is aleatory uncertainty. Subject to the caveat that several of the experts would have revised their estimates somewhat if resources had permitted, Figures B-9 through B-17 can be considered to exhibit the final estimates of the individual experts.

B.4 INTEGRATION

After receiving the Post-Workshop results, the Integrator team met several times for the purpose of providing their integration of the various estimates into the final estimates. To aid in the integration of the median ground-motion estimates, some effort was made in preparing figures showing the data and the various median estimates. This effort is discussed in Attachment B-8 (as noted earlier, if this elicitation exercise were done over, the data preparation would have been the initial task of Workshop I). It was not at all clear how the integration should proceed, but after some time a strategy arose. Basically, it was decided to

produce two estimates of the median ground motions, one by equally weighting the seven Experts 3 results, and the other by unequally weighting the four proponent results. In the latter case, the weights were strongly guided by the results of the Integrator's survey completed during the workshop (see Table B-3), except that Joyner's Experts 3 results were to be substituted for those of the Atkinson proponent estimates, because in the view of the Integrators, Joyner's spectral shape deviated less from the conventional Brune shape in the region between the two corner frequencies. These weights are given in Table B-6 (note that different weights are used for the median amplitudes and for the uncertainties). Both approaches produced similar results. Unfortunately, the figures showing the estimates obtained by applying unequal weights to the proponents' results were not prepared for all magnitudes and oscillator frequencies; they are given here for magnitude 5.5 and 1 Hz only. Integration results for all magnitudes and oscillator frequencies are provided only in tabular form in Tables B-8 and B-9.

The results for the mean amplitude and and epistemic uncertainty are contained in Figures B-18 through B-23 (except for Figure B-19, which shows results for unequal weights on the proponents' results). The mean shown is the geometric mean of the seven individual estimates. The upper and lower bars show the Integrators estimates of the epistemic uncertainty. These were computed by averaging the variances of the Experts 3 log uncertainties, giving zero weight to the Silva epistemic uncertainties, which the Integrator team judged to be unrealistically low in view of the spread of estimates shown in the median estimates. The upper and lower bars should also have contained a contribution from the expert-to-expert variation in the median ground motions, but the need for this additional term was discovered after the resources for the project were exhausted. It is expected that the increase in spread of the upper and lower bars would be small, since the new value would be given by the sum of the squares of the uncertainties, and the individual epistemic uncertainties are larger than the spread between the median estimates.

Tables B-8 and B-9 provide summaries of the estimates obtained for all magnitudes and distances elicited, using the two approaches for integration, and Table B-10 compares these estimates (estimates of the aleatory standard deviation will be discussed below). The median

estimates obtained using equal weights on experts are somewhat lower than those obtained using unequal weights on the proponents' results. The difference between the two sets of median estimates is at most 26%, which is not large given the epistemic uncertainties.

The estimates of epistemic uncertainty in the median are generally consistent between the two integration approaches. The only exception is 1 Hz, for which the weighted proponent estimates has a lower value. In general, the epistemic uncertainty is higher for m_{bLg} 7 than for m_{bLg} 5.5, as one would expect (due to the lack of data and to uncertainty about source scaling and the relationship between seismic moment and m_{bLg} at high magnitudes).

For the aleatory uncertainty, the proponents and experts were asked to provide both the median aleatory standard deviation (we will call this quantity $\bar{\sigma}$) and the epistemic uncertainty in the aleatory standard deviation (we will call this quantity σ_σ). Calculations show that σ_σ values of 0.2 or lower have only a minor effect on the ground-motion distribution within $\pm 2\bar{\sigma}$ and that this effect may be represented by replacing $\bar{\sigma}$ with the slightly larger quantity $[\bar{\sigma}^2+\sigma_\sigma^2]^{1/2}$ (we will call this quantity the aleatory standard deviation, or σ). Table B-11 lists the Experts 3 values of $\bar{\sigma}$ and σ_σ for a distance of 20 km and shows that only one expert used values of σ_σ greater than 0.2. Thus, it is appropriate to represent the integration results in terms of σ, without having to represent $\bar{\sigma}$ and σ_σ separately.

The integrated aleatory standard deviation was estimated in the same way as was the epistemic uncertainty, by combining the variances of the individual estimates. The results are shown in Figures B-24 through B-28 and in Tables B-8 and B-9. These figures indicate that the aleatory standard deviations are in rough agreement with the scatter in the data.

The estimates of aleatory uncertainty are generally consistent between the two integration approaches, although the value from weighted proponent estimates is slightly higher. The

aleatory uncertainty is slightly higher for low frequencies than for high frequencies and is also slightly higher for m_{bLg} 5.5 than for m_{bLg} 7. These trends with frequency and magnitude are consistent with the trends observed in empirical attenuation studies using WNA strong-motion data. The estimated values of aleatory uncertainty for 10 Hz and PGA are, however, significantly higher than values obtained using WNA strong-motion data, especially for large magnitudes. There are several possible explanations for these higher values. For instance, much of the CENA data come from small earthquakes (~ m_{bLg} 5) and from rock sites (both of these conditions are believed to produce higher scatter), the fact that the magnitude is specified in terms of m_{bLg} rather than moment magnitude, or the experts' difficulty in separating aleatory and epistemic uncertainties. This is another issue that would have benefited from additional Post-Workshop interaction with the experts.

B.4.1 Preferred Ground-Motion Estimates

The estimates obtained by combining the Experts 3 estimates using equal weights (Table B-8) are selected as the preferred estimates from this integration exercise. The main reason for this selection is that the Experts 3 estimates directly incorporate the feedback from all the exchanges of information that took place during Workshop II. The consistency between these results and the results obtained using unequal (expert-selected) weights to the proponents estimates (see Tables B-9 and B-10) suggests that the integration process is robust.

Potential users of these results are cautioned that the the estimates of aleatory uncertainty in Table B-8 for high-frequency ground motions may be too high, as was discussed above, and should be considered tentative.

B.4.2 Interpolation

The integration results in Table B-8 may be used in a PSHA by applying a suitable interpolation scheme over magnitude, distance, and frequency. Because the elicited magnitudes, distances, and frequencies are sparse[3], interpolation of the median estimates must

[3]The number of magnitude, distance, and frequency combinations for which to elicit ground-motion estimates was deliberately kept small. The Integrators felt that it was preferable to focus

be done very carefully. For instance, one may use an existing functional form (e.g., Atkinson and Boore, 1995, Toro et al., 1995) and adjust a small number of coefficients to match or approximate the estimates obtained here. Particular case must be used at short distances, with due consideration for the definition of distance being used.

Interpolation of the epistemic and aleatory standard deviations is less critical, as these quantities do not show a strong dependence on magnitude, distance, or frequency.

An additional issue is the epistemic correlation among magnitude-distance pairs (for a given frequency; see Chapter 6 for a discussion of this issue). The default assumption is perfect correlation (i.e., one can represent epistemic uncertainty using a family of attenuation equations that do not intersect each other). This assumption does not affect the mean hazard, gives a conservative estimate of the epistemic uncertainty, and it is a good approximation if uncertainty in the mean stress drop dominates the epistemic uncertainty in ground motion.

An alternative to the interpolation scheme discussed above is to represent the Integration results as a weighted combination of model predictions (for instance, in terms of the proponents' models). This alternative has the following two drawbacks: one must allow for weights that depend on magnitude and distance (requiring interpolation of the weights, and thereby negating some of the conceptual simplicity of the approach), and it may increase the proponents' visibility at the expense of the experts' (contrary to the tendency observed in the workshop). One advantage of this approach is that the epistemic correlation among magnitude-distance pairs is automatically built into the Integration results.

B.5 CONCLUDING OBSERVATIONS AND DISCUSSION

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the experts' efforts into obtaining high-quality estimates for a limited number of cases, rather than diluting the experts' efforts.

In general, the workshop was very successful. It substantiated a number of our beliefs about positive aspects of the Integrator process. It also pointed out several weaknesses in the process design; however, the good news is that the weaknesses suggested specific mechanisms for improvement.

Here we list the overall results of the Expert and Proponent interchange and the Integration Process. Specific results related to the survey were provided in an earlier section.

- The Proponents and Experts exhibited a striking amount of agreement, considering the range of different approaches and philosophies used to generate the numbers. Moreover, as the interaction progressed, the agreement increased (experts were asked to reassess over-night and after the workshop and those that did tended to bring their estimates and uncertainty ranges closer to the group average).

- The most heartening result of the workshop was the success of the information interchange that was engendered by the Integrator-facilitated proponent/expert process. In the process of isolating sources of disagreement, many common points of agreement were established and a number of points of unintended disagreement were revealed. The response of the experts, when queried about their feelings about the workshop, were summarized by one participant: "It is astonishing how much everyone agrees." The workshop seemed to generate a great deal of clarity and new understanding among the ground motion community on matters ranging from data to methodology to philosophy.

- The model median estimates and the rationale for them appeared to be well understood by the group. However, there appeared to be less clear understanding of the uncertainty ranges supplied by the Proponents and Experts. Several experts misinterpreted the questions (e.g., at least two experts supplied ten-ninety percentiles when asked for standard deviations), and there

was clearly some confusion concerning how to classify uncertainties as either aleatory or epistemic.

- The above observation makes it clear that, consistent with observations in other similar exercises, uncertainty elicitation needs to be done individually, at least until each expert is thoroughly familiar with the meaning and implications and subtleties of the uncertainty estimates. Written instructions are inadequate even for experts who are trained in probability and statistics. In order to provide reasonable judgments, experts need to be trained and the elicitation needs to be carefully structured to remove any possible biases.

- The proponent/expert distinction worked quite well. It solidified the conclusion from Workshop I that it is advantageous to focus discussion and debate on models, rather than individual experts. Viewing the individuals as expert interpreters of models that provide insights to the Integrators appears to be a very attractive alternative compared to the view of experts as advocates of their own models or assessments.

- Experts' estimates, after observing the model estimates, tended to be more tightly grouped than the model estimates themselves. This indicates that the experts are willing to take a broad view in which most or all approaches are viewed as providing some useful information.

- The largest changes in the median ground-motion estimates occurred before the workshop took place (Proponents to Experts 1); subsequent changes were less pervasive. This confirms that much valuable elicitation can and should be done prior to any group meeting, when the experts have time to think, study, and calculate. The experts should be provided with sufficient guidance and information (e.g., proponents' estimates, data).

- One view of the process used is that it puts the experts in the role of Integrators themselves. The experts' willingness to use information from different points of view would appear to be a good sign about the future viability of the Integrator process. An interpretation of the elicitation process is that the experts are actually being asked to provide the Integrator with their best assessment of how to integrate.

- It was highly useful to have the experts as a group generate the list of uncertain factors that lead to overall uncertainty in ground motion. It was also extremely useful as both a teaching exercise and in developing useful information to have the group categorize the different factors in terms of whether they contribute to aleatory uncertainty or epistemic uncertainty or both. This appears to be a far better idea than having the Integrators suggest a list of such factors prior to the workshop.

- The integration process was, for several reasons, necessarily incomplete:

  - The biggest impediment to the integration process was that it became clear that the Integrators did not understand explicitly enough the database on which the different model estimates and expert judgments were predicated. The lesson here is clear: future workshops should explicitly focus on the different databases in at least as much detail and as structured a way as Workshop I and Workshop II focused on modeling approaches. One idea is to try to design common formats for representing the raw data in a form that experts can compare easily.

  - The integration process was hampered to a lesser extent by a lack of understanding about the reasons underlying some of the experts' uncertainty bands. It is important to know explicitly, if an expert's epistemic uncertainty band is smaller than the range of model estimates, whether this represents an explicit down-weighting of the other model

estimates or is simply a misunderstanding of what the uncertainty band is intended to represent. Similarly, if an expert's uncertainty band is far wider than the range of model estimates, it is important to understand why. This suggests that there should be additional interaction between Integrators and experts, after the Integrators have fully digested the experts' estimates. This interaction may be in the form of conference calls (some plenary, some with each individual expert) and written communications.

- In spite of the above difficulties, and in spite of the short time available at the workshop itself (two hours), the Integrators were able to come up with tentative, but specific, median estimates and uncertainty bands about those estimates. Contributing to the ease of the integration process was the large amount of agreement among the experts; however, the promising observation is that even when the experts disagreed, the workshop had developed a reasonably clear picture of why they disagreed. Thus, the Integrators were able to address clearly defined ground-motion issues rather than having to guess why experts disagreed.

- The response of the experts to the Integrators preliminary estimates was fairly benign. Several factors probably contributed to this: 1) the integration was performed on estimates that were not final. At the workshop, we decided that another iteration of estimates was necessary, based on the information generated at the workshop; 2) Since there was a good deal of agreement among the experts, the Integrator position, which is fairly close to most of the individual experts' positions, was not controversial; and 3) the experts, by essentially playing the role of Integrators themselves in the workshop process, were probably psychologically much more prepared to accept the results of an integrated estimate than they would have been had they not had to go through the exercise themselves.

TABLE B-2

GROUND MOTION WORKSHOP II
INTEGRATOR SURVEY
BASIS FOR EXPERTS' ESTIMATES

EXPERT	Explicit Weights	Informal Weights	No Weights
Abrahamson		XXX	
Atkinson		XXX	
Bernreuter		XXX	
Campbell	XXX		
Joyner	XXX		
Silva	XXX		
Somerville		XXX	

TABLE B-3

GROUND MOTION WORKSHOP II
INTEGRATOR SURVEY
WEIGHTING THE FORECASTS

How would you weight the results if all four approaches were applied to a specific site application? (weights averaged over 7 experts)						
Frequency (Hz)	1	1	10	10	PGA	PGA
Magnitude (m_{bLg})	5.5	7.0	5.5	7.0	5.5	7.0
Distance (km)	20	20	20	20	20	20
Method	**AVERAGE WEIGHTS**					
Stochastic with Empirical Attenuation	46	42	42	41	42	41
Stochastic with Ray Theory Attenuation	19	19	23	22	23	22
Hybrid Empirical	14	13	14	16	14	16
Empirical Source Functions	22	25	22	22	22	22
Total	100	100	100	100	100	100

TABLE B-4

GROUND MOTION WORKSHOP II
INTEGRATOR SURVEY
RELATIVE FORECASTING UNCERTAINTY

How would you judge the relative forecasting error band assuming 100 for the approach that has the least error? (weights averaged over 7 experts)							
Frequency (Hz)	1	1	10	10	PGA	PGA	
Magnitude (m_{bLg})	5.5	7.0	5.5	7.0	5.5	7.0	
Distance (km)	20	20	20	20	20	20	AVG
Method	**RELATIVE ERROR BANDS**						
Stochastic with Empirical Attenuation	100	118	100	113	105	113	108
Stochastic with Ray Theory Attenuation	117	112	110	108	115	115	113
Hybrid Empirical	153	112	157	128	158	135	140
Empirical Source Functions	129	140	122	128	115	133	128
Average	125	120	122	119	123	124	122

TABLE B-5

GROUND MOTION WORKSHOP II
INTEGRATOR SURVEY -- EXPERT INPUTS:
CORRELATION AMONG MODEL FORECASTS

	Percent Correlation for Each Model Pair*								Avg. Percent Correlation for Each Model			
Expert	**SE SR**	**SE HE**	**SE ESF**	**SR HE**	**SR ESF**	**HE ESF**	**AVG**		**SE**	**SR**	**HE**	**ESF**
Abrahamson	50	25	10	25	20	0	**22**		28	32	17	10
Atkinson	33	33	33	67	33	33	**39**		30	44	44	33
Bernreuter	66	33	0	33	0	0	**22**		33	33	22	0
Campbell	33	33	67	67	33	33	**44**		44	44	44	44
Joyner	X	X	X	X	X	X	**X**		X	X	X	X
Silva	33	33	33	100	67	67	**56**		33	67	67	56
Somerville	67	33	67	33	33	67	**50**		56	44	44	56
AVERAGE	**47**	**32**	**35**	**54**	**31**	**33**	**39**		**38**	**44**	**40**	**33**

* Assumes for data display that: "0" = 0 "+" = 33 "++" = 67 "+++" = 100

SE: Stochastic with empirical attenuation (Atkinson)
SR: Stochastic with ray-theory attenuation (Silva)
HE: Hybrid empirical (Campbell)
ESF: Empirical source function (Somerville and Saikia)

TABLE B-6

FACTORS THAT CONTRIBUTE TO UNCERTAINTY IN GROUND MOTIONS
(prepared by Experts)

FACTOR	Dominant	Epistemic		Aleatory	
		P.S.	F.S.	P.S.	F.S.
PARAMETRIC					
Source					
m_{bLg} - M relationship (for predictions in terms of m_{bLg})	√large mag.	√	√	√	√
Stress Parameter (pt. source only)	√	√	×	√	×
Focal Depth	√small dist.	O	O	√	√
Rupture dimensions	√large mag.	×	√	×	√
Slip Distribution		×	O	×	O
Rise Time		×	O	×	O
Source Spectral Shape	√ 1 Hz	√	O	√	O
Rupture Velocity (Duration)		×	O	×	O
Source Mechanism		O	O	O	√
Path					
Geometric Attenuation		O	O	O	O
Anelastic Attenuation	√ large dist.	O	O	√	√
Duration vs. Distance (assumes no RVT for finite src.)	√ sm. mag	O	×	O	×
Crustal Structure	√ mod. dist.	O	O	O	×
Site					
Kappa	√ WNA, H. Freq.	O	O	√	√
Near-surface velocity structure		O	O	O	O
MODELING					
Performance vs. data, data quality, horiz. vs. vertical	√	√	√	√	√

Notes: P.S., Point Source; F.S, finite source; √ done; × not done; O could do, should do, or not used

TABLE B-7

WEIGHTS USED IN INTEGRATION

Method	Proponent	Weight for Median	Weight for Uncertainty
Hybrid Empirical	Campbell	0.14	0.17
Stochastic (2-corner, empirical geometric attenuation)	Atkinson (modif. by Joyner)	0.46	0.56
Stochastic (Brune spectrum, ray-theory geometric attenuation)	Silva	0.19	0
Empirical Source Function	Somerville and Saikia	0.22	0.27

TABLE B-8

INTEGRATION RESULTS: EQUAL WEIGHTS ON EXPERTS' ESTIMATES

f (Hz)	mbLg	R (km)	Median Amplitude (g)	Epistemic Std. Dev.	Aleatory Std. Dev.
1	5.5	20	1.09E-02	0.48	0.80
	5.5	70	2.27E-03	0.46	0.80
	5.5	200	9.36E-04	0.37	0.80
	7.0	20	1.67E-01	0.66	0.78
	7.0	70	4.50E-02	0.71	0.78
	7.0	200	1.82E-02	0.73	0.79
2.5	5.5	20	4.17E-02	0.34	0.77
	7.0	20	3.67E-01	0.53	0.73
10	5.5	20	1.55E-01	0.32	0.73
	5.5	70	2.58E-02	0.32	0.75
	7.0	20	8.45E-01	0.52	0.70
	7.0	70	1.88E-01	0.53	0.72
25	5.5	20	2.13E-01	0.34	0.73
	7.0	20	1.07E+00	0.51	0.70
PGA	5.5	70	1.28E-02	0.41	0.75
	7.0	70	9.36E-02	0.51	0.70

TABLE B-9

INTEGRATION RESULTS: UNEQUAL WEIGHTS ON PROPONENTS' ESTIMATES

f (Hz)	mbLg	R (km)	Median Amplitude (g)	Epistemic Std. Dev.	Aleatory Std. Dev.
1	5.5	20	1.01E-02	0.50	0.80
	5.5	70	2.07E-03	0.36	0.82
	5.5	200	9.10E-04	0.41	0.82
	7.0	20	1.67E-01	0.56	0.78
	7.0	70	4.16E-02	0.58	0.79
	7.0	200	1.65E-02	0.64	0.80
2.5	5.5	20	3.69E-02	0.39	0.80
	7.0	20	3.56E-01	0.67	0.78
10	5.5	20	1.24E-01	0.36	0.76
	5.5	70	1.90E-02	0.27	0.78
	7.0	20	7.31E-01	0.55	0.74
	7.0	70	1.61E-01	0.57	0.76
25	5.5	20	1.69E-01	0.36	0.75
	7.0	20	1.04E+00	0.55	0.73
PGA	5.5	70	9.77E-03	0.44	0.76
	7.0	70	8.07E-02	0.56	0.75

TABLE B-10

INTEGRATION RESULTS: COMPARISON OF INTEGRATION RESULTS - UNEQUAL WEIGHTS ON PROPONENTS VS. EQUAL WEIGHTS ON EXPERTS

f (Hz)	mbLg	R (km)	Median Amplitude (% diff.)	Epistemic Std. Dev. (diff.)	Aleatory Std. Dev. (diff.)
1	5.5	20	-8	0.02	0.00
	5.5	70	-9	-0.10	0.02
	5.5	200	-3	0.04	0.02
	7.0	20	-0	-0.09	-0.01
	7.0	70	-7	-0.13	0.01
	7.0	200	-9	-0.09	0.01
2.5	5.5	20	-12	0.05	0.03
	7.0	20	-3	0.14	0.05
10	5.5	20	-20	0.04	0.02
	5.5	70	-26	-0.05	0.03
	7.0	20	-13	0.03	0.03
	7.0	70	-14	0.05	0.04
25	5.5	20	-21	0.02	0.02
	7.0	20	-3	0.04	0.03
PGA	5.5	70	-24	0.04	0.02
	7.0	70	-14	0.05	0.05

Notes: diff.= Weighted Proponents - Experts
% diff.= (Weighted Proponents - Experts) / Experts

TABLE B-11

EXPERTS' ESTIMATES OF ALEATORY UNCERTAINTY

(Distance: 20 km)

mbLg	Expert	f (Hz)	σ	σ	σ
5.5	Abrahamson	1	0.75	0.10	0.76
5.5	Abrahamson	2.5	0.70	0.10	0.71
5.5	Abrahamson	10	0.70	0.10	0.71
5.5	Abrahamson	25	0.70	0.10	0.71
5.5	Atkinson	1	0.80	0.20	0.82
5.5	Atkinson	2.5	0.80	0.20	0.82
5.5	Atkinson	10	0.80	0.20	0.82
5.5	Atkinson	25	0.80	0.20	0.82
5.5	Bernreuter	1	0.70	0.30	0.76
5.5	Bernreuter	2.5	0.70	0.30	0.76
5.5	Bernreuter	10	0.60	0.30	0.67
5.5	Bernreuter	25	0.65	0.20	0.68
5.5	Campbell	1	0.82	0.15	0.83
5.5	Campbell	2.5	0.76	0.15	0.77
5.5	Campbell	10	0.68	0.15	0.70
5.5	Campbell	25	0.70	0.15	0.72
5.5	Joyner	1	0.80	0.20	0.82
5.5	Joyner	2.5	0.80	0.20	0.82
5.5	Joyner	10	0.80	0.20	0.82
5.5	Joyner	25	0.80	0.20	0.82
5.5	Silva	1	0.92	0.20	0.94
5.5	Silva	2.5	0.74	0.20	0.77
5.5	Silva	10	0.61	0.20	0.64
5.5	Silva	25	0.68	0.20	0.71
5.5	Somerville & Saikia	1	0.80	0.10	0.81
5.5	Somerville & Saikia	2.5	0.70	0.10	0.71
5.5	Somerville & Saikia	10	0.65	0.10	0.66
5.5	Somerville & Saikia	25	0.60	0.10	0.61

TABLE B-11 (continued)

mLg	Expert	f (Hz)	σ	σ	σ
7.0	Abrahamson	1	0.75	0.10	0.76
7.0	Abrahamson	2.5	0.70	0.10	0.71
7.0	Abrahamson	10	0.70	0.10	0.71
7.0	Abrahamson	25	0.70	0.10	0.71
7.0	Atkinson	1	0.80	0.20	0.82
7.0	Atkinson	2.5	0.80	0.20	0.82
7.0	Atkinson	10	0.80	0.20	0.82
7.0	Atkinson	25	0.80	0.20	0.82
7.0	Bernreuter	1	0.80	0.40	0.89
7.0	Bernreuter	2.5	0.70	0.30	0.76
7.0	Bernreuter	10	0.60	0.30	0.67
7.0	Bernreuter	25	0.60	0.30	0.67
7.0	Campbell	1	0.74	0.15	0.76
7.0	Campbell	2.5	0.68	0.15	0.70
7.0	Campbell	10	0.62	0.15	0.64
7.0	Campbell	25	0.64	0.15	0.66
7.0	Joyner	1	0.80	0.20	0.82
7.0	Joyner	2.5	0.80	0.20	0.82
7.0	Joyner	10	0.80	0.20	0.82
7.0	Joyner	25	0.80	0.20	0.82
7.0	Silva	1	0.80	0.20	0.82
7.0	Silva	2.5	0.64	0.20	0.67
7.0	Silva	10	0.51	0.20	0.55
7.0	Silva	25	0.60	0.20	0.63
7.0	Somerville & Saikia	1	0.70	0.15	0.72
7.0	Somerville & Saikia	2.5	0.60	0.15	0.62
7.0	Somerville & Saikia	10	0.55	0.15	0.57
7.0	Somerville & Saikia	25	0.55	0.15	0.57

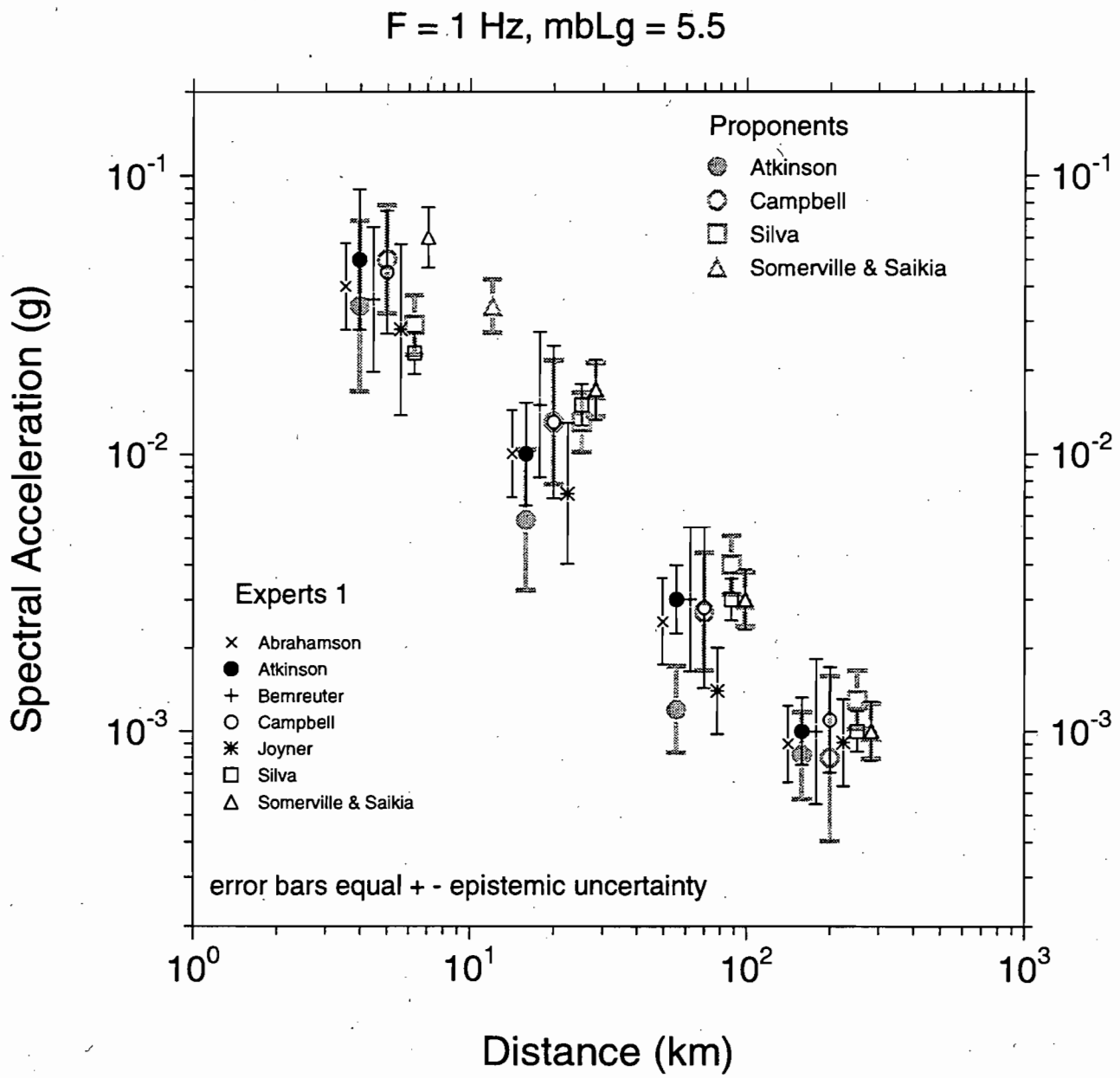

Figure B-1. Comparison of proponents' estimates (gray) to Experts 1 estimates (black) of 1-Hz spectral acceleration for m_{bLg} 5.5. The error bars represent the $\pm\sigma_{epistemic}$ range.

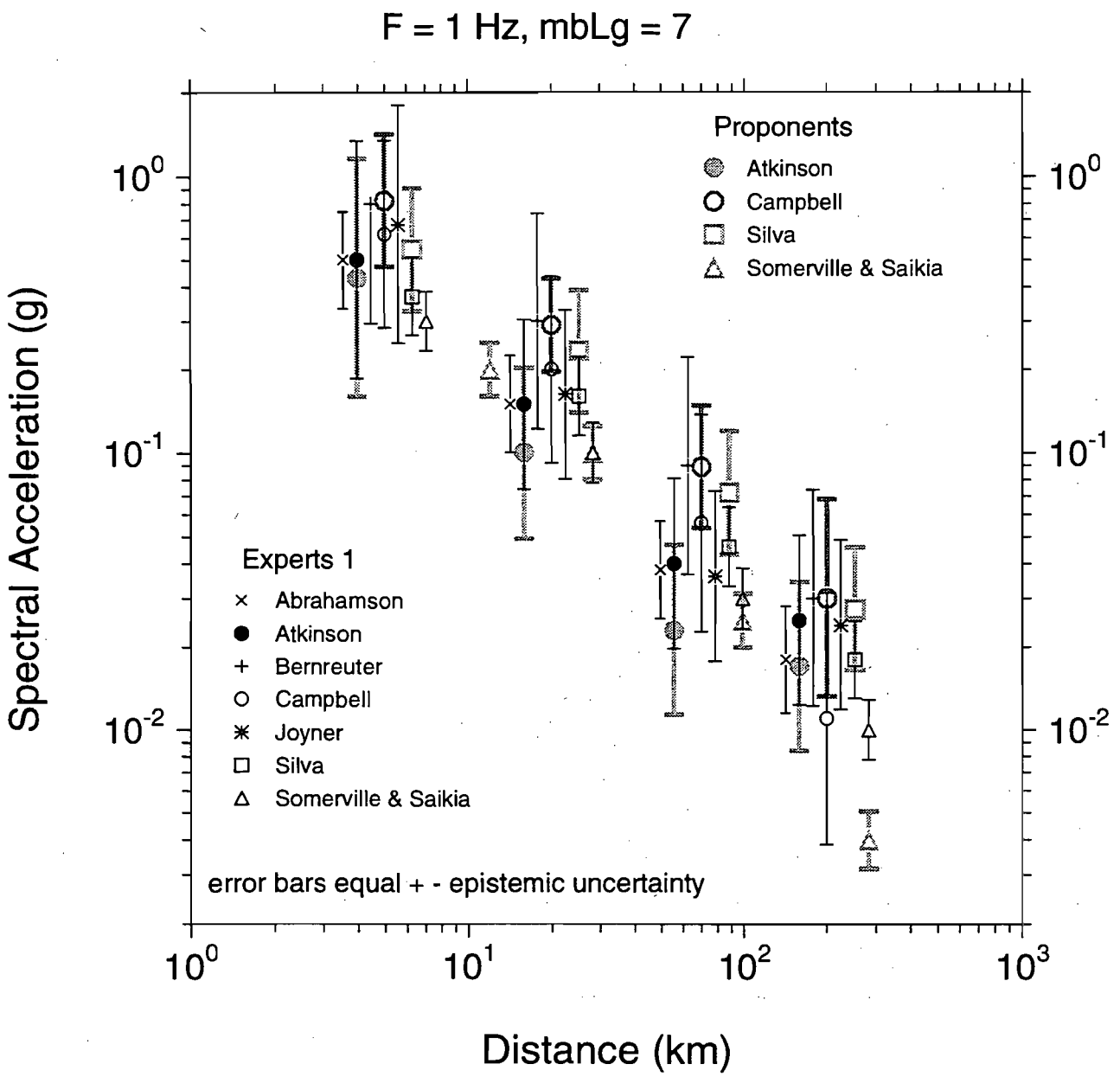

Figure B-2. Comparison of proponents' estimates (gray) to Experts 1 estimates (black) of 1-Hz spectral acceleration for m_{bLg} 7.0. The error bars represent the $\pm\sigma_{epistemic}$ range.

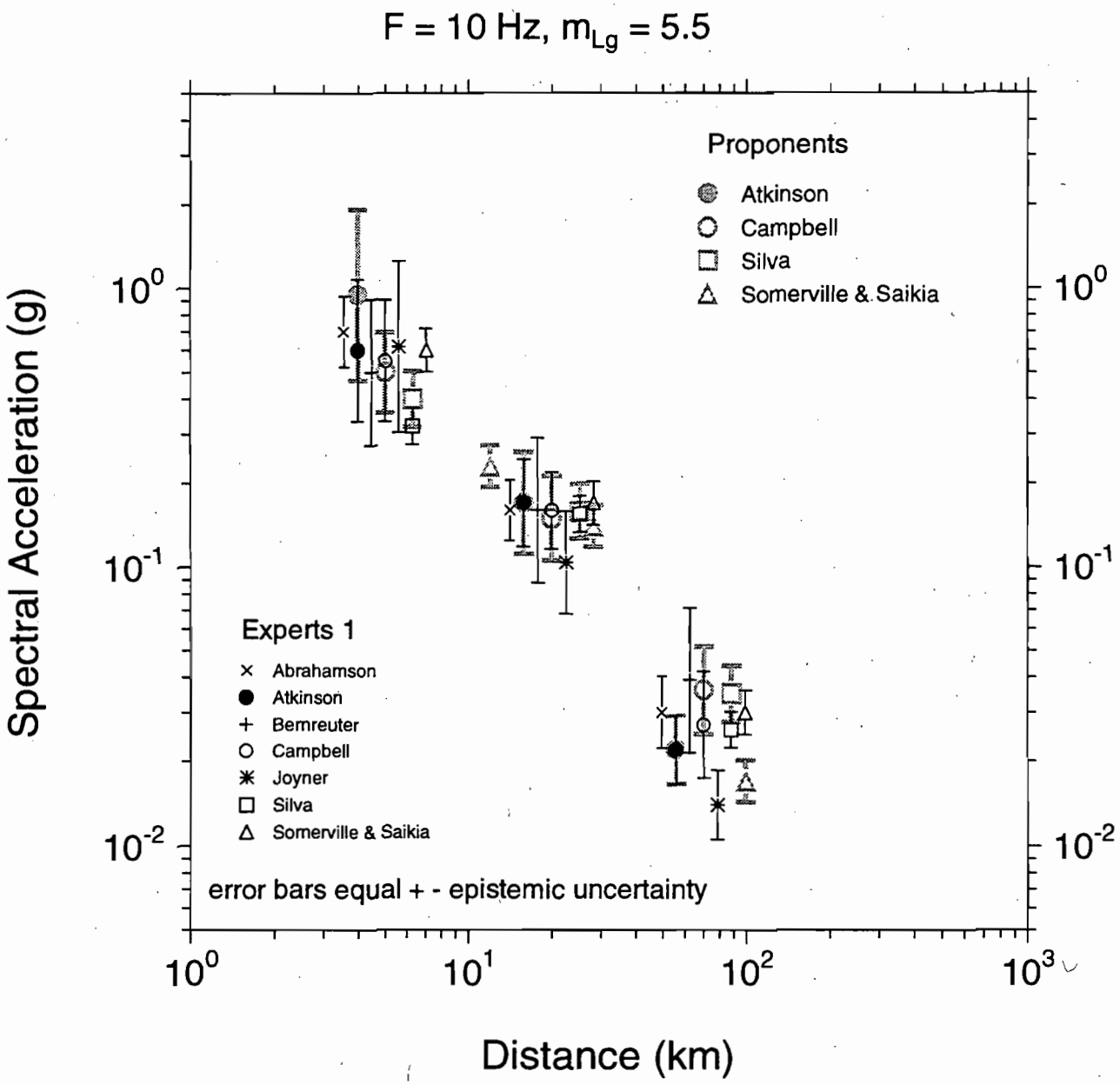

Figure B-3. Comparison of proponents' estimates (gray) to Experts 1 estimates (black) of 10-Hz spectral acceleration for m_{bLg} 5.5. The error bars represent the $\pm\sigma_{epistemic}$ range.

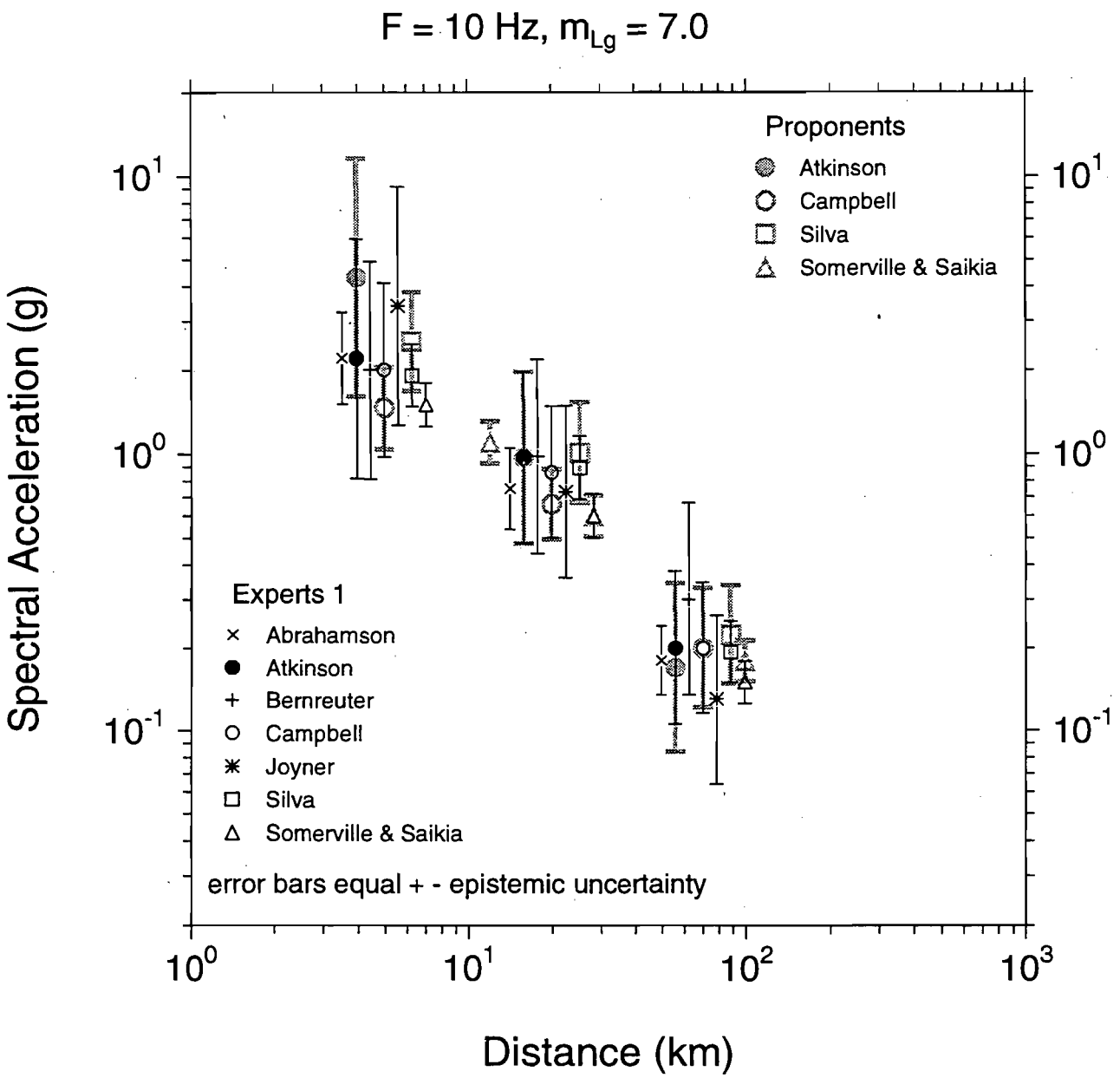

Figure B-4. Comparison of proponents' estimates (gray) to Experts 1 estimates (black) of 10-Hz spectral acceleration for m_{bLg} 7.0. The error bars represent the $\pm\sigma_{epistemic}$ range.

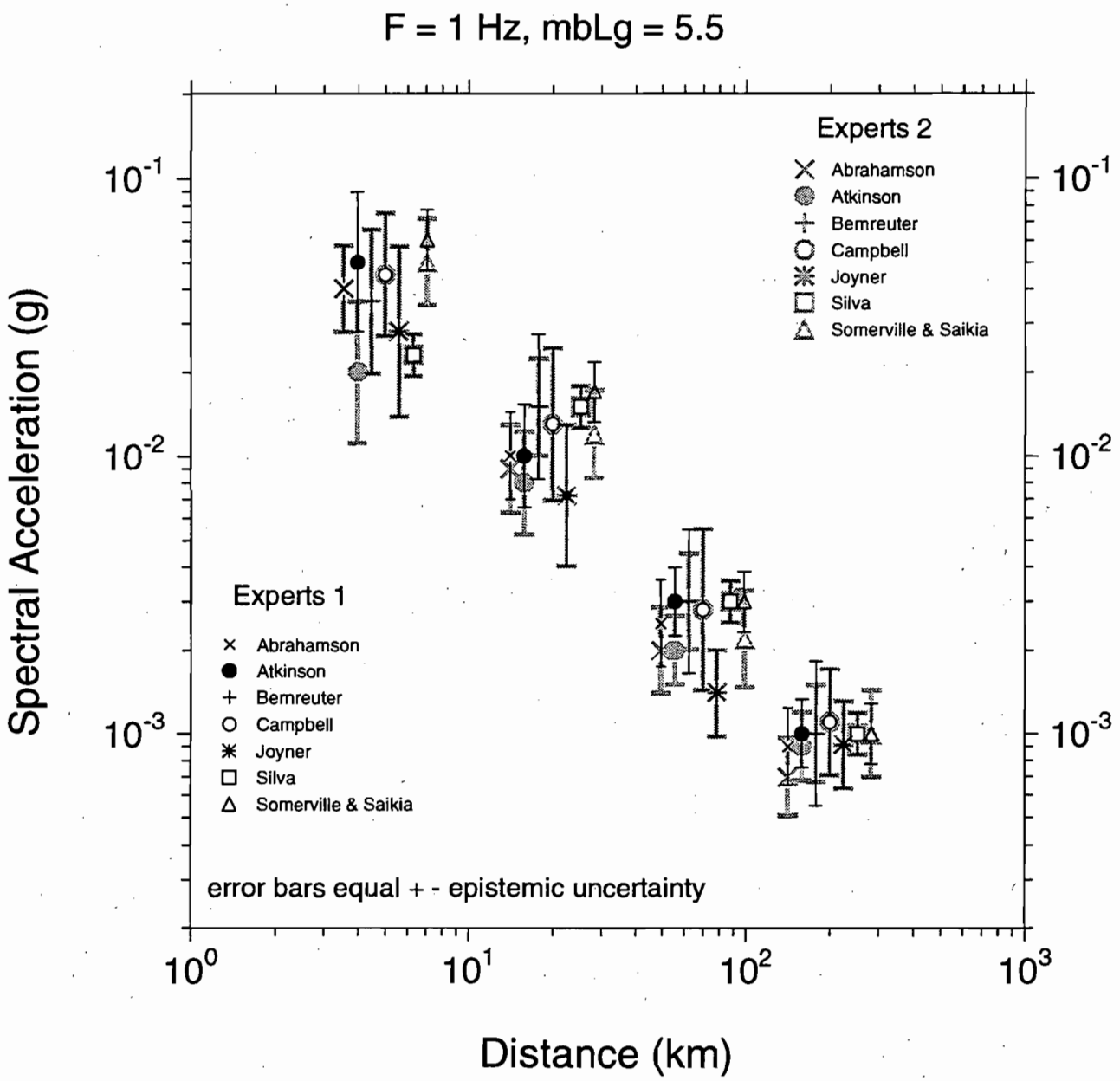

Figure B-5. Comparison of Expert 2 (gray) to Expert 1 (black) estimates of 1-Hz spectral acceleration for m_{bLg} 5.5. The error bars represent the $\pm\sigma_{epistemic}$ range.

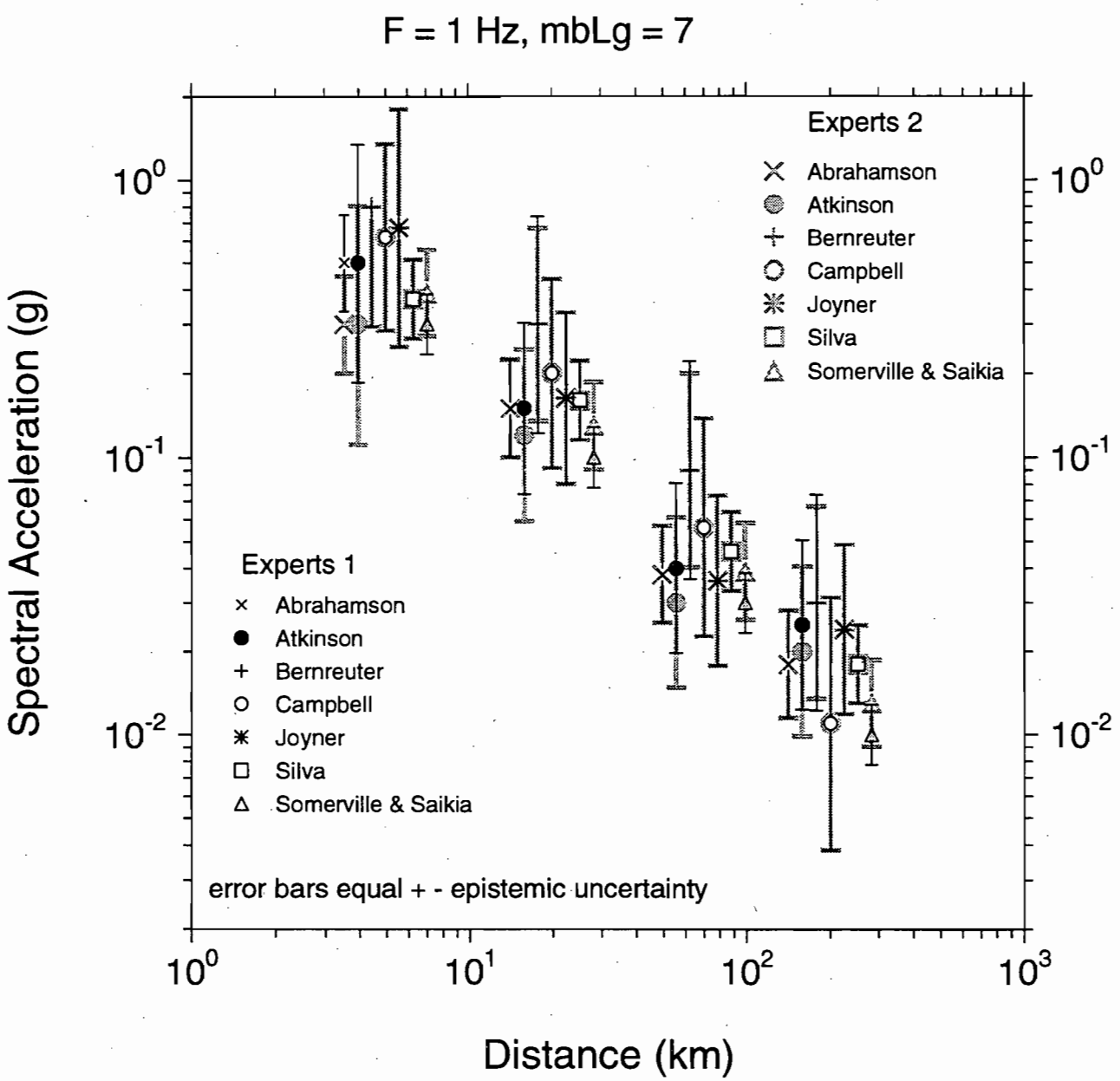

Figure B-6. Comparison of Expert 2 (gray) to Expert 1 (black) estimates of 1-Hz spectral acceleration for m_{bLg} 7.0. The error bars represent the $\pm\sigma_{epistemic}$ range.

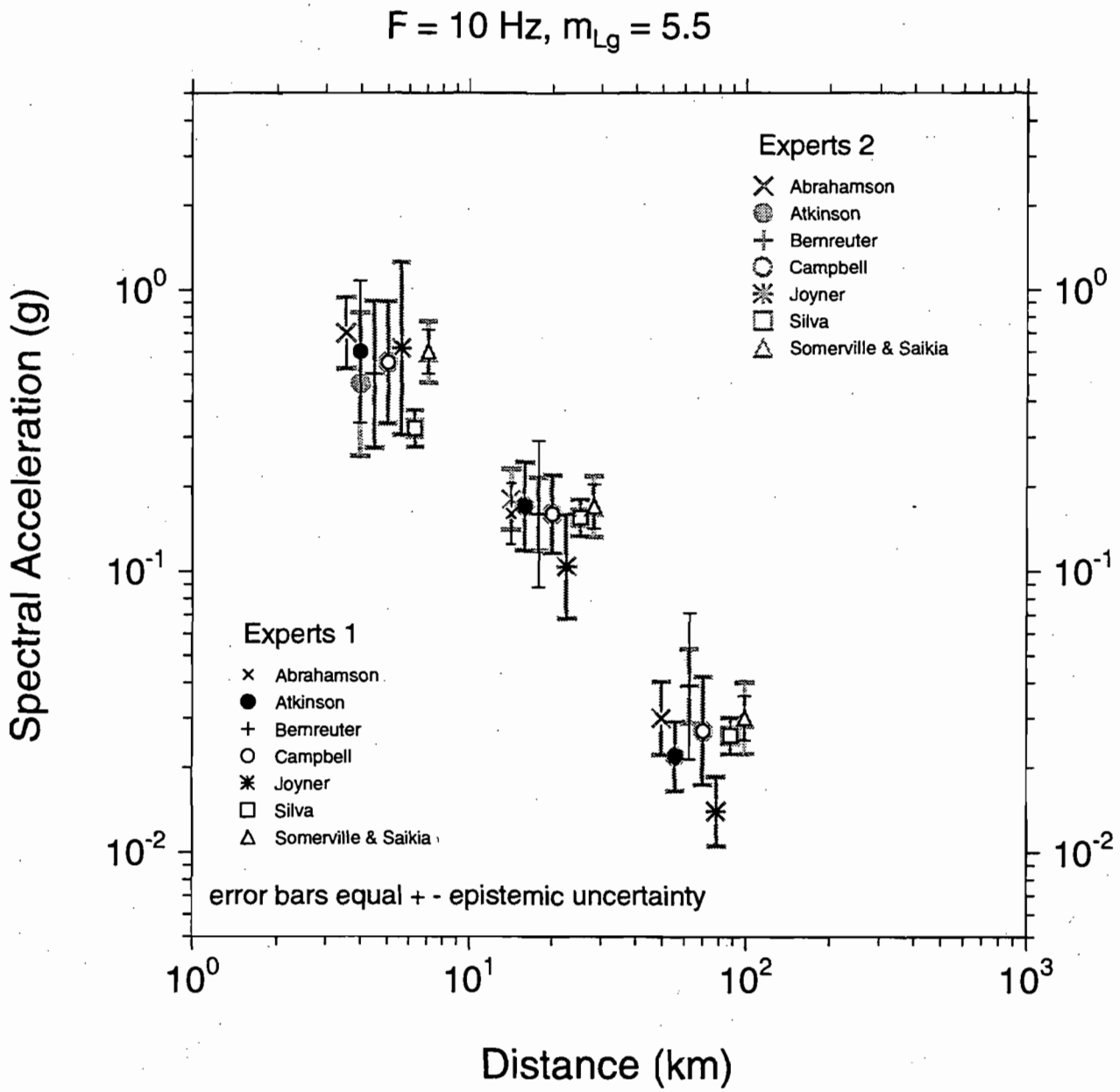

Figure B-7. Comparison of Expert 2 (gray) to Expert 1 (black) estimates of 10-Hz spectral acceleration for m_{bLg} 5.5. The error bars represent the $\pm\sigma_{epistemic}$ range.

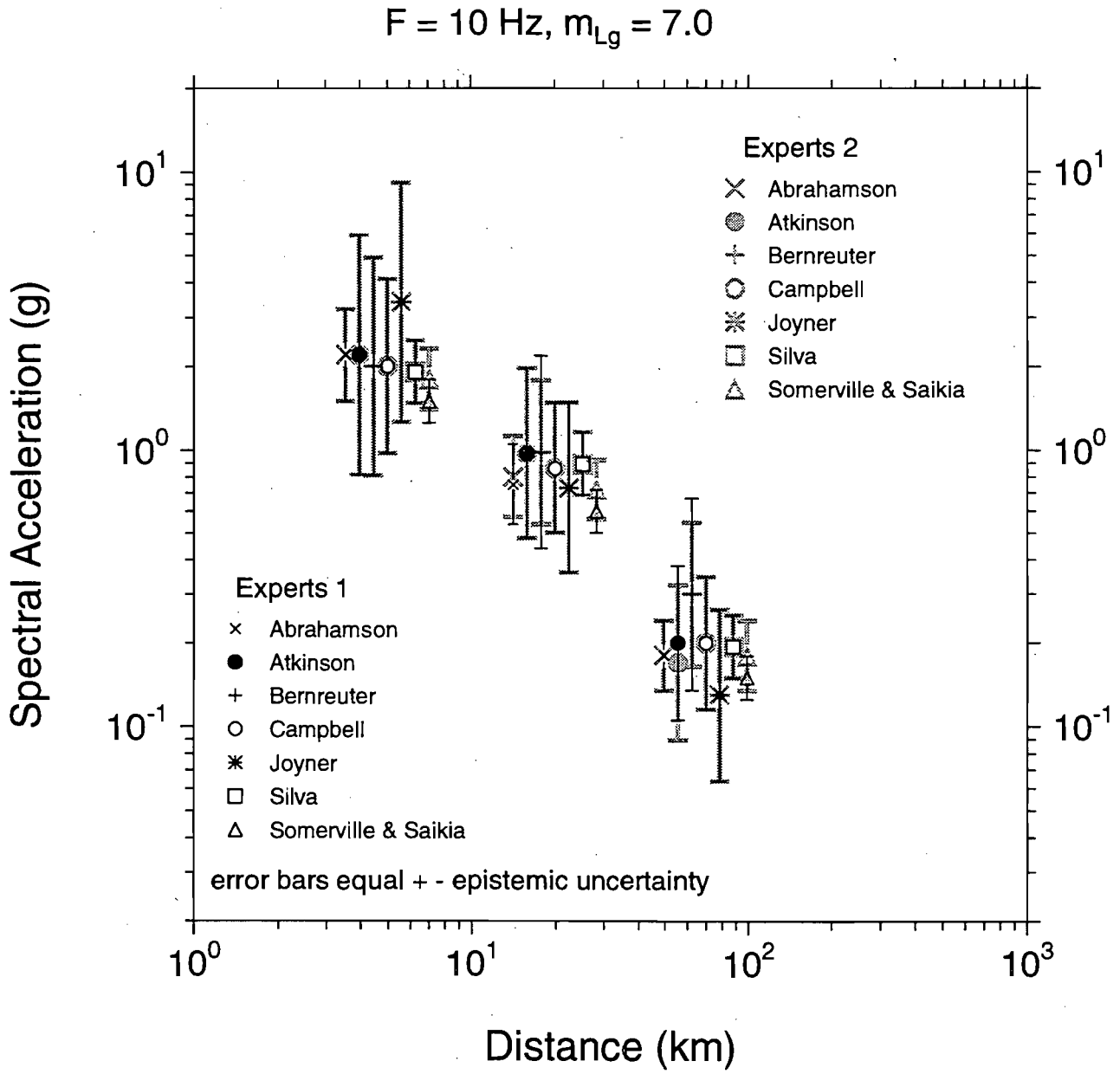

Figure B-8. Comparison of Expert 2 (gray) to Expert 1 (black) estimates of 10-Hz spectral acceleration for m_{bLg} 7.0. The error bars represent the $\pm\sigma_{epistemic}$ range.

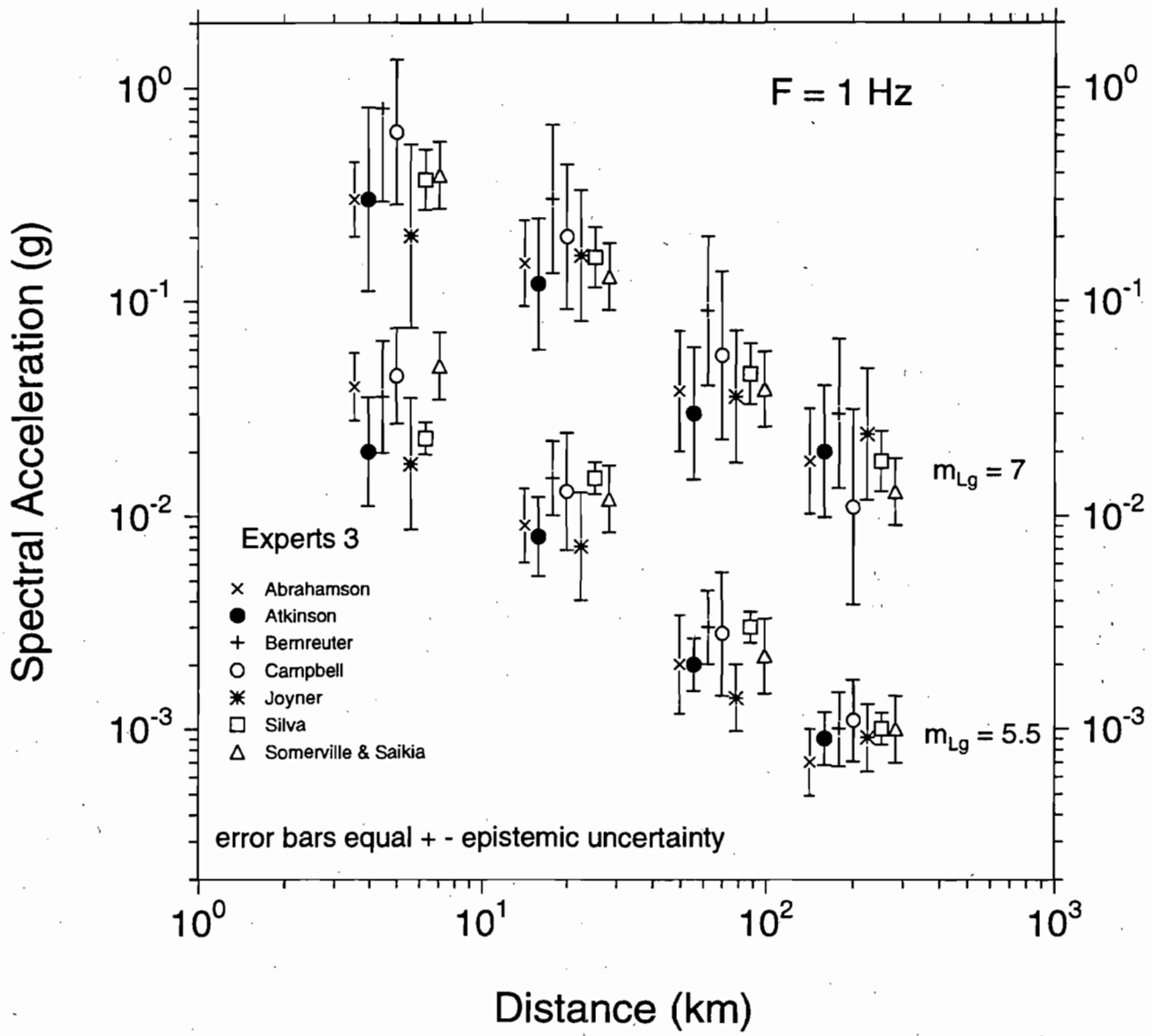

Figure B-9. Experts 3 estimates of 1-Hz spectral acceleration. The error bars indicate the experts' $\pm\sigma_{epistemic}$ range.

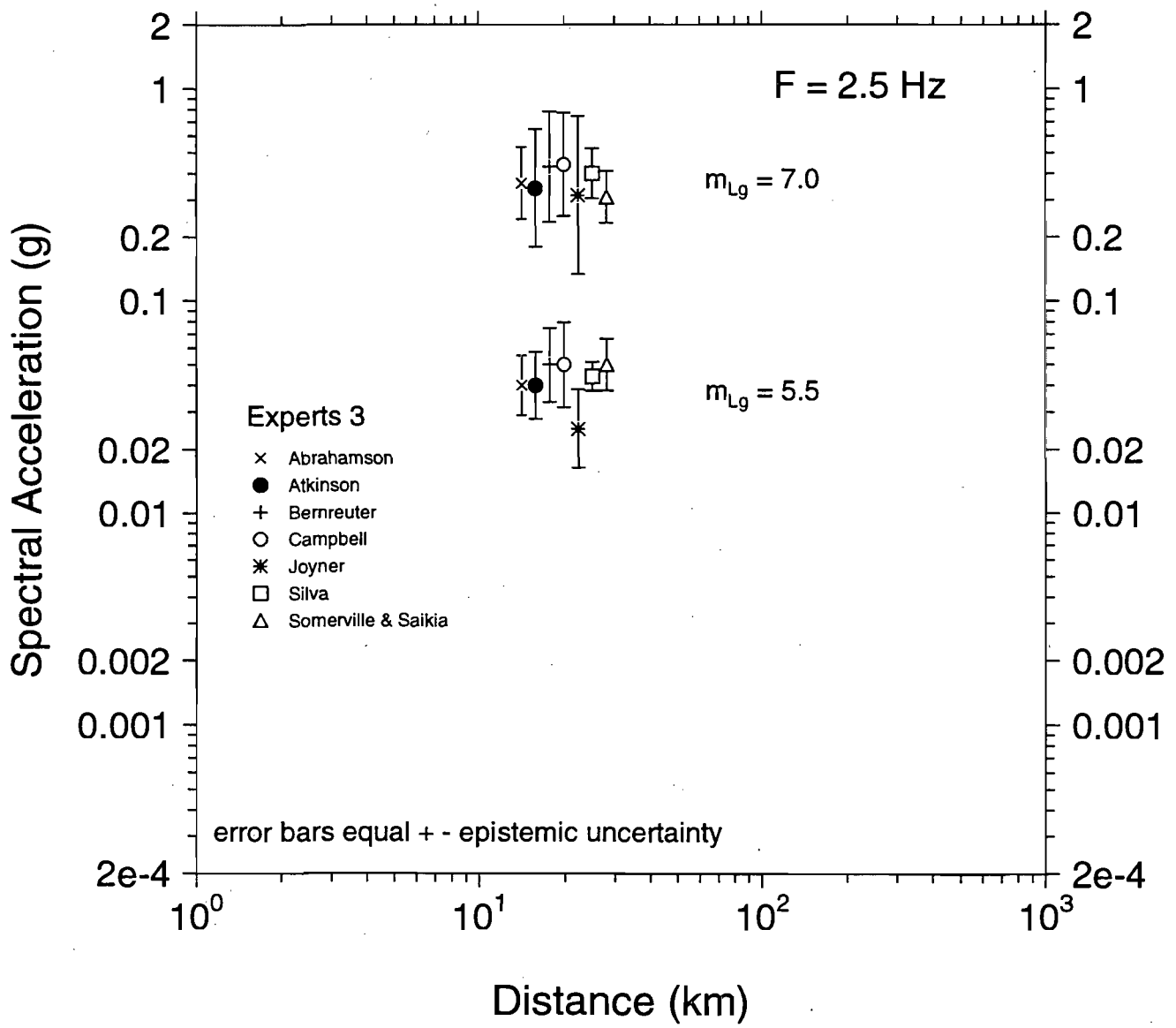

Figure B-10. Expert 3 median estimates of epistemic uncertainty in the median 1-Hz spectral acceleration for m_{bLg} 5.5.

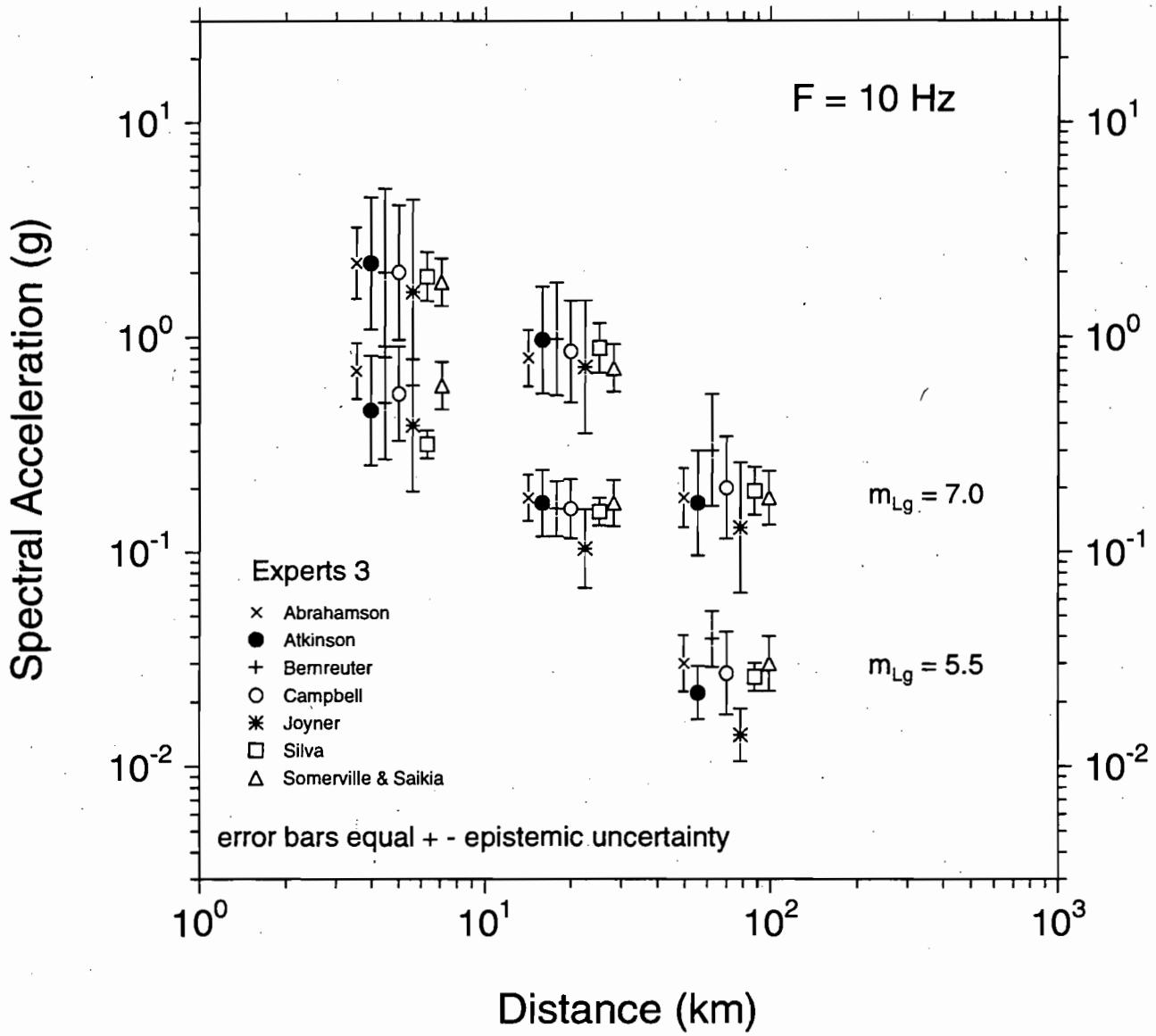

Figure B-11. Expert 3 median estimates of epistemic uncertainty in the median 1-Hz spectral acceleration for m_{bLg} 7.0.

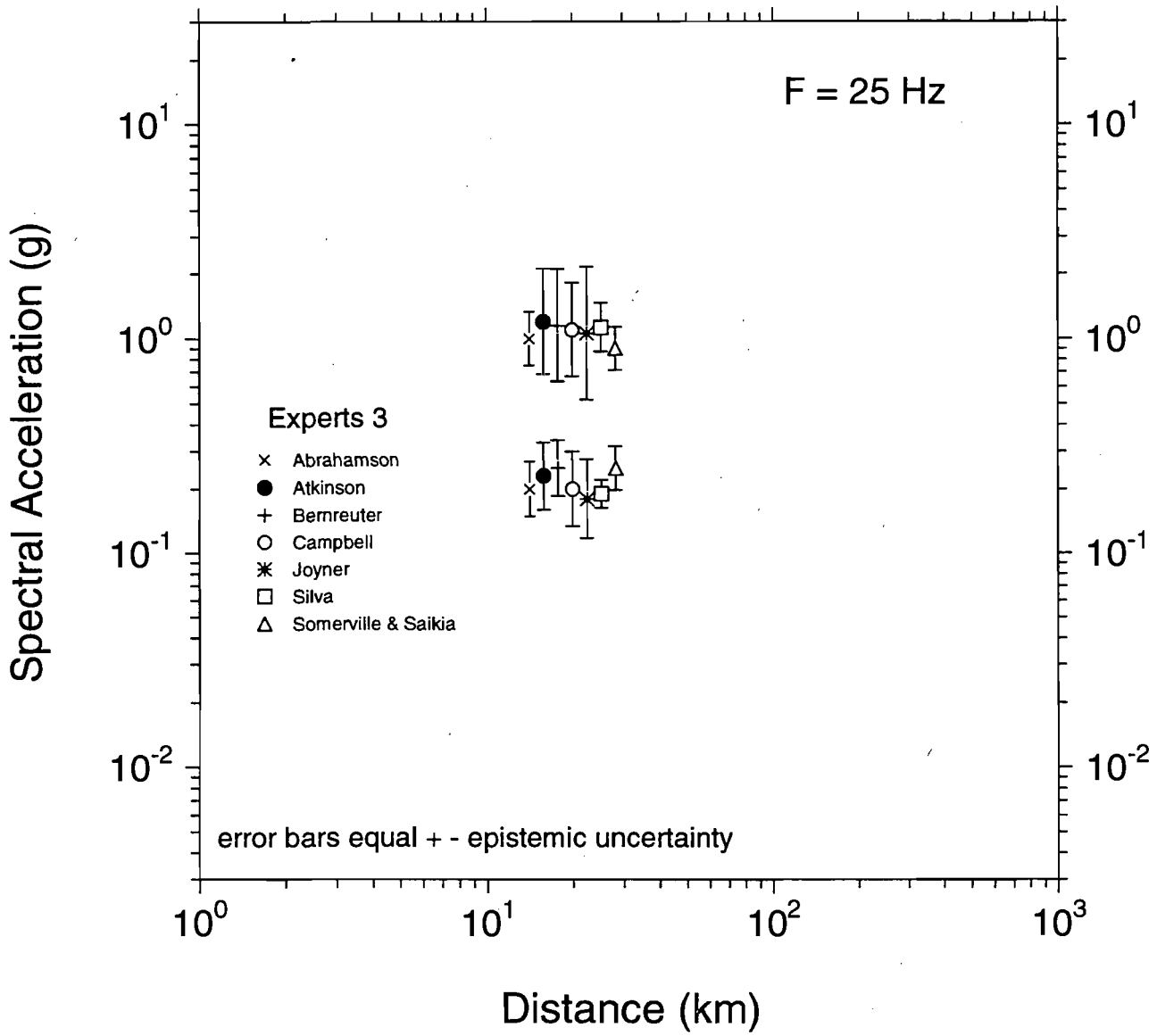

Figure B-12. Expert 3 median estimates of the aleatory uncertainty in 1-Hz spectral acceleration for m_{bLg} 5.5.

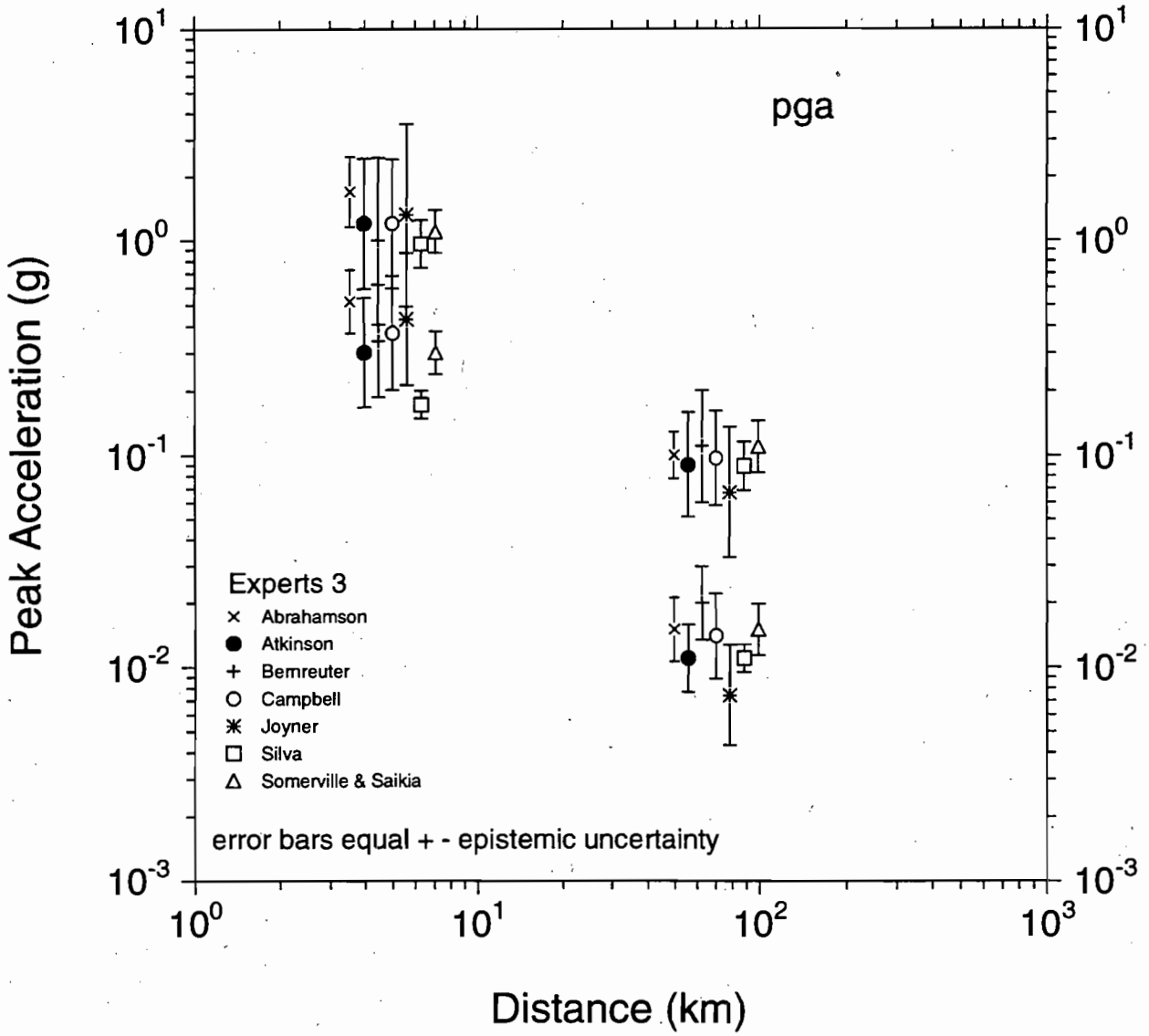

Figure B-13. Expert 3 median estimates of the aleatory uncertainty in 1-Hz spectral acceleration for m_{bLg} 7.0.

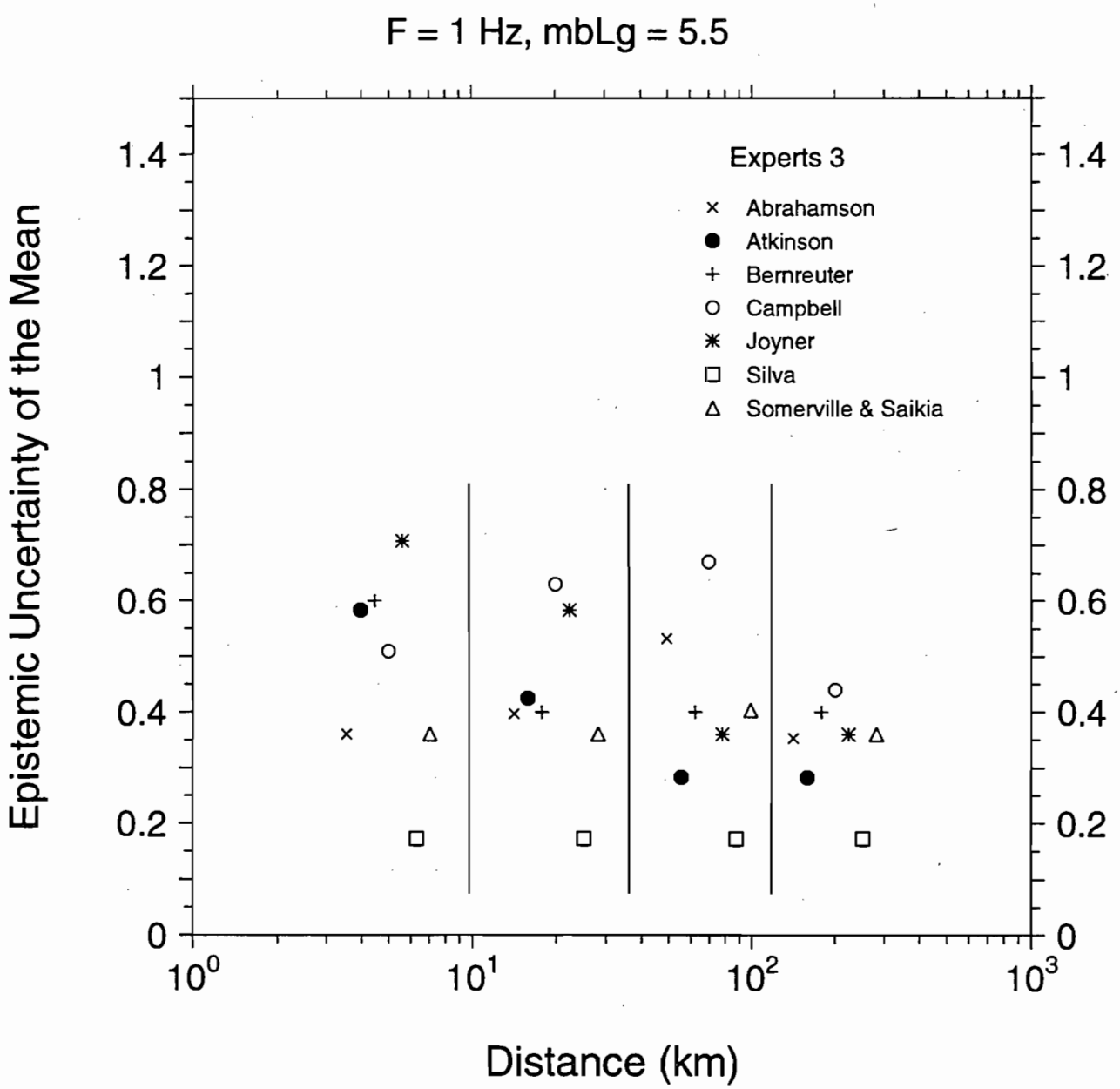

Figure B-14. Experts 3 estimates of 2.5-Hz spectral acceleration. The error bars indicate the experts' $\pm\sigma_{epistemic}$ range.

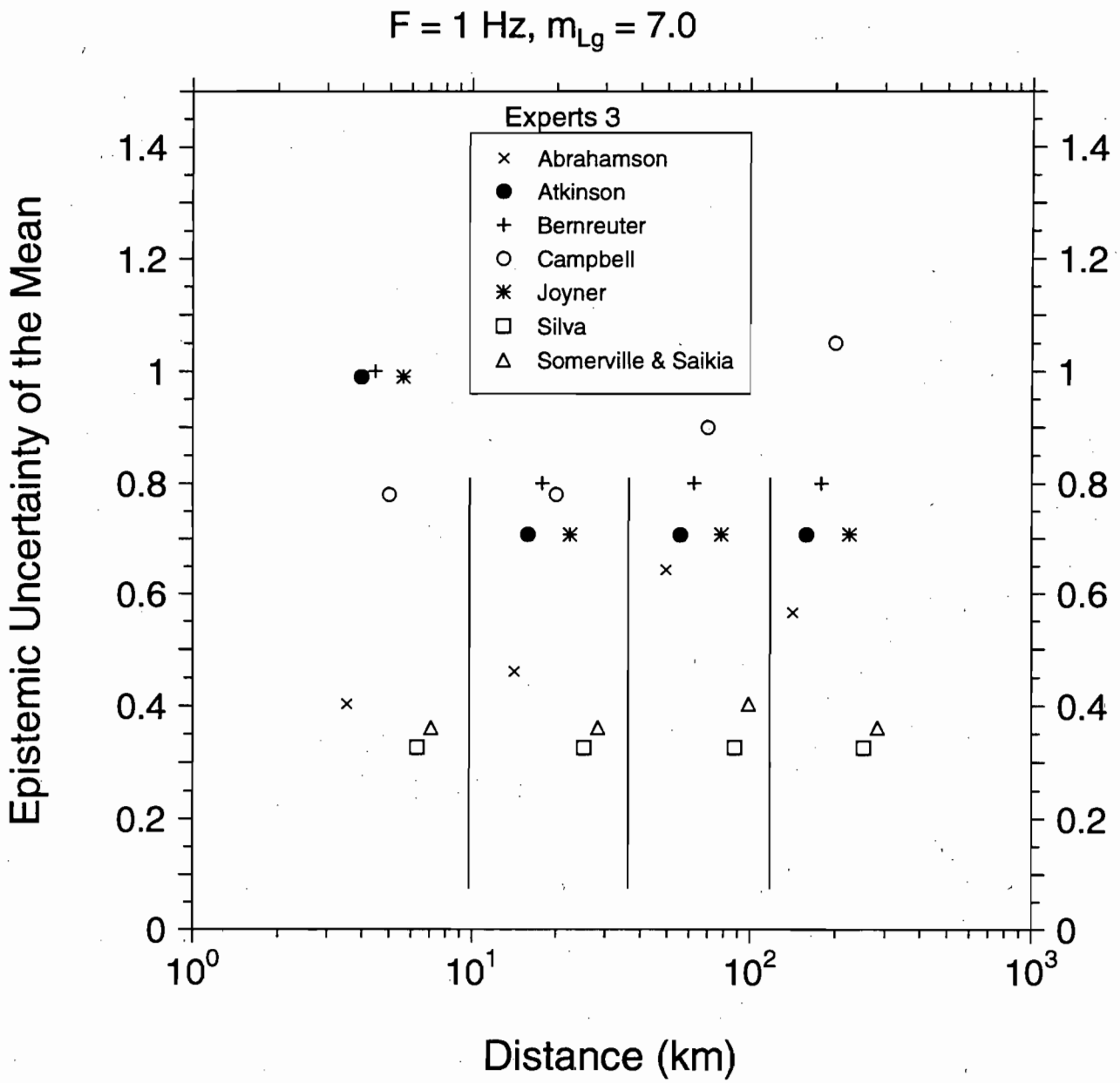

Figure B-15. Experts 3 estimates of 10-Hz spectral acceleration. The error bars indicate the experts' $\pm\sigma_{epistemic}$ range.

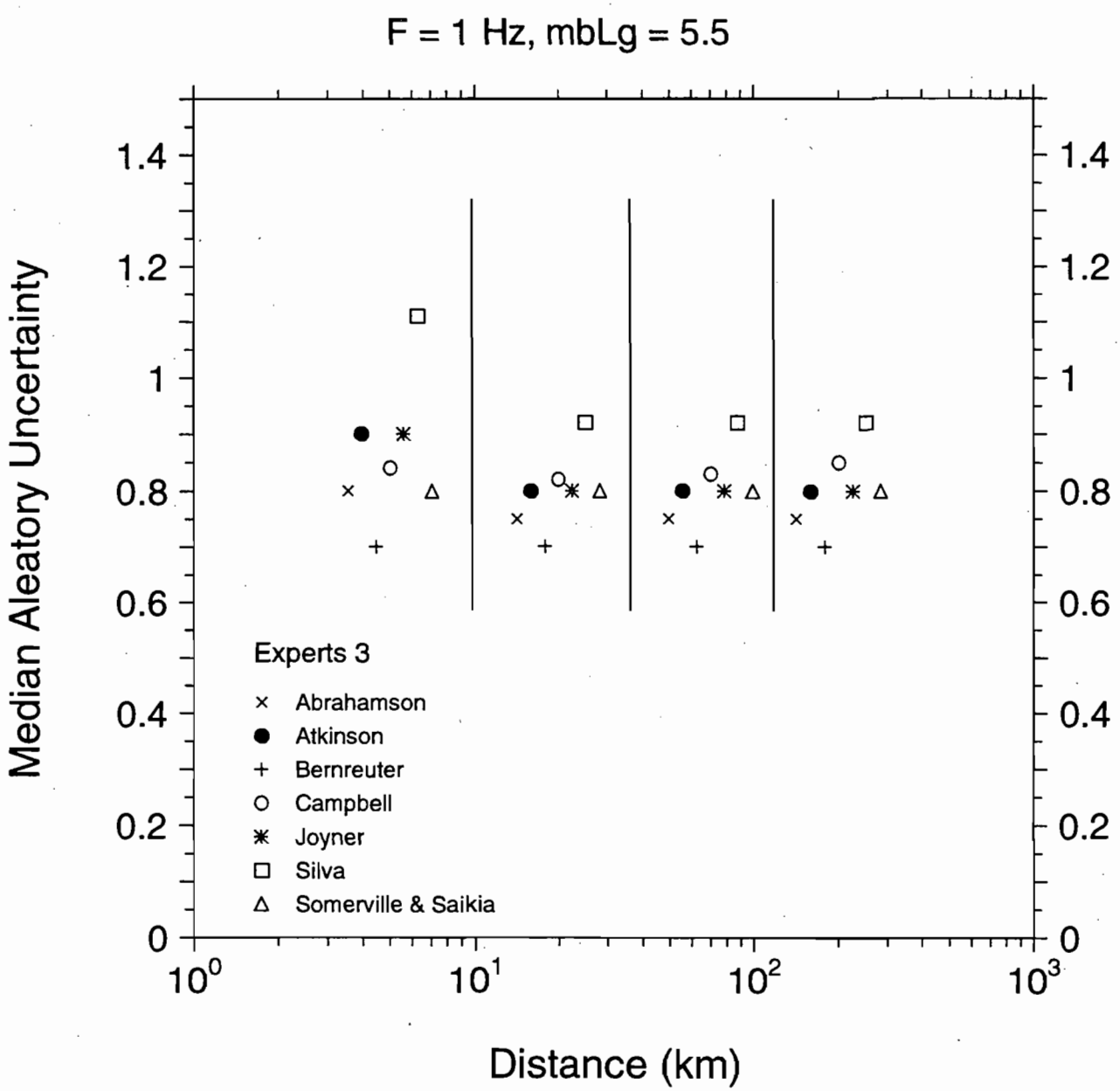

Figure B-16. Experts 3 estimates of 25-Hz spectral acceleration. The error bars indicate the experts' $\pm\sigma_{epistemic}$ range.

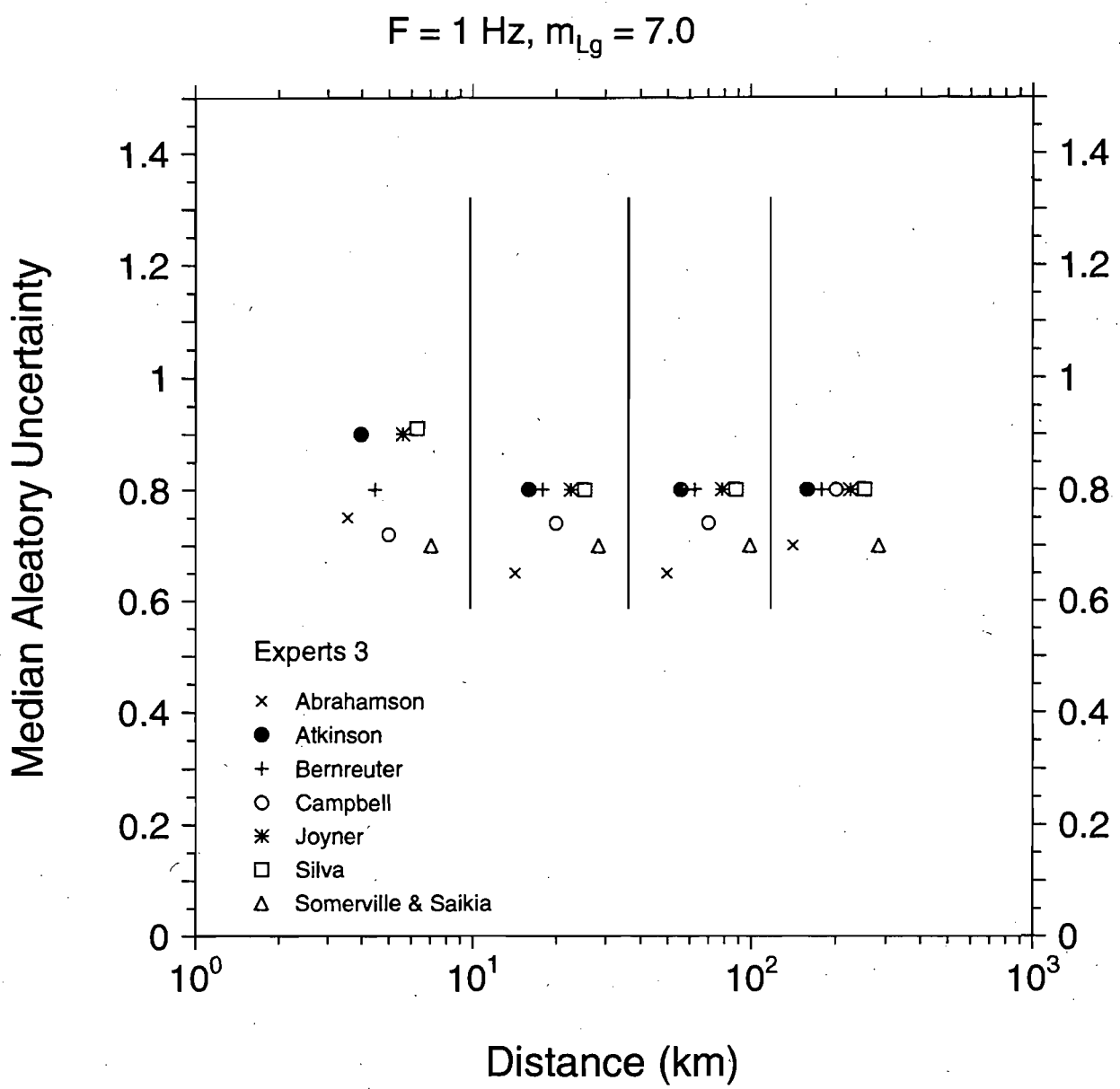

Figure B-17. Expert 3 estimates of PGA. The error bars indicate the experts' $\pm\sigma_{epistemic}$ range.

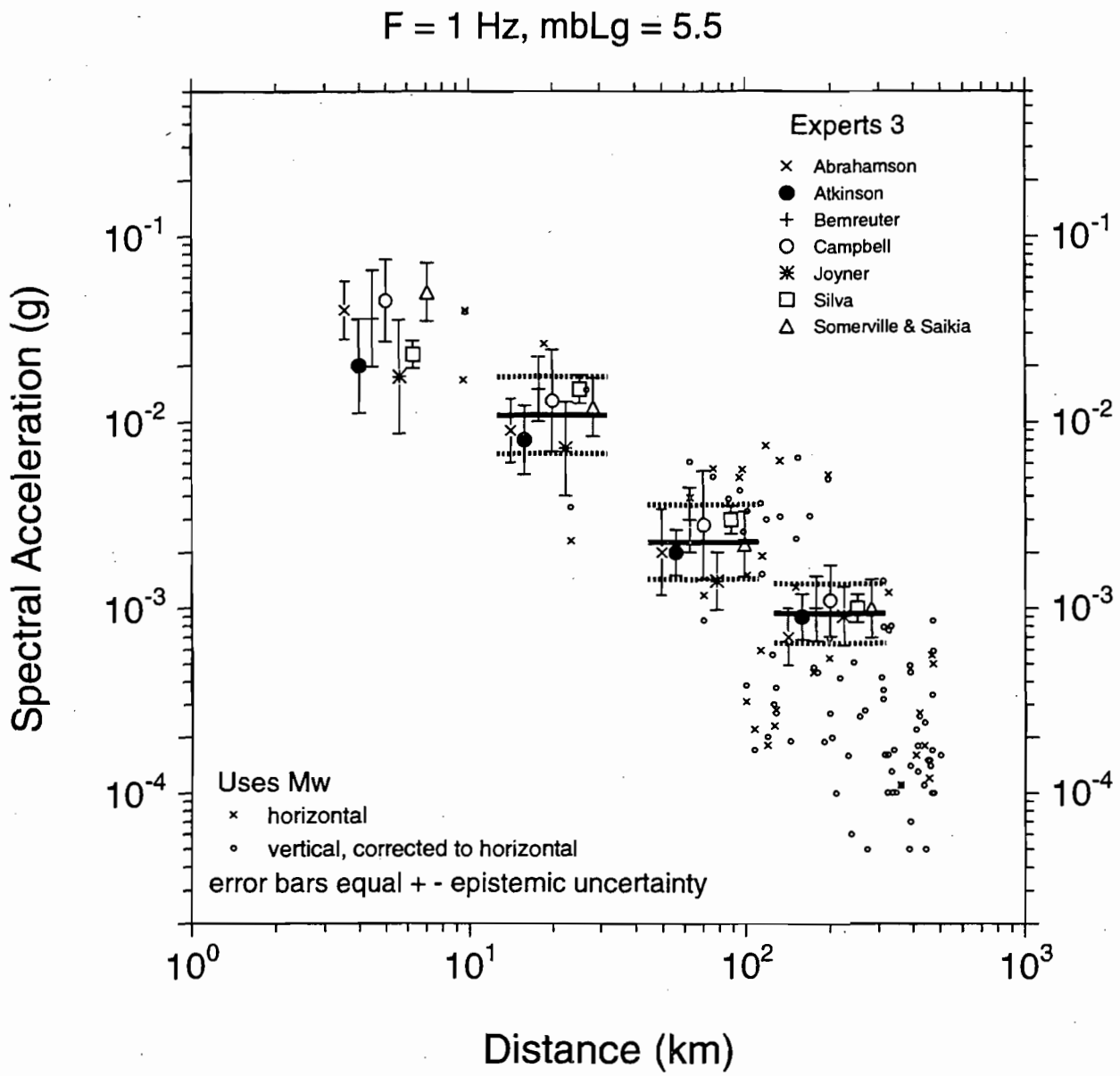

Figure B-18. Comparison of integration results (median amplitude $\pm\sigma_{epistemic}$) using equal weights on the Expert 3 estimates (horizontal lines) and Expert 3 estimates of 1-Hz spectral acceleration for m_{bLg} 5.5. The small symbols represent data.

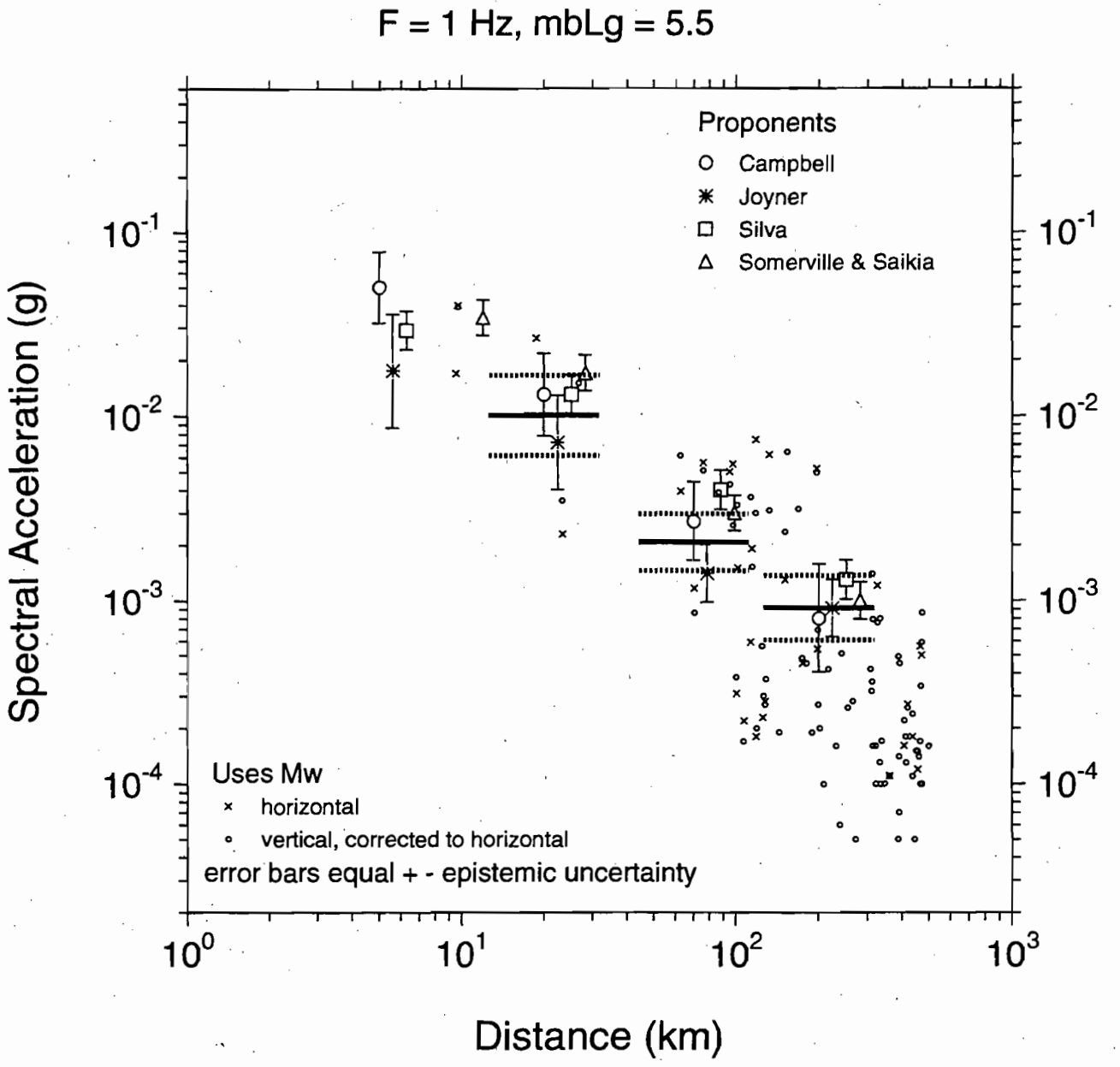

Figure B-19. Comparison of integration results (median amplitude $\pm\sigma_{epistemic}$) using unequal weights on the proponents' estimates of 1-Hz spectral acceleration for m_{bLg} 5.5. The small symbols represent data.

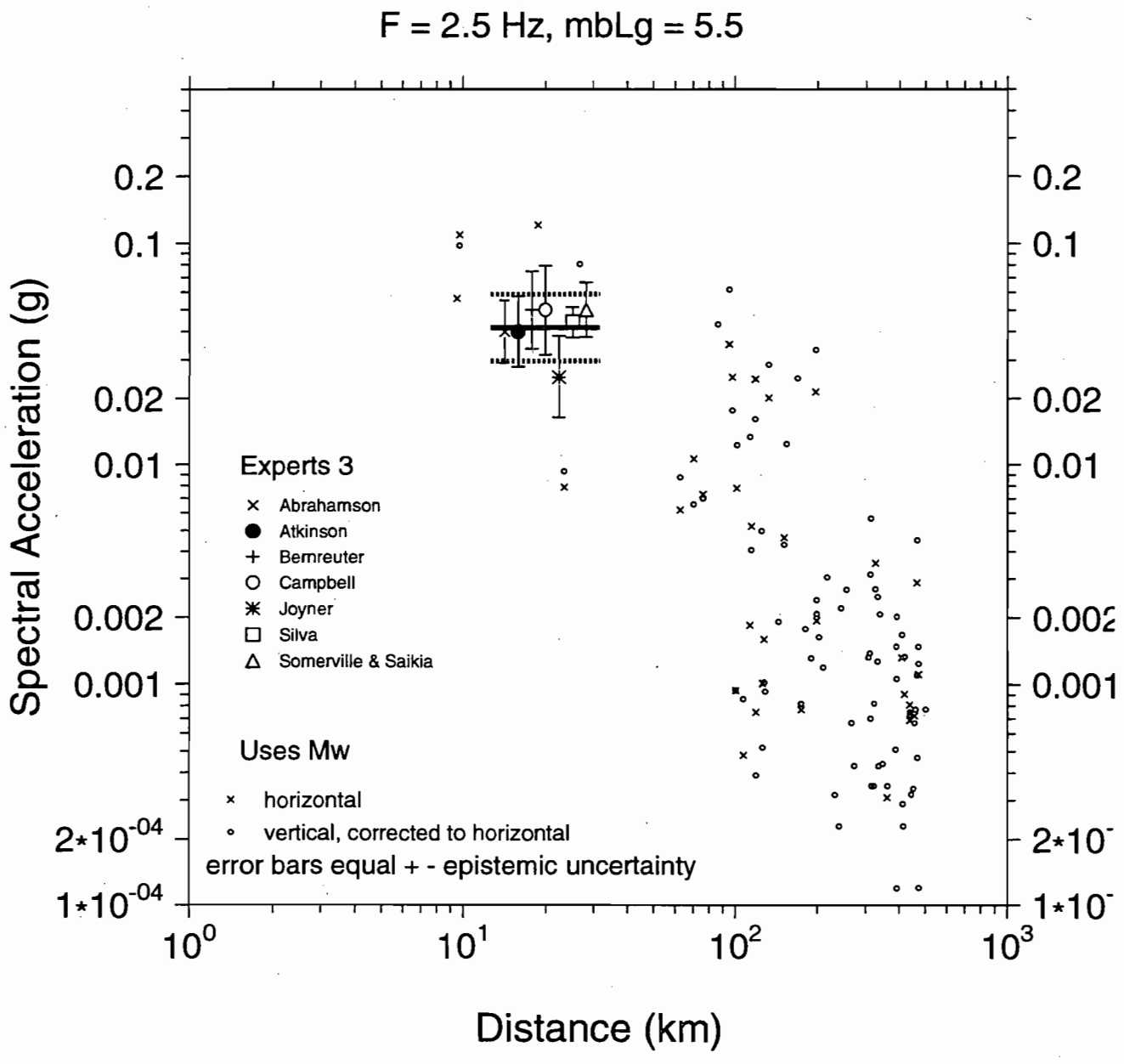

Figure B-20. Comparison of integration results (median amplitude $\pm\sigma_{epistemic}$) using equal weights on the Expert 3 estimates (horizontal lines) and Expert 3 estimates of 2.5-Hz spectral acceleration for m_{bLg} 5.5. The small symbols represent data.

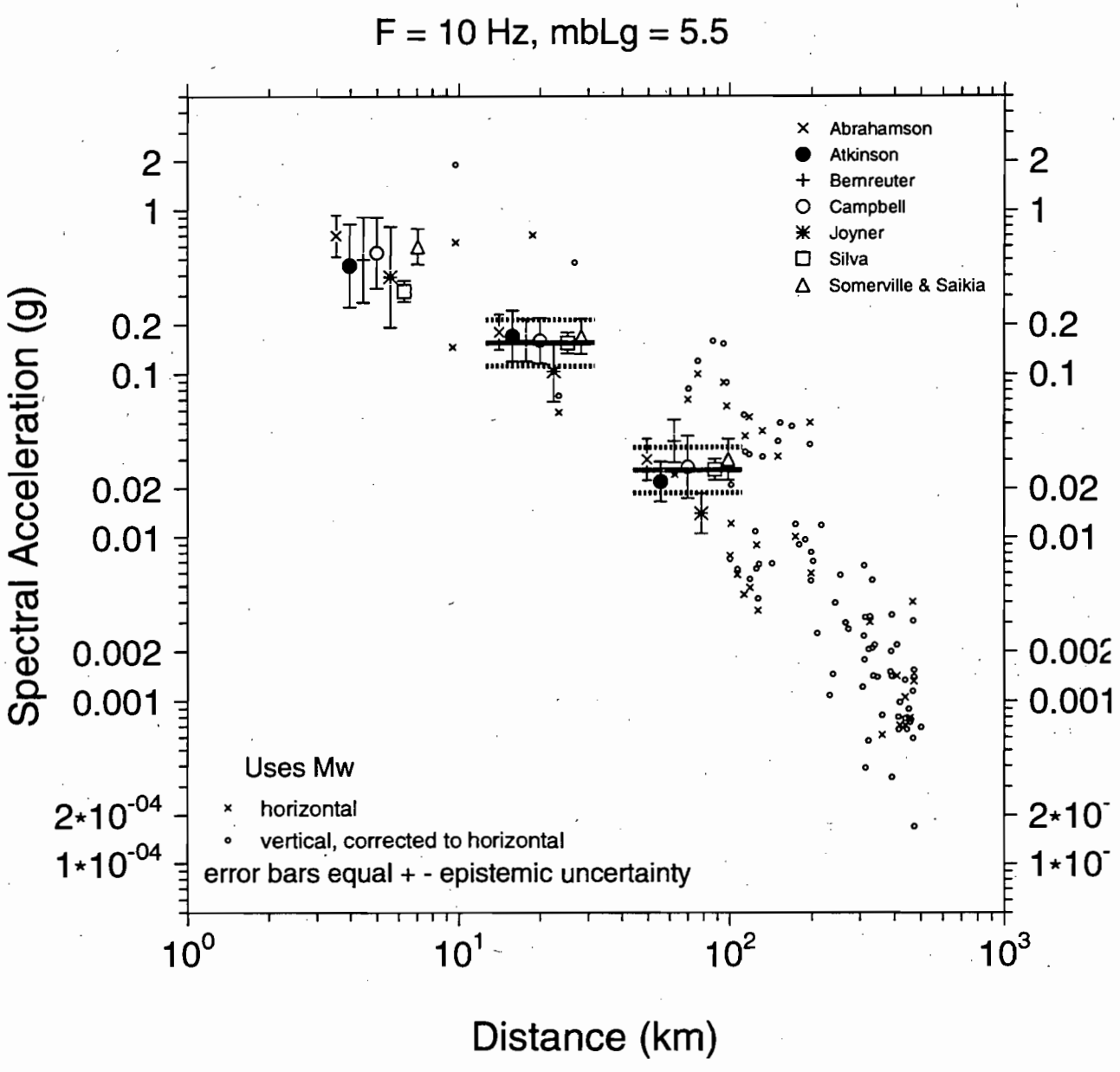

Figure B-21. Comparison of integration results (median amplitude $\pm\sigma_{epistemic}$) using equal weights on the Expert 3 estimates (horizontal lines) and Expert 3 estimates of 10-Hz spectral acceleration for m_{bLg} 5.5. The small symbols represent data.

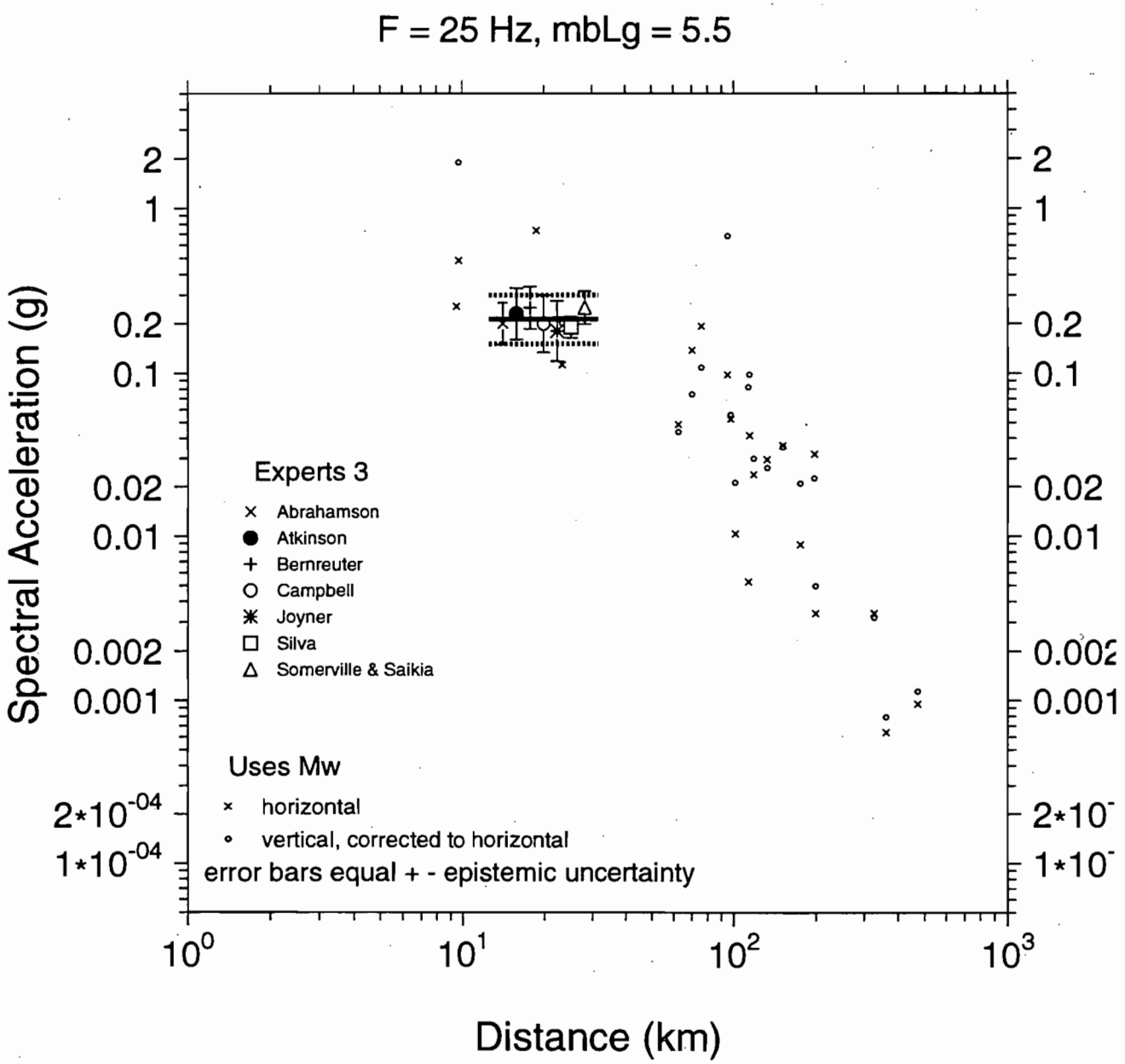

Figure B-22. Comparison of integration results (median amplitude $\pm\sigma_{epistemic}$) using equal weights on the Expert 3 estimates (horizontal lines) and Expert 3 estimates of 25-Hz spectral acceleration for m_{bLg} 5.5. The small symbols represent data.

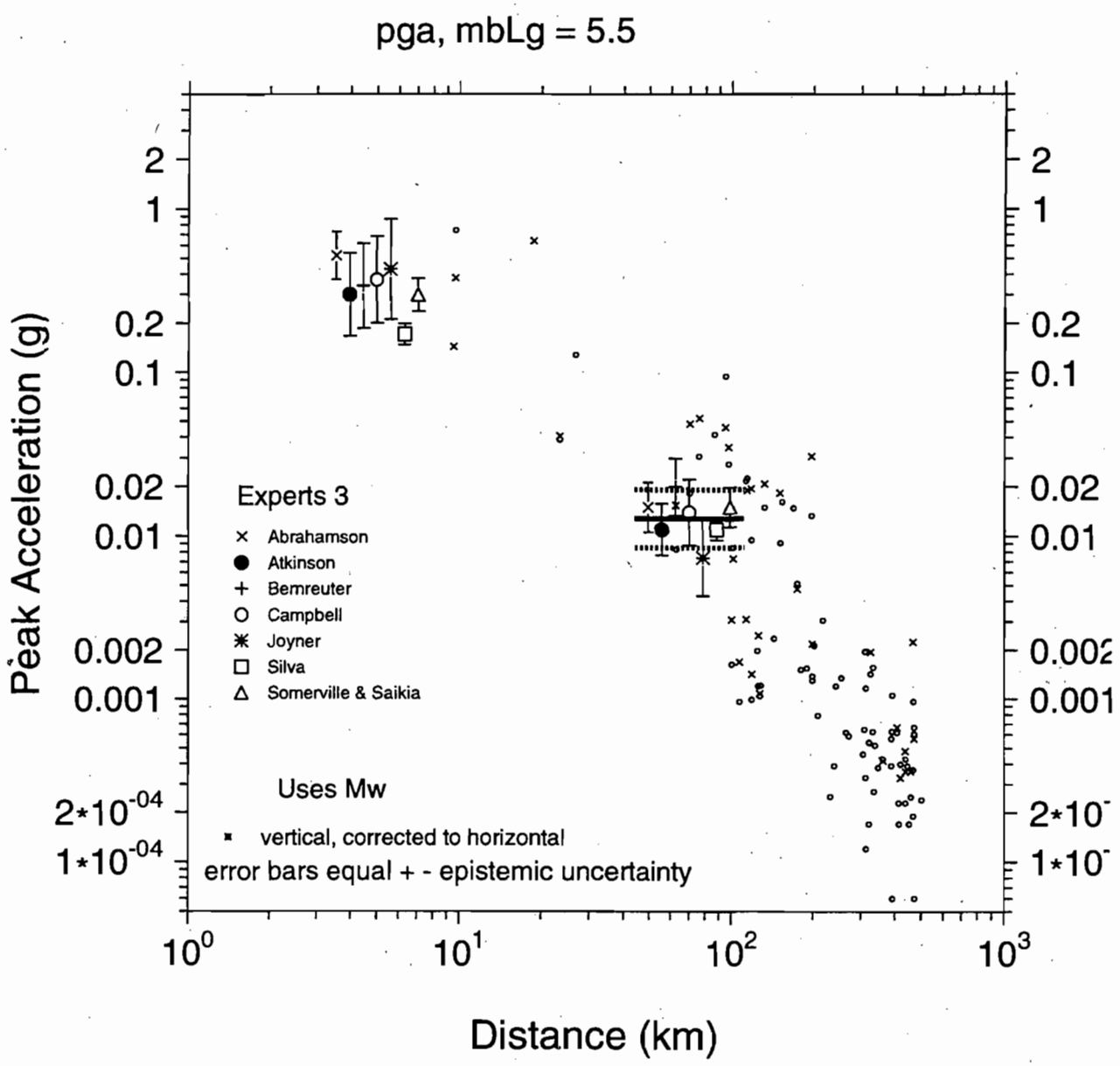

Figure B-23. Comparison of integration results (median amplitude $\pm\sigma_{epistemic}$) using equal weights on the Expert 3 estimates (horizontal lines) and Expert 3 estimates of PGA for m_{bLg} 5.5. The small symbols represent data.

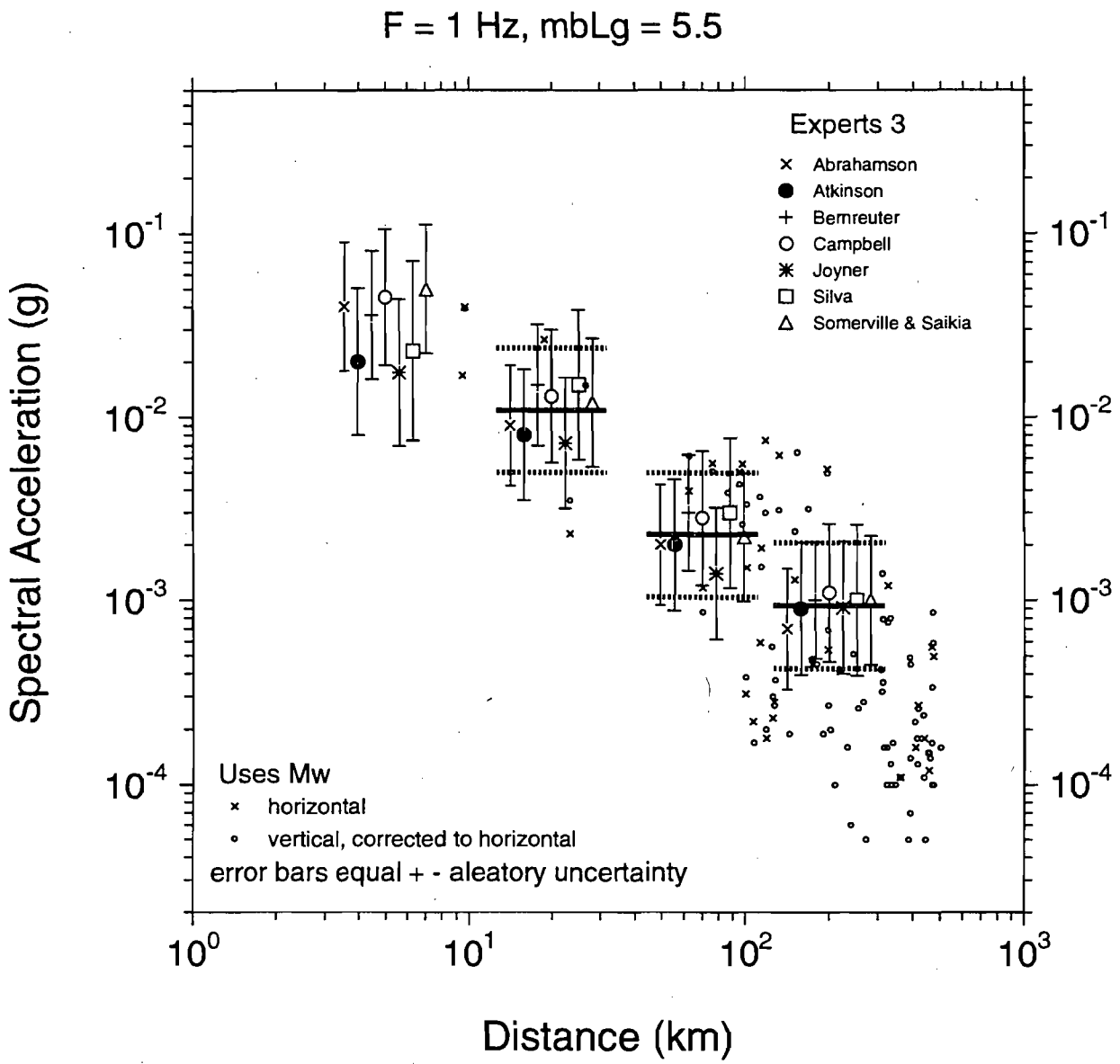

Figure B-24. Comparison of integration results (median amplitude $\pm\sigma_{aleatory}$) using equal weights on the Expert 3 estimates (horizontal lines) and Expert 3 estimates of 1-Hz spectral acceleration for m_{bLg} 5.5. The small symbols represent data.

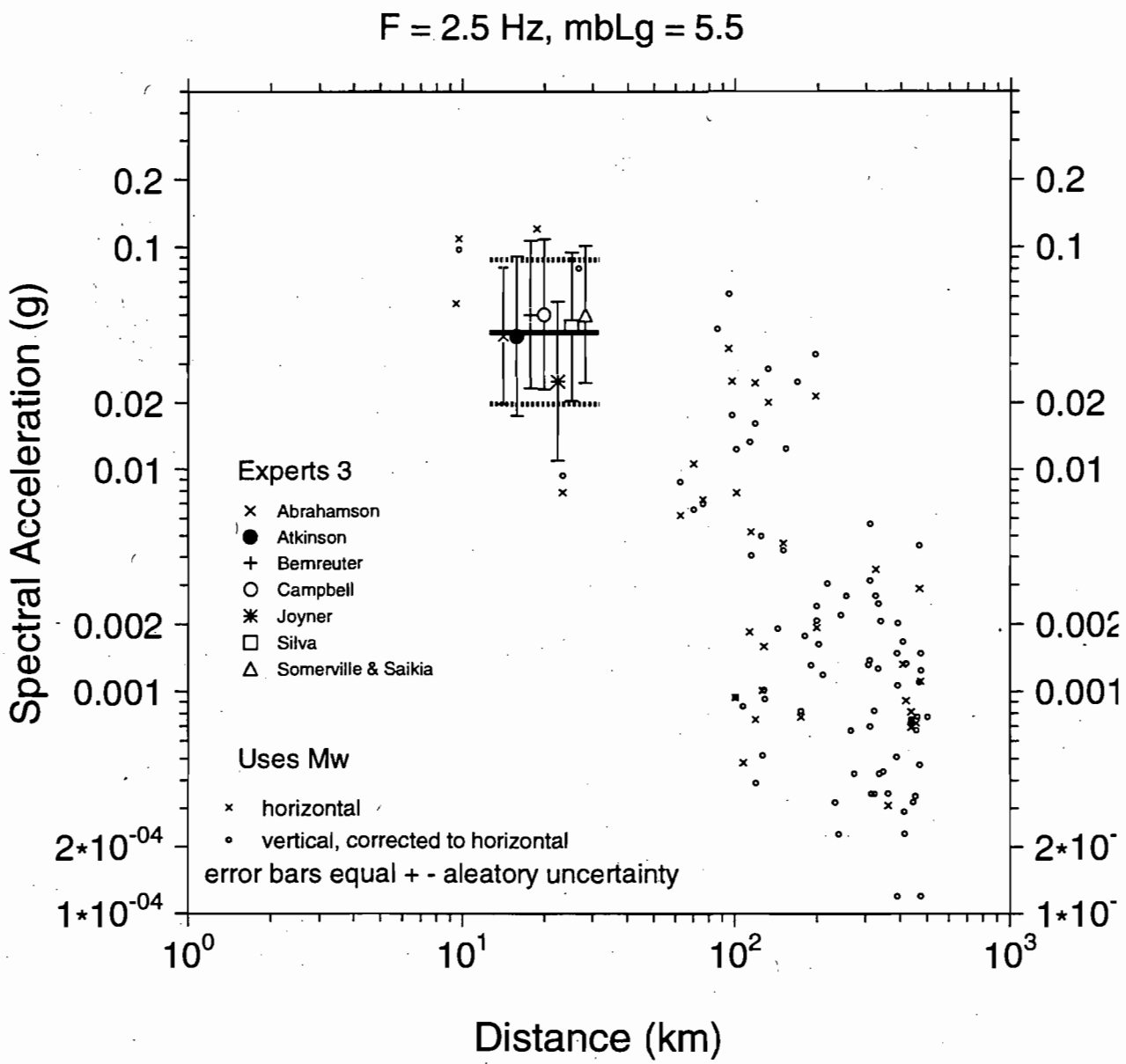

Figure B-25. Comparison of integration results (median amplitude $\pm\sigma_{aleatory}$) using equal weights on the Expert 3 estimates (horizontal lines) and Expert 3 estimates of 2.5-Hz spectral acceleration for m_{bLg} 5.5. The small symbols represent data.

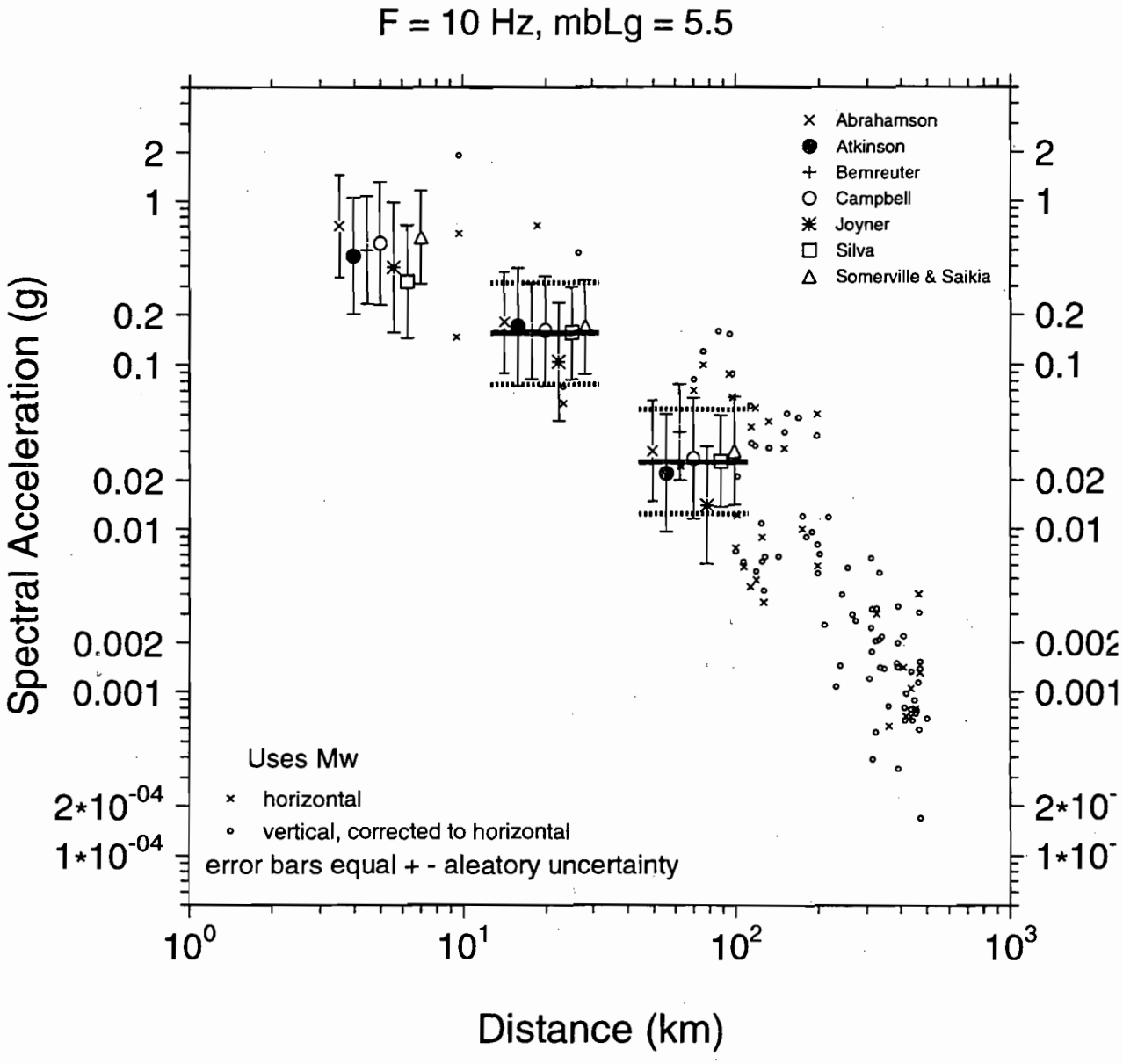

Figure B-26. Comparison of integration results (median amplitude $\pm\sigma_{aleatory}$) using equal weights on the Expert 3 estimates (horizontal lines) and Expert 3 estimates of 10-Hz spectral acceleration for m_{bLg} 5.5. The small symbols represent data.

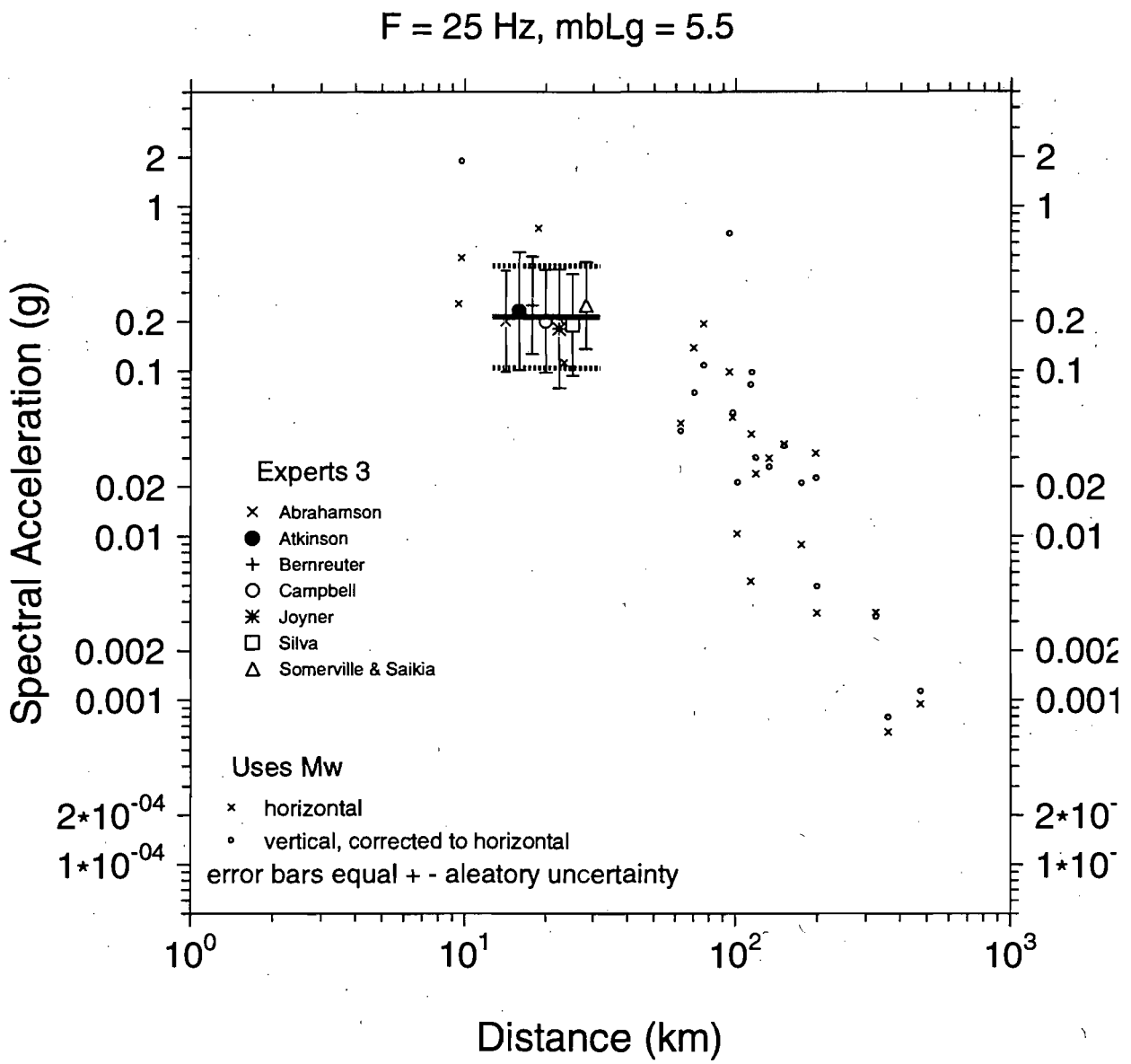

Figure B-27. Comparison of integration results (median amplitude $\pm\sigma_{aleatory}$) using equal weights on the Expert 3 estimates (horizontal lines) and Expert 3 estimates of 25-Hz spectral acceleration for m_{bLg} 5.5. The small symbols represent data.

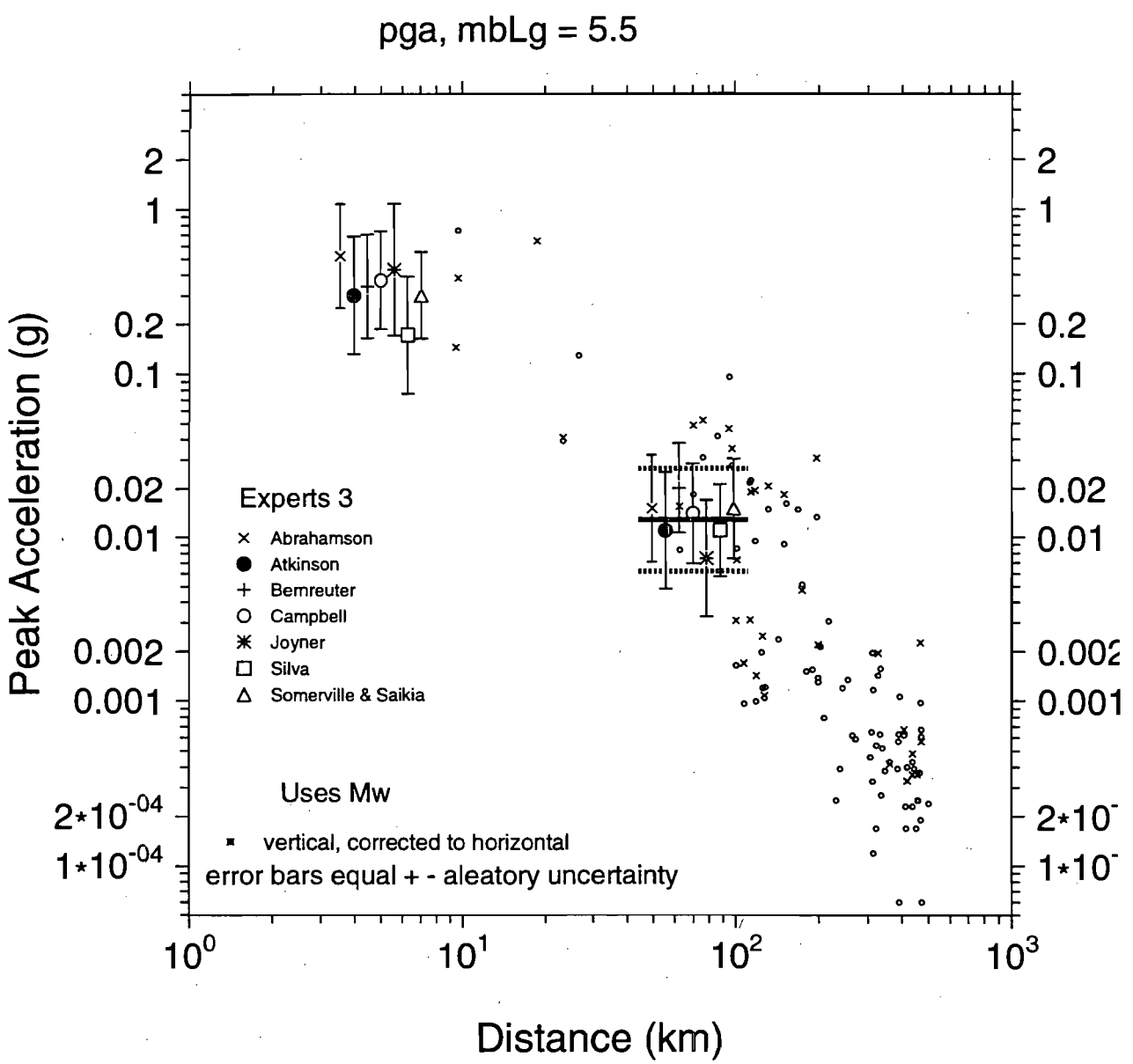

Figure B-28. Comparison of integration results (median amplitude $\pm\sigma_{aleatory}$) using equal weights on the Expert 3 estimates (horizontal lines) and Expert 3 estimates of PGA for m_{bLg} 5.5. The small symbols represent data.

ATTACHMENTS

B-1 Proponents' Results
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- b. Results and documentation . . . . . B - 84
- c. Plots of median ± epistemic uncertainty B-213

B-2 Experts 1 (Pre-Workshop) Results
- a. Instructions B-224
- b. Results and documentation B-242
- c. Plots of median ± epistemic uncertainty B-362
- d. Plots of median ± total uncertainty B-372
- e. Plots of epistemic uncertainty B-378
- f. Plots of aleatory uncertainty B-388
- g. Plots of total uncertainty B-398

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- b. Plots B-406

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- b. Plots of median ± epistemic uncertainty B-451

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B-7 Experts 3 (Post-Workshop) Results
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B-8 Preparation of Data B-503

ATTACHMENT B-1

PROPONENTS' RESULTS

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SSHAC SECOND GROUND-MOTION WORKSHOP

INSTRUCTIONS FOR PROPONENTS

Gabriel R. Toro
Risk Engineering, Inc.
May27, 1994

As part of the preparations for the second SSHAC Ground Motion Workshop, we are asking you to prepare and document ground-motion estimates for a specific tectonic province and for a suite of magnitudes, distances, and frequencies of engineering interest. We are testing a format for these estimates that is somewhat different from those used in past ground-motion elicitation efforts. Your estimates, along with the estimates prepared by other proponents, will be distributed to other participating ground-motion experts. This set of results will be a key input in the development of a composite ground-motion model.

The definition of the problem is as follows:

- Site location: northeastern United States or southeastern Canada
- Site conditions Eastern United States Rock (2800 m/s average shear-wave velocity over the top 30 m)
- Magnitudes, distances (to closest point on rupture), and oscillator frequencies as given below:

Distance to closest point on rupture (km)	m_{Lg} 5.5	m_{Lg} 7
5	1 Hz, 10 Hz, PGA	1 Hz*, 10 Hz*, PGA
20	1 Hz*, 2.5 Hz*, 10 Hz*, 25 Hz*	1 Hz*, 2.5 Hz, 10 Hz*, 25 Hz*
70	1 Hz, 10 Hz, PGA	1 Hz, 10 Hz, PGA
200	1 Hz	1 Hz*

where the asterisks denote debating points (i.e., predictions on which we will focus the comparisons and discussions).

For each magnitude-distance-frequency combination, you are asked to provide the following information:

1 an estimate of the median ground-motion amplitude (5% damped spectral acceleration or PGA),

2 an estimate of the epistemic uncertainty associated with that estimate of the median (you are also asked to partition this epistemic uncertainty into its parametric and modeling components)

3 a central estimate of the aleatory uncertainty (about the true median) anticipated in future observations of ground motions under the same conditions (i.e., same magnitude, distance, geographic region, and site conditions; this aleatory uncertainty is typically represented by the standard deviation σ, which we will call $\sigma_{\ln[\text{amplitude}],\ \text{aleatory}}$ for the sake of clarity),

4 epistemic uncertainty associated with the aleatory uncertainty (i.e., uncertainty about the true value of $\sigma_{\ln[\text{amplitude}],\ \text{aleatory}}$),

5 parametric sensitivities.

The definition of epistemic and aleatory uncertainties follows the "white paper" distributed prior to the first workshop, and are repeated below:

> Epistemic Uncertainty. Uncertainty that is due to incomplete knowledge and data about the physics of the earthquake process. In principle, epistemic uncertainty can be reduced by the collection of additional information.
>
> Aleatory Uncertainty. Uncertainty that is inherent to the unpredictable nature of future events. It represents unique details of source, path, and site response that cannot be quantified before the earthquake occurs. Given a model, one cannot reduce the aleatory uncertainty by collection of additional information.

The epistemic uncertainty about the median amplitude is further sub-divided into two components: parametric and modeling. The parametric component represents, for example, uncertainty about the median amplitude due to uncertainty about the median stress drop for the eastern U.S. (e.g., is it 120 bars?, does it increase with seismic moment?). The modeling component relates to uncertainty about the model's systematic bias (i.e., $\ln[\text{Amplitude}]_{\text{true}} - \ln[\text{Amplitude}]_{\text{predicted}}$). Such bias may be introduced by the model's functional form or by parameters that are not treated explicitly as uncertain. Uncertainty about the size of the bias arises because the data available for model validation are few and are often outside the magnitude-distance range of engineering interest. The Appendix to these instructions, and the white paper distributed prior to the first workshop, contain examples on these distinctions. In addition, you may contact David Boore, Allin Cornell, or myself, if you have any question about these distinctions or if you wish to discuss their validity or usefulness.

In the evaluation of epistemic and aleatory uncertainties, you should use whichever method you think is appropriate (e.g., propagation of parameter and modeling uncertainties, use of empirical

data from ENA or other regions, and/or direct subjective assessments). Your assessment of aleatory uncertainty should be conditional on the independent variables given (i.e., m_{Lg}, closest distance, geographic region, and site conditions). If your model contains additional independent variables (e.g., stress drop, focal depth, rupture dimensions, depth to basement), you should incorporate the effect of uncertainty in these variables on the total aleatory uncertainty requested above.

The parametric sensitivity results will help other experts modify your estimates if they wish to use your model but they wish to make some modifications in the model parameters. You should indicate the sensitivity of your estimate to the three most important model parameters (you should try to anticipate the parameters that another expert would be most likely to change).

Format of Results and Documentation

Estimates of Median and Uncertainties. Your results for the prescribed magnitudes, distances, and frequencies should be provided in the attached forms 1 through 5. Debating points are identified by thick rectangles; magnitude-distance-frequency combinations for which no input is required are shaded. You may wish to submit, in addition, graphical results, tables, and/or equations that cover a wider magnitude-distance-frequency range; we encourage but do not require such results. The functional forms you provide may prove helpful because, ultimately, we shall have to provide predictions over a continuous range of magnitude and distance.

Each component of the epistemic uncertainty may be represented adequately by lognormal distributions (in which case you would enter the logarithmic standard deviation [using natural logs]), or by discrete, triangular, uniform, or other distributions. We encourage you to concentrate your attention on the extent of the spread (as measured, for example, by the logarithmic standard deviation of the median; i.e., $\sigma_{\ln[\text{median}]\text{epistemic}}$), rather than on the fine details of the distribution shape (i.e., lognormal vs. triangular).

The aleatory uncertainty may also be represented by any distribution, but the lognormal distribution is expected to be adequate (so, you would simply specify $\sigma_{\ln[\text{Ampl}],\text{aleatory}}$). You should also specify truncation, if appropriate. To specify the epistemic uncertainty about the proper value of $\sigma_{\ln[\text{Ampl}],\text{aleatory}}$, you may use multiple values of $\sigma_{\ln[\text{Ampl}],\text{aleatory}}$ with associated weights or, again, any other simple measure of "spread".

Parametric Sensitivity Results. Please report the sensitivity of the median estimate to changes in the median values of the three most important (and likely to change) parameters, using forms 1S to 5S. The following are three possible formats for the sensitivity to a parameter:

1. For a scalar parameter, such as stress drop, report the quantity $\partial \ln[\text{Amplitude}] / \partial \text{Parameter}$, evaluated with all parameters set at their median or base-case values.

2. For a scalar parameter, report the estimates obtained by changing the parameter of interest to an "interesting" value (e.g., the logarithmic mean+σ value of stress drop), report the parameter value and the corresponding estimate of the median ground-motion amplitude.

3. For a non-scalar parameter whose uncertainty is represented by a moderate number of discrete alternatives with associated weights (e.g., crustal velocity structure), describe the alternatives and their weights and report the median predictions obtained with each alternative.

Alternatively, you may wish to use another format for representing parametric uncertainties. Your sensitivity results should, however, allow another expert to adjust your median estimates without extensive calculations or any software.

Documentation. Please provide three to ten pages of documentation, summarizing the approach and parameters used to generate your predictions, including how the two uncertainty estimates were obtained. In addition, you should briefly discuss the following three topics:

1. strengths and weaknesses of your approach, applicability of your approach to each of the magnitude-distance-frequency ranges of interest;

2. qualitative discussion of whether the hard-rock site considered here is representative of rock sites in CEUS

3. qualitative discussion of how your results would be different for other regions within CEUS.

You may wish to include relevant papers and reports as appendices.

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 1: Page __ of __

Proponent: _____

Approach: _____

Ground Motion Measure: 1-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

Proponent: _____

Approach: _____

Ground Motion Measure: 2.5-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

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Proponent: _____

Approach: _____

Ground Motion Measure: 10-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

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Proponent: _____

Approach: _____

Ground Motion Measure: 25-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

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Proponent: _____

Approach: _____

Ground Motion Measure: Peak Ground Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

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Proponent: _____

Approach: _____

Sensitivity Results: Ground Motion Measure: 1-Hz Spectral Acceleration (g)

Distance	Quantity	m_{Lg} 5.5	m_{Lg} 7.0
5 km			
20 km			
70 km			
200 km			

Comments/footnotes:

Proponent: _____

Approach: _____

Sensitivity Results: Ground Motion Measure: 2.5-Hz Spectral Acceleration (g)

Distance	Quantity	m_{Lg} 5.5	m_{Lg} 7.0
5 km			
20 km			
70 km			
200 km			

Comments/footnotes:

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Proponent: _____

Approach: _____

Sensitivity Results: Ground Motion Measure: 10-Hz Spectral Acceleration (g)

Distance	Quantity	m_{Lg} 5.5	m_{Lg} 7.0
5 km			
20 km			
70 km			
200 km			

Comments/footnotes:

Proponent: _____

Approach: _____

Sensitivity Results: Ground Motion Measure: 25-Hz Spectral Acceleration (g)

Distance	Quantity	m_{Lg} 5.5	m_{Lg} 7.0
5 km			
20 km			
70 km			
200 km			

Comments/footnotes:

Proponent: _____

Approach: _____

Sensitivity Results: Ground Motion Measure: Peak Ground Acceleration (g)

Distance	Quantity	m_{Lg} 5.5	m_{Lg} 7.0
5 km			
20 km			
70 km			
200 km			

Comments/footnotes:

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APPENDIX

THE PARTITION AND ESTIMATION OF UNCERTAINTY

In the "white paper" on uncertainty, we developed a two-way partition of uncertainty, as follows:

a) Is this uncertainty that can be reduced with the collection of additional data? (epistemic vs. aleatory)

b) Is this uncertainty due to a parameter of the model that is explicitly treated as uncertain? (parametric vs. modeling)

The table that follows contains examples of the four types of uncertainty resulting from this partitioning.

	Epistemic	Aleatory
Modeling	Uncertainty about the true model bias (i.e, to what extent model has a tendency to over- or under-predict observations)	Unexplained scatter due to physical processes not included in the model
Parametric	Median stress drop for ENA, depth distribution, etc.	Event-to-event variation in stress drop or focal depth, etc

In this exercise, we are asking you to report the two components of epistemic uncertainty and the combined (parametric+modeling) aleatory uncertainty. The example that follows should clarify these definitions.

Assume that there are thousands of records from earthquakes in the region of interest, all having the magnitude (m_x), same distance (r_x), and same site category (s_x) for the prediction

at hand. Given these data, we can compute the true value of the median[1] ground-motion amplitude at a certain frequency as

$$\ln[Amplitude]_{\text{true median}} = \frac{1}{n}\sum_{i=1}^{n} \ln[Amplitude]_{\text{observed},\, i} \tag{1}$$

where n is the number of records.

Assume also that we have a deterministic predictive model (e.g., a physical model, a stochastic model, or an empirical attenuation function) of the form:

$$\ln[Amplitude]_{\text{pred}} = f(m, r, \text{ site category; } \boldsymbol{P}) \tag{2}$$

where $\boldsymbol{P}$ is a vector of explicit model parameters (e.g., stress drop, focal depth, slip distribution, etc.) and that we know the parameter values $\boldsymbol{P}_i$ for each record. By comparing predictions (for the same magnitude, distance, and site category of interest) to observations, we can quantify the model bias

$$\frac{1}{n}\sum_{i=1}^{n} \left(\ln[Amplitude]_{\text{observed},\, i} - f(m_x, r_x, s_x;\ \boldsymbol{P}_i)\right) \tag{3}$$

or

$$\ln[Amplitude]_{\text{true median}} - \frac{1}{n}\sum_{i=1}^{n} f(m_x, r_x, s_x;\ \boldsymbol{P}_i) \tag{3a}$$

One can also compute the associated aleatory uncertainty (which is due to aleatory variations in all source, path, and site factors other than region, magnitude, distance, and site category) from the observed scatter as

$$\sigma_{\ln[Amplitude],\text{aleatory}} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} \left(\ln[Amplitude]_{\text{observed},\, i} - \ln[Amplitude]_{\text{true median}}\right)^2} \tag{4}$$

In reality, the number of available records for the desired magnitude, distance, and site category is small at best. Thus, there is statistical uncertainty about the true value of the model bias in Equation 3 (this is epistemic modeling uncertainty) and about the standard

[1]We are using the term median in a loose sense. Strictly speaking, the quantity in Equation 1 is the logarithmic-mean amplitude, which is equal to the median amplitude only if the amplitude follows a log-normal distribution.

deviation $\sigma_{\ln[Amplitude],\text{aleatory}}$ in Equation 4 (this is epistemic uncertainty, containing both model and parametric components).

Limitations in the data also introduce a parametric component of epistemic uncertainty in physical ground-motion models. This uncertainty is due to uncertainty about the true distributions of model parameters. In the hypothetical situation where one has many records and one knows $\boldsymbol{P}_i$ for each record, one would know the median stress drop exactly (though one would not know the stress drop for the next event). The extent of this uncertainty depends on the uncertainty in the median stress drop and on the sensitivity of $f(m_x, r_x, s_x;\ \boldsymbol{P})$ to stress drop.

In practice, the data are so limited that one is required to use data from other magnitudes, distances, and site categories to estimate the bias, epistemic modeling uncertainty, epistemic parametric uncertainty, and aleatory uncertainty. In doing this, there is the implicit assumption that the predictive model $f(m,r,\text{site category};\ \boldsymbol{P})$ is equally good, and has the same bias, for (m_x, r_x, s_x) and for the magnitudes, distances, and site categories represented in the data. This assumption introduces additional epistemic uncertainty, which may quantified by considering alternative models.

Some Possible Approaches

The following is a brief description of some of the techniques available for the estimation of bias, epistemic uncertainty, and aleatory uncertainty. Additional details are found in the White Paper on Uncertainty that was distributed prior to the first workshop.

Physical and Stochastic Models. The 1993 EPRI study provides an example of the Abrahamson et al. (1991) formulation of uncertainty. Modeling uncertainty is calculated by comparing observed spectral accelerations to predictions obtained using parameters $\boldsymbol{P}_i$ appropriate to each event and site. These comparisons yield estimates of the bias

$$\mu = \frac{1}{n}\sum_{i=1}^{n}\left(\ln[Amplitude]_{\text{observed},\,i} - f(m_i, r_i, s_i;\ \boldsymbol{P}_i)\right) \tag{5}$$

and the standard error

$$\text{std. error} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(\ln[Amplitude]_{\text{observed},\,i} - f(m_i, r_i, c_i; \boldsymbol{P}_i) - \mu\right)^2} \tag{6}$$

The standard error serves as an estimate of the aleatory modeling uncertainty (i.e., physical process and parameters not included in the predictive model, which cause seemingly random scatter). The epistemic modeling uncertainty (i.e., uncertainty in the bias) should be estimated as (std. error)/$(n')^{1/2}$, where n' is the equivalent number of independent observations (this number is smaller than n because of correlation among records from the same event). In the

EPRI study, additional epistemic modeling uncertainty was introduced by site-specific correction terms. Additional epistemic modeling uncertainty may arise due to the existence of competing models.

The epistemic and aleatory uncertainty in the model parameters $\boldsymbol{P}_i$ (e.g., uncertainty in the median stress drop and uncertainty in the stress drop for the next event) introduce epistemic parametric and aleatory parametric uncertainties in the predictions. The contributions of stress drop to the epistemic parametric and aleatory parametric uncertainties are approximately[2] equal to

$$\left[\frac{\partial f(m,r,\text{site category; } \boldsymbol{P})}{\partial \ln\Delta\sigma}\right]_{\boldsymbol{P}=\boldsymbol{P}_{\text{median}}} \times \sigma_{\overline{\ln\Delta\sigma}} \tag{7}$$

and

$$\left[\frac{\partial f(m,r,\text{site category; } \boldsymbol{P})}{\partial \ln\Delta\sigma}\right]_{\boldsymbol{P}=\boldsymbol{P}_{\text{median}}} \times \sigma_{\ln\Delta\sigma} \tag{8}$$

where $\sigma_{\overline{\ln\Delta\sigma}}$ is the logarithmic standard deviation representing epistemic uncertainty in the median stress drop (i.e., how well do we know the median stress drop that we would observe if we studied earthquakes in the region for thousands of years) and $\sigma_{\ln\Delta\sigma}$ is the logarithmic standard deviation representing aleatory uncertainty (i.e., the event-to-event scatter in $\ln[\Delta\sigma]$ that we would observe if we studied earthquakes in the region for thousands of years). Assuming that the uncertainties about all explicit model parameters in $\boldsymbol{P}$ are independent (i.e., no trade-offs), the total epistemic parametric and aleatory parametric uncertainties are approximately equal to

$$\sqrt{\sum_j \left\{\left[\frac{\partial f(m,r,\text{site category; } \boldsymbol{P})}{\partial \ln p_j}\right]_{\boldsymbol{P}=\boldsymbol{P}_{\text{median}}} \times \sigma_{\overline{p_j}}\right\}^2} \tag{9}$$

and
where the summations extend over all model parameters. Alternatively, one may use logic-trees to calculate the parametric uncertainties, as was done in the EPRI study.

The aleatory uncertainty (modeling+parametric) may also be calculated directly using records from the same region or from other regions. If the magnitudes and distances in the differ substantially from the magnitude and distance for which a prediction is being made, there is a

[2] The result is approximate because it involves linearization of f(m,r, site category; $\boldsymbol{P}$) with respect to one of the parameters in $\boldsymbol{P}$.

$$\sqrt{\sum_j \left\{ \left[\frac{\partial f(m,r,\text{site category; } \boldsymbol{P})}{\partial \ln p_j} \right]_{\boldsymbol{P}=\boldsymbol{P}_{\text{median}}} \times \sigma_{p_j} \right\}^2} \tag{10}$$

problem with different sensitivity to a parameter (such as Q) at different magnitudes and distances. If residual standard deviations from another region are being used to estimate the aleatory uncertainty in a region with limited data, one should keep in mind the following considerations: (1) if the regression contained additional explanatory variables (e.g., focal depth, style of faulting), these variables should be treated as uncertain parameters and integrated over in order to obtain a revised estimate of aleatory uncertainty; and (2) the residual standard deviation may contain some effects other than aleatory uncertainty (e.g., lack of fit, undetected regional variations in the data set).

Empirical Attenuation Equations. In empirical attenuation equations, the empirically derived coefficients take the role of parameters. These coefficients have no aleatory uncertainty (i.e., they are assumed to be the same for all events and sites). The calculated statistical uncertainty in these coefficients is typically very small and not representative of the true epistemic uncertainty. Differences among empirical models developed by different investigators (using somewhat different data sets and functional forms) is a better representation of epistemic uncertainty.

Modeling uncertainty is characterized by the residual standard deviation σ. This standard deviation contains both aleatory and epistemic components, but it is typically taken as all aleatory.

If empirical attenuation equations are used in a hybrid mode (i.e., the empirical attenuation equations are modified to account for regional differences in source scaling, magnitude definition, path effects, or site effects), such corrections introduce epistemic parametric uncertainty, which should be considered.

If the attenuation equations contain explanatory variables other than magnitude, distance, and site category, one must treat these explanatory variables as uncertain parameters (as was done with physical models). Thus, one must integrate over these parameters, considering the appropriate distribution of the parameter in the region of interest. For instance, if parameter Z represents faulting style in the attenuation equation

$$\ln[\text{Amplitude}] = g(m,r,\text{site category},Z) \tag{11}$$

and the probability of distribution of faulting styles in the region of interest is given by $p_Z(z_1)$, $p_Z(z_2)$, ... $p_Z(z_m)$, then the attenuation equation without Z is equal to
and the aleatory parametric uncertainty due to Z is characterized by a standard deviation equal to

$$g^*(m_x, r_x, s_x) = \sum_{k=1}^{m} p_Z(z_k)\, g(m_x, r_x, s_x, z_k) \tag{12}$$

$$\sqrt{\sum_{k=1}^{m} p_Z(z_k) \left(g(m_x, r_x, s_x, z_k) - g^*(m_x, r_x, s_x)\right)^2} \tag{13}$$

This standard deviation, and other parametric standard deviations, should be combined with the residual standard deviation (using a square root of the sum of the squares formula), to obtain the total aleatory uncertainty associated with g*(m,r,s) (i.e., for predictions in terms of magnitude, distance, and site category).

Changes in the definition of magnitude or distance can be treated in a similar manner. For instance, if the original attenuation equation uses distance definition R_1 and one wants to change to R_2, one may perform calculations similar to those in Equations 12 and 13 (but in integral form), using the conditional probability density function $f_{R_1|R_2,m,r}(r_1;\ r_2, m, r)$. If distance definition R_2 is superior to R_1, this approach will yield a higher residual standard deviation for R_2, because it ignores dependence between the regression residuals and $R_1|R_2,m,r$.

DOCUMENTATION OF GROUND MOTION ESTIMATES FOR ENA

Gail M. Atkinson, June 13, 1994

This note documents the ground motion estimates prepared for the SSHAC Ground Motion Workshop (July 1994). My estimates were prepared using the stochastic ground motion model, with methodology and parameter values as described in Atkinson and Boore (1994), and attached as Appendix A. Unfortunately the actual numerical values of the predicted motions given in the paper in Appendix A are in error, due to a programming error. However the methodology and input parameters are correct as stated, and the ground motion values given here are correct. The key parameters of the model, as described in Appendix A, are an empirical source model for ENA earthquakes, as a function of moment magnitude (M) (Atkinson, 1993a), an empirical attenuation form (Atkinson and Mereu, 1992), and an empirical duration model (Atkinson, 1993b). These three input components to the model were obtained largely from analysis of recent seismological data (over 1500 records from earthquakes in southeastern Canada and the northeastern U.S., of $3<M<6$), supplemented with analyses of regional and teleseismic data from historical ENA earthquakes (Street and Turcotte, 1977; Ebel et al., 1986; Somerville et al., 1987), and MMI intensity data (Hanks and Johnston, 1992). The aim of the empirical analyses was to bring together relevant data from a variety of sources, and use it to define the essential building blocks of the stochastic model. A calibration study (Atkinson and Somerville, 1994) provided confidence that the

stochastic model can provide unbiased ground motion estimates for frequencies of 1 to 10 Hz, provided that these essential building blocks can be defined.

The target events of m_N 5.5 and m_N 7.0 have been assumed to have moment magnitudes of 5.0 and 7.0, respectively. Because of the uncertainty in these **M** values, the aleatory uncertainty in the predictions is large (ie. use of m_N in specifying source spectrum leads to large inter-event variability). I based the median aleatory uncertainty on empirical analysis of ENA response spectra data, as described in Appendix B. (The uncertainty in 1-Hz amplitudes for m_N-based predictions was assumed to be somewhat lower than given in Appendix B for 1 Hz, but higher than given in B for 10 Hz. The reason is that the m_N values in Appendix B are for ECTN instruments, whereas I assume that the U.S. catalogue m_N would be WWSSN where available.) Note in Appendix B that if the estimates had been for either moment or high-frequency magnitude, the aleatory uncertainty would have been much lower (0.55 versus 0.8). My estimated uncertainty in the aleatory sigma is subjective, based on examination of the data from Appendix B, and knowledge of typical sigma values for other (ie. California) data sets.

The epistemic uncertainty features zero median bias, based on comparisons of our predictions the data listed in Appendix B. The uncertainty in the bias is a guesstimate, based on the limitations of the data used to estimate the median bias, as well as the limitations of the data used to constrain the model

parameters. The parametric epistemic uncertainty is also a guesstimate, and is also based on limitations of the database used to constrain model parameters. These uncertainties must vary in some fairly sophisticated fashion with magnitude, distance and frequency. But in the time frame provided a detailed analysis of these uncertainties was not feasible. I have therefore used rather arbitrary values of either 0.2, 0.3, 0.5, or even 0.7 (ln units), in each of these boxes, according to whether I believe each uncertainty to be 'low', 'medium', 'high', or 'very high'. My apologies to those that favor partial differential equations, HP calculators, 50 ways to partition your table, and so on.

For the parametric sensitivity results, I have focused on the most 'interesting' parameters for each frequency. For 1 to 2.5 Hz, I think that the shape of the source spectrum (Brune versus empirical) merits attention. For 10 Hz I have examined stress drop. For 25 Hz and PGA I have looked at kappa. Duration is important for all frequencies, but I have shown its influence just at 1 Hz and 2.5 Hz.

I must note that I am uncomfortable with the estimates at R=5 km, particularly for M 7. I would not normally apply these estimates to R<10 km, since the model does not treat the many near-source effects that may significantly affect motions very close to the source.

Regarding the specified rock condition, EUS rock with β = 2.8 km/s, I have assumed that this is comparable to the

conditions at ECTN seismometer sites in southeastern Canada. Since my input parameters implicitly assume zero average amplification for such sites, I have not amplified the ground motion predictions for surficial rock response. Any such amplification would be small in any case; the maximum amplification due to impedance contrast would be a factor of about 1.16 ($\sqrt{(3.8/2.8)}$, where 3.8 is the assumed value of β at midcrustal depths).

Proponent: G.M. Atkinson

Approach: Stochastic with empirical inputs

Ground Motion Measure: 1-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.034	0.43
	epistemic uncertainty	parametric (ln)	0.5	0.7
		median bias	0.0	0.0
		uncert. in bias (ln)	0.5	0.7
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
20 km	median amplitude		0.0058	0.10
	epistemic uncertainty	parametric (ln)	0.5	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.3	0.5
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
70 km	median amplitude		0.0012	0.023
	epistemic uncertainty	parametric (ln)	0.5	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.2	0.5
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
200 km	median amplitude		0.00082	0.017
	epistemic uncertainty	parametric (ln)	0.5	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.2	0.5
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2

Comments/footnotes:

$m_N 5.5 \simeq M 5.0$
$m_N 7.0 \simeq M 7.0$

Aleatory uncertainty based on m_N.
If M/m had been used, I would give $\sigma_{ln} = 0.55$ for all frequencies.
Uncertainty in σ for M/m would be 0.1

Proponent: G.M. Atkinson

Approach: Stochastic

Ground Motion Measure: 2.5-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.032	0.34
	epistemic uncertainty	parametric (ln)	0.3	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.3	0.7
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

Proponent: G.M. Atkinson

Approach: Stochastic

Ground Motion Measure: 10-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.95	4.3
	epistemic uncertainty	parametric (ln)	0.5	0.7
		median bias	0.0	0.0
		uncert. in bias (ln)	0.5	0.7
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
20 km	median amplitude		0.17	0.97
	epistemic uncertainty	parametric (ln)	0.3	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.3	0.5
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
70 km	median amplitude		0.022	0.17
	epistemic uncertainty	parametric (ln)	0.2	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.2	0.5
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

Proponent: Gail Atkinson

Approach: Stochastic

Ground Motion Measure: 25-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.26	1.3
	epistemic uncertainty	parametric (ln)	0.3	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.3	0.5
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

Proponent: G.M. Atkinson

Approach: Stochastic

Ground Motion Measure: Peak Ground Acceleration (g)

Distance	Quantity		m_{L_g} 5.5	m_{L_g} 7.0
5 km	median amplitude		0.77	2.8
	epistemic uncertainty	parametric (ln)	0.5	0.7
		median bias	0.0	0.0
		uncert. in bias (ln)	0.5	0.7
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude		0.011	0.084
	epistemic uncertainty	parametric (ln)	0.5	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.2	0.5
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

Proponent: G.M. Atkinson

Approach: Stochastic

Sensitivity Results; Ground Motion Measure: 1-Hz Spectral Acceleration (g)

Distance	Quantity	m_{Lg} 5.5	m_{Lg} 7.0
5 km	Base Case	0.034	0.43
	Brune shape	0.041	1.0
	Alt. durn	0.026	0.52
20 km	Base	0.0058	0.10
	Brune	0.010	0.26
	Alt. Durn	0.0078	0.13
70 km	Base	0.0012	0.023
	Brune	0.0022	0.056
	Alt. Durn	0.0014	0.027
200 km	Base	0.00082	0.017
	Brune	0.0016	0.034
	Alt. Durn	0.00077	0.015

Comments/footnotes:

Brune has $\Delta\sigma = 180$ bars, with source durn. $1/f_0$.
Alt. Durn is $1/f_0$ for $R < 50$ km
then $1/f_0 + 0.05R$ for $R \geq 70$ km.

Proponent: G.M. Atkinson

Approach: Stochastic

Sensitivity Results: Ground Motion Measure: 2.5-Hz Spectral Acceleration (g)

Distance	Quantity	m_{Lg} 5.5	m_{Lg} 7.0
5 km			
20 km	Base Case	0.032	0.34
	Brune shape	0.051	0.54
	Alt. durn	0.030	0.41
70 km			
200 km			

Comments/footnotes:

Brune shape has $\Delta\sigma$ = 180 bars

Proponent: G.M. Atkinson

Approach: Stochastic

Sensitivity Results: Ground Motion Measure: 10-Hz Spectral Acceleration (g)

Distance	Quantity	m_{Lg} 5.5	m_{Lg} 7.0
5 km	Base Case	0.95	4.3*
	Brune 180 bars	1.1	6.0*
	Brune 500 bars	2.0	12.*
20 km	Base Case	0.17	0.97
	Brune 180 bars	0.16	1.1
	Brune 500 bars	0.35	2.5
70 km	Base Case	0.022	0.17
	Brune 180 bars	0.022	0.18
	Brune 500 bars	0.045	0.42
200 km			

Comments/footnotes:

* I don't believe values would be this high; near-source effects for M7 should be considered. I would normally use R≥10 km, which would reduce these by a factor of 2.

Proponent: G.M. Atkinson

Approach: Stochastic

Sensitivity Results: Ground Motion Measure: 25-Hz Spectral Acceleration (g)

Distance	Quantity	m_{Lg} 5.5	m_{Lg} 7.0
5 km			
20 km	Base Case	0.26	1.3
	kappa = 0.006	0.16	0.84
70 km			
200 km			

Comments/footnotes:

Proponent: G.M. Atkinson

Approach: Stochastic

Sensitivity Results: Ground Motion Measure: Peak Ground Acceleration (g)

Distance	Quantity	m_{Lg} 5.5	m_{Lg} 7.0
5 km	Base Case	0.77	2.8
	kappa=0.006	0.51	1.8
20 km			
70 km	Base Case	0.011	0.084
	kappa=0.006	0.0079	0.062
200 km			

Comments/footnotes:

GROUND MOTION RELATIONS FOR EASTERN NORTH AMERICA

GAIL M. ATKINSON AND DAVID M. BOORE

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ABSTRACT

Predictive relations are developed for ground motions from eastern North American earthquakes of $4.0 \leq M \leq 7.25$ at distances of $10 \leq R \leq 500$ km. The predicted parameters are response spectra at frequencies of 0.5 Hz to 20 Hz, and peak ground acceleration and velocity. The predictions are derived from an empirically-based stochastic ground-motion model. The relations differ from previous work in the improved empirical definition of input parameters, and empirical validation of results. The relations are in demonstrable agreement with ground motions from earthquakes of M 4 to 5. There are insufficient data to adequately judge the relations at larger magnitudes, although they appear to be consistent with data from the Saguenay (M 5.8) and Nahanni (M 6.8) earthquakes. The underlying model parameters are well-constrained by empirical data for events as large as M 7.

INTRODUCTION

Ground-motion relations describing peak ground motions and response spectra as functions of earthquake magnitude and distance are of paramount importance in the assessment of earthquake hazard to engineered structures. In recent years, ground-motion relations for eastern North America (ENA) have been based on a stochastic model (eg. Boore and Atkinson, 1987; Toro and McGuire, 1987; EPRI, 1988; Atkinson and Boore, 1990). The model has its origins in the work of Hanks and McGuire (1981), who showed that observed high-frequency ground-motions can be predicted by assuming the motion is bandlimited Gaussian noise, whose amplitude spectrum is given by a simple seismological model of the source and propagation processes. Their model has fundamentally changed the way in which ground motion relations are developed, in providing a simple physical framework by which to interpret empirical observations.

For western North America (WNA), it has been shown that the Brune (1970) source model, with a stress parameter of about 100 bars, provides accurate estimates of average ground motions when used in conjunction with the stochastic model (Hanks and McGuire, 1981; Boore, 1983; Boore et al., 1992). For ENA, previous applications (referenced above) have also assumed the 100-bar Brune source model. This assumption was justified based on inferences from a few moderate (M 4 to 5) ENA events (Atkinson, 1989) and teleseismic data from larger historical earthquakes (Somerville et al., 1987). The 1988 Saguenay, Quebec earthquake (M 5.8), by contrast, differed dramatically from the predictions

of the simple Brune model (Boore and Atkinson, 1992), raising questions concerning the validity of the underlying source model for large events and the adequacy of our knowledge concerning ENA source spectra. These concerns were heightened by the work of Boatwright and Choy (1993), who showed that the teleseismic spectra of large intraplate events generally depart from the Brune model; intraplate earthquakes appear to have two corner frequencies.

Recent earthquakes have also highlighted wave-propagation issues that were not addressed in the development of previous ENA ground-motion relations. Specifically, theoretical studies of wave propagation in a layered crust indicate that the decay of ground-motion amplitudes may be depth dependent, and that the decay pattern may be significantly disrupted in the distance range from about 60 to 120 km; in this distance range the direct wave is joined by the first postcritical reflections from internal crustal interfaces and the Moho discontinuity (Burger et al., 1987). It has been suggested that this phenomenon was at least partly responsible for the large ground-motion amplitudes observed at distances near 100 km during the Saguenay (Somerville et al., 1990) and Loma Prieta (Fletcher and Boatwright, 1991; Campbell, 1991) earthquakes.

Recent empirical studies of over 1500 seismograms from ENA earthquakes in the magnitude range from 3.5 to 7 have provided significant new information on ENA ground-motion processes. The recent studies show that: (i) source spectra for ENA earthquakes of **M** > 4 deviate significantly from the Brune 100-bar model

(Atkinson, 1993a); (ii) the attenuation of spectral amplitudes is slightly disrupted by the transition from direct-wave to Lg-wave spreading, suggesting a hinged trilinear form for the attenuation curve (Atkinson and Mereu, 1992); (iii) the duration of motion increases with distance in a complex manner (Atkinson, 1993b); and (iv) the ratio of horizontal-to-vertical component ground motions is frequency-dependent, but independent of distance (Atkinson, 1993b). These studies were based on data derived largely from earthquakes in southeastern Canada and the northeastern United States. Detailed simulation studies (EPRI, 1993) suggest that ground-motion relations should show little regional variability over most of ENA, with the exception of the Gulf Coast region. Therefore ground-motion relations derived from data in southeastern Canada and the northeastern U.S. should be applicable over most of ENA.

In this paper, we use the new information on ENA source and attenuation processes to revise our 1987 ground-motion relations. The method used to develop the ground-motion relations is briefly reviewed, with emphasis on the data defining each of the input parameters. Predictive relations are developed for peak ground motion and response spectra for rock sites, and compared to available ground-motion data.

APPROACH

Review of the Basic Method. The ground-motion predictions are based on the stochastic model, including both the random-process theory and time-domain implementations. In both approaches,

ground motion is modeled as bandlimited Gaussian noise; the radiated energy is assumed to be evenly-distributed over a specified duration. The method is quite general and can be used to predict many amplitude and instrument-response parameters.

The method begins with the specification of the Fourier amplitude spectrum of ground acceleration as a function of seismic moment and distance, $A(M_o,R,f)$, which can be represented by:

$$A(M_o,R,f) = E(M_o,f)\ D(R,f)\ P(f)\ I(f). \qquad (1)$$

$E(M_o,f)$ is the earthquake source spectrum for a specified seismic moment (ie. Fourier spectrum of the ground acceleration at a distance of 1 km). $D(R,f)$ is a diminution function that models the geometric and anelastic attenuation of the spectrum as a function of hypocentral distance (R). $P(f)$ is a high-cut filter that rapidly reduces amplitudes at very high frequencies ($f>>10$ Hz); it may be based on either the f_{max} model (Hanks, 1982) or the kappa model (Anderson and Hough, 1984). $I(f)$ is a filter used to shape the spectrum to correspond to the particular ground-motion measure of interest. For example, for the computation of response spectra I is the response of an oscillator to ground acceleration. For free-field ground-motion parameters, I is simply

$$I(f) = 1/(2\ \pi\ f)^p \qquad (2)$$

where $p = 0$ for acceleration, 1 for velocity, or 2 for displacement.

The time-domain implementation of the stochastic method (Boore, 1983) begins with the generation of a windowed

acceleration-time-series, comprised of random Gaussian noise with zero mean amplitude; the variance is chosen such that the spectral amplitude is unity on average. The duration of the window is specified as a function of magnitude and distance. The spectrum of the windowed time series is multiplied by the desired amplitude spectrum ($A(M_o,R,f)$ from equation (1)). The filtered spectrum is then transformed back into the time domain to yield a simulated earthquake record for that magnitude and distance.

The random-process approach uses Parseval's theorem to relate the spectral amplitudes ($A(M_o,R,f)$) to root-mean-square (rms) amplitudes in the time domain. Equations from random-process theory are used to obtain expected values of peak amplitudes from the rms amplitudes. For details of these methods, refer to Hanks and McGuire (1981), Boore (1983), and Boore and Atkinson (1987).

Input Parameters. The input parameters for the method include all terms of equation (1), and the duration of motion. The simulations will apply to the random horizontal component of the shear phase of ground motion.

The earthquake source spectrum ($E(M_o,f)$) for the horizontal component of ground motion is given by a functional form which represents the addition of two Brune spectra (Atkinson, 1993a):

$$E(M_o,f) = C\ (2\pi f)^2\ M_o\ \{(1-\epsilon)/[1+(f/f_A)^2] + \epsilon/[1+(f/f_B)^2]\} \qquad (3)$$

where $C = R_p\ F\ V\ /\ (4\pi\rho\beta^3\ R)$, with $R = 1$ km, R_p = average radiation pattern (=0.55), F = free surface amplification (=2.0), V = partition onto two horizontal components (=0.71), ρ = crustal density (=2.8 gm/cm^3), and β = shear wave velocity (=3.8 km/sec).

The values for the crustal constants are based on the seismic reflection/refraction data of Mereu et al. (1986) for southeastern Canada, for the average focal depth of events in the region (10 km). The choice of reference depth for β is not critical because there is little dependence of shear wave velocity on depth for ENA hard-rock sites; this also implies that near-surface amplification due to impedance contrasts is negligible for hard-rock sites (Boore and Atkinson, 1987). The parameters ϵ, f_A and f_B are functions of seismic moment, given for $4 \leq \mathbf{M} \leq 7$ by:

$$\log \epsilon = 2.52 - 0.637\ \mathbf{M} \tag{4}$$

$$\log f_A = 2.41 - 0.533\ \mathbf{M} \tag{5}$$

$$\log f_B = 1.43 - 0.188\ \mathbf{M} \tag{6}$$

Equation (3) was derived by combining analysis of spectral data in the frequency range from 1 to 10 Hz (22 ENA earthquakes of $4 \leq \mathbf{M} \leq 7$, with moments and corner frequencies (f_A and f_B) inferred from spectral data and teleseismic models (Somerville et al., 1987; Boatwright and Choy, 1992). The use of equation (3) for magnitudes as large as 7.25 represents a slight extrapolation.

Figure 1 compares the new source model to the 100-bar Brune model used in our 1987 ground-motion relations. The complexity of shape is required in order to reconcile observations over the 1 to 10 Hz frequency band with the seismic moment of the events. Equation (3) is the simplest functional form that could be found to match both spectral amplitudes and corner frequencies. It is an empirical representation rather than a theoretical model. The rather dramatic reduction of spectral amplitudes at intermediate

frequencies, relative to the Brune model, is an important implication of equation (3). This feature is a consequence of the spectral-amplitude and corner-frequency data; it is not an artifact of the selected functional form. The sag in spectral amplitudes at intermediate frequencies is largely driven by the observation that 1-Hz spectral amplitudes are low, relative to those that would be inferred by a simpler interpolation between the moment-end of the spectrum and its high-frequency end. The amplitudes predicted by equation (3) are well-constrained by data for frequencies of 1 Hz and greater, for $4 \leq \mathbf{M} < 7$. Examination of strong-motion data from the Saguenay (**M** 5.8) and Nahanni (**M** 6.8) earthquakes suggests that the shape is appropriate for frequencies at least as low as 0.5 Hz; for these earthquakes the observed ratio of 1 Hz to 0.5 Hz spectral amplitudes is well-predicted by equation (3). The amplitudes cannot be verified for lower frequencies, and therefore the ground-motion predictions are restricted to $f \geq 0.5$ Hz.

The attenuation of spectral amplitudes with distance (D(R,f)) is given by the hinged trilinear form of Atkinson and Mereu (1992). Based on 1500 seismograms from 100 earthquakes of magnitude m_N 3 to 6.5, they found that spectral-amplitude decay due to geometric spreading is approximately independent of frequency. The observed decay is given by $R^{-1.1}$ for distances from R=10 to R=70 km. From R=70 to R=130 km, there is no apparent geometric spreading. For R>130 km, spectral amplitude decay due to geometric spreading can by modeled as $R^{-0.5}$. The associated Q model is $Q = 670\ f^{0.33}$, where the anelastic

attenuation of spectral amplitudes is then given by $\exp(-\pi f R / \beta Q(f))$. The overall attenuation is obtained as the product of the geometric and anelastic attenuation terms. (Note: For distances R<10 km, the geometric spreading is assumed to be given by R^{-1}; this assumption was also made in deriving the source spectra from the empirical observations.) No apparent dependence of the attenuation on focal depth was observed. The empirical attenuation is applicable for distances large enough to allow the source to be treated as a point. Finite-fault effects might alter the observed attenuation in the near-source region, but this would only be significant for large (M>6.5) earthquakes.

For the high-cut filter we use (Boore, 1986):

$$P(f) = [1 + (f/f_{max})^8]^{-\frac{1}{2}} \quad (7)$$

where f_{max} is the high-frequency cut-off proposed by Hanks (1982). For ENA we have assumed a value of f_{max} = 50 Hz based on a review of very limited data. An alternative would be to use the kappa filter suggested by Anderson and Hough (1984):

$$P(f) = \exp(-\pi k f) \quad (8)$$

where k is the high-frequency decay-slope on plots of log spectra versus frequency (for near-source distances for which anelastic attenuation is negligible). The kappa filter is not as abrupt as the f_{max} filter; it represents a gradual diminution of spectral amplitudes with increasing frequency, rather than an upper limit on frequency. Many of the ENA spectra that we have reviewed are apparently flat out to frequencies of 20 Hz, above which there are no data (we approach the upper corner-frequency of the recording instruments). In this case a meaningful estimate of

either kappa or f_{max} is not really possible. This is illustrated for several typical ECTN records (at R<100 km) in Figure 2. We have therefore chosen to use the f_{max} filter with a high cut-off value (50 Hz), to avoid artificially diminishing high-frequency amplitudes. Beware that predictions for frequencies above 20 Hz, and peak ground acceleration, depend critically on this parameter. If very high frequencies are of interest, more information is needed on P(f). For the present application, we assume that frequencies above 20 Hz are not of engineering interest.

The final input element of the stochastic predictions is the duration model. The duration model generally has two terms:

$$T = T_o + b\ R \tag{9}$$

where T_o is the source duration and b R represents a distance-dependent term which accounts for dispersion. For the source duration, we assume that $T_o = 1/(2f_A)$ (Boatwright and Choy, 1992), where f_A is the lowest corner frequency in the source spectrum, as given by equation 5. This source-duration estimate is compatible with the ENA source-duration data of Somerville et al. (1987). The source durations given by $1/(2f_A)$ are within 10% of those used in our previous (1987) study. (In 1987 we assumed a source duration of $1/f_o$, where f_o was the corner frequency of the Brune model; note $f_A<f_o<f_B$).

The empirical basis for the distance-duration term is the collection of 1500 ECTN seismographs used to define the attenuation function. Atkinson (1993b) computed, for each record, the duration which matches the observed relationship

between the peak ground velocity (PGV) and the Fourier spectrum, using random-process-theory equations. For this study we have taken a closer look at these duration data. Because most of the earthquakes in the ECTN database are small, the distance-dependent term of equation (9) dominates the duration; the bR term can therefore be determined with confidence by subtracting a simple estimate of T_o from the total duration. For this purpose, we assume $T_o = 1/f_o$, rather than $1/(2f_A)$, since most events in the duration dataset are too small (M<4) for the two-corner model to be applicable. These distance-dependent duration terms ($T-T_o$) are averaged within narrow distance bins in Figure 3. The distance-dependence of duration is modeled as trilinear, using the transition distances 70 and 130 km for consistency with the attenuation model; the slope b is 0.16 for $10 \leq R \leq 70$ km, -0.03 for $70 < R \leq 130$ km, and 0.04 for $130 < R < 1000$ km. The negative slope in the transition zone from direct-wave to Lg-phase (70 to 130 km) reflects the fact that, as more rays arrive, additional energy is being injected within the time-window of the signal. The random-process model requires a decrease in duration in order to correctly predict the enhanced time-domain amplitudes which result.

Choice of Magnitude Scale. The above equations provide all the information needed to simulate the horizontal component of ground motion for hard-rock sites as a function of moment magnitude and hypocentral distance. We choose to develop the ground-motion equations in terms of moment magnitude, rather than the more widely-catalogued (but more ambiguously defined) Nuttli magnitude

(m_N). We prefer **M** because it has a simple physical interpretation (Hanks and Kanamori, 1979), and because there is some hope of being able to specify **M** for a future expected earthquake based on geological evidence. **M** has been estimated for most of the large historical ENA earthquakes from special studies. For moderate ($m_N \leq 6$) catalogued events for which no estimates of **M** are available, **M** can be estimated from the empirical relationship shown on Figure 4 (Atkinson, 1993a):

$$\mathbf{M} = -0.39 + 0.98\ m_N \quad ; \quad m_N \leq 6 \tag{10}$$

The standard error of an estimate is 0.15. This relationship should not be extrapolated to $m_N > 6$, since theoretically there is significant curvature to the m_N versus **M** relation at large magnitudes (Boore and Atkinson, 1987). This curvature cannot be defined by the empirical data due to the paucity of large events and the large uncertainties in estimated values of both **M** and m_N for a few critical historical earthquakes (1925 Charlevoix, 1935 Timiskaming). It can be defined theoretically, but only by making particular assumptions regarding the instrument type and distance at which m_N is measured. One such theoretical relation is (Boore and Atkinson, 1987):

$$\mathbf{M} = 2.715 - 0.277\ m_N + 0.127\ m_N^2 \tag{11}$$

We suggest using equation (10) for $m_N \leq 5.5$, and equation (11) for $m_N > 5.5$.

It is straightforward and practical to conduct seismic hazard analyses based on **M** rather than m_N. In fact, the ability to predict **M** from m_N, or vice-versa, is implicit in any process that converts the **M**-based predictive model to an equivalent m_N-

based model. It may be argued that the use of m_N should result in lower variability of high-frequency ground motions, since m_N is measured at higher frequencies than **M**. Contrary to this expectation, Atkinson (1993a) found that the standard error of the common logarithm of the estimated high-frequency spectral amplitude is 0.17 for predictions based on **M**, and 0.19 for predictions based on m_N. This suggests that intermediate-frequency magnitude (m_N) does not predict high-frequency amplitude with any greater precision than does low-frequency magnitude (**M**). Thus there appears to be no advantage to using m_N.

If it is desired to make ground-motion predictions based on a magnitude scale which more closely describes high-frequency motions, the high-frequency magnitude scale (**m**) proposed by Atkinson and Hanks (1994) can be used. **m** can be defined for modern events based on seismographic data, or for historical events based on felt area. Since **M** = **m** on average, by definition, separate ground-motion relations in terms of **m** are not required; simply use the observed **m** in place of **M** in the predictive relations, for frequencies above f_B. For example, referring to the list of **m** values in Table 4, the high-frequency (f>2 Hz) amplitudes from the Saguenay earthquake could be predicted from our ground-motion relations using a magnitude of 6.5.

NOTE: The rest of the paper is not included since results contain a programming error.

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FIGURE CAPTIONS

FIGURE 1 - Comparison of horizontal-component source spectra (R = 1 km) for the ENA empirical model with those of the 100-bar Brune model, for **M** 5, 6 and 7. (from Atkinson, 1993a)

FIGURE 2 - Typical plots of acceleration spectra versus frequency for ENA events near the source, showing the apparent lack of high-frequency decay (kappa).

FIGURE 3 - Mean of the rms duration minus the source duration, averaged by 15-km distance bins. Vertical bars show 90% confidence limits on the estimate of the mean. Trilinear line is that used in the stochastic simulations. Simple straight line is 0.05 R, the distance-duration term used in previous (1990) simulations.

FIGURE 4 - Relationship between Lg magnitude (m_N) and moment magnitude (**M**). Data are from the ECTN (**M** values of Atkinson, 1993a; m_N values from Geophysics Division, Geological Survey of Canada), and from Boore and Atkinson (1987). Dotted line is the least-squares fit to the data (see equation (10)). Solid line is the theoretical relation of Boore and Atkinson (1987). Line connecting empty to filled square shows alternative **M** estimates for the Timiskaming earthquake. (from Atkinson, 1993a)

FIGURE 5 - Predicted response spectral values (PSA for 5% damping) for four frequencies and peak ground acceleration (PGA) and velocity (PGV), for **M** 4.0 ( ), 5.5 (+), and 7.0 (*). Symbols show ground motion predictions. Lines show quadratic equations of Table 1.

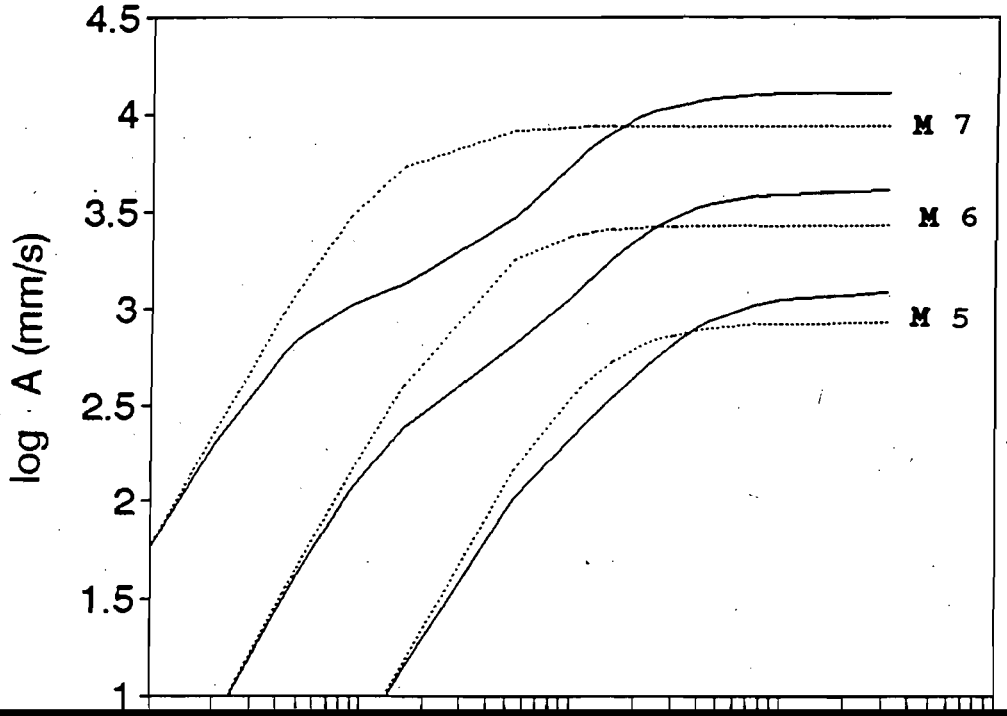
FIGURE 6 - Comparison of results of probabilistic hazard analysis, for probabilities of 0.002 p.a. (lower lines) and 0.0001 p.a. (upper lines), obtained using 'exact' ground motion relations (heavy solid), new quadratic approximation (light solid), and the Atkinson and Boore (1990) relations (dotted). Comparisons are provided for areas of low, moderate and high hazard. The expected PGA is plotted for reference at an arbitrary frequency of 100 Hz, with an arbitrary straight-line connection between the 20-Hz PSA and the PGA.

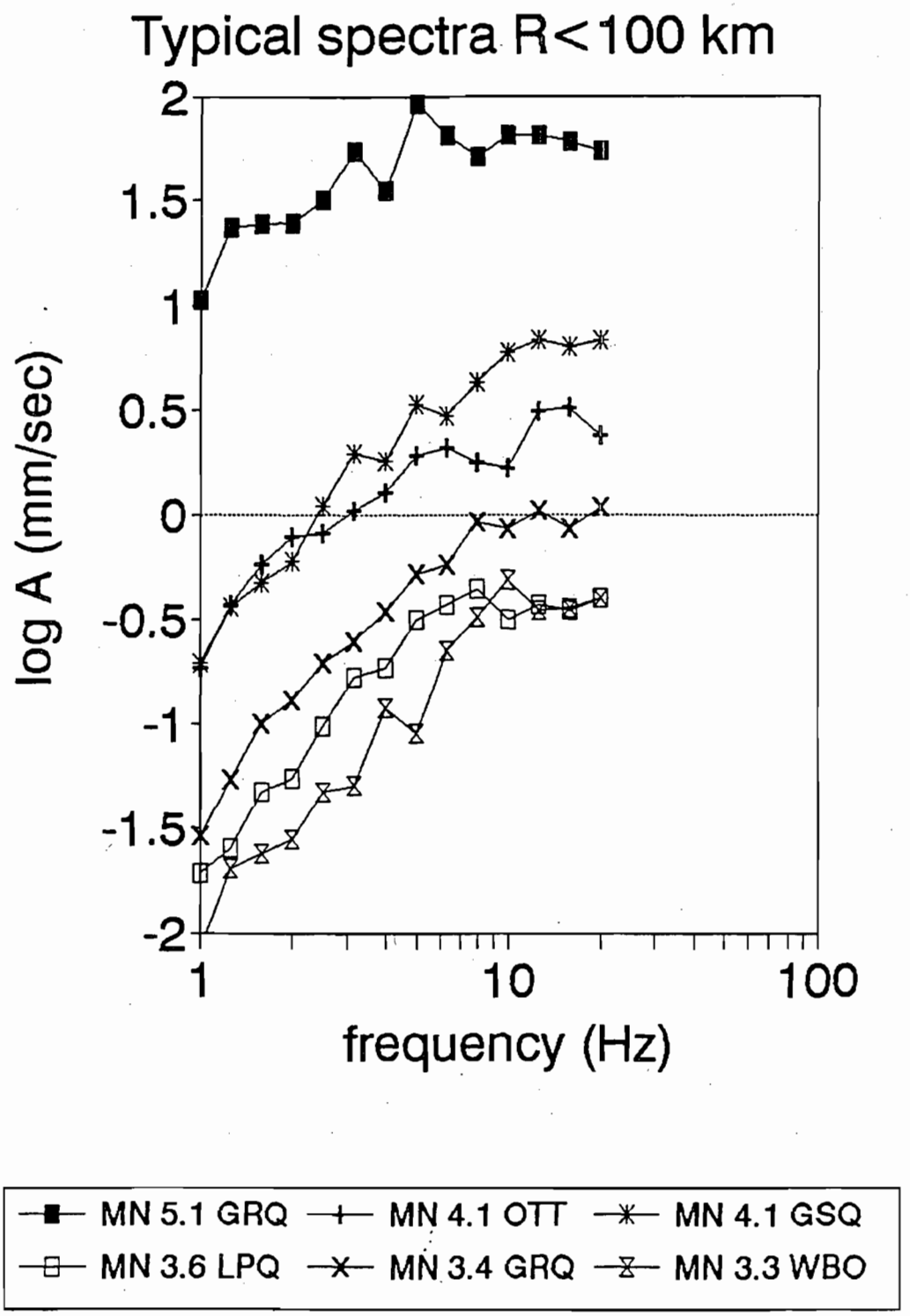
FIGURE 7- Differences (residuals in log units) between observed and predicted ground motions as a function of **M**, for oscillator frequencies of 1, 2, 5 and 10 Hz (mainshocks only).

FIGURE 8 - Differences (residuals in log units) between observed and predicted ground motions as a function of distance, for oscillator frequencies of 1, 2, 5 and 10 Hz.

ENA Model vs. Brune 100 bars

M = 5, 6, 7

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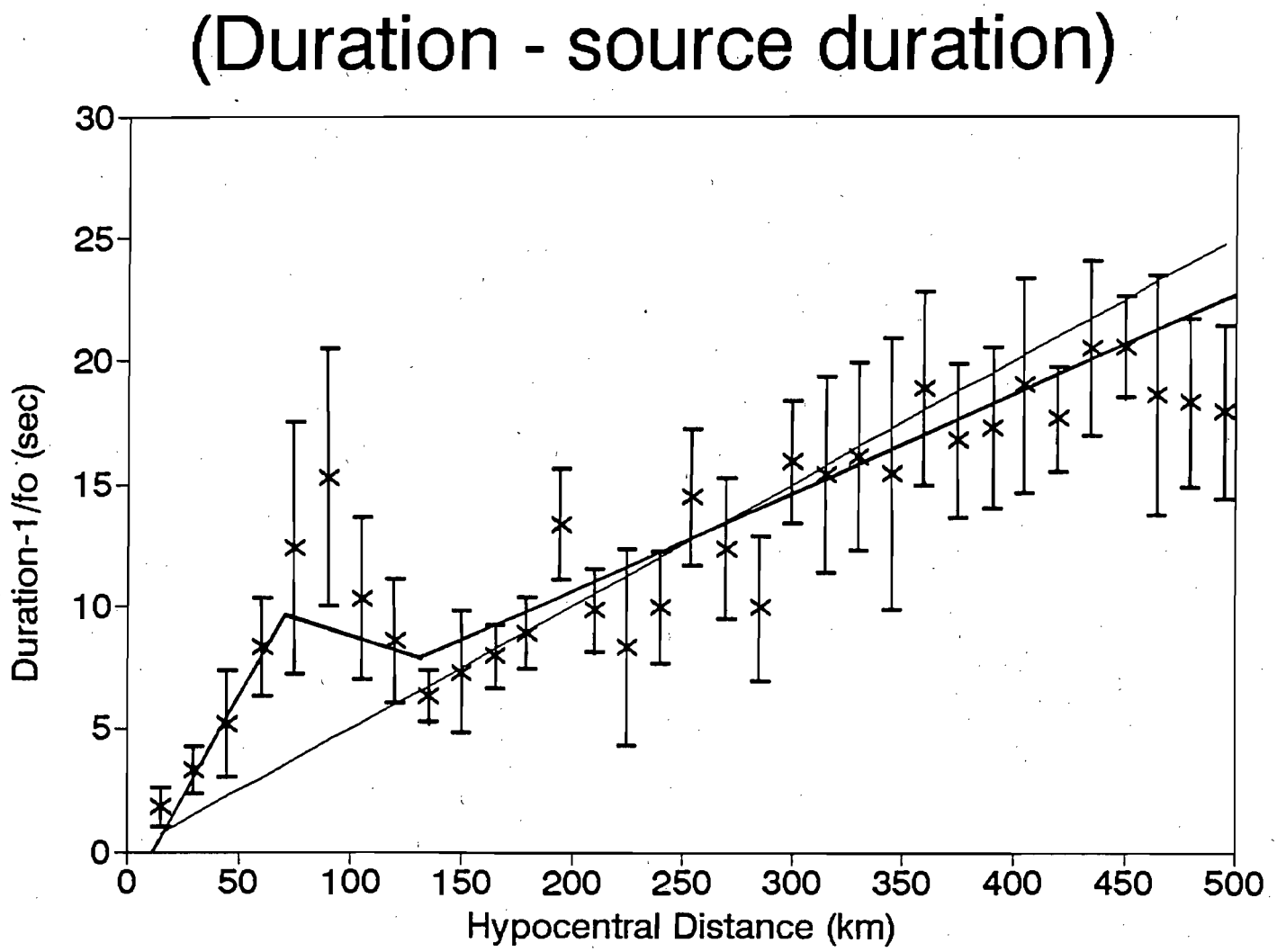
1.5
1
0.5
0
-0.5
-1
-1.5
-2
1
10
100
frequency (Hz)
MN 5.1 GRQ
MN 4.1 OTT
MN 4.1 GSQ
MN 3.6 LPQ
MN 3.4 GRQ
MN 3.3 WBO


(Duration - source duration)
Duration-1/fo (sec)
Hypocentral Distance (km)
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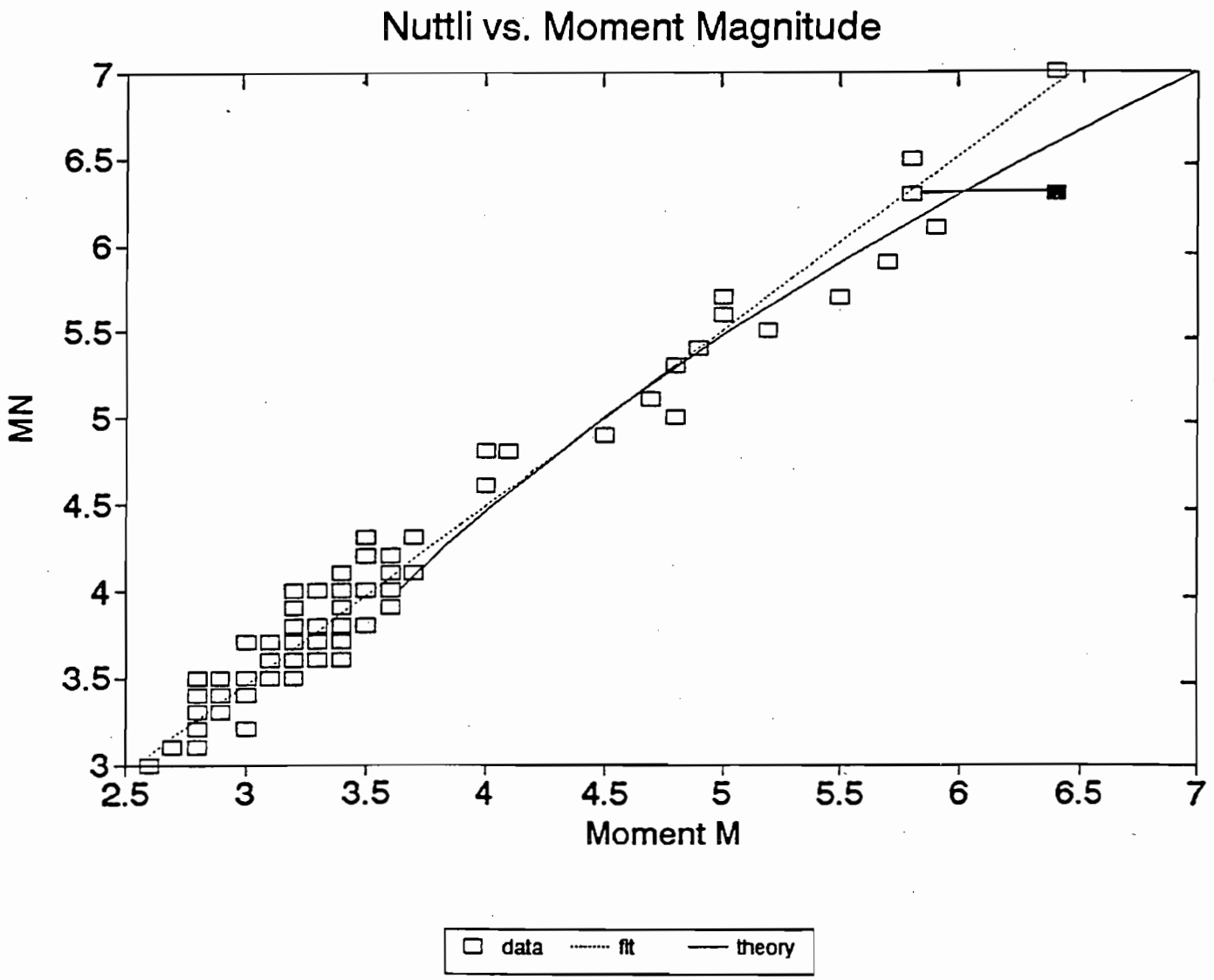
10
15
20
25
30
0
50
100
150
200
250
300
350
400
450
500


Nuttli vs. Moment Magnitude
MN
Moment M
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
data
fit
theory

OPTIMAL CHOICE OF MAGNITUDE SCALES FOR SEISMIC HAZARD ESTIMATES IN EASTERN NORTH AMERICA

by Gail Marie Atkinson: Draft 2 - June 10, 1994

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INTRODUCTION

There are currently several magnitude scales that are used to describe the size of earthquakes in eastern North America (ENA). These include **M** (moment magnitude; Hanks and Kanamori, 1979), m_N (Nuttli or Lg magnitude; Nuttli, 1973) and, most recently, **m** (Atkinson and Hanks, 1994). Each of these scales measures ground motion amplitude in a different frequency band: **M** is a low-frequency measure, m_N typically measures amplitudes in the 1 to 2 Hz frequency band (although this depends on the instrumentation), and **m** measures high-frequency (5 to 10 Hz) motions.

The choice of magnitude scale is an important issue for seismic hazard analysis. It implicitly dictates the physical underpinning of the most fundamental building block of any seismic hazard analysis: the earthquake catalogue. In a typical probabilistic hazard analysis (ie. Cornell, 1968; McGuire, 1977), the choice of magnitude scales enters the analysis in two ways: (i) through the magnitude recurrence relations, which describe the frequency of occurrence of earthquakes as a function of magnitude, within each seismic source zone; and (ii) through the ground motion

relations, which are used to estimate the severity of ground shaking at a site, as a function of earthquake magnitude and distance.

Current ground motion relations for ENA (Boore and Atkinson, 1987; Toro and McGuire, 1987; EPRI, 1993; Atkinson and Boore, 1994; Toro et al., 1995) specify the earthquake source spectrum based on magnitude. Consequently, the ability of each magnitude scale to estimate the source spectrum has significant implications for the uncertainty involved with the use of the ground motion relations. This uncertainty is currently a controversial issue; it is being carefully studied by major research organizations such the Electric Power Research Institute, Lawrence Livermore National Laboratory, and a special panel convened by the National Academy of Science.

The purpose of this note is to discuss the pros and cons of each of the above three choices of magnitude scales. I propose an optimal solution for seismic hazard analyses: the best choice is to use **M** for estimating low-frequency ground motions (f<2 Hz) and **m** for high-frequency ground motions (f>2 Hz). If only one magnitude scale is to be used, the choice should be based on the most-critical frequency range for the application.

The note is motivated by the importance of this choice for the reduction of aleatoric uncertainty (ie. randomness) in ground motion estimation. Aleatoric uncertainty is characterized by the standard deviation (sigma) of median

ground motion predictions (illustrated in Figures 1 and 2). This random uncertainty has a significant impact on probabilistic seismic hazard estimates. Specifically, a large degree of random scatter in the median ground motion relations leads to larger expected ground motions, for any probability level, than does a small degree of scatter. This situation is a consequence of the nature of the distributions; simply stated, the number of small earthquakes that might produce larger-than-average ground motions outweighs the number of large earthquakes that might produce smaller-than-average ground motions.

REVIEW OF MAGNITUDE ALTERNATIVES FOR HAZARD COMPUTATIONS

Moment Magnitude

Moment magnitude has the advantage of conceptual simplicity. It is a physically-based measure of the size of an earthquake. This means that there is some hope of being able to estimate **M** for future events from geologic constraints on the size of the fault plane. Moreover, seismic moment is the fundamental measure of earthquake source strength upon which current ENA ground motion models (Boore and Atkinson, 1987; Toro and McGuire, 1987; EPRI, 1993; Atkinson and Boore, 1994) are based. The use of moment magnitude therefore removes the need to convert the ground motion predictions to another magnitude scale. **M** is fairly-well determined for ENA earthquakes. Most large historic earthquakes have **M** values that have been determined

by studies of teleseismic or regional records (eg. Ebel et al., 1986). Moment magnitudes have also been published for many recent small events (eg. Atkinson, 1993). For small-to-moderate earthquakes ($3.0 \leq \mathbf{M} \leq 5.5$) with unknown **M**, a well-constrained empirical relationship can be used to estimate **M** from the more widely-catalogued m_N values (Atkinson, 1993): $\mathbf{M} = -0.39 + 0.98\ m_N$.

A final advantage of using **M** in ENA is that it simplifies comparisons with the west, since **M** is routinely catalogued for California earthquakes.

An oft-cited disadvantage of **M** is that it is a long-period measure, whereas for engineering purposes we are most interested in predicting the high-frequency amplitudes of ground motion. High-frequency ground-motion predictions based on **M** would tend to have greater uncertainty than predictions based on other magnitude measures, obtained at higher frequencies. (As will be shown in the following section, this is only partially true.) Another disadvantage is that **M** is not yet widely-catalogued in ENA, so that a somewhat laborious catalogue conversion is required. Finally, the relationship between **M** and MMI shows a large degree of scatter (Hanks and Johnston, 1992). Consequently there is large uncertainty in **M** estimates for large pre-instrumental earthquakes.

Nuttli Magnitude

Nuttli magnitude is the most widely-catalogued measure of the size of ENA earthquakes. Considerable effort has

gone into developing reliable catalogues of past events in terms of m_N. Observatory procedures for determining m_N for contemporary events are well-developed and work smoothly. In short, m_N has the considerable advantage of inertia. It typically measures ground motions in the 1 to 2 Hz frequency band, which is a relevant frequency range for many engineered structures.

The problem with m_N is that its physical interpretation, in terms of the models upon which ground motion predictions are based, is ambiguous. The relationship between m_N and the earthquake source spectrum depends on the instrumentation and distance at which the measurements were made, as well as the stress drop of the event (eg. Atkinson and Boore, 1987; EPRI, 1993). Also, m_N measures only a narrow frequency band of the ground motion, which may not be predictive of the motion at higher or lower frequencies. These factors introduce much uncertainty into the prediction of ground motion amplitudes from m_N, since current methods use earthquake magnitude to estimate the entire earthquake source spectrum.

High-frequency Magnitude

High-frequency magnitude measures the level of the earthquake source spectrum at frequencies above the corner frequency. Since the corner frequency decreases with increasing magnitude, the bandwidth of this measure increases with increasing magnitude. For damaging earthquakes, say those with $M > 5$, the frequency range for m

is about 2 to 10 Hz. **m** is therefore a good predictor of the earthquake source spectrum in the frequency range of engineering interest, by definition. This makes it particularly well-suited to ground motion predictions based on current methods. It is related to seismic moment in a fairly simple manner, since **m** = **M** for events of average stress drop (Atkinson and Hanks, 1994).

m has the considerable advantage of being well-determined by the felt area of an earthquake (Atkinson and Hanks, 1994). The use of **m** thus reduces the uncertainty in estimating ground motions from the large pre-instrumental earthquakes that are so important to seismic hazard in ENA.

There are significant disadvantages to using **m** in seismic hazard analyses at this time. It is a new scale and is therefore almost completely uncatalogued. Developing new catalogues in terms of **m** is a straightforward task but would entail considerable effort. It will likely be several years before reliable catalogues for old events are compiled. Changing observatory practices to include computation of **m** for modern events is also not a trivial process. Finally, uncertainty in the relationship between **m** and spectral amplitude grows as frequency decreases. Therefore **m** is not a particularly good magnitude measure for predicting ground motion amplitudes at frequencies less than 2 Hz, except for large (**M**>6) earthquakes.

UNCERTAINTIES IN GROUND MOTION PREDICTION

The pros and cons of each magnitude scale for the prediction of ground motion amplitudes are best appreciated through data comparisons. Table 1 lists ENA earthquakes for which we have response spectra data. Only mainshock data are included because aftershocks tend to have lower stress drops (Boore and Atkinson, 1989; Atkinson, 1993), and thus have systematically lower ground motion amplitudes. Only rock sites are included since the predictive ground motion relations are for rock. Figures 1 and 2 convey some appreciation for the distribution of the data in magnitude and distance.

The data set of Table 1 should be considered a biased sample in terms of stress drop. The 1988 Saguenay and 1990 Mont Laurier earthquakes both had stress drops of about 500 bars. Analysis of seismographic data indicates that such high-stress events represent about 15% to 20% of ENA earthquakes (Atkinson, 1993). By contrast, these two events represent about half of the records listed in Table 1 (and 25% of the events). The potential bias is a factor that should be kept in mind in interpreting these data. For example, Atkinson and Boore (1994) found that 1-to-10 Hz PSA data from the events of Table 1 are on average about 25% higher than their predictions, made in terms of **M**, if all *records* are weighted equally. However if all *events* are weighted equally, then this apparent bias disappears. This is because the equal-record weighting implicitly gives the

high-stress earthquakes a weight of ½, whereas the equal-event weighting gives them a weight of ¼; the latter weight is more consistent with the percentage of high-stress events within the broader seismological database for ENA.

Current ground motion relations should be capable of predicting the ENA ground motion data correctly on average (ie. zero mean residual), provided that the sample bias is adequately accounted for, regardless of which magnitude scale is selected. However the random scatter of the data about the mean relations, as characterized by the standard deviation of the residuals (sigma), will vary according to how well the magnitude scale predicts the source spectrum. In this section I examine the implications of each magnitude scale for 'sigma'.

The random scatter of the ground motion relations has two components: intra-event (1) and inter-event (2). These components are illustrated in Figures 1 and 2, respectively. The total random variability is determined by $\sigma_t = \sqrt{(\sigma_1^2 + \sigma_2^2)}$ (Joyner and Boore, 1981). The intra-event component was determined to be 0.20 log units (Atkinson, 1993), independent of distance and frequency (1-10 Hz), based on examination of over 1000 ENA Fourier spectra. This value is applicable to the response spectral data of Table 1 on average (Figure 1), although some events (in particular Mont Laurier) appear to have a higher degree of scatter. This component of scatter is, of course, independent of the magnitude scale.

The inter-event component of scatter can be estimated from the Table 1 data, for predictions based on each magnitude scale. For each frequency, I calculate the average residual for each of the eight earthquakes, by comparing the data to ground motion predictions made using the Atkinson and Boore (1994) model, for the particular magnitude scale (Figure 2). The standard deviation of these eight residuals is then an estimate of the inter-event variability. Combining the inter-event variability with the intra-event variability of 0.20, by the addition rule shown above, gives the total random variability as a function of frequency for each magnitude scale, as shown in Table 2.

Table 2 indicates that **M** provides estimates with the least amount of random uncertainty for frequencies less than or equal to 2 Hz. **m** provides the lowest uncertainty for frequencies greater than 2 Hz. m_N-based predictions have the highest amount of uncertainty at all frequencies. This is a good reason *not* to choose m_N for ground motion predictions.

It is important to keep in mind that the figures quoted in Table 2 are based on a set of only eight earthquakes, and that the values quoted are therefore uncertain. Furthermore, the average magnitude of the eight events is only 5.0. For larger magnitudes, which are particularly critical for seismic hazard estimation, the frequency range for which **m** provides the lowest uncertainty would extend to lower frequencies. The frequency range over which **M** is superior

would also shift to lower frequencies. Consequently, for large events, **m** would be expected to have less uncertainty than **M** over the entire 1 to 10 Hz frequency band.

CONCLUSION

The optimal choice of magnitude scale for seismic hazard computations is that which reduces random uncertainty in ground motion predictions to the lowest possible level. For moderate earthquakes, **M** is optimal for frequencies of 2 Hz or less, while **m** is optimal for greater frequencies. m_N is not an optimal choice in any frequency band. If a single magnitude scale is to be used, then **m** will be the best choice in most cases, for two reasons: (i) for large (**M**>6) events, it will yield the lowest uncertainty in predicted ground motions over the major frequency band of engineering interest (1 to 10 Hz); and (ii) it is the only magnitude that can be reliably determined for both modern and pre-instrumental earthquakes.

Using the optimal magnitude scale has a significant impact on seismic hazard estimates. Of course, the effect will vary from site-to-site. For many cases, though, the magnitude-recurrence parameters in terms of **m** will not differ significantly from those in terms of **M**, because **m** = **M** on average. For such cases there will be a reduction in computed ground motion when **m** is used for high-frequency parameters; the reduction is associated entirely with the lower sigma for **m** as opposed **M**. Sample calculations suggest

that the reduction could be about 20% to 30%, for estimated ground motions at probabilities of 0.001 to 0.0001 per annum. Is this a sleight of hand ? It might appear that way, but actually the lower estimate is a real consequence of reduced uncertainty in the levels of high-frequency ground motion experienced during past earthquakes. This reduction in uncertainty comes from gathering and utilizing the information that is most closely correlated with high-frequency ground motion levels. Much of this data is available for past ENA events, and can certainly be catalogued if we are willing to expend the effort. So if we are serious about reducing uncertainty in ground motion predictions, we should go ahead and *just do it*.

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TABLE 1 - Summary of data for comparison with ground motion predictions

Event		M	M_N	m	stress(bars)	No. obs.	dist.(km)
Gaza	82/01/19	4.0	4.8	4.0	86	5	200 -1000
Goodnow	83/10/07	5.0	5.6	4.8	113	13	200 - 800
Nahanni	85/12/23	6.8	6.1	6.2	53	6	8 - 23
Painesville	86/01/31	4.8	5.3	4.8	149	9	20 -1000
Ohio	86/07/12	4.5	4.9	4.5	154	5	700 -1000
Saguenay FS	88/11/23	4.1	4.6	4.2	190	10	100 - 500
Saguenay	88/11/25	5.8	6.5	6.5	517	29	50 - 700
Mt. Laurier	90/10/19	4.7	5.1	5.4	517	14	30 - 500

Notes: Only mainshocks are included. All records were obtained from the Geophysics Division of the Geological Survey of Canada. High-frequency magnitude is defined as: $\mathbf{m} = 2 \log a_{hf} + 3$, where a_{hf} is the amplitude of the Fourier spectrum of acceleration (cm/s, horizontal component, on rock), at a distance of 10 km from the source. It may be estimated for ENA earthquakes from PGV (horizontal component of peak ground velocity, on rock, in cm/s) using the following, for $R \leq 630$ km (Atkinson and Hanks, 1994):

$\mathbf{m} = 2.85 + 1.48 \log PGV_1$ for $\mathbf{M} \geq 4.2$

$\mathbf{m} = 3.34 + 0.902 \log PGV_1$ for $\mathbf{M} < 4.2$

where $\log PGV_1 = \log PGV + \log R + 0.00131\ R$, and R is hypocentral distance.

TABLE 2 - Total random variability in ground motions for ENA

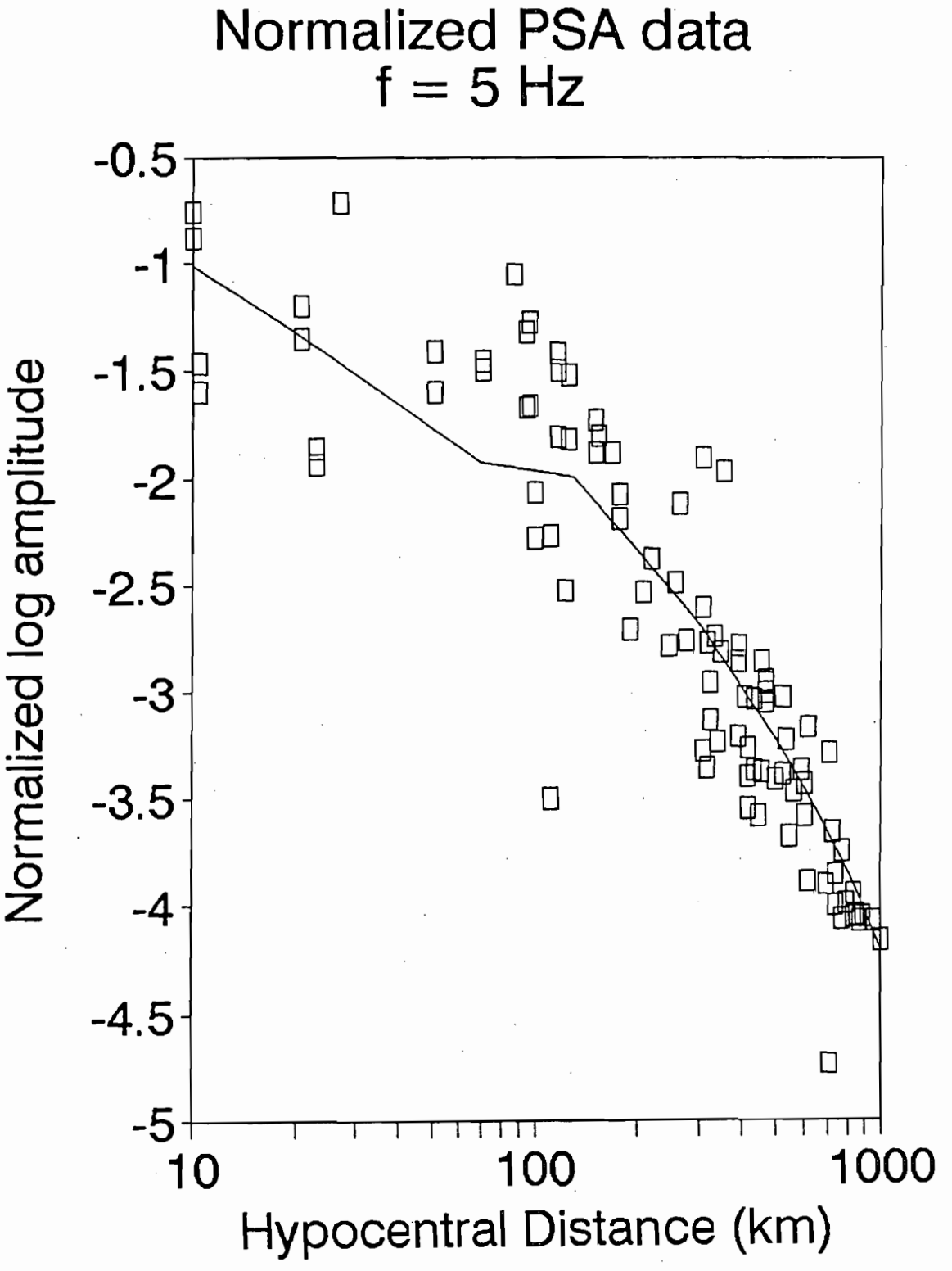
MAGNITUDE SCALE	Standard deviation of residuals for PSA:			
	1 Hz	2 Hz	5 Hz	10 Hz
m_N	0.43	0.34	0.31	0.29
M	0.24	0.24	0.26	0.27
m	0.31	0.30	0.23	0.24

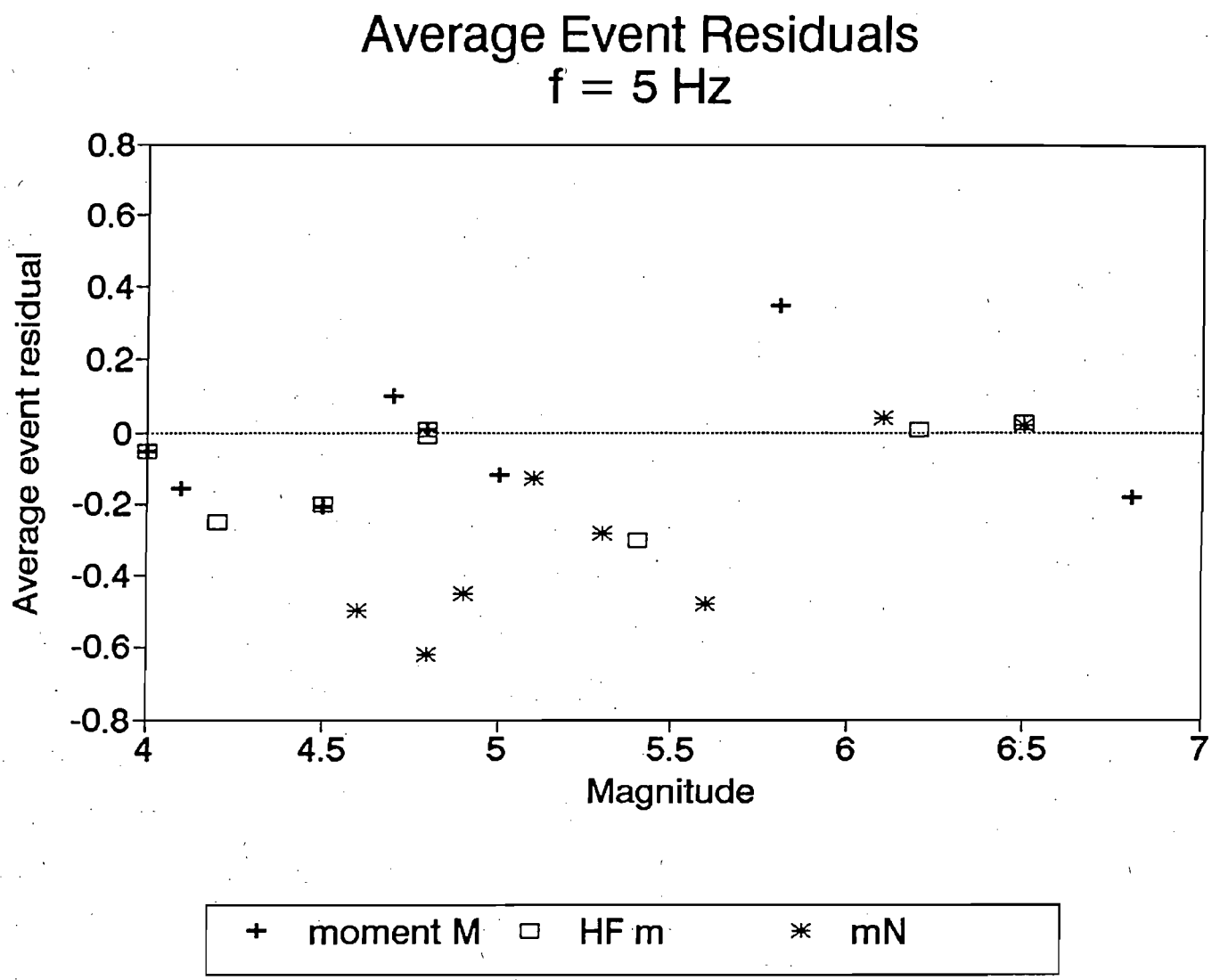
Notes: PSA is the 5% damped pseudo-acceleration. Residuals apply to rock sites, for mainshocks only. The variability (standard deviation of residuals, σ_t) was obtained as $\sigma_t = \sqrt{(\sigma_1^2 + \sigma_2^2)}$, where the intra-event variability (σ_1) is 0.20 for all cases. All numbers are log (base 10) units.

FIGURE CAPTIONS

FIGURE 1 - Illustration of intra-event variability for the data listed in Table 1. Symbols show the normalized 5-Hz pseudo-acceleration values; line shows the average attenuation with distance. The normalization was done by subtracting, from each (log) 5-Hz PSA value, the average (log) 5-Hz source amplitude for the event.

FIGURE 2 - Inter-event variability for the data listed in Table 1. Symbols show the average (log) 5-Hz PSA residual for each event, as a function of magnitude. Residuals are shown for ground motion predictions based on **M** (plus symbols), **m** (squares), and m_N (asterisks).


Normalized PSA data
f = 5 Hz
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
Normalized log amplitude
10
100
1000
Hypocentral Distance (km)


Average Event Residuals
f = 5 Hz
Average event residual
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
4
4.5
5
5.5
6
6.5
7
Magnitude
moment M
HF m
mN

SUMMARY OF HYBRID EMPIRICAL APPROACH FOR ESTIMATING GROUND MOTIONS IN THE CENTRAL AND EASTERN UNITED STATES

SECOND SSHAC GROUND-MOTION WORKSHOP
Palo Alto, California
July 27-28, 1994

Kenneth W. Campbell
EQE *International*, Inc.
Evergreen, Colorado

INTRODUCTION

The Hybrid Empirical approach for estimating ground motions in the Central and Eastern United States (CEUS) was developed as an alternative to the theoretical models that have become the *de facto* standard for the region. The method takes estimates of ground motion from empirical attenuation relationships developed for the Western United States (WUS) and adjusts them to account for differences in the source, path, and site effects between the two regions.

The method is a hybrid of the true empirical approach in that it uses empirical estimates from a region other than that for which the estimates are being made, and as applied, uses theoretical models for both regions to develop factors for making the necessary regional adjustments.

As stated in the instructions for the second SSHAC Ground Motion Workshop, the estimates were made for a hypothetical site located in the northeastern United States and southeastern Canada. The site conditions are described as Eastern United States Rock (i.e., a site having an average shear-wave velocity of 2800 m/sec over the top 30 m). The magnitudes, distances, and ground-motion parameters for which estimates were provided are shown on the attached tables and figures.

METHODOLOGY

Median Ground Motion

The following steps were used to develop the median ground-motion estimates provided in the attached tables and figures.

1. Empirical attenuation relationships developed by Sadigh et al. (1986), Joyner and Boore (1988), and Campbell (1989) were used to estimate median ground-motion parameters for a hypothetical site on WUS Soil. For this purpose, each model was given equal weight. Estimates on Soil rather than Rock were used because the Rock relationships are based on a significantly smaller number of recordings, and a significant number of these recordings are located on abutments of dams and are subject to potential topographic and dam-abutment interaction effects. Although it was not possible for the current effort, attenuation relationships for WUS Rock could be used as an alternative method of developing empirical ground-motion estimates.

2. Empirical estimates for WUS Soil were adjusted to approximate those expected on WUS Rock using the amplitude and frequency dependent site amplification factors that have been recently developed for inclusion in an upcoming revision of the NEHRP *Recommended Provisions for the Development of Seismic Regulations for New Buildings* (e.g., Borcherdt, 1994). For this purpose, WUS Soil was assigned to either Site Class SC-III (0.8 weight) or SC-II (0.2 weight) and WUS Rock was assigned to either Site Class SC-II (0.8 weight) or SC-Ib (0.2 weight), based on a preliminary assessment of the site conditions of recordings in the WUS empirical database.

3. Empirical estimates for WUS Rock were adjusted to approximate those expected on CEUS Rock using the ratio between theoretical ground motions calculated for the two regions. The model used for this purpose was based on the band-limited white noise stochastic simulation method originally proposed by Boore (1983). The model was used with median source, path, and site parameters recommended by EPRI (1993) for Mid-continent CEUS Rock and by W. Silva (written comm., 1993) for WUS Rock. Although beyond the scope of this project, this procedure could be generalized to incorporate alternative source, path, and site characterization models as well as alternative theoretical models for estimating ground motions in the two regions.

Uncertainty

As requested, I have provided estimates of both the epistemic and aleatory uncertainty associated with the median predictions. Due to limitations in the empirical attenuation relationships as well as budget and time constraints, it was not possible to partition the epistemic uncertainty into its parametric and modeling components, nor was it possible to provide an estimate of the epistemic uncertainty associated with the aleatory uncertainty. Additional effort would be required in order to estimate these uncertainties.

The following steps were used to develop the uncertainties in the median ground-motion estimates provided in the attached tables and figures.

1. Aleatory uncertainty was estimated from the standard errors of regression associated with the attenuation relationships used to develop the median ground motions for WUS Soil, assuming equal weight for the three relationships. These standard errors include both true aleatory as well as parametric modeling uncertainty, but there has been no attempt to separate these two components of uncertainty. For the time being, the standard errors are treated as all aleatory uncertainty and a concerted effort was made not to double count the parametric modeling component of this uncertainty in estimating epistemic uncertainty.

2. The parametric component of the epistemic uncertainty was assumed to be zero, since it was inherently included in the aleatory uncertainty..

3. The modeling component of the epistemic uncertainty was estimated from the following three sources of variability: (1) uncertainty associated with the median estimates of ground motion on WUS Soil (approximated by the variability in the median estimates provided by the three empirical attenuation relationships), (2) uncertainty in the median amplification factors used to adjust median estimates of ground motion on WUS Soil to those on WUS Rock (approximated by the uncertainty associated with assigning the generic Soil and Rock sites to one of the Site Classes defined by Borcherdt, 1994), and (3) uncertainty in the models used to adjust the median estimates of ground motion for WUS Rock to those on CEUS Rock (approximated as the epistemic modeling uncertainty associated with the CEUS model developed by EPRI, 1993, since it was assumed that epistemic modeling uncertainty associated with the WUS model is already included in the aleatory uncertainty).

Sensitivity

There was insufficient time in which to perform a sensitivity analysis. It is hoped that this analysis will be completed prior to the workshop.

RESULTS

Estimates of the median ground motions, the epistemic uncertainty, and the aleatory uncertainty for the magnitudes, distances, and ground-motion parameters of interest in this study are summarized in the attached tables. A comparison of the median estimates with those based on the Mid-continent ground-motion model for the CEUS developed by EPRI (1993) are shown on the attached figures.

DISCUSSION

The methodology developed in this study is intended to be a prototype of a proposed alternative model for estimating ground motions in the CEUS. Due to the limited budget and time constraints of this study, it was not possible to fully develop or implement this procedure. The fully developed procedure could perceivably include additional empirical attenuation relationships, additional site-amplification models, and/or additional models to account for regional differences in source, path, and site effects that would make the method considerably more robust.

Because of the constraints of the project, I simply adopted the Mid-continent model developed by EPRI (1993) for the CEUS. Although this model appears to meet the general description for site location and site conditions for which the ground-motion estimates were to be made, there might be refinements to this model that would make it more applicable to the northeastern United States and southeastern Canada.

The hard rock site for which estimates were made in this study is not typical of sites in the CEUS that are located on sediments (e.g., the Mississippi Valley). For these sites, these hard-rock ground motions would have to be adjusted for the response of local site conditions. Since the estimates provided by the Hybrid Empirical approach are intended to be used only for the higher ground motions associated with relatively large magnitudes and short distances (see below), I do not believe that estimates based on this method would be significantly different for other regions in the CEUS. The biggest difference in the estimated ground motions are likely to be caused by differences in local site conditions, which will result in large site-to-site differences in both observed and calculated ground motions both within as well as between regions.

The inherent strength in the Hybrid Empirical method is that it relies on ground-motion models that are well constrained by actual ground-motion recordings. As a result, the attenuation and magnitude scaling characteristics of the models are based on observation rather than theoretical assumptions. This is particular significant for near-source estimates, which are strongly affected by the complex geometric, kinematic, and dynamic characteristics of the rupture process — effects that are not easily predicted theoretically.

The inherent weakness in the method is its potential inclusion of unknown source, path, and site characteristics that are unique to the WUS and not accounted for in the models used to adjust for regional differences in these characteristics. An additional weakness, at least in the current application of the method, involves the procedure used to adjust the ground-motion estimates on WUS Soil to those expected on WUS Rock. Estimates on WUS Rock, especially if it is characterized as Site Class SC-II, may still incorporate some

nonlinear site effects that are not accounted for in the theoretical models used to adjust these estimates to CEUS Rock. If this is true, the higher ground-motions associated with near-source estimates at large magnitudes would be somewhat underestimated by this procedure. It might, however, be possible to overcome this weakness with additional studies. Finally, the method incorporates a weakness inherent in the WUS empirical attenuation relationships: these relationships become unreliable and should not be used to estimate ground motions for distances beyond of about 100 km and for magnitudes less than about moment magnitude 5.

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SSHAC SECOND
GROUND MOTION WORKSHOP

Form 1: Page __ of __

Proponent: Ken Campbell

Approach: Hybrid Empirical

Ground Motion Measure: 1-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Le} 5.5	m_{Le} 7.0
5 km	median amplitude		0.050	0.82
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.45	0.55
	aleatory uncertainty	median σ	0.74	0.57
		uncertainty in σ		
20 km	median amplitude		0.013	0.29
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.51	0.39
	aleatory uncertainty	median σ	0.74	0.57
		uncertainty in σ		
70 km	median amplitude		0.0027	0.089
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.49	0.51
	aleatory uncertainty	median σ	0.74	0.57
		uncertainty in σ		
200 km	median amplitude		0.00080	0.030
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.68	0.82
	aleatory uncertainty	median σ	0.74	0.57
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 2: Page __ of __

Proponent: Ken Campbell

Approach: Hybrid Empirical

Ground Motion Measure: 2.5-Hz Spectral Acceleration (g)

Distance	Quantity		m_{L_g} 5.5	m_{L_g} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.051	0.43
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.48	0.35
	aleatory uncertainty	median σ	0.69	0.52
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

Proponent: Ken Campbell

Approach: Hybrid Empirical

Ground Motion Measure: 10-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.50	1.46
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.33	0.34
	aleatory uncertainty	median σ	0.64	0.49
		uncertainty in σ		
20 km	median amplitude		0.15	0.66
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.35	0.29
	aleatory uncertainty	median σ	0.64	0.49
		uncertainty in σ		
70 km	median amplitude		0.036	0.20
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.36	0.50
	aleatory uncertainty	median σ	0.64	0.49
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

Proponent: Ken Campbell

Approach: Hybrid Empirical

Ground Motion Measure: 25-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.22	0.90
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.34	0.29
	aleatory uncertainty	median σ	0.65	0.48
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

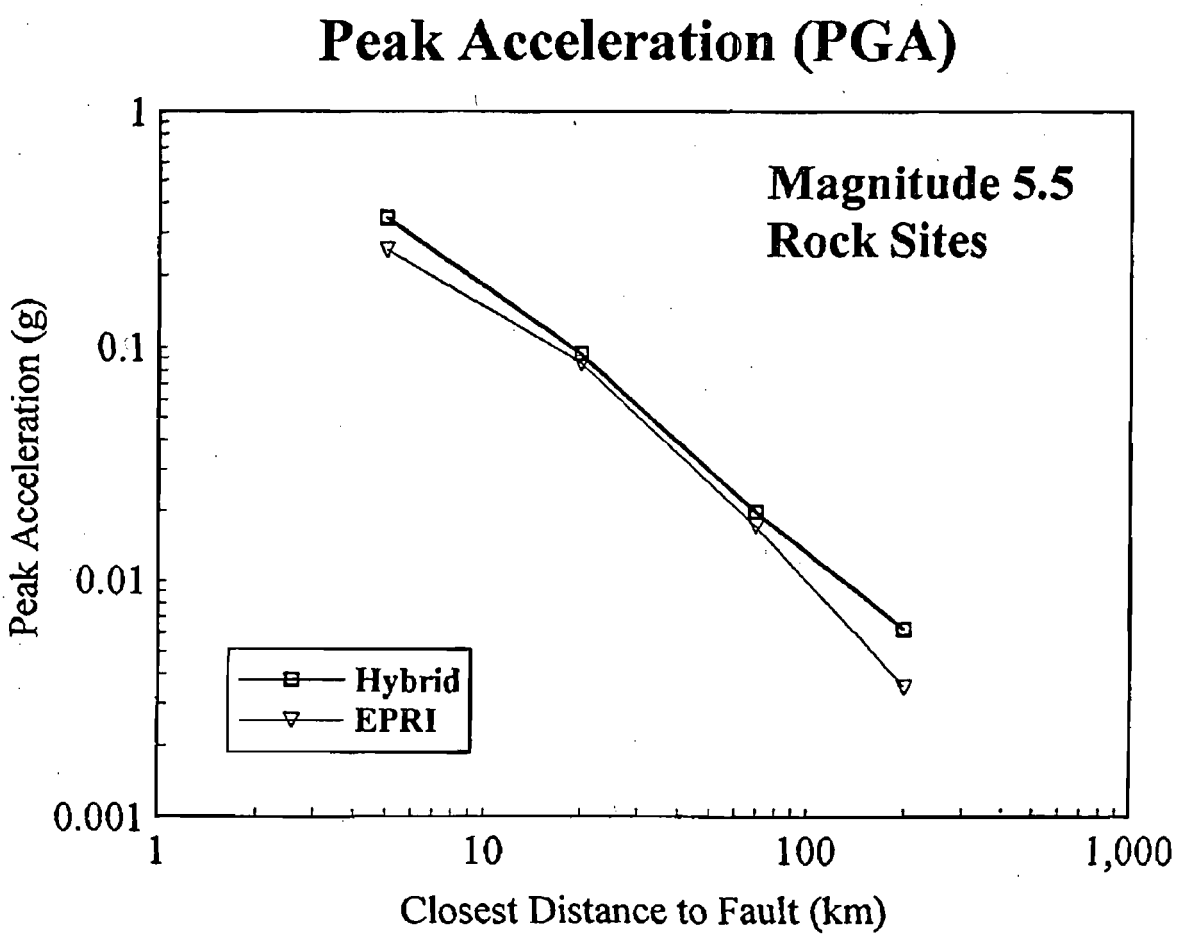
Proponent: Ken Campbell

Approach: Hybrid Empirical

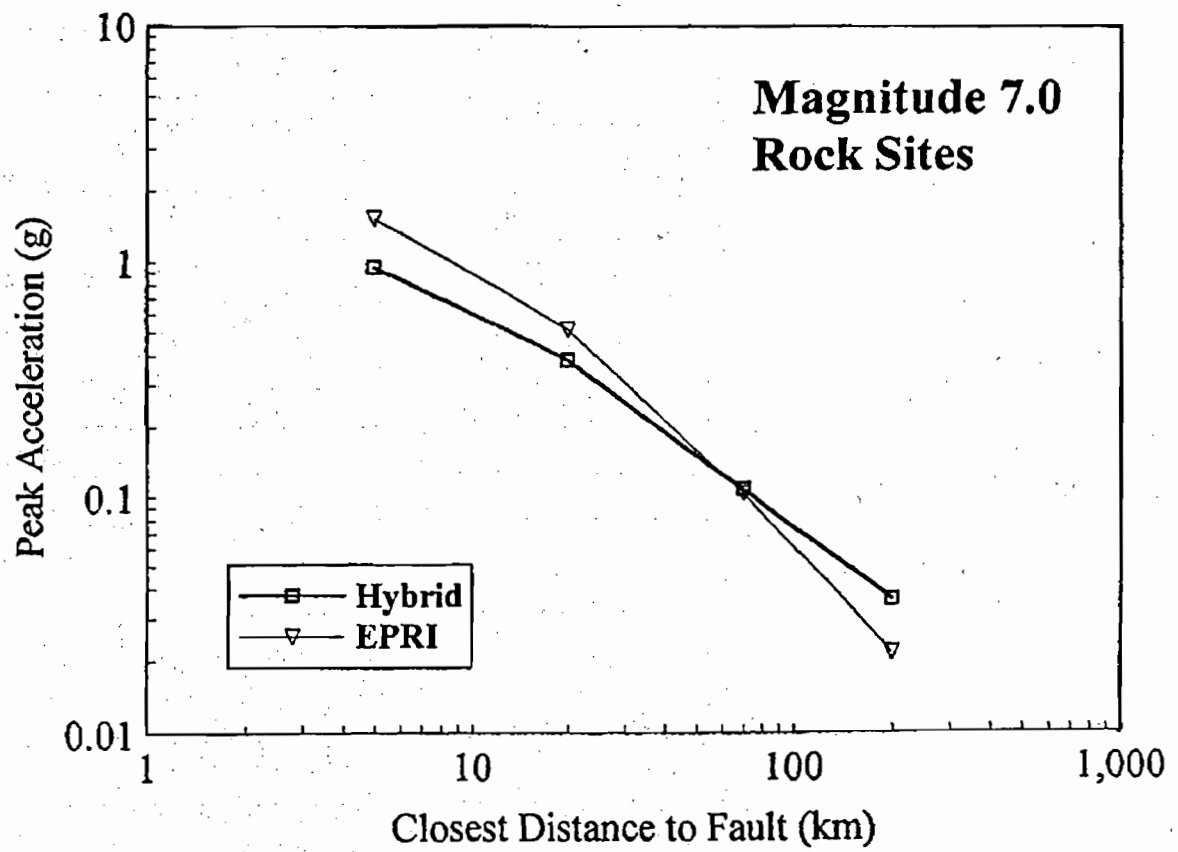
Ground Motion Measure: Peak Ground Acceleration (g)

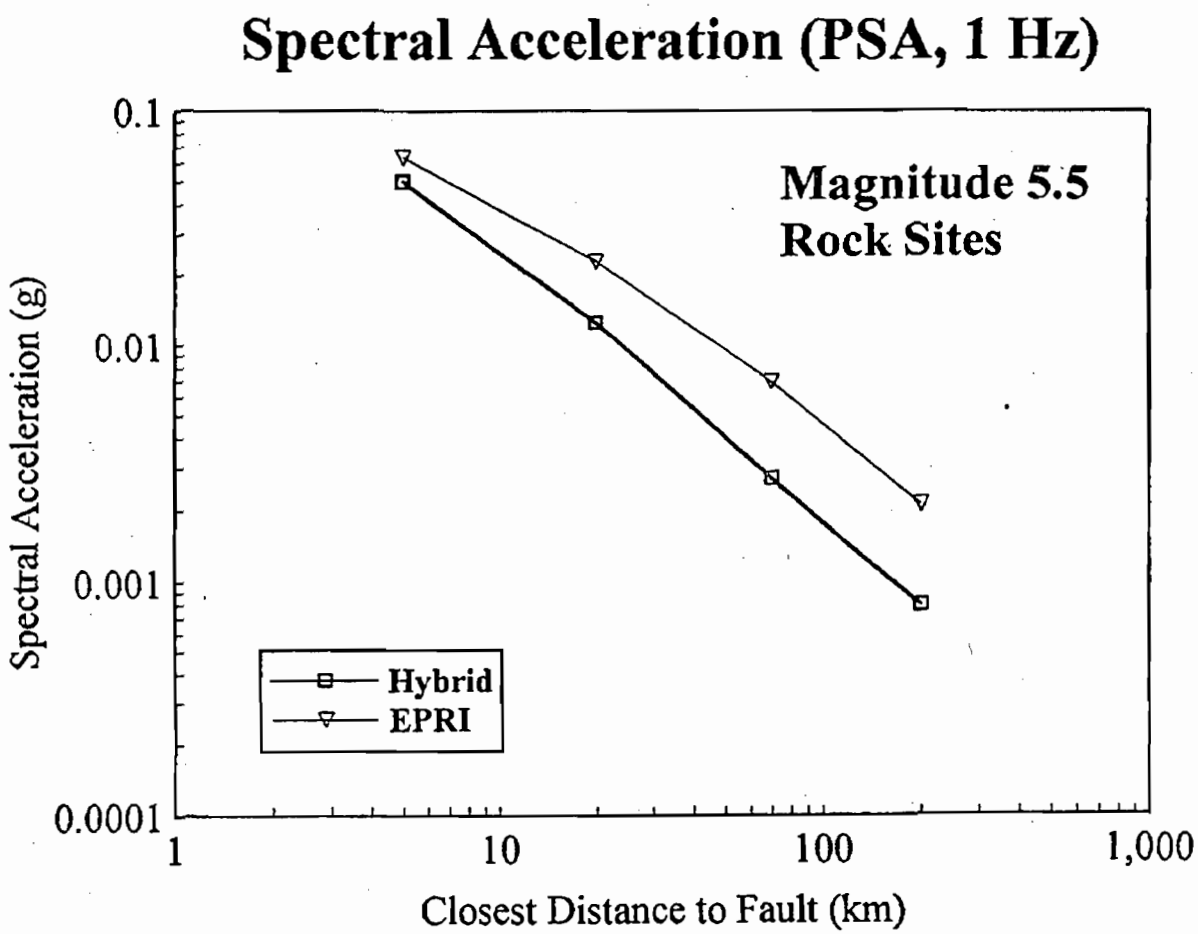
Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.35	0.95
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.38	0.33
	aleatory uncertainty	median σ	0.57	0.48
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude		0.020	0.11
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.41	0.39
	aleatory uncertainty	median σ	0.57	0.48
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

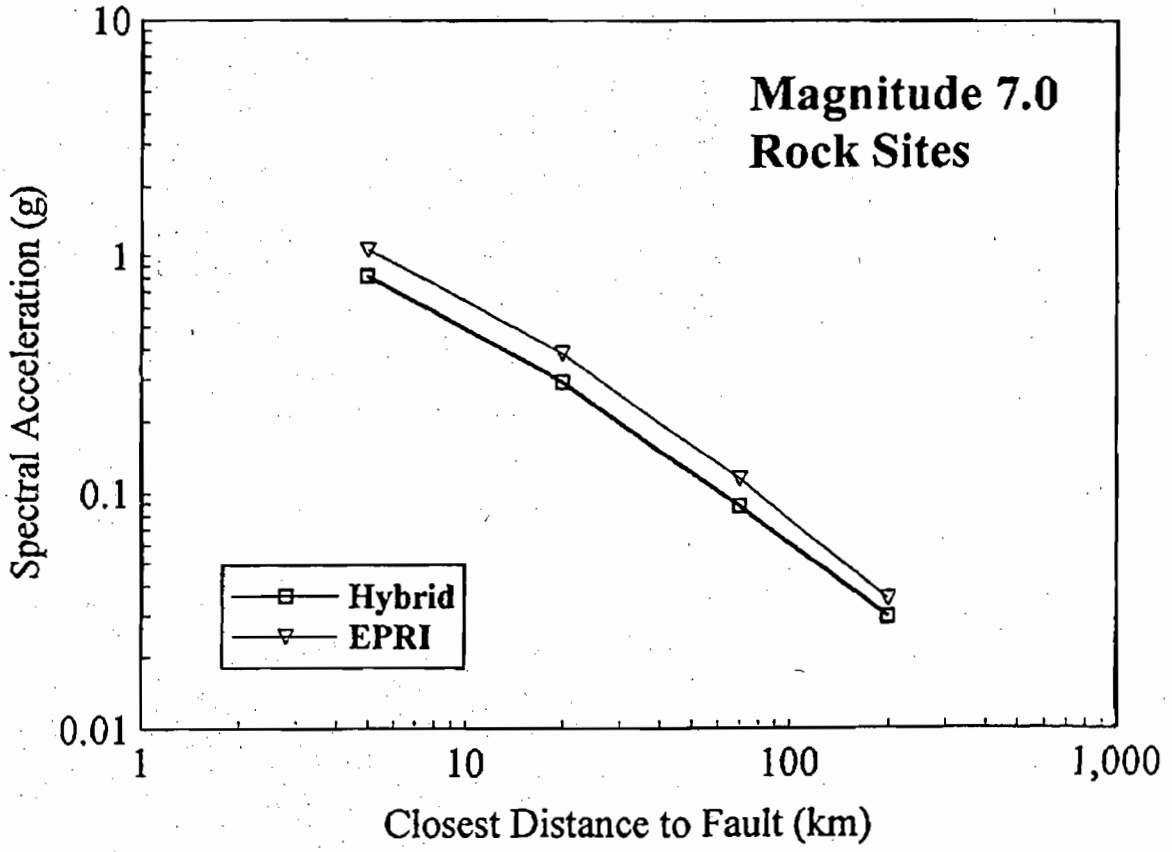

Peak Acceleration (PGA)
Magnitude 5.5
Rock Sites
Peak Acceleration (g)
1
0.1
0.01
0.001
1
10
100
1,000
Closest Distance to Fault (km)
Hybrid
EPRI

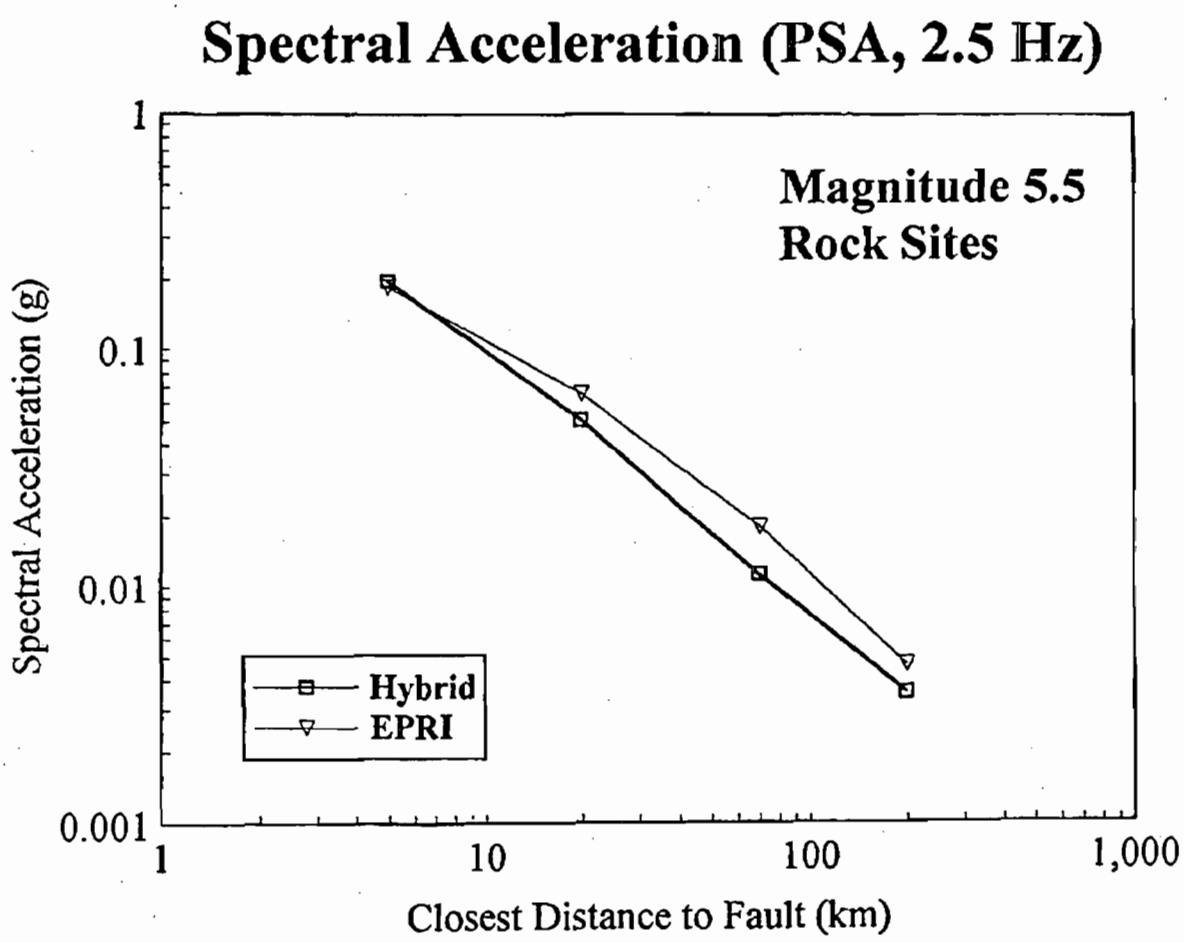
Peak Acceleration (PGA)




Spectral Acceleration (PSA, 1 Hz)
Magnitude 5.5
Rock Sites
Hybrid
EPRI
Spectral Acceleration (g)
0.1
0.01
0.001
0.0001
1
10
100
1,000
Closest Distance to Fault (km)

Spectral Acceleration (PSA, 1 Hz)




Spectral Acceleration (PSA, 2.5 Hz)
Magnitude 5.5
Rock Sites
Spectral Acceleration (g)
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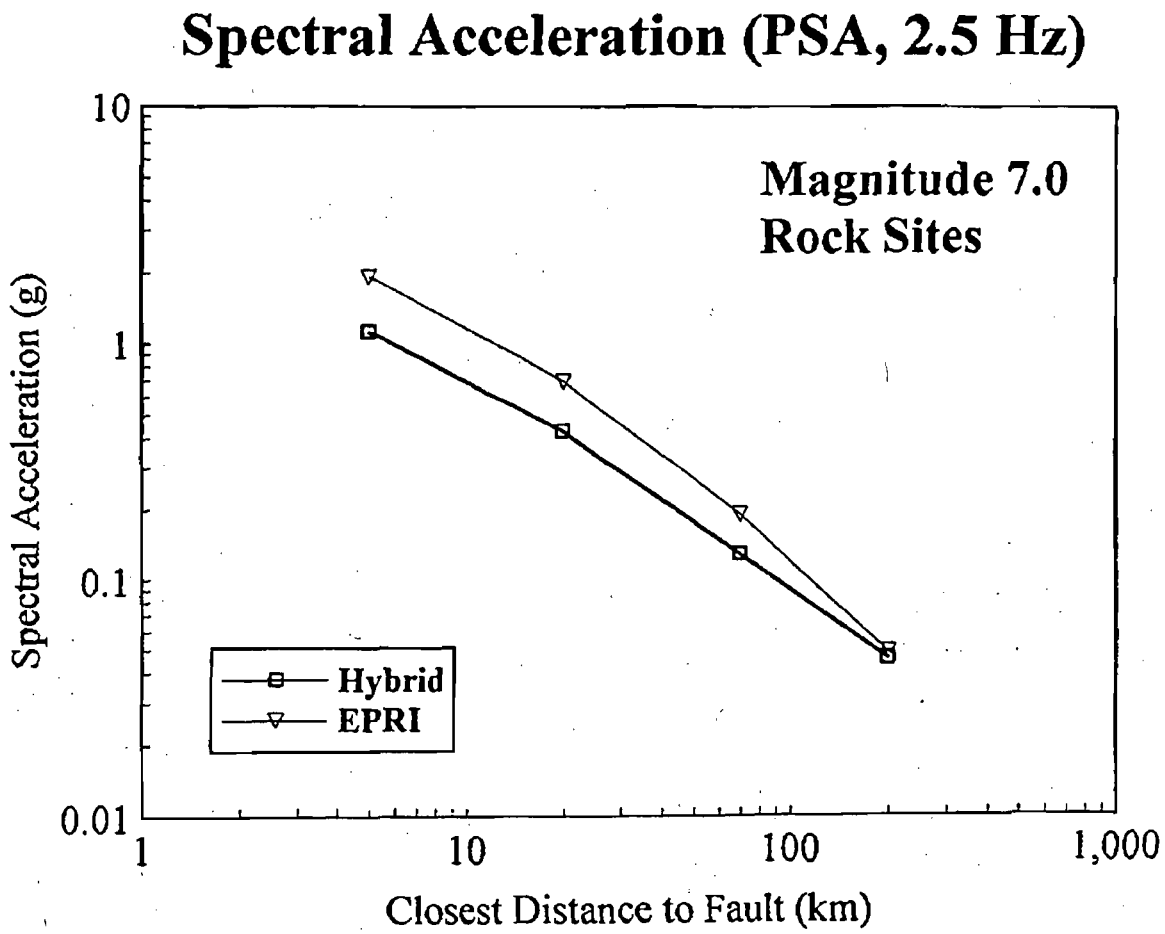
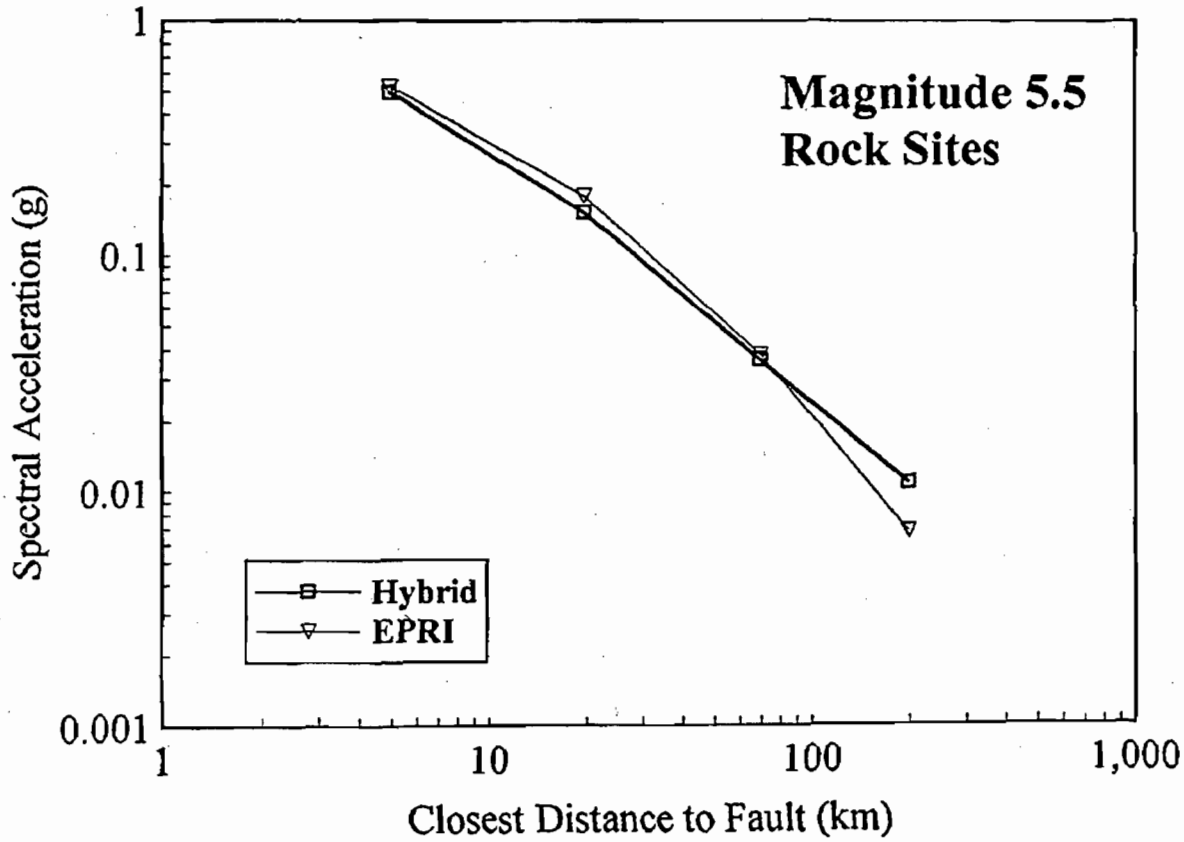
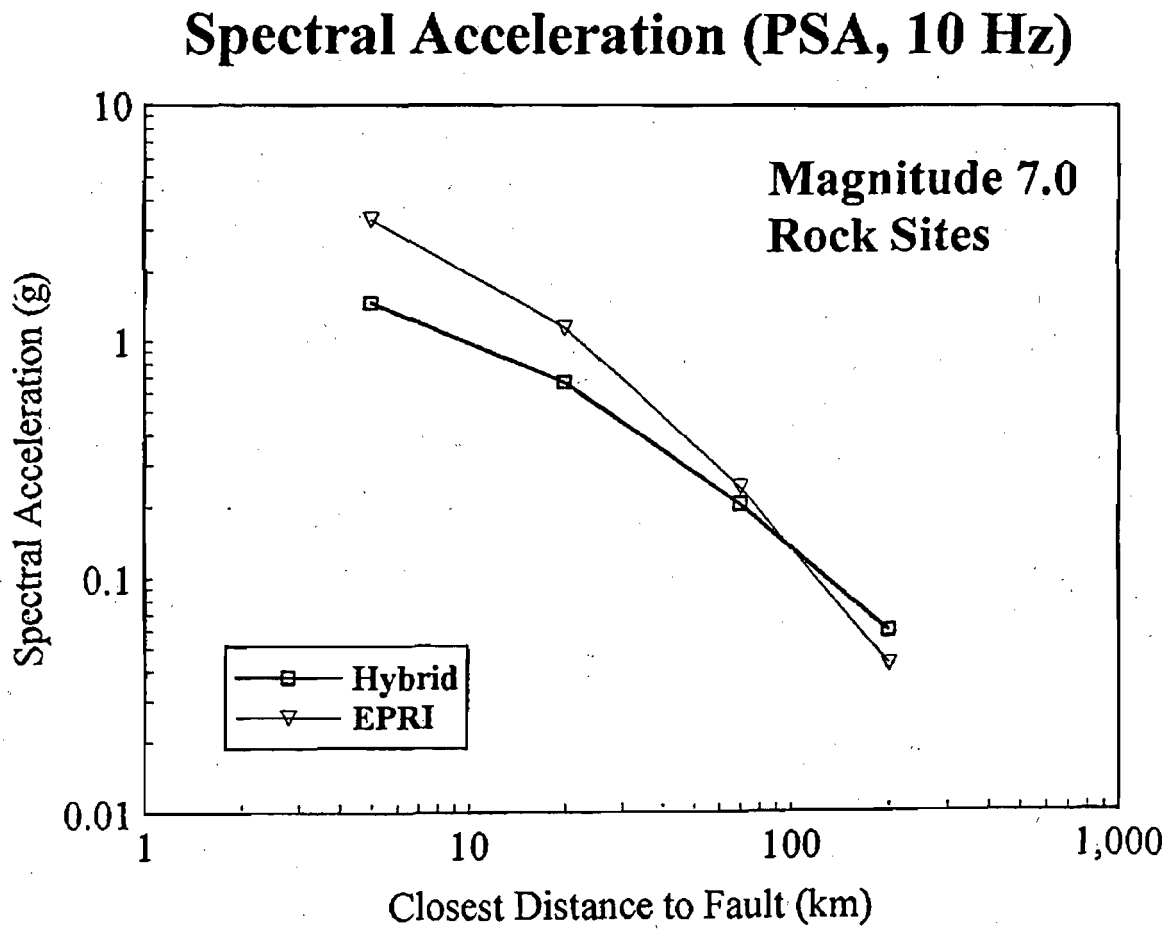
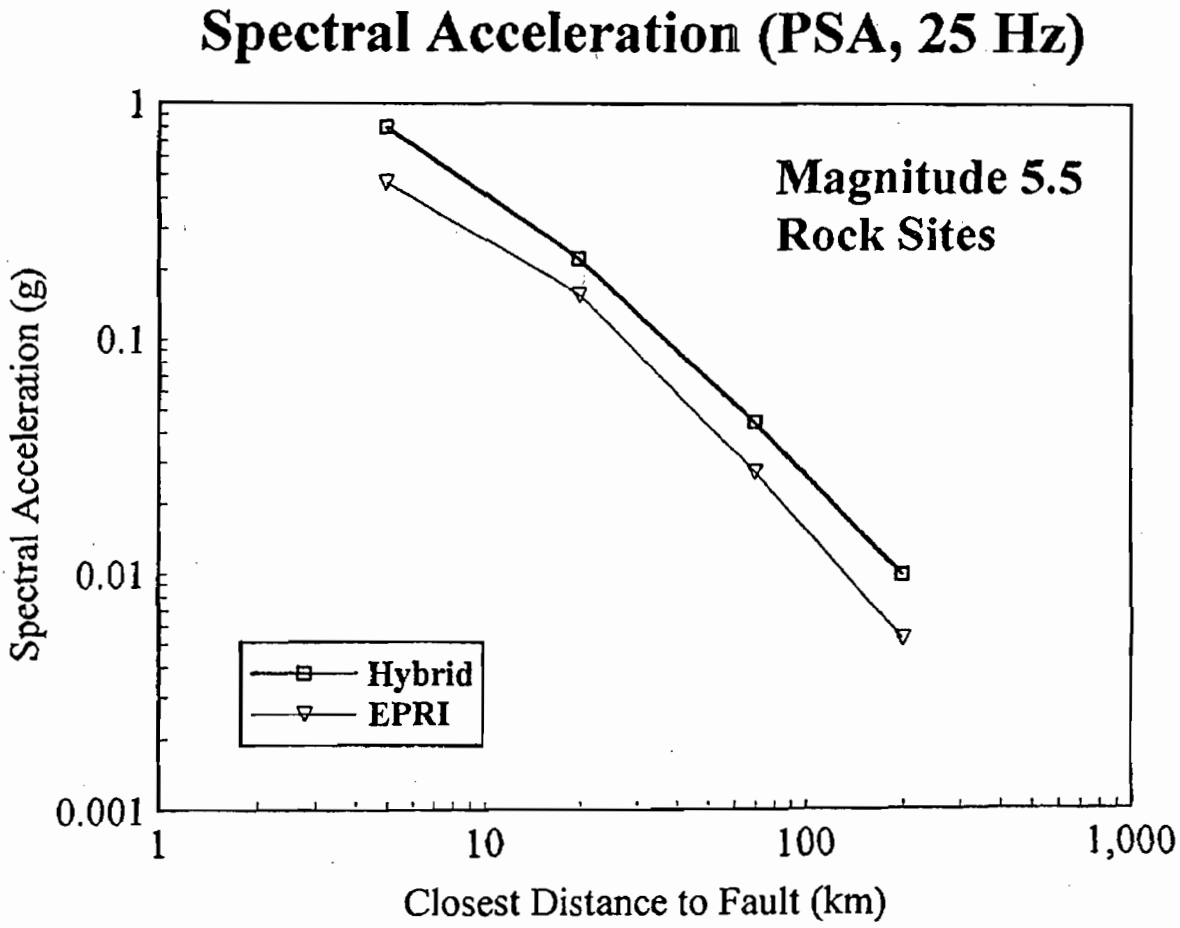
0.1
0.01
0.001
1
10
100
1,000
Closest Distance to Fault (km)
Hybrid
EPRI

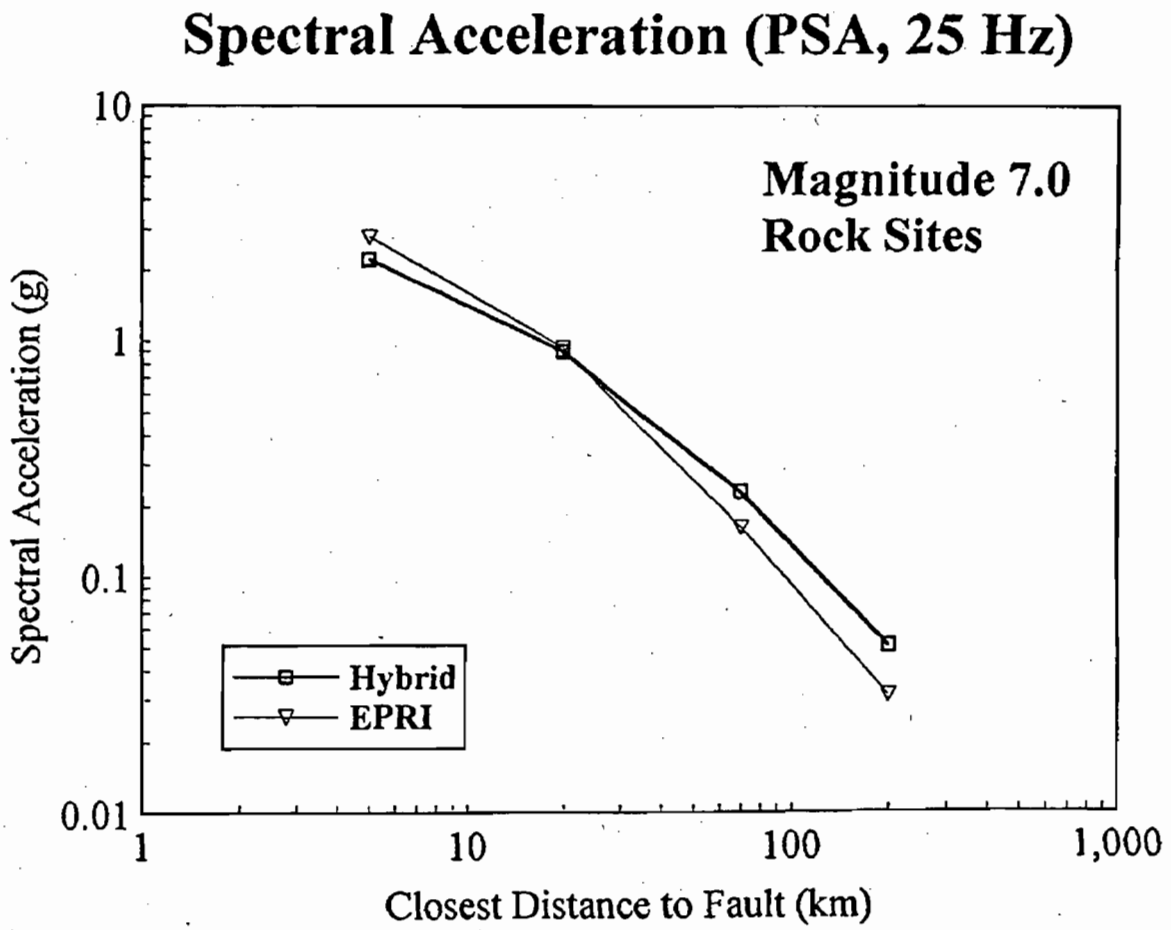

Spectral Acceleration (PSA, 2.5 Hz)
Magnitude 7.0
Rock Sites
Spectral Acceleration (g)
10
1
0.1
0.01
1
10
100
1,000
Closest Distance to Fault (km)
Hybrid
EPRI

Spectral Acceleration (PSA, 10 Hz)




Spectral Acceleration (PSA, 10 Hz)
Magnitude 7.0
Rock Sites
Hybrid
EPRI
Spectral Acceleration (g)
10
1
0.1
0.01
1
10
100
1,000
Closest Distance to Fault (km)


Spectral Acceleration (PSA, 25 Hz)
Magnitude 5.5
Rock Sites
Hybrid
EPRI
Spectral Acceleration (g)
1
0.1
0.01
0.001
1
10
100
1,000
Closest Distance to Fault (km)


Spectral Acceleration (PSA, 25 Hz)
Magnitude 7.0
Rock Sites
Hybrid
EPRI
Spectral Acceleration (g)
10
1
0.1
0.01
1
10
100
1,000
Closest Distance to Fault (km)

SSHAC SECOND GROUND-MOTION WORKSHOP

GROUND MOTION ESTIMATES AND DOCUMENTATION

by

Walter J. Silva
Pacific Engineering and Analysis
July 5, 1994

Proponent: WALT SILVA

Approach: EPRI 1993

Ground Motion Measure: 1-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.044 g	0.814 g
	epistemic uncertainty	parametric (ln)	0.14	0.47
		median bias	-0.4	-0.4
		uncert. in bias (ln)	0.2	0.2
	aleatory uncertainty	median σ	1.11	0.91
		uncertainty in σ	0.2	0.2
20 km	median amplitude		0.019 g	0.348 g
	epistemic uncertainty	parametric (ln)	0.14	0.47
		median bias	-0.4	-0.4
		uncert. in bias (ln)	0.2	0.2
	aleatory uncertainty	median σ	0.92	0.8
		uncertainty in σ	0.2	0.2
70 km	median amplitude		0.006 g	0.107 g
	epistemic uncertainty	parametric (ln)	0.14	0.47
		median bias	-0.4	-0.4
		uncert. in bias (ln)	0.2	0.2
	aleatory uncertainty	median σ	0.92	0.8
		uncertainty in σ	0.2	0.2
200 km	median amplitude		0.002 g	0.041 g
	epistemic uncertainty	parametric (ln)	0.14	0.47
		median bias	-0.4	-0.4
		uncert. in bias (ln)	0.2	0.2
	aleatory uncertainty	median σ	0.92	0.8
		uncertainty in σ	0.2	0.2

Comments/footnotes:

Proponent: WALT SILVA

Approach: EPRI, 1993

Ground Motion Measure: 2.5-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.056 g	0.667 g
	epistemic uncertainty	parametric (ln)	0.12	0.38
		median bias	-0.3	-0.3
		uncert. in bias (ln)	0.2	0.2
	aleatory uncertainty	median σ	0.74	0.64
		uncertainty in σ	0.2	0.2
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

Proponent: WALT SILVA

Approach: EPRI, 1993

Ground Motion Measure: 10-Hz Spectral Acceleration (g)

Distance	Quantity		m_{L_c} 5.5	m_{L_c} 7.0
5 km	median amplitude		0.443 g	2.801 g
	epistemic uncertainty	parametric (ln)	0.11	0.36
		median bias	-0.1	-0.1
		uncert. in bias (ln)	0.2	0.2
	aleatory uncertainty	median σ	0.77	0.69
		uncertainty in σ	0.2	0.2
20 km	median amplitude		0.176 g	1.116 g
	epistemic uncertainty	parametric (ln)	0.11	0.36
		median bias	-0.1	-0.1
		uncert. in bias (ln)	0.2	0.2
	aleatory uncertainty	median σ	0.61	0.51
		uncertainty in σ	0.2	0.2
70 km	median amplitude		0.039 g	0.248 g
	epistemic uncertainty	parametric (ln)	0.11	0.36
		median bias	-0.1	-0.1
		uncert. in bias (ln)	0.2	0.2
	aleatory uncertainty	median σ	0.61	0.51
		uncertainty in σ	0.2	0.2
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

Proponent: WALT SILVA

Approach: EPRI, 1993

Ground Motion Measure: 25-Hz Spectral Acceleration (g)

Distance	Quantity		m_{L_c} 5.5	m_{L_c} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.196	1.169
	epistemic uncertainty	parametric (ln)	0.11	0.36
		median bias	-0.1	-0.1
		uncert. in bias (ln)	0.2	0.2
	aleatory uncertainty	median σ	0.68	0.60
		uncertainty in σ	0.2	0.2
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

Proponent: WALT SILVA

Approach: EPRI, 1993

Ground Motion Measure: Peak Ground Acceleration (g)

Distance	Quantity		m_{L_g} 5.5	m_{L_g} 7.0
5 km	median amplitude		0.209 g	1.264 g
	epistemic uncertainty	parametric (ln)	0.11	0.36
		median bias	-0.1	-0.1
		uncert. in bias (ln)	0.2	0.2
	aleatory uncertainty	median σ	0.79	0.72
		uncertainty in σ	0.2	0.2
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude		0.016 g	0.099 g
	epistemic uncertainty	parametric (ln)	0.11	0.36
		median bias	-0.1	-0.1
		uncert. in bias (ln)	0.2	0.2
	aleatory uncertainty	median σ	0.62	0.52
		uncertainty in σ	0.2	0.2
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

INFLUENCE MATRIX, mblg = 5.5,7.5
ENA(see note)

1 Hz

	5(km)	20(km)	70(km)	200(km)
median depth	100	5	0	0
stress drop	60	60	60	60
kappa	1	1	1	1
crust	30	30	50	50

2.5 HZ

	5(km)	20(km)	70(km)	200(km)
median depth	100	5	0	0
stress drop	60	60	60	60
kappa	10	10	10	10
crust	30	30	50	50

10 HZ

	5(km)	20(km)	70(km)	200(km)
median depth	100	5	0	0
stress drop	60	60	60	60
kappa	30	30	30	30
crust	30	30	50	100

25 HZ(AND PGA, see table 1)

	5(km)	20(km)	70(km)	200(km)
median depth	100	5	0	0
stress drop	60	60	60	60
kappa	60	60	60	60
crust	30	30	50	100

note:Matrix values represent a maximum median % change in 5% damped spectral acceleration or pga values for a 100 % change in parameter median value. The difference between small and large magnitudes is much less than the uncertianities and is neglected.

Median Parameter Values(EPRI, 1993)
source depth = 10 km
stress drop = 120 bars
kappa = 0.006 sec
crust = Midcontinent

Stress drop: Source of influence is Figure 1

Kappa: These influence values depend strongly on the median kappa value. If the median kappa value doubles the effect of kappa approximately doubles. See Figure 2.

Crust: For the crust a 100% change would represent a substantially different structure as represented, for example, by the Gulf Coast structure where large differences exist in shallow velocities which affect amplification at 1 Hz and above and in Q(f) which affects higher frequnecies and at large distances. The maximum median effect refers to the average result after considering variation in structure(velocity and Q) and in source depth. After considering reasonable variation the effects of post critical reflections become rather subtle and is reflected in the smooth increase in crustal influence with distance. This effect is also seen in the EPRI(1993) attenuation curves for the Midcontinent and Gulf Coast structres.

PROPONENT: Walt Silva

Approach: EPRI(1993), stochastic point-source model

Epistemic Parametric: Eq. 9-3
Median Bias: Figure 3-6a
Uncertainty in Bias: Figure 3-6a 90% limit

Aletory Uncertainty: Eq. 9-3
Uncertainty of Uncertainty: Taken from range in standard errors of several empirical attenuation relations.

Strength of Approach
1) Accurate: comparable modeling variability and bias compared to more computationally rigorous approaches,
2) Simplicity: minimum of free parameters results in simplest physically plausable model and therefore more robust than more sophisticated models with a larger number of parameters and associated uncertainities to constrain,
3) Controlling parameters can be determined from small earthquakes,
4) Computationally attractive: easily able to generate the large number of synthetic data required to accomodate parametric uncertainities(anyone can code and run the model),
5) Transparency: simplicity of model allows easy assessment(by examining equations) of parametric effects. An important consideration in a regulatory environment. Simplicity is appealing to regulators as parameters (sources of uncertainty) can't be hidden. This results in a greater confidence in validation exercises.

Weakness of Approach
1) Point-source: Neglects saturation effects due to source finiteness.
2) Wave propagation: Uses asymptotic ray theory which is strickly correct at high frequencies.

Applicability
The approach is applicable to the prescribed conditions.

Site conditions
The prescribed site conditions(vs=2800 m/s over top 30 m, k=0.006 sec) represent very hard rock and consequently minimize site effects (except at 25hz where a 100% increase in kappa decreases ground motions by about 60%). These conditions may not represent average rock sites in the larger CEUS. Table 2 lists velocities averaged over 30m at nuclear power stations located in the CEUS and founded on rock. The average is closer to 2000 m/sec(6000 ft/sec) which, according to Figure 2, might be associated with a kappa value of about 0.01 sec. For such sites kappa would have a much greater influence.

From the influence matrix, the maximum average parametric effect is 100% and from Figure 3 the average soil site effect can exceed 100%(factor of 2). Site variability is a significant factor in the variability of strong ground motions. At rock sites, for higher kappa values() 0.006 sec), the shallow velocities are lower(Figure 4) resulting in amplification. At rock sites the same process exists as at soil sites: amplification due to a velocity gradient and deamplification due to damping(material and scattering). The result is a large component of variability. If SSHAC does not consider site effects it is difficult to see how variability can be addressed to a more refined extent than in the EPRI work. The significant aspect of the EPRI analysis of variability is that the variability is dominated by randomness (aletory).The epistemic variability is small suggesting that we have confidence in our models. The shortcoming in the EPRI study is that it did not include an analysis of uncertainty of site effects in the context of the total model. It seems to me that a reasonably definitive assessment of variability and its partition into aletory and epistemic parts awaits resolution

of the uncertainity associated with site effects. I do believe that the total uncertainty arrived at in the EPRI study is probably about right. The site part is buried somewhere and we need to dig it out.

Other regions within CEUS
Following EPRI only the Gulf Coast region would have significantly different motions than the rest of the
CEUS(EPRI Midcontinent model). The motion for the Gulf Coast are larger in close due to the lower velocity
in the shallow crust but crossover at distance due to the lower Q(f).

TABLE 1

MOMENT MAGNITUDE, CORNER FREQUENCY, PEAK ACCELERATION, AND PEAK PARTICLE VELOCITY AT R = 10 KM FOR STANDARD WNA AND ENA PARAMETERS

WNA

M	f_C (Hz)	A_P (g)	f_P** (Hz)	V_P (cm/s)	f_P (Hz)	V_P/A_P (cm/s/g)
2.5	17.594	0.003	15.03	0.05	9.93	15.73
3.5	5.563	0.020	10.47	0.43	6.37	21.46
4.5	1.759	0.072	7.84	2.50	3.91	34.80
5.5	0.556	0.178	6.86	9.73	2.45	54.52
6.5	0.176	0.378	6.56	32.17	1.55	85.00
7.5	0.056	0.756	6.48	87.95	1.13	116.40

ENA

M	f_C (Hz)	A_P (g)	f_P (Hz)	V_P (cm/s)	f_P** (Hz)	V_P/A_P (cm/s/g)
2.5	19.244	0.017	38.70	0.09	25.54	5.49
3.5	6.084	0.055	31.15	0.51	14.55	9.28
4.5	1.924	0.133	27.43	2.17	7.92	16.37
5.5	0.608	0.283	25.98	8.22	4.32	29.07
6.5	0.192	0.567	25.47	28.63	2.44	50.46
7.5	0.061	1.104	25.32	81.76	1.67	74.03

**Predominant frequencies estimated from random process theory

NUCLEAR POWER PLANT ROCK SITE VELOCITIES
AVERAGES OVER 100 FT OF ROCK

Plant	S-wave Velocity (fps)	P-wave Velocity (fps)
Arkansas	5350	12250
Bellefonte	9227	17584
Braidwood	3583	7930
Byron	4138	10531
Catawba	5910	10140
Comanche Peak	5940	10820
Davis-Besse	6700	12700
Dresden	4817	8122
Fermi	6634	12160
Ginna	7200	12800
Haddam Neck	----	12500
Limerick	5950	12500
Yankee	7000	14000
McGuire	7200	12044
Millstone	6500	13267
Nine Mile Pt	7000	14000
North Anna	5750	14500
Oconee	----	9669
Peach Bottom	----	11500
Perry	4450	9700
Quad Cities	6300	10400
Seabrook	9000	16455
Sequoyah	6860	13019
Shearon Harris	5352	11480
Summer	7120	14750
Susquehanna	6363	13253
Three Mile Island	----	9750
Vermont Yankee	6500	13500
Watts Bar	6285	11406
Average	6285.16	12163.10

$$\frac{\overline{Vp}}{\overline{Vs}} = 1.935$$

$$\sigma = 0.318$$

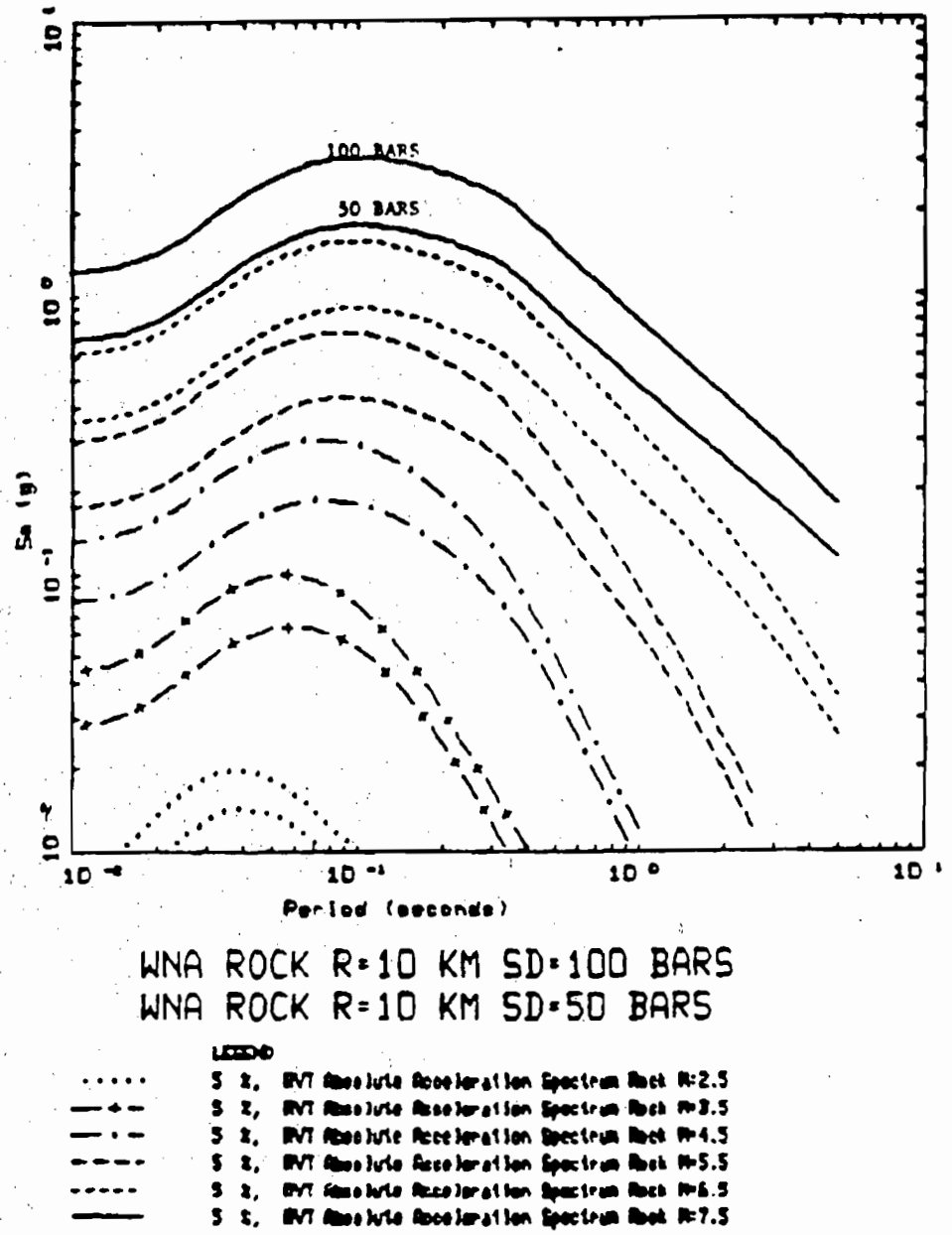
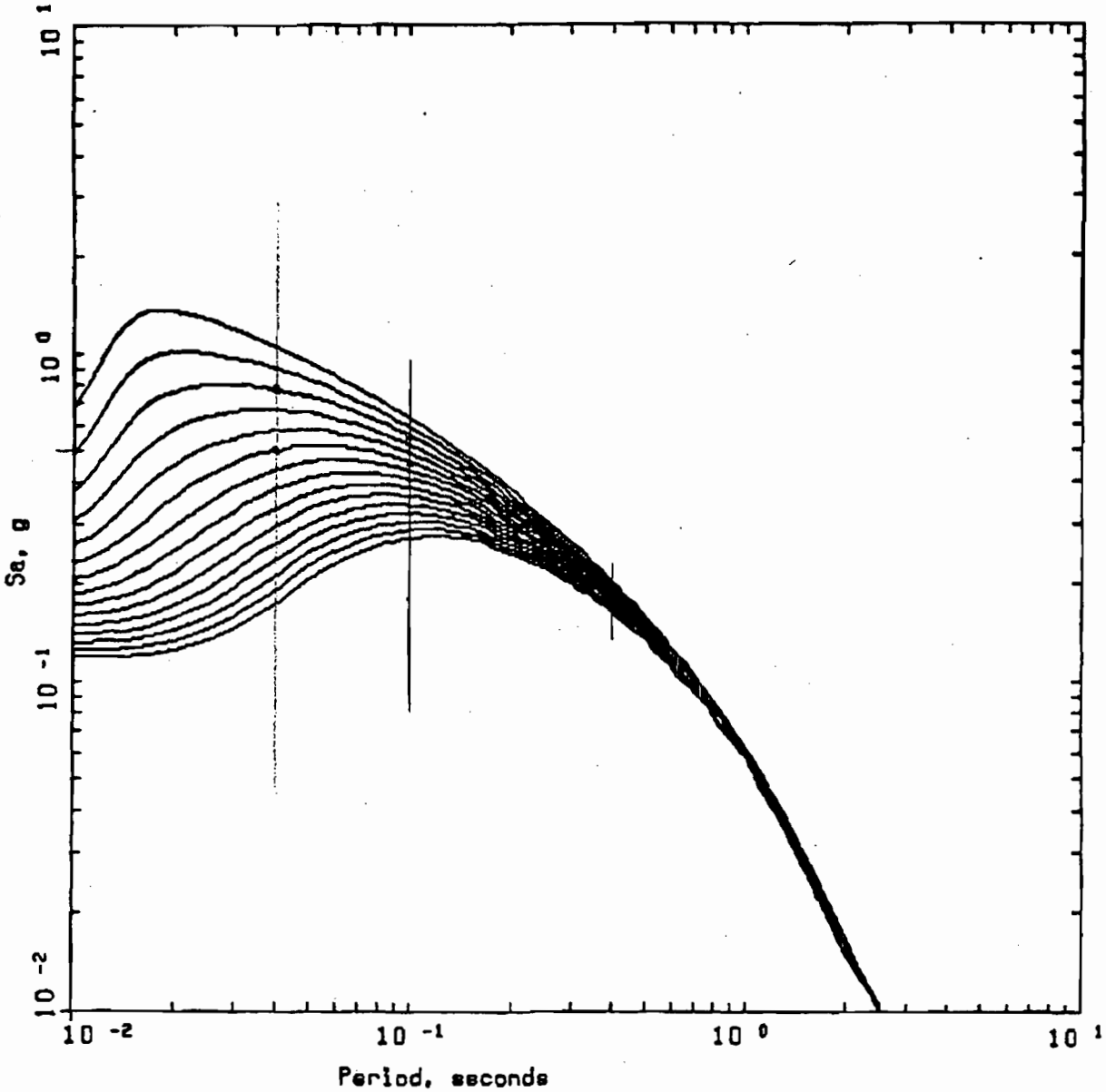


Figure 1. Comparisoin of 5% absolute acceleration response spectra (Sa) computed for WNA parameters (Table 2) for stress parameters of 50 and 100 bars.



ENA ROCK R=10 KM Mw=5.5
FILTER=75.0Hz (5) 10 SEC (5)

LEGEND

RASCALS:RVT Spectrum Rock M=5.5 KAPPA=0.002 SEC
RASCALS:RVT Spectrum Rock M=5.5 KAPPA=0.004 SEC
RASCALS:RVT Spectrum Rock M=5.5 KAPPA=0.006 SEC
RASCALS:RVT Spectrum Rock M=5.5 KAPPA=0.008 SEC
RASCALS:RVT Spectrum Rock M=5.5 KAPPA=0.010 SEC
RASCALS:RVT Spectrum Rock M=5.5 KAPPA=0.012 SEC
RASCALS:RVT Spectrum Rock M=5.5 KAPPA=0.014 SEC
RASCALS:RVT Spectrum Rock M=5.5 KAPPA=0.016 SEC
RASCALS:RVT Spectrum Rock M=5.5 KAPPA=0.018 SEC
RASCALS:RVT Spectrum Rock M=5.5 KAPPA=0.020 SEC
RASCALS:RVT Spectrum Rock M=5.5 KAPPA=0.022 SEC
RASCALS:RVT Spectrum Rock M=5.5 KAPPA=0.024 SEC
RASCALS:RVT Spectrum Rock M=5.5 KAPPA=0.026 SEC
RASCALS:RVT Spectrum Rock M=5.5 KAPPA=0.028 SEC
RASCALS:RVT Spectrum Rock M=5.5 KAPPA=0.030 SEC

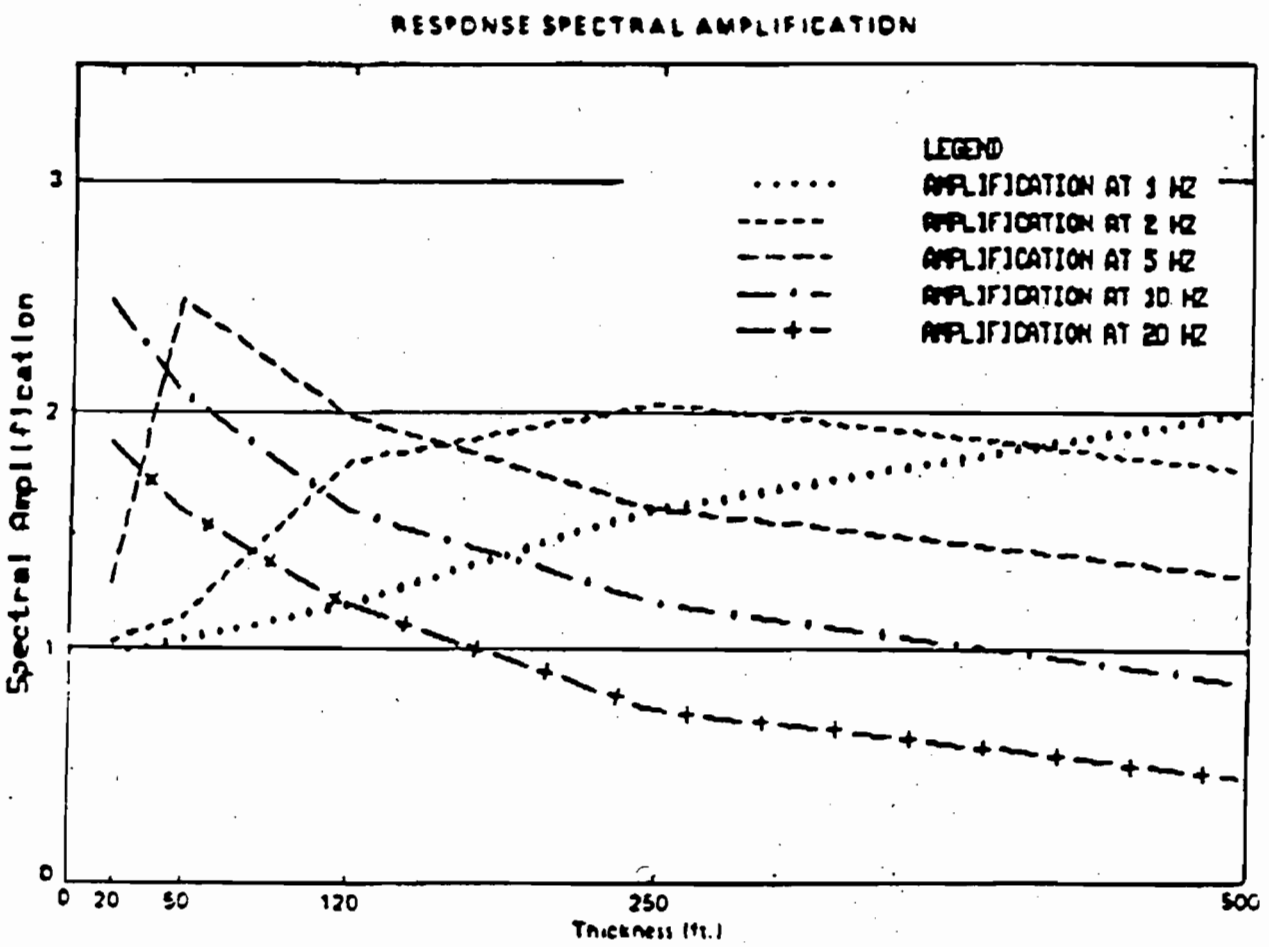
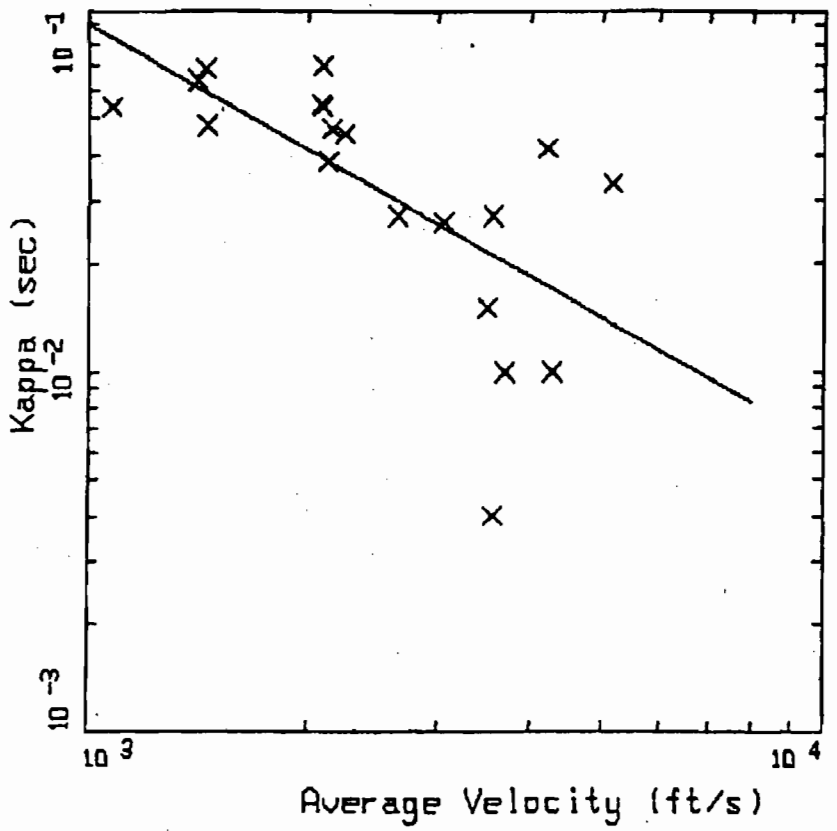


Figure3 . Plot of computed 5% response spectral amplification factors for five site categories (Figure 22) for a 0.5 g level of input (rock outcrop) motion. Curves represent frequencies of 1, 2, 5, 10 and 20 Hz.



ROCK SITES (WNA)

KAPPA VS AVERAGE (OVER 100 FT) VELOCITY

LEGEND

× DATA

——— LOG(KAPPA) = 2.40939 - 1.15099 * LOG(VELOCITY IN FT/S)

SSHAC SECOND GROUND MOTION WORKSHOP

Menlo Park July 28-29 1994

DOCUMENTATION OF GROUND MOTION ESTIMATES

Prepared June 29, 1994

PROPONENTS: Paul Somerville and Chandan Saikia, Woodward-Clyde

APPROACH: Advanced Numerical Modeling

PART 1. METHOD

The advanced numerical modeling method is described in Appendix 1, which is taken from Section 3.3 of EPRI Report TR-102293-V1. The method, termed the semi-empirical ground motion model in that report, is described in Section 3.3.1, and its validation against recorded data is described in Section 3.3.2. The modeling variability and bias derived from the validation are described in Part 2.2, and Parts 3.2 and 3.3 of this documentation, respectively.

PART 2. PROCEDURE FOR ESTIMATION OF ALEATORY UNCERTAINTY

2.1 ALEATORY PARAMETRIC UNCERTAINTY

The base case parameters and their assumed distributions used in the estimation of aleatory parametric uncertainty are summarized in the tables in Appendix 2.

2.1.1. Crustal Structure and Focal Depth

Crustal structure and focal depth are treated together because they are coupled.

Depth distribution: median 11 km; 0.5 sigma lognormal

We assume equal weighting of four different crustal structures within the Northern Grenville - Superior region, shown in Figure 5-23 of EPRI Report TR-102293-V1 which is reproduced in Appendix 2 as Figure 2.1.

Resulting uncertainty in ground motions: Standard error is distance and frequency dependent, as given by the Grenville curves in EPRI Report TR-102293-V1 Figure 5-27, reproduced in Appendix 2 as Figures 2.2 through 2.4. For 1 Hz, the standard errors for 10, 20, 70 and 200 km distance are 0.30, 0.24, 0.35, and 0.38 respectively. For higher frequencies, the corresponding standard errors are 0.30, 0.24, 0.44, and 0.24 respectively.

2.1.2 Stress Drop

The stress drop is used solely to fix the fault rupture area for a given seismic moment. The median value, estimated from the source duration of 14 ENA events (updated from Somerville et al., 1987), is 100 bars. The standard error in $\log_e$stress drop derived from the estimated rupture areas and seismic moments of twelve crustal events is 0.7 (Somerville and Abrahamson, 1991); this relationship is shown in Appendix 2, Figure 2.5. We use this value of 0.7 to represent the variability in $\log_e$stress drop due to variability in rupture area.

Uncertainty in ground motions due to 0.70 uncertainty in $\log_e$stress drop = 0.28; this does not have significant distance and period dependence, as shown in Appendix 2, Figure 2.6.

2.1.3. Seismic Moment M_o

In our model, earthquake size is specified by seismic moment M_o, so we need to convert from m_{blg} to M_o. We use a relation between $\log_{10}M_o$ and m_{blg} based on 13 ENA events updated from Somerville et al., 1987, shown in Appendix 2, Figure 2.7, where data are well modeled by a linear relation:

$$\text{Log}_{10} M_o = 1.2\ m_{blg} + 17.2$$

standard error of $\log_e M_o$ = 0.26
standard error of mean of $\log_e M_o$ = 0.07

Uncertainty in ground motions due to 0.26 uncertainty in $\log_e$Mo: 0.11 (1 Hz); 0.09 (other periods). This should be removed from aleatory uncertainty when predicting ground motions from seismic moment M_o or moment magnitude M_w. Note that:

m_{blg} of 7.0 corresponds to M_o of 4.0×10^{25} dyne-cm and M_w of 6.4
m_{blg} of 5.5 corresponds to M_o of 6.3×10^{23} dyne-cm and M_w of 5.2

There is no significant correlation evident in the relationship between the m_{blg} residuals from this relationship and stress drop, as indicated in Appendix 2, Figure 2.8. This means that we cannot offset this additional source of aleatory uncertainty.

2.1.4. Q_o

The median value of Q_o is taken to be 750, and its uncertainty is assumed to be lognormal with a standard error of 0.4 The effects of this uncertainty are both distance and frequency dependent.

2.1.5. Kappa

The median value of kappa is taken to be 0.006 sec, and its uncertainty is assumed to be lognormal with a standard error of 0.4 The effects of this uncertainty are frequency dependent.

2.1.6. Other source parameters

Variability in source parameters other than stress drop, seismic moment and focal depth considered above contribute to variability in estimated ground motions. One of these is focal mechanism, but we expect most earthquakes in the northeastern United States and southeastern Canada to have thrust mechanisms (Somerville et al., 1987), so variation in focal mechanism may not have a large effect. Other causes of variability in source effects include the distribution of slip on the fault surface, and the location of the hypocenter on the fault surface. The uncertainty in ground motions due to variations in these source parameters is estimated to be 0.20, independent of distance and period.

2.1.7. Overall Aleatory Parametric Uncertainty

Overall aleatory parametric uncertainty is calculated by combining the above six components.

2.2. MODELING UNCERTAINTY

The modeling uncertainty is derived from the standard error in goodness of fit between recorded and simulated acceleration time histories, as described in EPRI Report TR-102293-V1, Ch. 3. Section 3.3.2. The modeling uncertainty is documented in Section 3.3.3 and shown in Figure 3-15b, which is reproduced in Appendix 2, Figure 2.9. The standard error is period dependent but not distance dependent.

2.3. OVERALL ALEATORY UNCERTAINTY

This is calculated by combining the parametric uncertainty and the modeling uncertainty following the procedure of Abrahamson et al. (1990).

2.4. EPISTEMIC UNCERTAINTY IN OVERALL ALEATORY UNCERTAINTY

This is estimated to be 0.1 based on judgment.

PART 3. PROCEDURE FOR ESTIMATION OF EPISTEMIC UNCERTAINTY

3.1. EPISTEMIC PARAMETRIC UNCERTAINTY

3.1.1. Stress drop

Standard error of mean of $\log_e$stress drop derived from rupture area = 0.2

Effect on ground motion amplitudes = 0.08 (1 Hz); 0.07 (other frequencies)

3.1.2. Seismic Moment

Standard error of mean of $\log_e$ seismic moment for a given m_{blg} = 0.07

Effect on ground motion amplitudes = 0.10 (1 Hz); 0.08 (other frequencies)

3.1.3. Overall Parametric Uncertainty

Esttimated by combining the effect of stress drop and seismic moment: 0.13 (1 Hz); 0.10 (other frequencies)

3.2. MEDIAN BIAS

Derived from bias in goodness of fit between recorded and simulated acceleration time histories for a total of 39 recordings of the Loma Prieta, Whittier Narrows, Nahanni and Saguenay earthquakes. This is documented in EPRI, Report TR-102293-V1, Ch. 3. Section 3.3.3, and illustrated in figure 3-15a which is reproduced in Appendix 3 as Figure 3.1. The bias is not significantly different from zero for frequencies of 2.5, 10, 25Hz and pga. An underprediction by 20% was removed from the predicted motions for 1 Hz, so the bias for all frequencies is reported to be zero.

3.3. UNCERTAINTY IN MEDIAN BIAS

The uncertainty in the median bias is derived from the 90% confidence intervals shown in Figure 3.1 of Appendix 3. It ranges from 0.18 at 1 Hz to 0.12 for pga.

PART 4. DISCUSSION

4.1 STRENGTHS

The advanced numerical modeling method that we use for strong motion prediction is based on standard time-domain methods for estimating earthquake source parameters and analyzing seismic wave propagation. It can therefore be readily applied using standard parameterizations of the earthquake source and crustal structure. The method can be made broadband by the incorporation of long-period contributions using synthetic seismograms, which makes it accurate from very long periods (including DC) to high frequencies.

The advanced numerical modeling method has a large potential for development because the new broadband stations of the National Seismic Network provide data that allow us to significantly improve our source and wave propagation models for eastern North America.

The advanced numerical modeling method has been extensively validated against strong motion data from California, and has been validated against most of the available data from eastern North America.

In the advanced numerical modeling method, the attenuation function is determined by the crustal structure and the source depth using standard wave propagation models. It has predictive power in many locations in eastern North America where knowledge of crustal structure and source depth is available but no strong ground motion data exist.

The Green's functions used by the method need only be calculated once for a given crustal structure. They can then be archived on the INTERNET for use by multiple investigators in ground motion modeling and seismic source inversion.

4.2 WEAKNESSES

Green's functions could but currently do not include scattering and the effects of local non-planar structure, which may be important at high frequencies.

The methodology for including scattering is to represent it in the empirical source functions that we use, which we do not correct for scattering effects. At present, we do not have a large number of strong motion recordings from which to derive empirical source functions. Instead, we use empirical source functions from western North American events with kappa corrections. The scattering conditions represented by these may not be optimal for eastern North America.

4.3 APPLICABILITY TO MAGNITUDE/DISTANCE/FREQUENCY RANGES

The Advanced Numerical Modeling method is applicable for all of the combinations of the magnitude, distance and frequency values specified in the Instructions to Proponents.

4.4 REPRESENTATIVENESS OF HARD ROCK SITE

The hard rock site (2.8 km/sec average shear wave velocity over the top 30 m) is probably representative of unweathered crystalline rock sites in the northeastern United States and southeastern Canada. It may not be representative of sedimentary rock sites in the Central and Eastern United States.

4.5 HOW RESULTS WOULD DIFFER IN OTHER REGIONS WITHIN CEUS

The ground motion estimates presented here are for the northeastern United States or southeastern Canada (region 10 in our regionalization of crustal structure) as requested in the instructions for proponents. The variability of median ground motions (5 Hz response spectral acceleration at 5% damping) for a moment magnitude 6.5 earthquake calculated using the crustal structure models for all 16 regions of eastern North America is illustrated in Figure 5-46 from EPRI TR-102293-V1, which is reproduced as Figure 4.1 in Appendix 4. The intra-region variability about the median ground motions due to uncertainty in crustal structure may be different in different regions. This is illustrated in Figures 2.2 through 2.4 in Appendix 2, where the intra-region variability for the Grenville and New Madrid regions are compared. The variability in the Grenville region is largest for distances around 100 km and is produced by variability in the depth of the Moho. In contrast, the variability in the New Madrid region is largest for distances around 60 km, and is produced by variability in the depth of the Conrad.

PART 5. BIBLIOGRAPHY

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PART 6. ESTIMATES OF MEDIAN AND UNCERTAINTIES

Estimates of median ground motion values and their uncertainties are given in Tables 1 through 5 that follow. Explicit calculations have been done for uncertainties in the ground motion estimates for $m_{blg} = 7$. While complete explicit calculations have not been done for the uncertainties for $m_{blg} = 5.5$, all of the available calculations indicate that to a first approximation the uncertainties for these two magnitudes can be assumed to be equal.

Estimates for a closest distance of 5 km are not available. In their place, estimates for a closest distance of 12 km are given.

The breakdown of the aleatory uncertainty into parametric and modeling components, and the breakdown of the parametric component into contributions from individual model parameters, is given in Tables 1S through 5S that follow.

The reported aleatory uncertainty is for predicting ground motions given an earthquake size expressed as m_{blg}. The uncertainty due to seismic moment should be removed from the aleatory uncertainty when predicting ground motions from seismic moment M_o or moment magnitude M_w.

Proponent: Somerville / Saikia

Approach: Advanced Numerical Modeling

Ground Motion Measure: 1-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
12 ~~8~~ km	median amplitude		0.034	0.20
	epistemic uncertainty	parametric (ln)	*	0.13
		median bias	*	0
		uncert. in bias (ln)	*	0.18
	aleatory uncertainty	median σ	*	0.81
		uncertainty in σ	*	0.1
20 km	median amplitude		0.017	0.10
	epistemic uncertainty	parametric (ln)	*	0.13
		median bias	*	0
		uncert. in bias (ln)	*	0.18
	aleatory uncertainty	median σ	*	0.79
		uncertainty in σ	*	0.1
70 km	median amplitude		0.003	0.025
	epistemic uncertainty	parametric (ln)	*	0.13
		median bias	*	0
		uncert. in bias (ln)	*	0.18
	aleatory uncertainty	median σ	*	0.84
		uncertainty in σ	*	0.1
200 km	median amplitude		0.001	0.004
	epistemic uncertainty	parametric (ln)	*	0.13
		median bias	*	0
		uncert. in bias (ln)	*	0.18
	aleatory uncertainty	median σ	*	0.85
		uncertainty in σ	*	0.1

Comments/footnotes:

* assumed to be the same as for mLg 7.0

Proponent: Somerville / Saikia

Approach: Advanced Numerical Modeling

Ground Motion Measure: 2.5-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.07	0.32
	epistemic uncertainty	parametric (ln)	*	0.10
		median bias	*	0
		uncert. in bias (ln)	*	0.18
	aleatory uncertainty	median σ	*	0.82
		uncertainty in σ	*	0.1
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

* assumed to be the same as for m_{Lg} 7.0

Proponent: Somerville/Saikia

Approach: Advanced Numerical Modeling

Ground Motion Measure: 10-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
12 km	median amplitude		0.23	1.10
	epistemic uncertainty	parametric (ln)	*	0.10
		median bias	*	0
		uncert. in bias (ln)	*	0.14
	aleatory uncertainty	median σ	*	0.68
		uncertainty in σ	*	0.1
20 km	median amplitude		0.14	0.60
	epistemic uncertainty	parametric (ln)	*	0.10
		median bias	*	0
		uncert. in bias (ln)	*	0.14
	aleatory uncertainty	median σ	*	0.66
		uncertainty in σ	*	0.1
70 km	median amplitude		0.017	0.18
	epistemic uncertainty	parametric (ln)	*	0.10
		median bias	*	0
		uncert. in bias (ln)	*	0.14
	aleatory uncertainty	median σ	*	0.76
		uncertainty in σ	*	0.1
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

* assumed to be the same as for m_{Lg} 7.0

Proponent: Somerville / Saikia

Approach: Advanced Numerical Modeling

Ground Motion Measure: 25-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.13	1.1
	epistemic uncertainty	parametric (ln)	*	0.10
		median bias	*	0
		uncert. in bias (ln)	*	0.12
	aleatory uncertainty	median σ	*	0.64
		uncertainty in σ	*	0.1
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

* assumed to be the same as for m_{Lg} 7.0

Proponent: Somerville / Saikia

Approach: Advanced Numerical Modeling

Ground Motion Measure: Peak Ground Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
12 ~~X~~ km	median amplitude		0.13	0.71
	epistemic uncertainty	parametric (ln)	*	0.10
		median bias	*	0
		uncert. in bias (ln)	*	0.12
	aleatory uncertainty	median σ	*	0.64
		uncertainty in σ	*	0.1
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude		0.01	0.10
	epistemic uncertainty	parametric (ln)	*	0.10
		median bias	*	0
		uncert. in bias (ln)	*	0.12
	aleatory uncertainty	median σ	*	0.73
		uncertainty in σ	*	0.1
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

* assumed to be the same as for m_{Lg} 7.0

PART 7. PARAMETRIC SENSITIVITY RESULTS

The ground motion sensitivities to three model parameters: focal depth and crustal structure; stress drop; and seismic moment are listed on Forms 1S through 5S that follow. All are expressed as the standard error of the natural logarithm of the ground motion parameter corresponding to the standard error in the model parameter. Explicit calculations have been done for $m_{blg} = 7$. While complete explicit calculations have not been done for $m_{blg} = 5.5$, all of the available calculations indicate that to a first approximation the sensitivies for these two magnitudes can be assumed to be equal.

Estimates for a closest distance of 5 km are not available. In their place, estimates for a closest distance of 12 km are given.

In the Comments/footnotes section, we show calculations of the total aleatory uncertainty including the sensitivities given above. The subtotal of parametric uncertainty for the three listed parameters is shown first, followed by that due to Qo and Kappa and that estimated for other source parameters. These are then combined to give total parametric uncertainty. This is combined in turn with the modeling uncertainty to yield the total aleatory uncertainty, which is reported on Forms 1 through 5.

The reported total aleatory uncertainty is for predicting ground motions given an earthquake size expressed as m_{blg}. The uncertainty due to seismic moment should be removed from the aleatory uncertainty when predicting ground motions from seismic moment M_o or moment magnitude M_w.

Proponent: Somerville / Saikia

Approach: Advanced Numerical Modeling

Sensitivity Results: Ground Motion Measure: 1-Hz Spectral Acceleration (g)

Distance	Quantity	m_{Lg} 5.5	m_{Lg} 7.0
12 ~~8~~ km	Focal Depth + Crustal Struct.	*	0.30
	Stress Drop	*	0.28
	Seismic Moment	*	0.11
20 km		*	0.24
	"	*	0.28
		*	0.11
70 km		*	0.35
	"	*	0.28
		*	0.11
200 km		*	0.38
	"	*	0.28
		*	0.11

Comments/footnotes:

Subtotal – parametric	0.42	0.38	0.46	0.48
Q_0 and K	0.01	0.01	0.03	0.10
other parametric	0.20	0.20	0.20	0.20
Total Parametric	0.47	0.43	0.50	0.53
Modeling	0.67	0.67	0.67	0.67
Total Aleatory	0.81	0.79	0.84	0.85

* assumed to be the same as for m_{Lg} 7.0

Proponent: Somerville / Saikia

Approach: Advanced Numerical Modeling

Sensitivity Results: Ground Motion Measure: 2.5-Hz Spectral Acceleration (g)

Distance	Quantity	m_{Lg} 5.5	m_{Lg} 7.0
5 km			
20 km	Focal Depth + Crustal Struct	*	0.24
	Stress Drop	*	0.28
	Seismic Moment	*	0.09
70 km			
200 km			

Comments/footnotes:

Subtotal - parametric	*	0.38
Qo and K	*	0.0
other parametric	*	0.20
Total Parametric	*	0.43
Modeling	*	0.70
Total Aleatory	*	0.82

* assumed to be the same as for m_{Lg} 7.0

Proponent: Somerville / Saikia

Approach: Advanced Numerical Modeling

Sensitivity Results: Ground Motion Measure: 10-Hz Spectral Acceleration (g)

Distance	Quantity	m_{Lg} 5.5	m_{Lg} 7.0
12 & km	Focal Depth + Crustal Struct	*	0.30
	Stress Drop	*	0.28
	Seismic Moment	*	0.09
20 km		*	0.24
	"	*	0.28
		*	0.09
70 km		*	0.44
	"	*	0.28
		*	0.09
200 km			

Comments/footnotes:

Subtotal - parametric	*	0.42	0.38	0.53
Qo and K	*	0.05	0.05	0.11
other parametric	*	0.20	0.20	0.20
Total Parametric	*	0.47	0.43	0.58
Modeling	*	0.50	0.50	0.50
Total Aleatory	*	0.68	0.66	0.76

* assumed to be the same as for m_{Lg} 7.0

Proponent: Somerville / Saikia

Approach: Advanced Numerical Modeling

Sensitivity Results: Ground Motion Measure: 25-Hz Spectral Acceleration (g)

Distance	Quantity	m_{Lg} 5.5	m_{Lg} 7.0
5 km			
20 km	Focal Depth + Crustal Struct	*	0.24
	Stress Drop	*	0.28
	Seismic Moment	*	0.09
70 km			
200 km			

Comments/footnotes:

Subtotal - parametric	*	0.38
Qo and K	*	0.15
other parametric	*	0.20
Total Parametric	*	0.45
Modeling	*	0.46
Total Aleatory	*	0.64

* assumed to be the same as for m_{Lg} 7.0

Proponent: Somerville / Saikia

Approach: Advanced Numerical Modeling

Sensitivity Results: Ground Motion Measure: Peak Ground Acceleration (g)

Distance	Quantity	m_{Lg} 5.5	m_{Lg} 7.0
12 ~~8~~ km	Focal Depth & Crustal Struct	*	0.30
	Stress Drop	*	0.28
	Seismic Moment	*	0.09
20 km			
70 km		*	0.44
		*	0.28
		*	0.09
200 km			

Comments/footnotes:

Subtotal - parametric	*	0.42	0.53
Q_0 and K	*	0.15	0.18
other parametric	*	0.20	0.20
Total Parametric	*	0.49	0.59
Modeling	*	0.42	0.42
Total Aleatory	*	0.64	0.73

* assumed to be the same as for m_{Lg} 7.0

APPENDIX 1.

DESCRIPTION OF THE ADVANCED NUMERICAL MODELING METHOD

3.3 Semi-Empirical Ground Motion Model

At frequencies below about 2 Hz, the principal features of strong ground motions can be modeled using deterministic models of the earthquake source. The ability of synthetic seismograms to match recorded strong ground motions at low frequencies has been clearly demonstrated during the past decade; a summary of events studied is given in Mendoza at Hartzell (1988) and Heaton (1990). However, at the higher frequencies of interest for this study, strong ground motions are highly affected by stochastic processes. The modeling procedure described below combines empirical and theoretical approaches to modeling ground motion effects in order to capture the essence of both deterministic and stochastic elements of ground motion. The combined semi-empirical model is used in this study to quantify path effects or, more precisely, contributions to ground motion variability made by wave propagation in the earth's crust (Section 5).

3.3.1 Model Description

In the semi-empirical ground motion modeling approach, near-source recordings of small earthquakes are used as empirical source functions to provide a realistic representation of effects such as source radiation that are difficult to deterministically model at high frequencies due to their stochastic behavior. Wave propagation effects are modeled using simplified transfer functions or Green's functions that are designed to transfer empirical source functions from their recording sites to those required for use in simulations at a specific site. The details of the simulation procedure are described by Wald et al. (1988a) and Somerville et al. (1991), and are summarized in Appendix 3.B.

The procedure is illustrated schematically in Figure 3-7. The fault is divided into discrete elements, and the motions from these elements are lagged and summed across the fault to simulate the propagation of rupture over the fault surface. A stochastic component is included in the speeds of fault slip and rupture propagation to simulate heterogeneity in rupture dynamics. Large scale asperities (areas of concentrated slip and high-frequency radiation) are introduced by varying the slip distribution over the fault surface.

The Green's functions are calculated using the method of generalized rays (Helmberger and Harkrider, 1978). Rays corresponding to the direct P and S waves and to the primary reflection (and head wave beyond critical angle) from each interface below the source are included, as shown schematically in Figure 3-8. The overall seismogram is produced by summing these various rays, which generally arrive at the site at different times. The amplitude and time relationships between these arrivals change with distance, producing seismograms whose amplitudes and durations change with distance. In a homogeneous half space, the rate at which ground motion decays with distance is the inverse source distance, 1/R. At source-site distances less than the critical distance (the distance beyond which all seismic energy is reflected back to the surface from a given boundary), the interference between the upgoing wave and waves reflected due to the velocity gradient below the source causes attenuation more rapid that 1/R. Beyond the critical distance, however, critical reflections cause the

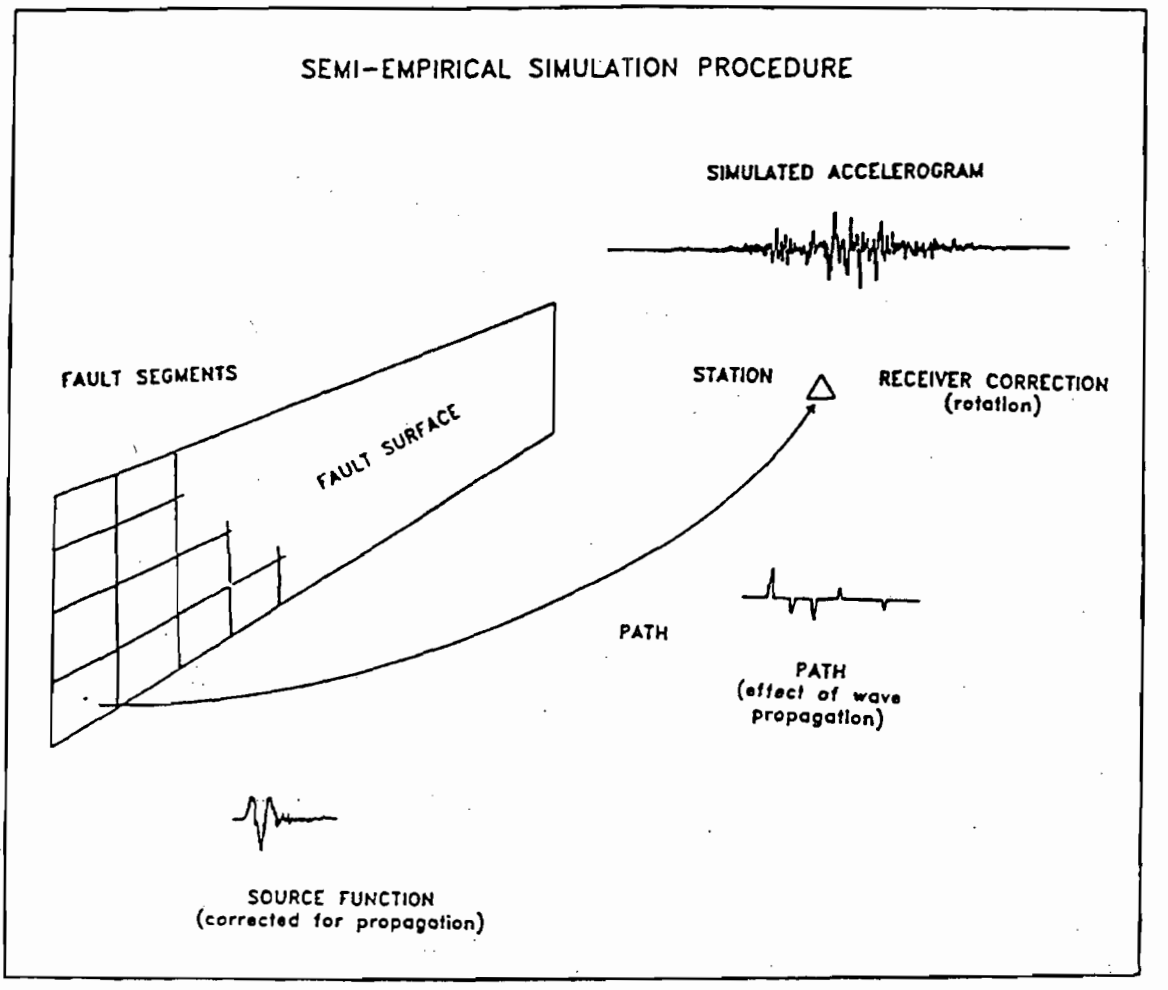


Figure 3-7. Schematic diagram of the ground motion simulation procedure. Source: Somerville et al., 1990.

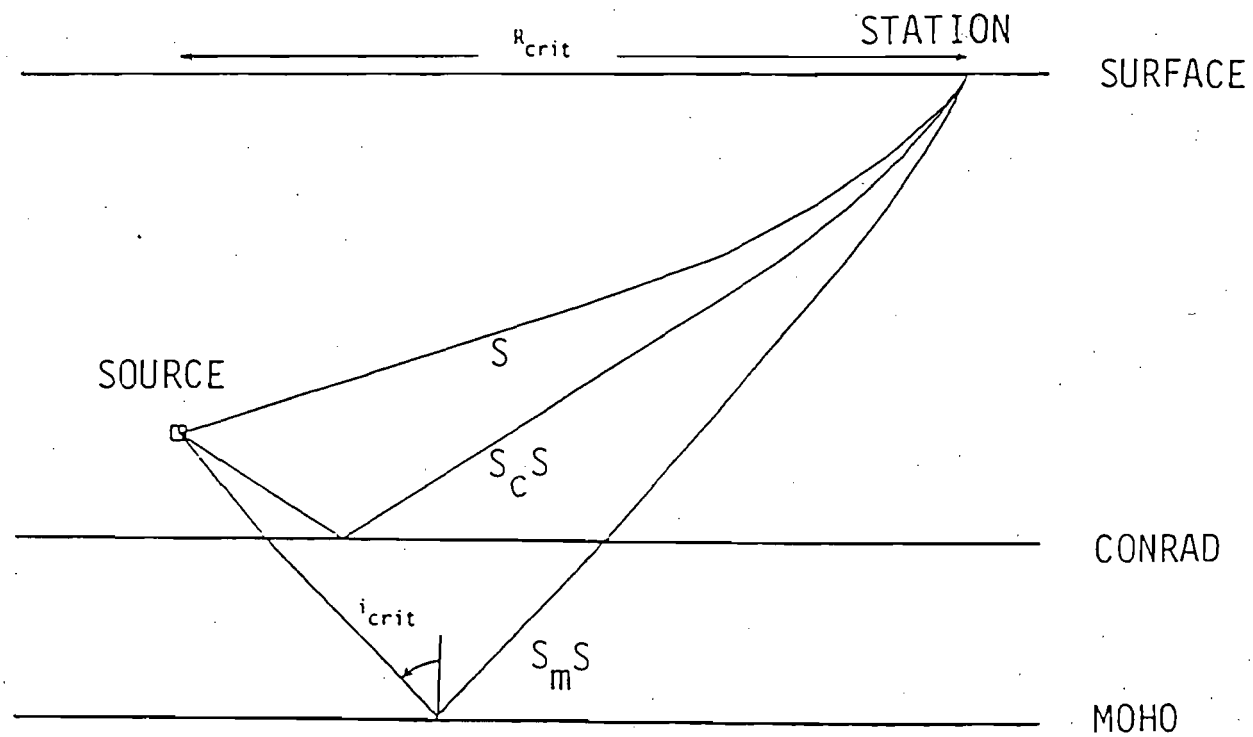


Figure 3-8. Schematic diagram of the wave propagation model, with direct waves (S) and waves S_cS and S_mS reflected from the Conrad and Moho layers. At the critical angle (i_{crit}), the incident wave is totally reflected back to the surface at distances starting at the critical distance R_{crit}.

attenuation to be less rapid than 1/R. Thus the peak amplitudes and duration of the seismogram are a function of the crustal structure and focal depth.

The simplified Green's functions that are used, described further by Somerville et al. (1991), are the response of the crust for P, SV and SH potentials. The receiver function is represented empirically, as described below, and the radiation pattern is assigned an average value. At high frequencies, the small set of rays that used are expected to contain most of the important arrivals out to distances of 200 km. To realistically model the wave propagation at greater distances, it would be necessary to include a much larger set of rays, or use the frequency-wavenumber integration method in place of the generalized ray method. In this application, then, ground motion modeling is not extended beyond 200 km distance.

3.3.2 Model Validation

The semi-empirical ground motion model has been validated against strong motion records of several earthquakes. These include the 1979 Imperial Valley earthquake (Wald et al., 1988a); the 1987 Whittier Narrows earthquake ((Wald et al., 1988b); Saikia, 1992), the 1988 Nahanni earthquake (Somerville et al., 1990); the 1989 Loma Prieta earthquake (Somerville et al., 1992a,b), and the 1985 Michoacan, Mexico and Valparaiso, Chile earthquakes (Somerville et al., 1991).

For the purposes of this study, a validation of the method was performed using a standard set of procedures for four earthquakes: the 1989 Loma Prieta earthquake (55 stations); the 1987 Whittier Narrows earthquake (37 stations); the 1988 Nahanni earthquake (3 stations); and the

Table 3-7

Source Parameters of Earthquakes Used in Validation of Semi-Empirical Simulation Method

Earthquake	Seismic Moment (x 10^{25} dyne cm)	Depth to Top Center (km)	Fault Length (km)	Fault Width (km)	Strike	Dip	Rake	Rupture Velocity (km/sec)	Rise Time (sec)
1985 Nahanni	17.6	3.56	32	15	180	22	110	2.7	0.96
1987 Whittier Narrows	1.0	12.35	12	9	280	30	110	2.5	0.40
1988 Saguenay	0.5	23.14	4	6	323	65	78	3.0	0.40
1989 Loma Prieta	29.5	3.38	40	18	128	70	140	2.7	1.14

1988 Saguenay earthquake (9 stations), for a total of 104 recordings. All available digital strong motion data at source-site distances of less than about 200 km were used in the validation, regardless of site conditions. The simulation method is described in Section 3.3.1 and Appendix 3.B. The standard procedures were as follows. For each event, published slip models were used to characterize the source, and published crustal structure models were used to characterize the wave propagation path. The source and path models are described by Hartzell and Iida (190) and Wald et al. (1989) respectively for the Whittier Narrows earthquake; Somerville et al. (1990) for the Saguenay earthquake; EPRI (1992) for the Nahanni earthquake; and Wald et al. (1992) for the Loma Prieta earthquake. Where these slip models included multiple time windows, a slip model was derived having a single time window. The source models of the four events are summarized in Table 3-7. The stations used in the validation of the four events are listed in Tables 3-8 through 3-11.

The empirical source functions were derived from the October 15, 1979 Imperial Valley aftershock. These empirical source functions represent a seismic moment of 0.6×10^{24} dyne-cm and a fault element size of 4km x 3km. For the Saguenay and Nahanni events, these source functions were modified for eastern North American source conditions to have a kappa value of 0.006 sec, while for the Whittier Narrows and Loma Prieta events the source functions were unmodified and retained an average kappa value of 0.055 sec. Unlike the stochastic model, the semi-empirical model does not include the Brune stress-drop as a specified parameter (from which the corner frequency and high-frequency spectral level are derived). Instead, the stress drop and ground motion levels at high frequencies are a function of the high-frequency ground motion levels embodied in the empirical source functions and the source duration of the finite rupture.

APPENDIX 2.

DOCUMENTATION OF ALEATORY UNCERTAINTY

Table 1. Base Case for Sensitivity Studies

Parameter	Value
Stress-Drop	100 bars
Focal Depth	11 km
Mechanism	45° dip, 90°rake
Kappa	0.006 sec
$Q = Q_0 f^{\eta}$	$750 f^{0.5}$
Crustal Velocity Structure	Grenville
Mw	6.5

Table 2. Sensitivity Runs for Rock Sites

Parameter	Distribution	Median	S.E.
Stress-Drop	lognormal	100 bars	0.7
Focal Depth	lognormal	11 km	0.5
Kappa - Hard Rock	lognormal	0.006 sec	0.4
Kappa - Soft Rock	lognormal	0.04 sec	0.4
Q_0	lognormal	750	0.4
η	normal	0.50	0.3
Crustal Velocity Structure	uniform	-	-

A. West Quebec
B. Gradient
C. Charlevoix
D. Berry

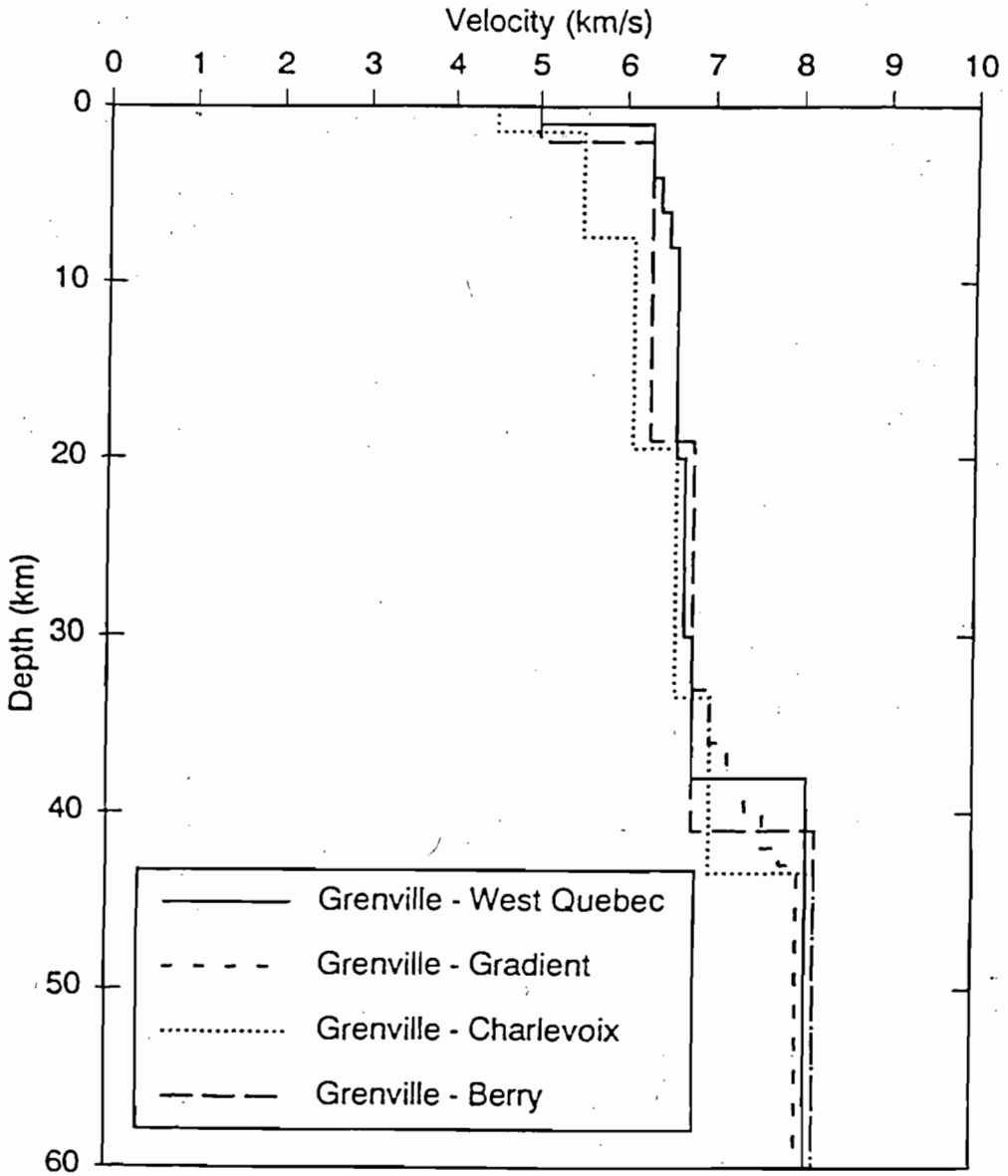


Figure 5-23. Four velocity models used for the Grenville region to represent variability of the velocity model within a region.

The West Quebec model for the Central Metasedimentary Belt near Mont Laurier, Quebec was derived from the profile for Point C in Line CD in Mereu et al. (1986). The Gradient model for the Central Metasedimentary Belt was derived from Point C (the same point as in the West Quebec model) in the intersecting Line CB in the same study. The Gradient model is identical to the West Quebec model above 30 km, but below 30 km has a velocity gradient to a deeper Moho in place of a step change in velocity at the Moho. The Charlevoix model for the north shore of the St. Lawrence River in Quebec was derived by Somerville et al. (1990) using data from the Saguenay earthquake sequence of 1988. The Berry model for northeast Quebec was derived by Berry and Fuchs (1973).

The four crustal models for the New Madrid Rift region are listed in Table 5-11 and shown in Figure 5-24. The

the maximum standard error is shifted to distances of 80 to 120 km again associated with the variation in Moho depth. The depth of the Moho affects the distance range at which the maximum standard error occurs. In general, the deeper the Moho, the larger the distance at which the maximum occurs.

In Figures 5-25 and 5-26 the variation of ground motion for a given crustal structure is shown for three depths. To account for the variability in focal depth, the ground motion variability is computed using a weighted average over focal depths where the weights are given by the EAA generic depth distribution (Table 5-9). The standard errors of the mean spectral acceleration are shown in Figures 5-27a,b,c for 1, 5, and 15 Hz.

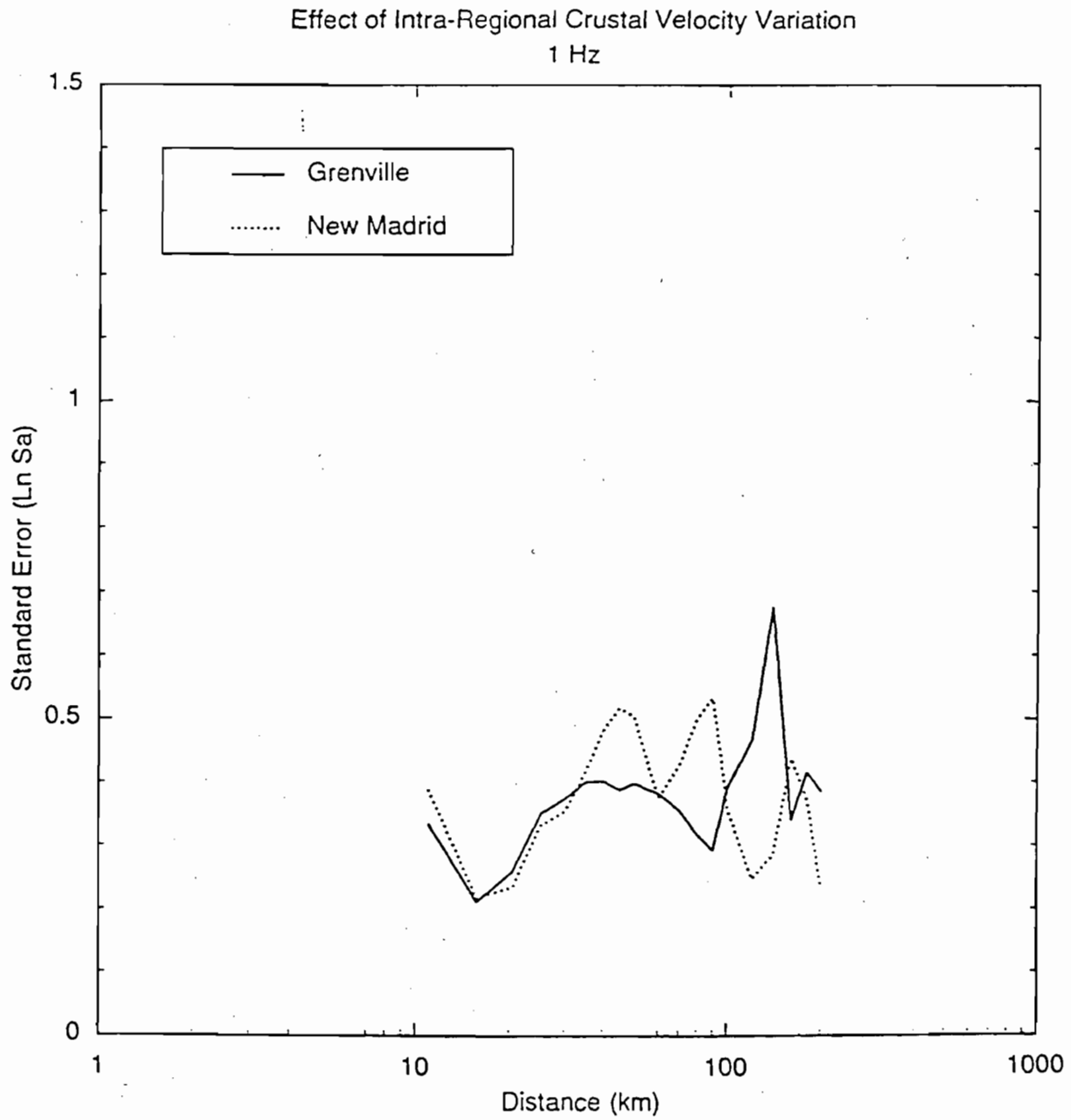


Figure 5-27a. Variability of spectral acceleration at 1 Hz due to crustal velocity uncertainty within the Grenville and New Madrid region. The variability includes variability in focal depth.

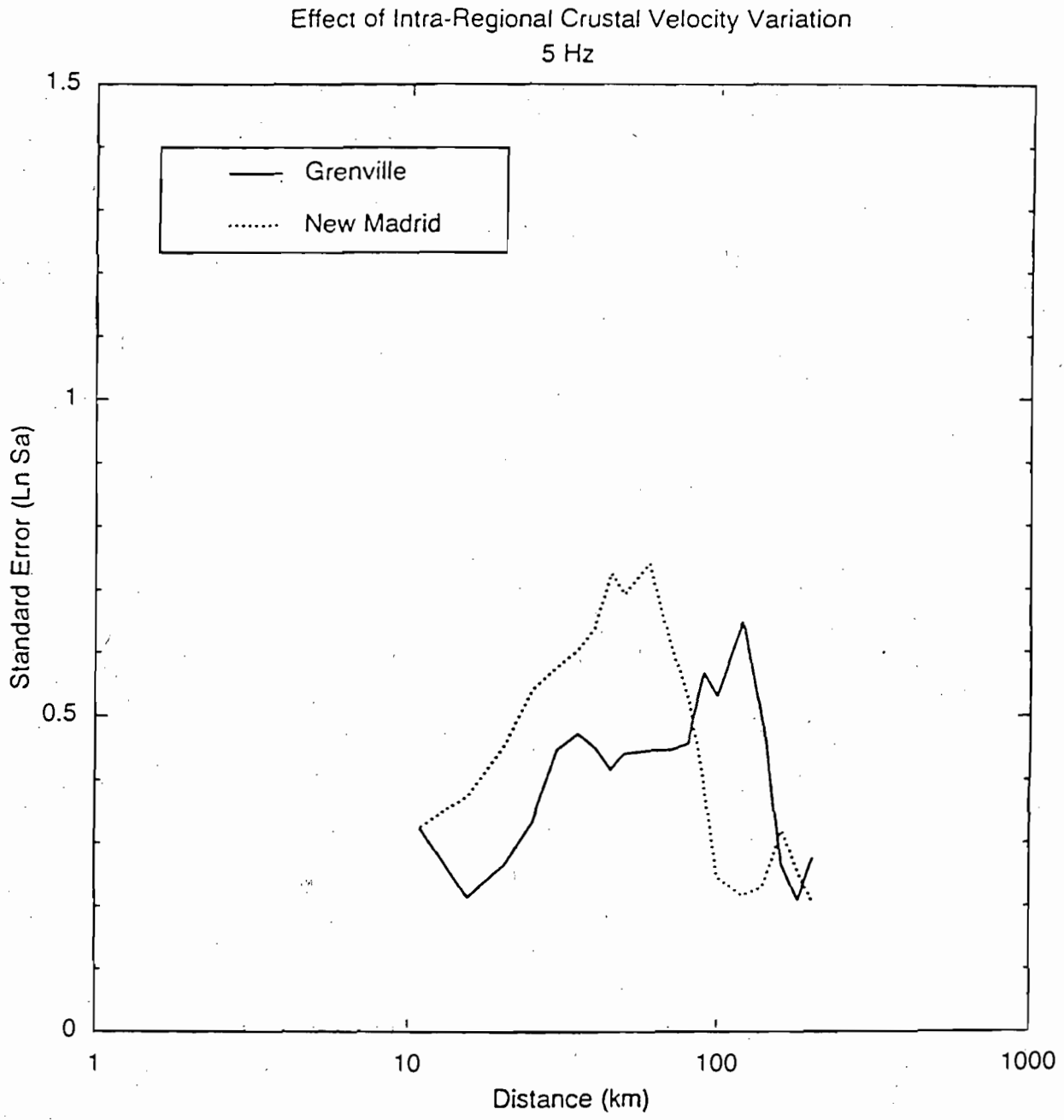


Figure 5-27b. Variability of spectral acceleration at 5 Hz due to crustal velocity uncertainty within the Grenville and New Madrid region. The variability includes variability in focal depth.

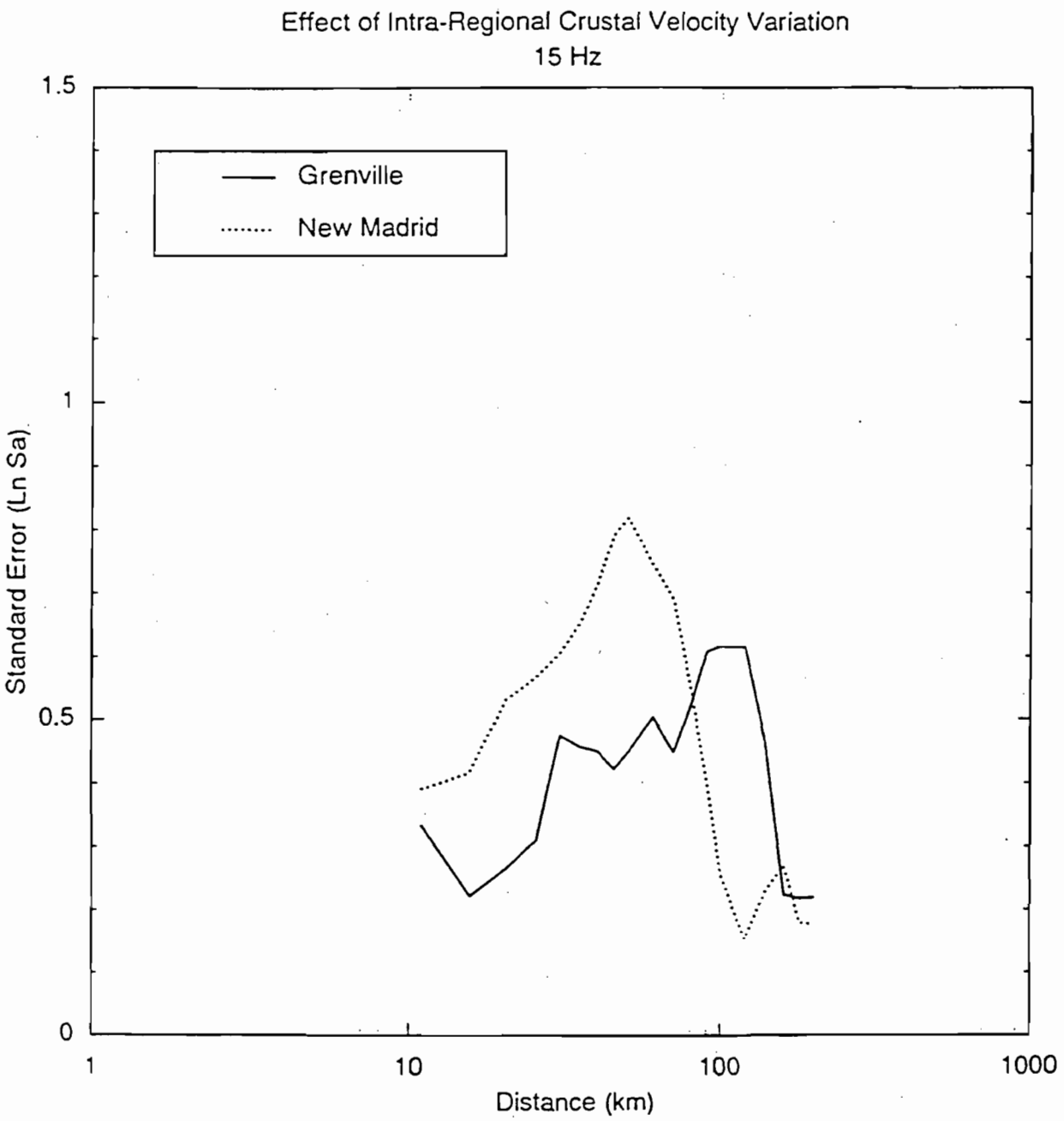
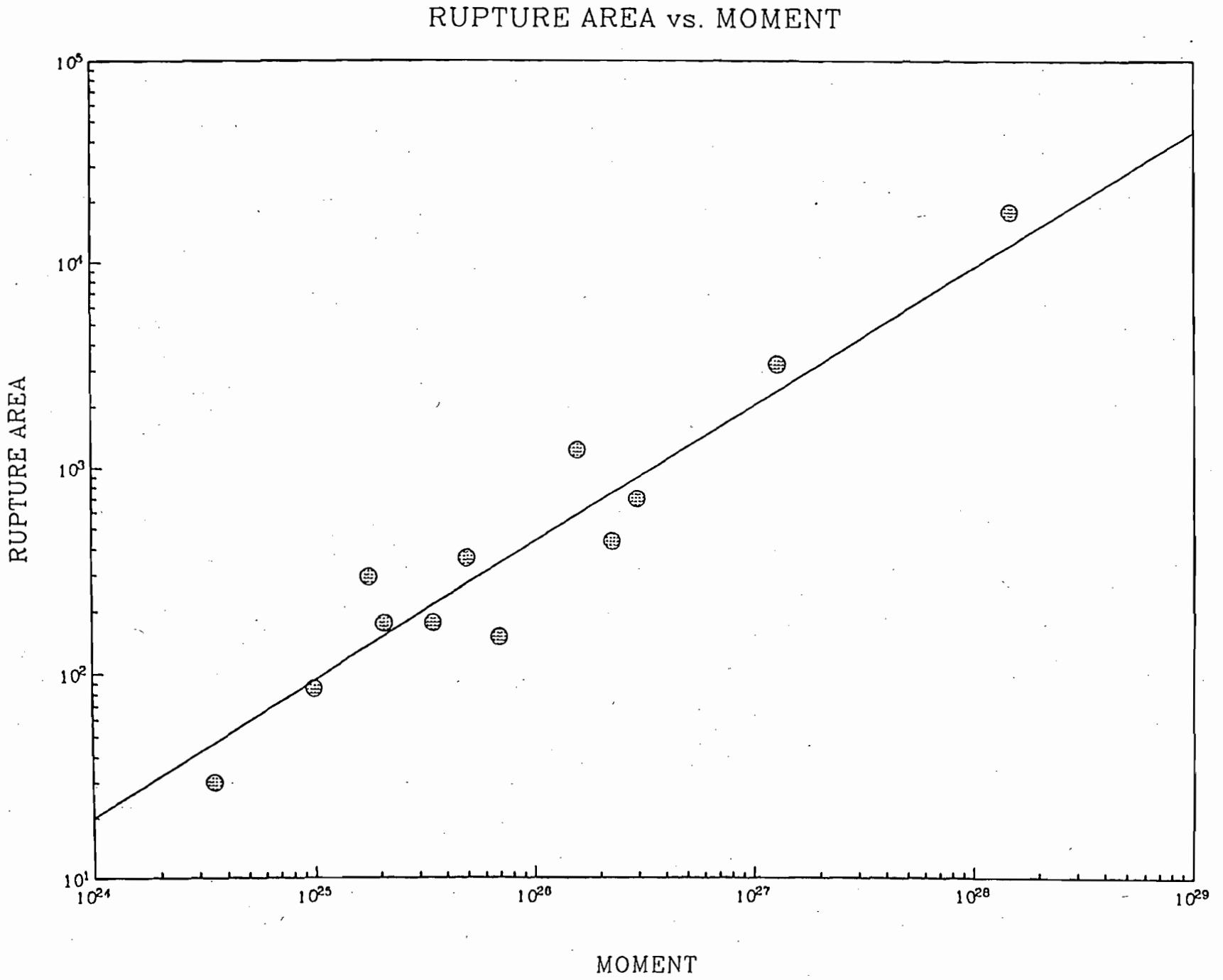
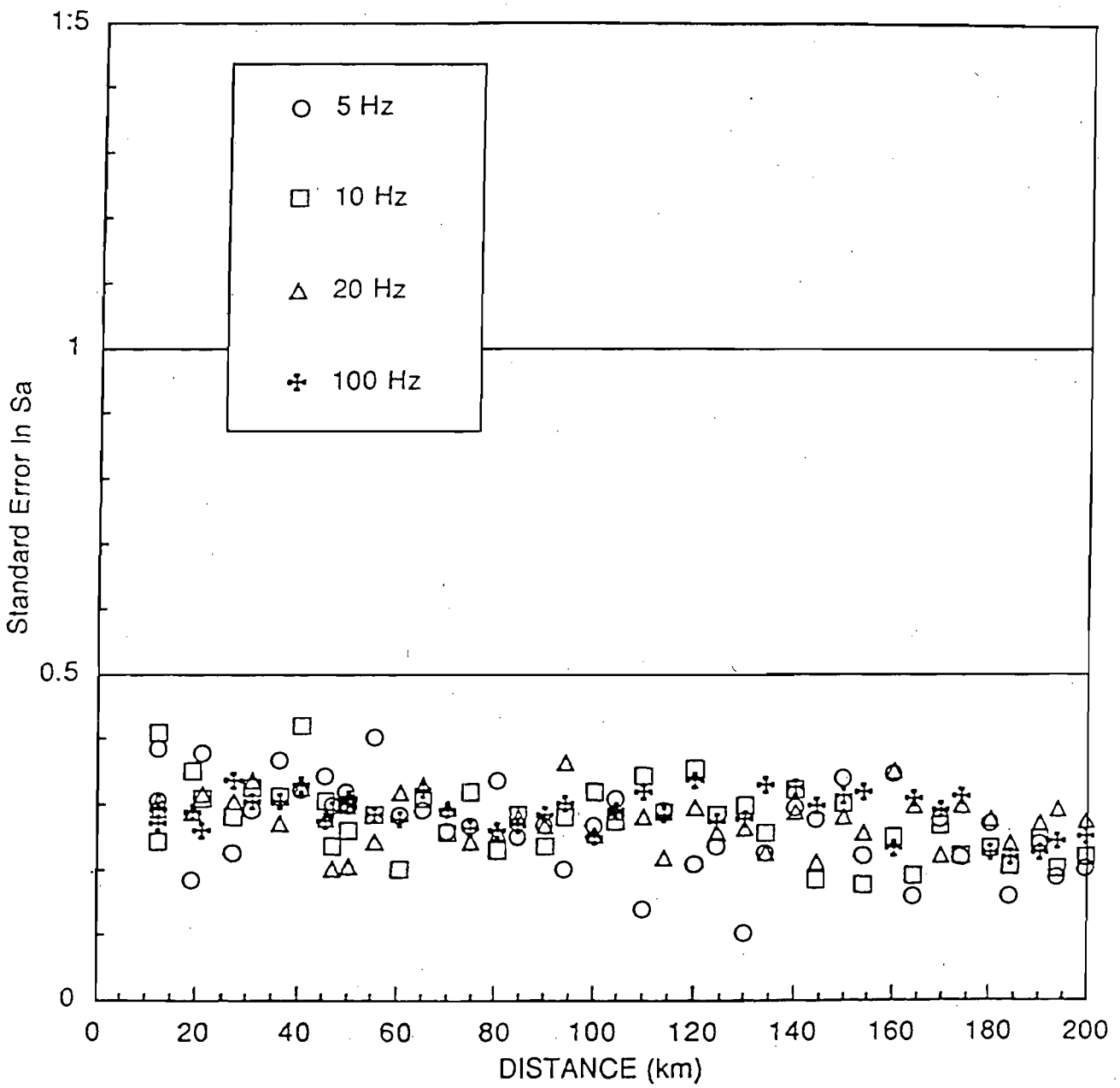


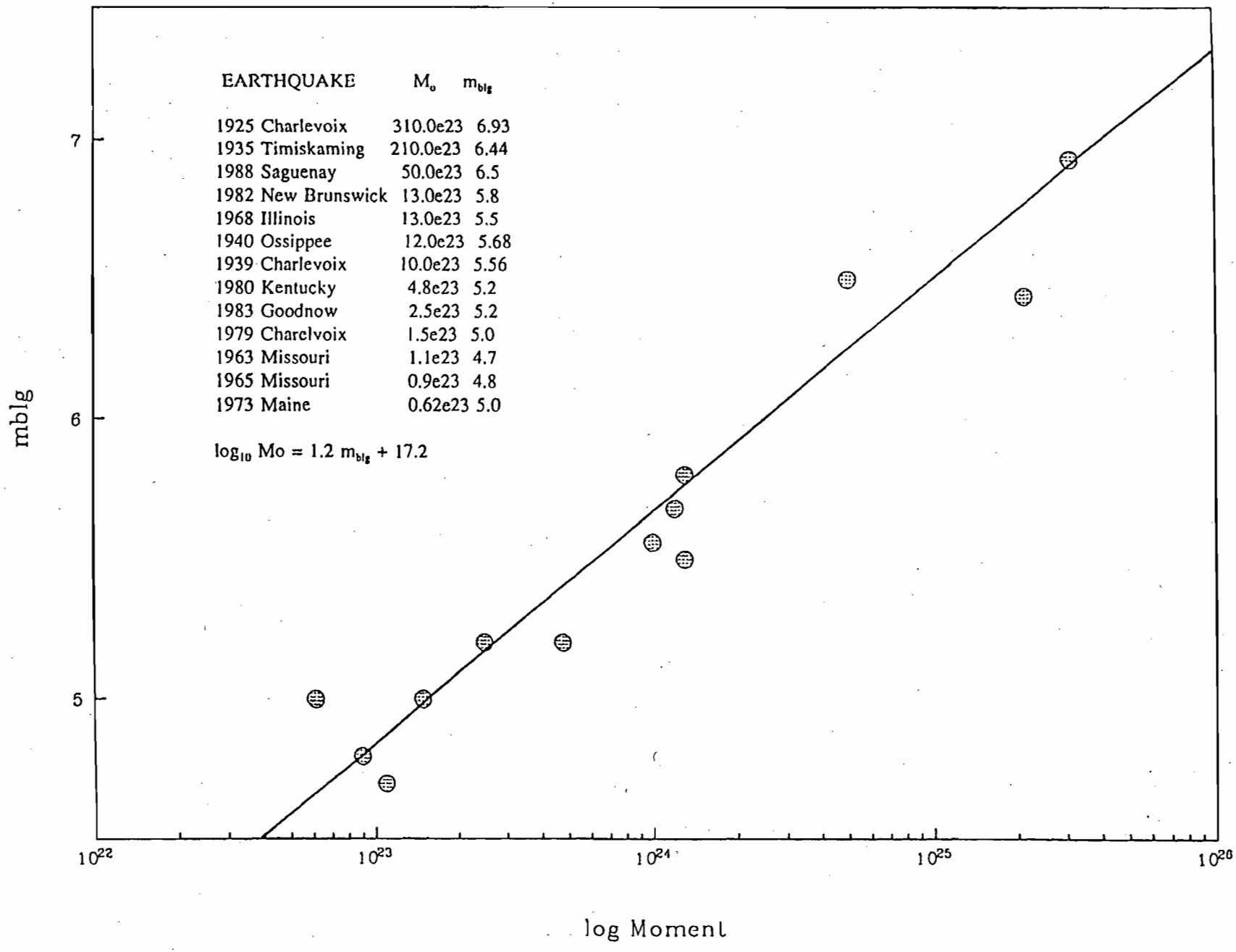
Figure 5-27c. Variability of spectral acceleration at 15 Hz due to crustal velocity uncertainty within the Grenville and New Madrid region. The variability includes variability in focal depth.

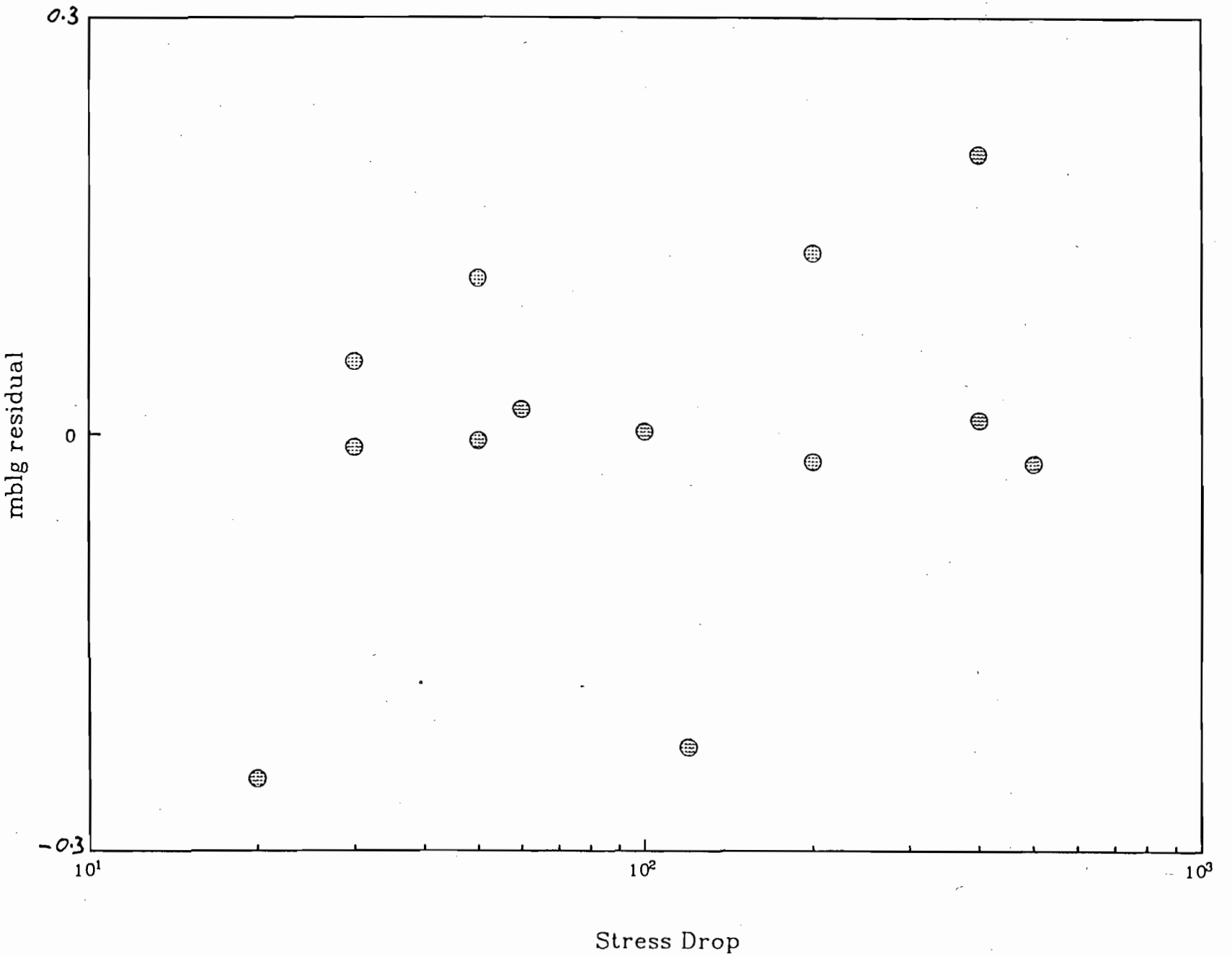


Relation between rupture area and seismic moment. Dots represent individual events, and the line is a least-squares fit under the constraint of self-similarity (slope = 2/3).

WCC Sensitivity: Stress-Drop




EARTHQUAKE M_o m_{blg}
1925 Charlevoix 310.0e23 6.93
1935 Timiskaming 210.0e23 6.44
1988 Saguenay 50.0e23 6.5
1982 New Brunswick 13.0e23 5.8
1968 Illinois 13.0e23 5.5
1940 Ossippee 12.0e23 5.68
1939 Charlevoix 10.0e23 5.56
1980 Kentucky 4.8e23 5.2
1983 Goodnow 2.5e23 5.2
1979 Charelvoix 1.5e23 5.0
1963 Missouri 1.1e23 4.7
1965 Missouri 0.9e23 4.8
1973 Maine 0.62e23 5.0
$\log_{10} Mo = 1.2\ m_{blg} + 17.2$
mblg
7
6
5
10^{22}
10^{23}
10^{24}
10^{25}
10^{26}
log Moment


0.3
0
-0.3
mblg residual
10^1
10^2
10^3
Stress Drop

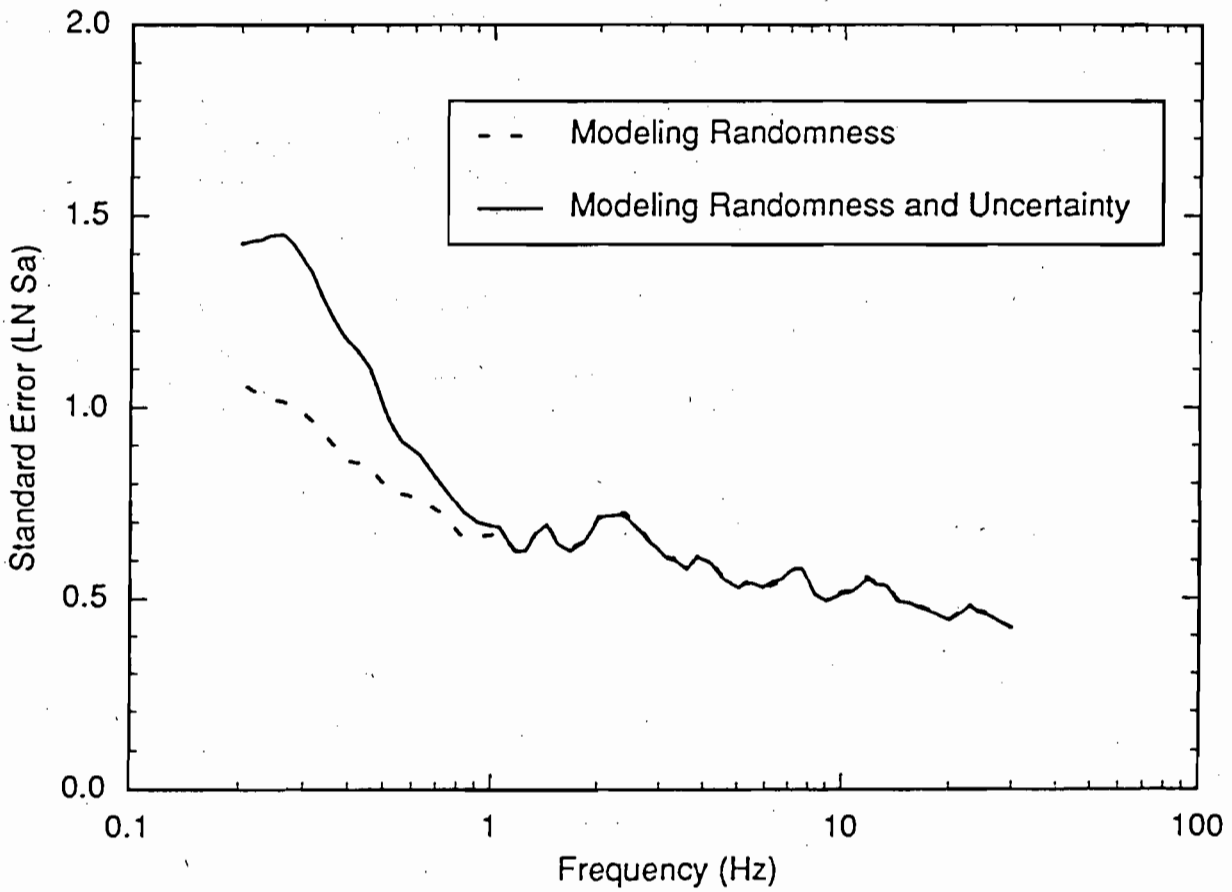


Figure 3-15b. Modeling variability (natural log) computed from recordings at the subset of 39 stations for the Loma Prieta, Whittier Narrows, Nahanni, and Saguenay earthquakes using the semi-empirical ground motion model. Dashed line, total variability (modeling uncertainty plus randomness); solid line, corrected for model bias.

APPENDIX 3.

DOCUMENTATION OF EPISTEMIC UNCERTAINTY

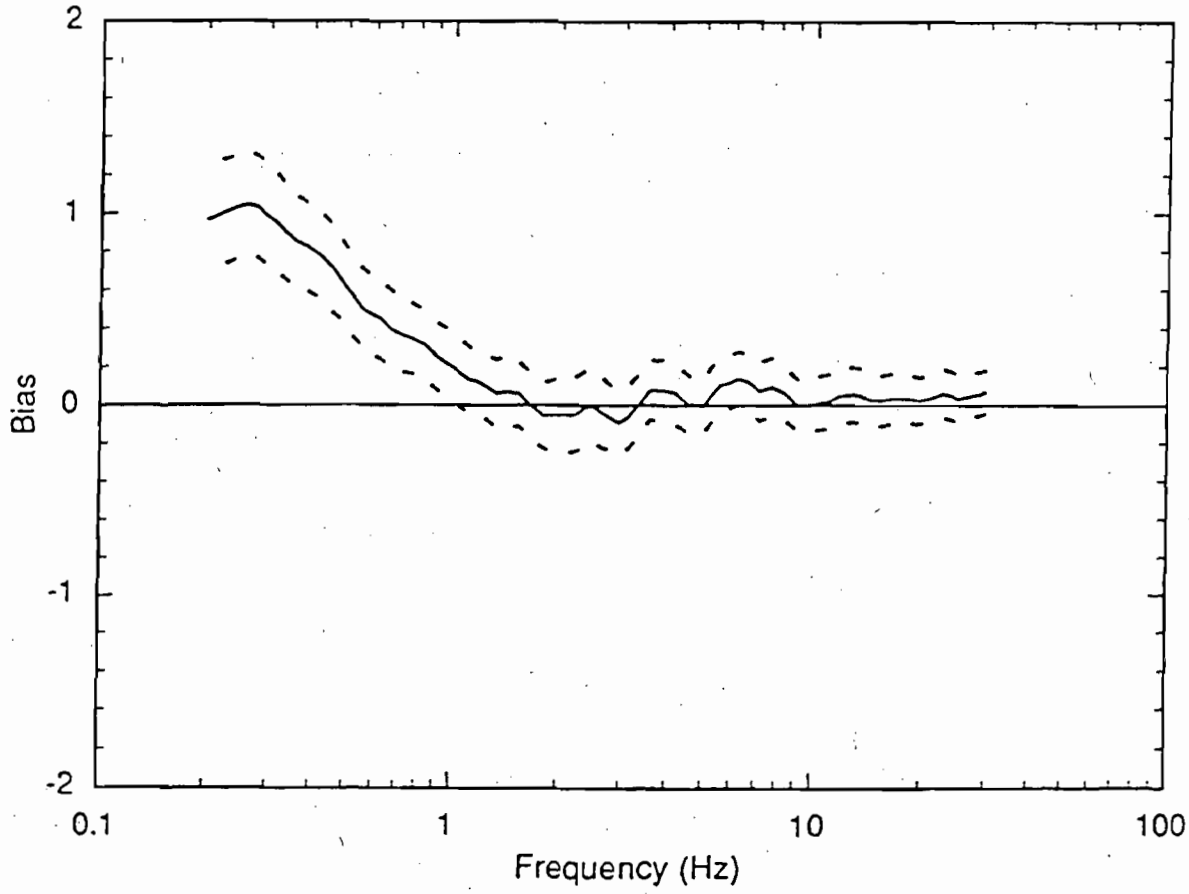


Figure 3-15a. Modeling bias computed from recordings at the subset of 39 stations for the Loma Prieta, Whittier Narrows, Nahanni, and Saguenay earthquakes using the semi-empirical ground motion model. Dashed lines represent 90% confidence limits.

APPENDIX 4.

DOCUMENTATION OF INTER-REGIONAL VARIATIONS

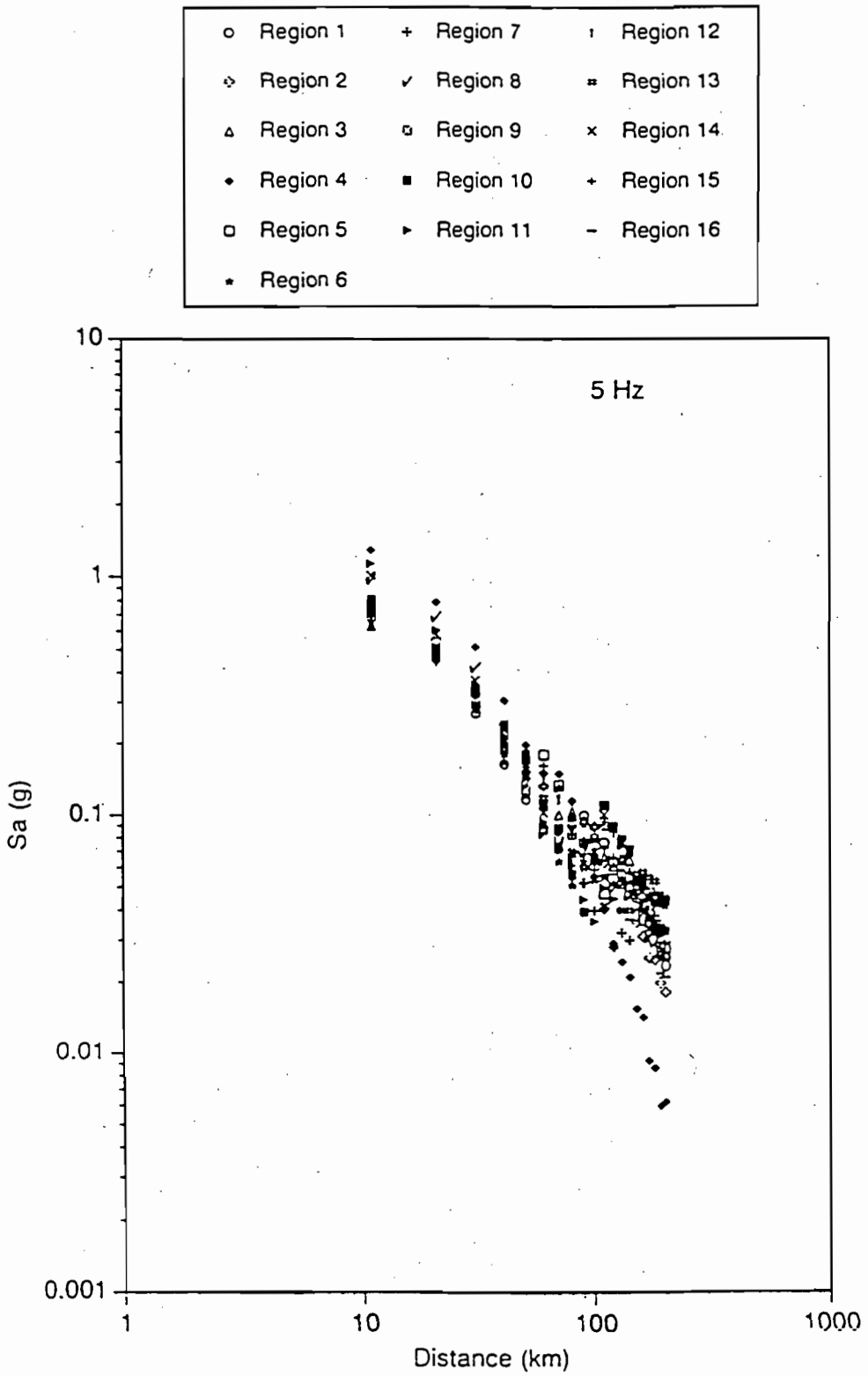
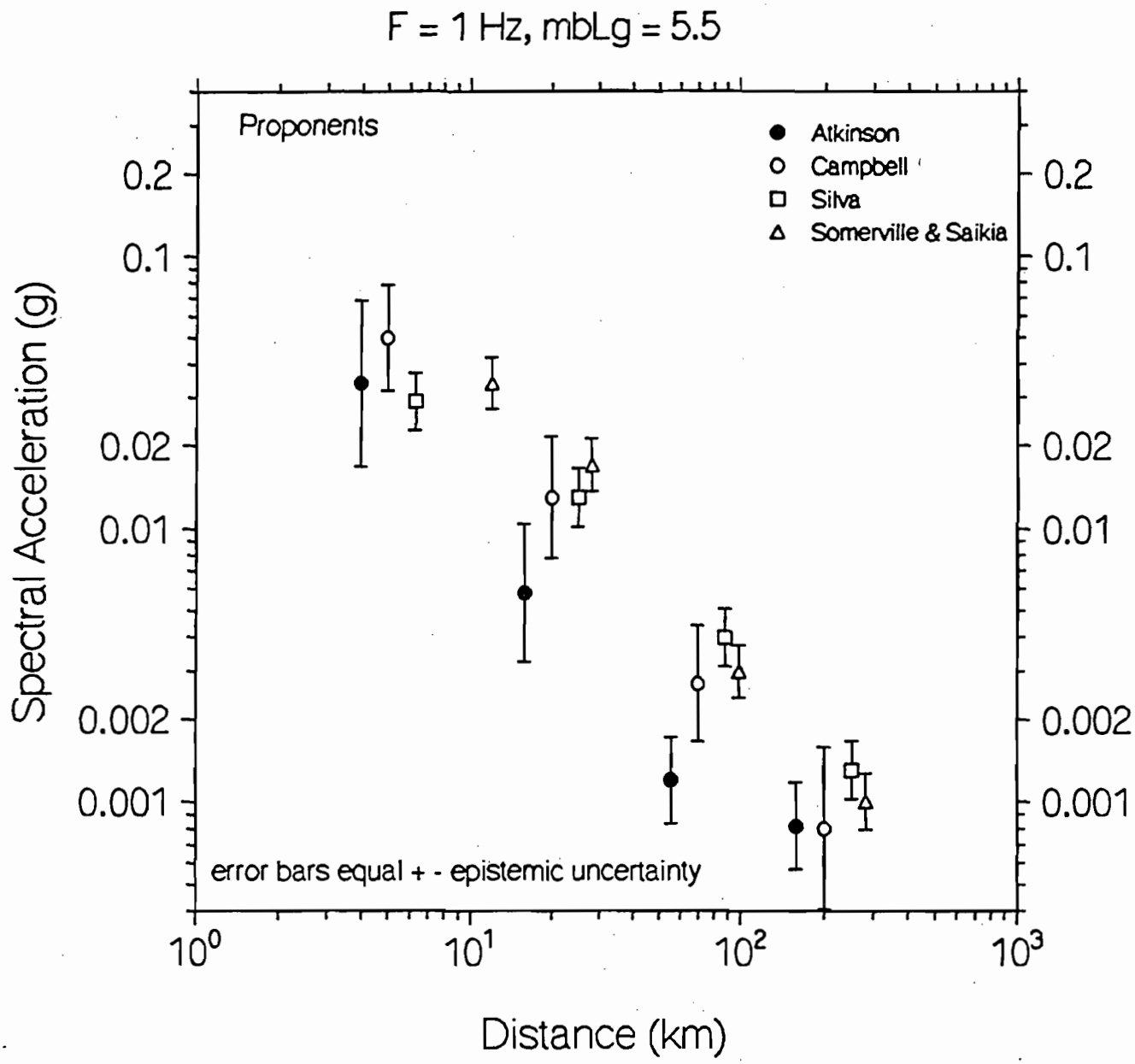
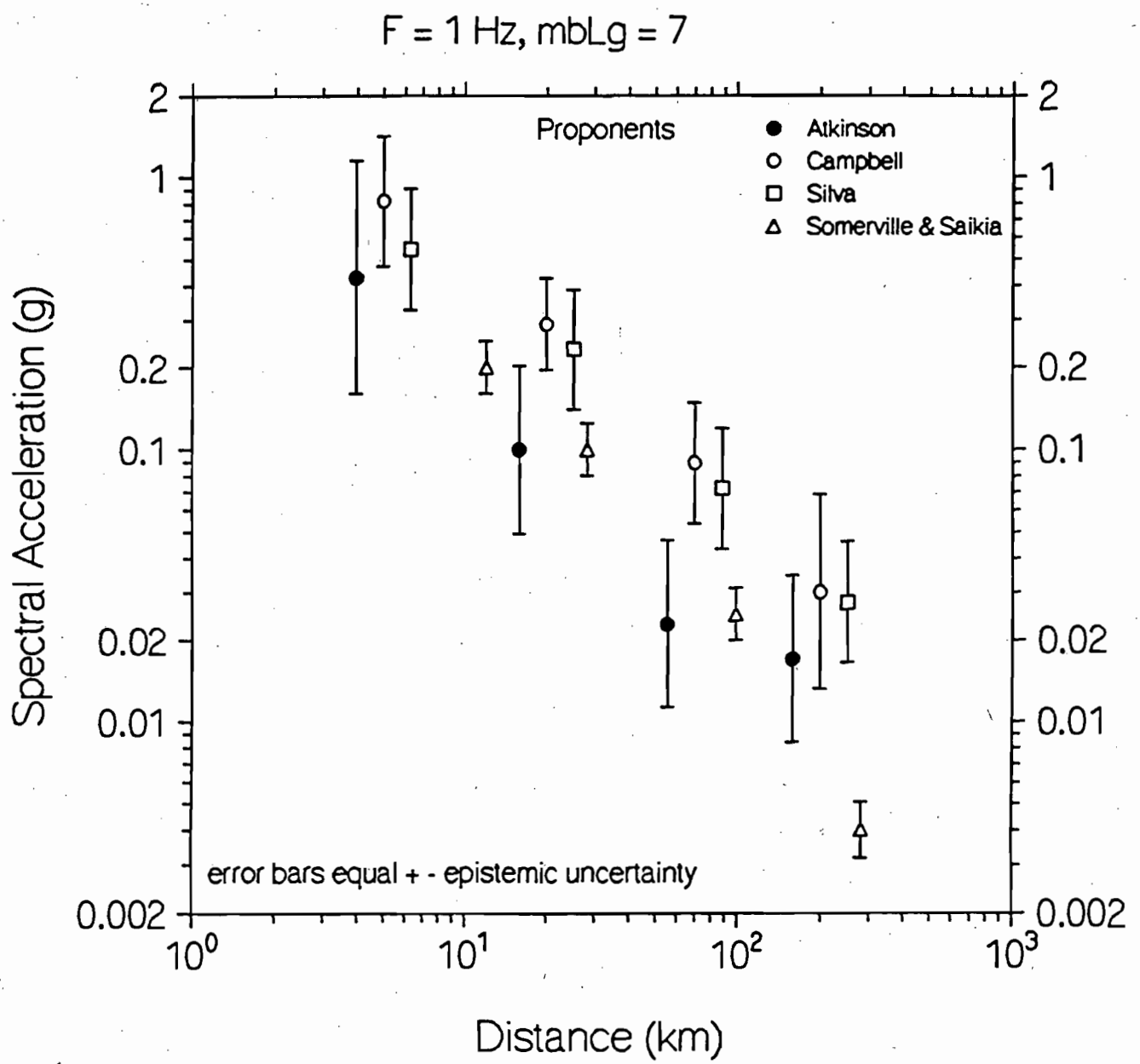
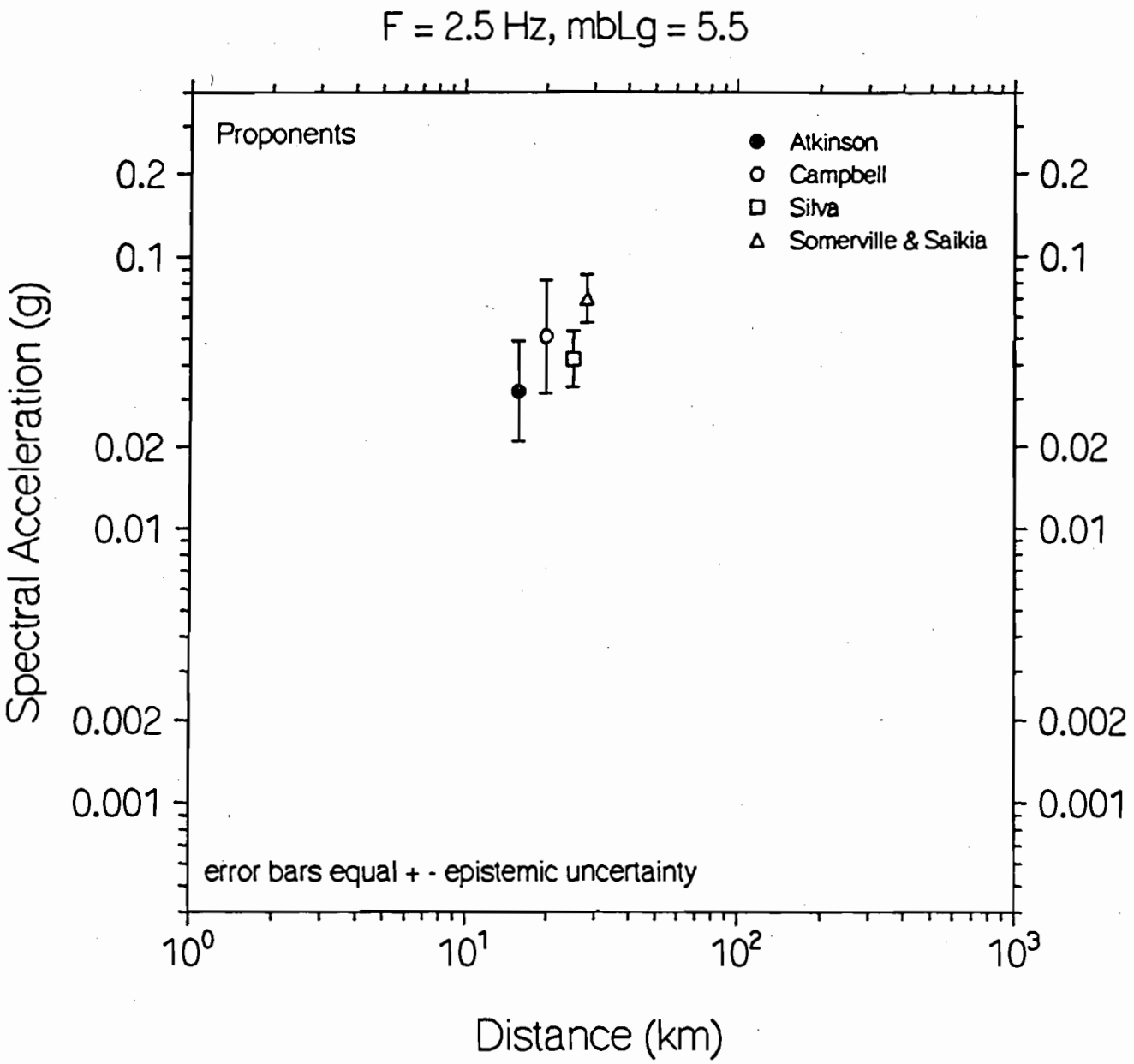
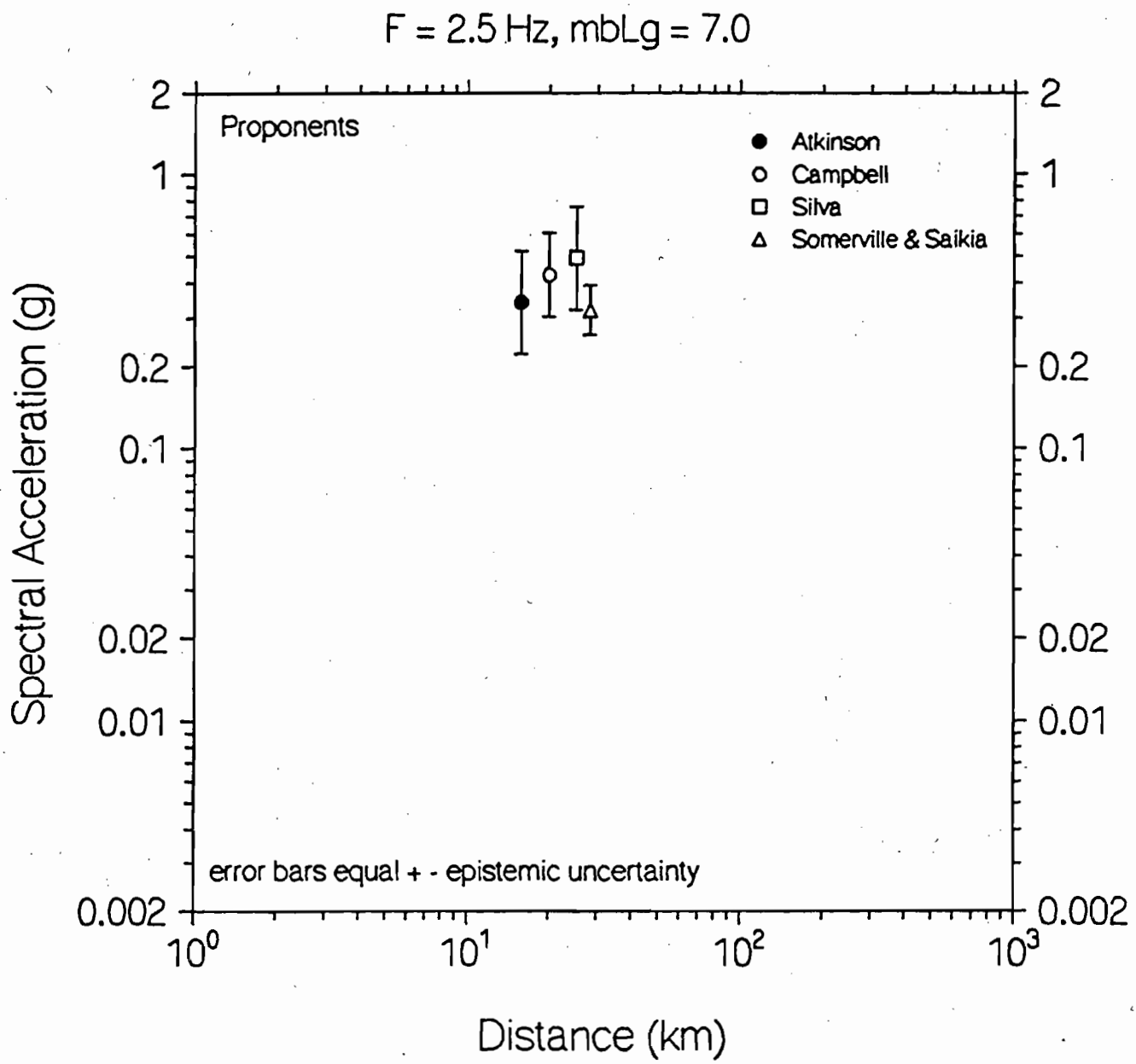


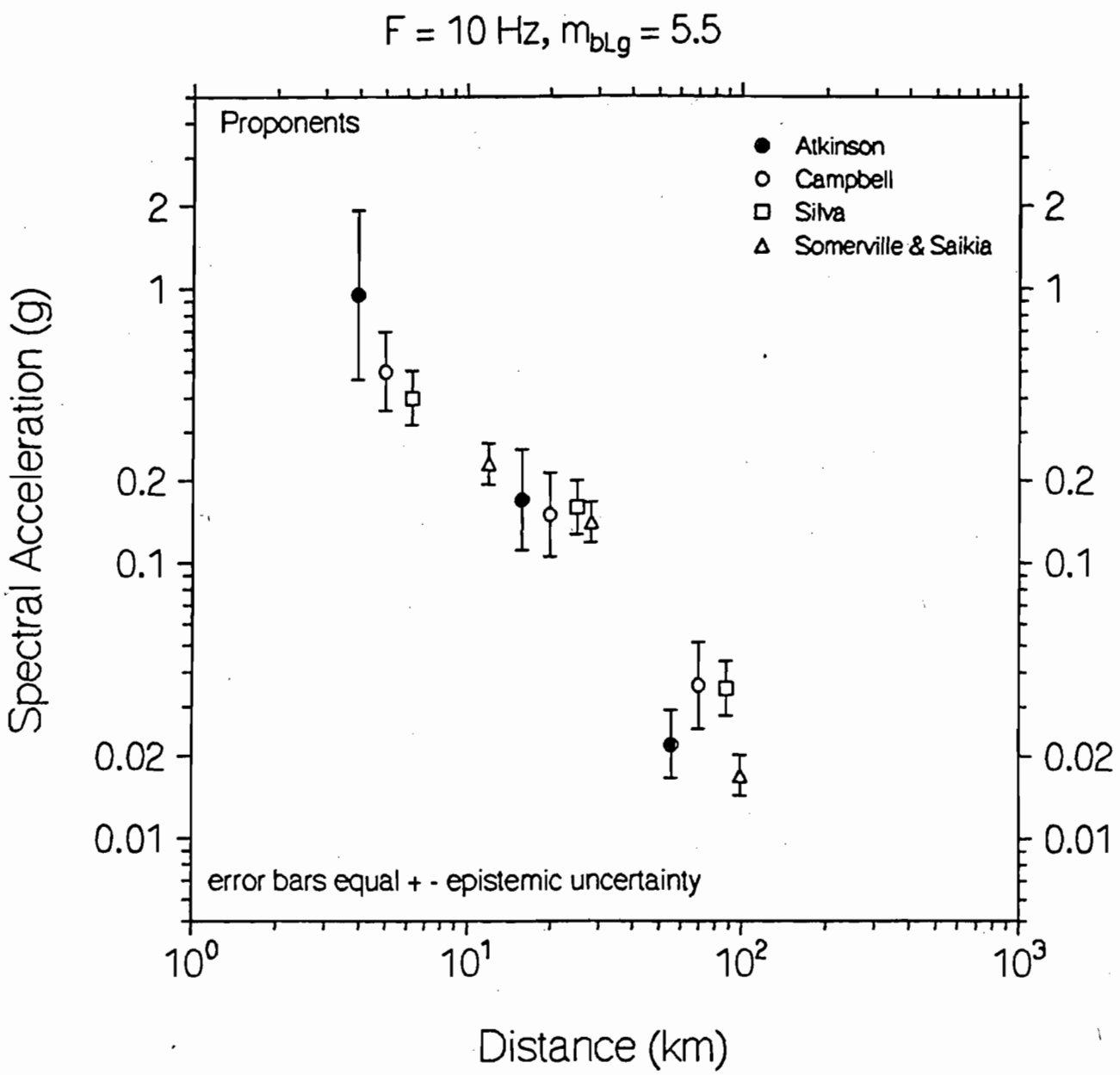
Figure 5-46. Comparison of median ground motion attenuation of spectral acceleration at 5 Hz for the 16 regions.

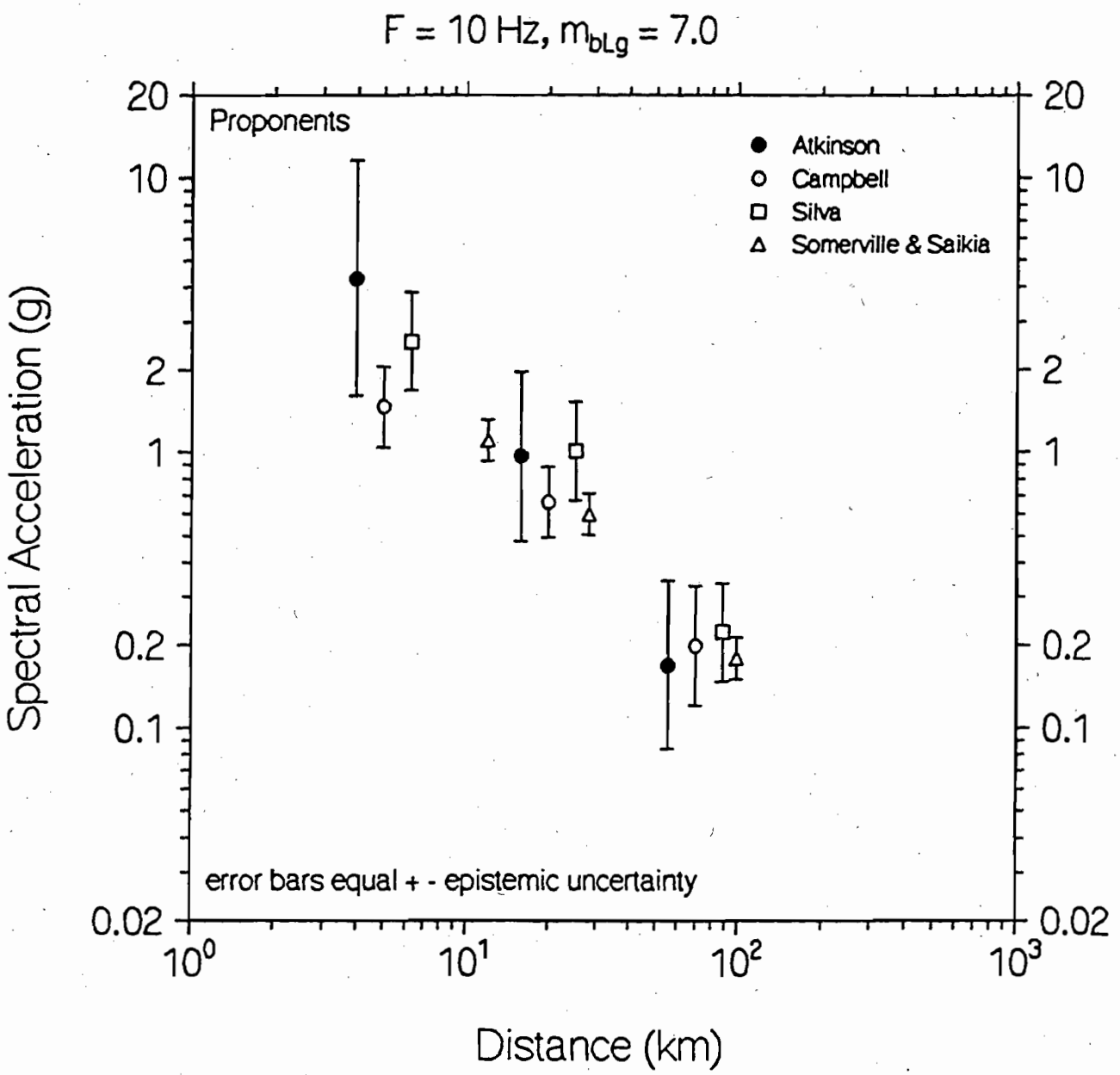

F = 1 Hz, mbLg = 5.5
Proponents
Atkinson
Campbell
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty
Spectral Acceleration (g)
0.2
0.1
0.02
0.01
0.002
0.001
10^0
10^1
10^2
10^3
Distance (km)

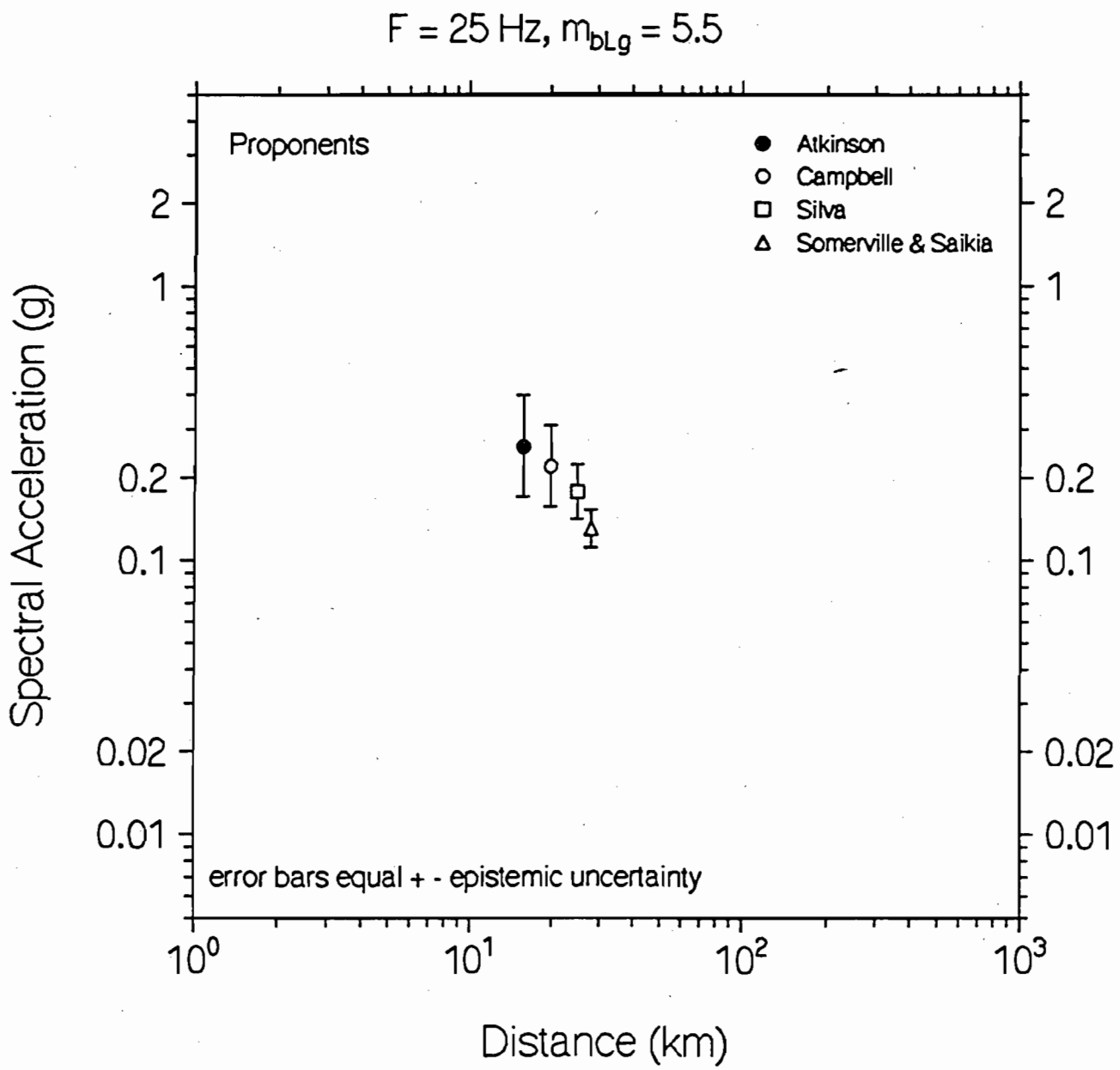

F = 1 Hz, mbLg = 7
Proponents
Atkinson
Campbell
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty
Spectral Acceleration (g)
Distance (km)
2
1
0.2
0.1
0.02
0.01
0.002
10^0
10^1
10^2
10^3

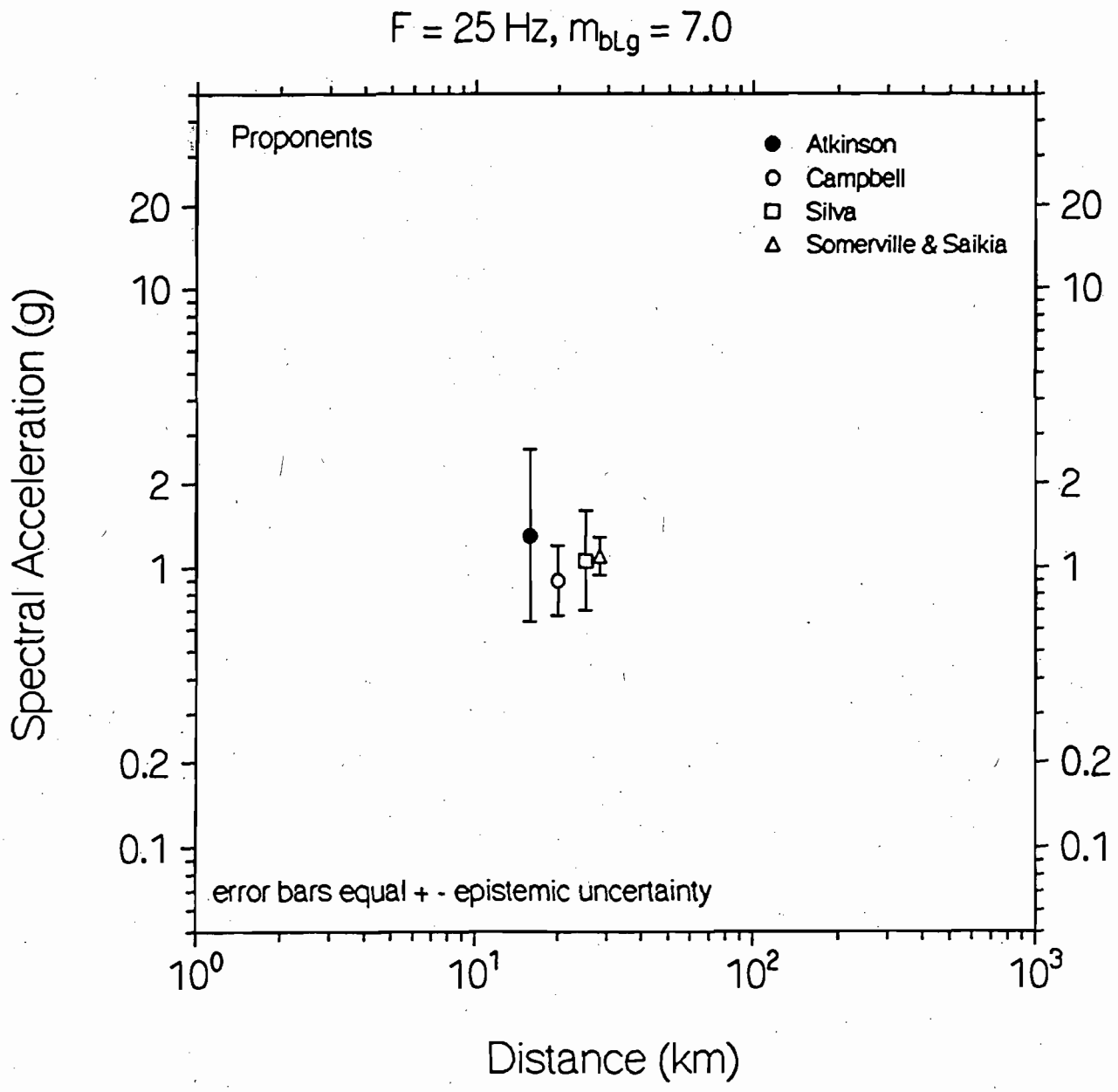

F = 2.5 Hz, mbLg = 5.5
Proponents
Atkinson
Campbell
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty
Spectral Acceleration (g)
0.2
0.1
0.02
0.01
0.002
0.001
10^0
10^1
10^2
10^3
Distance (km)

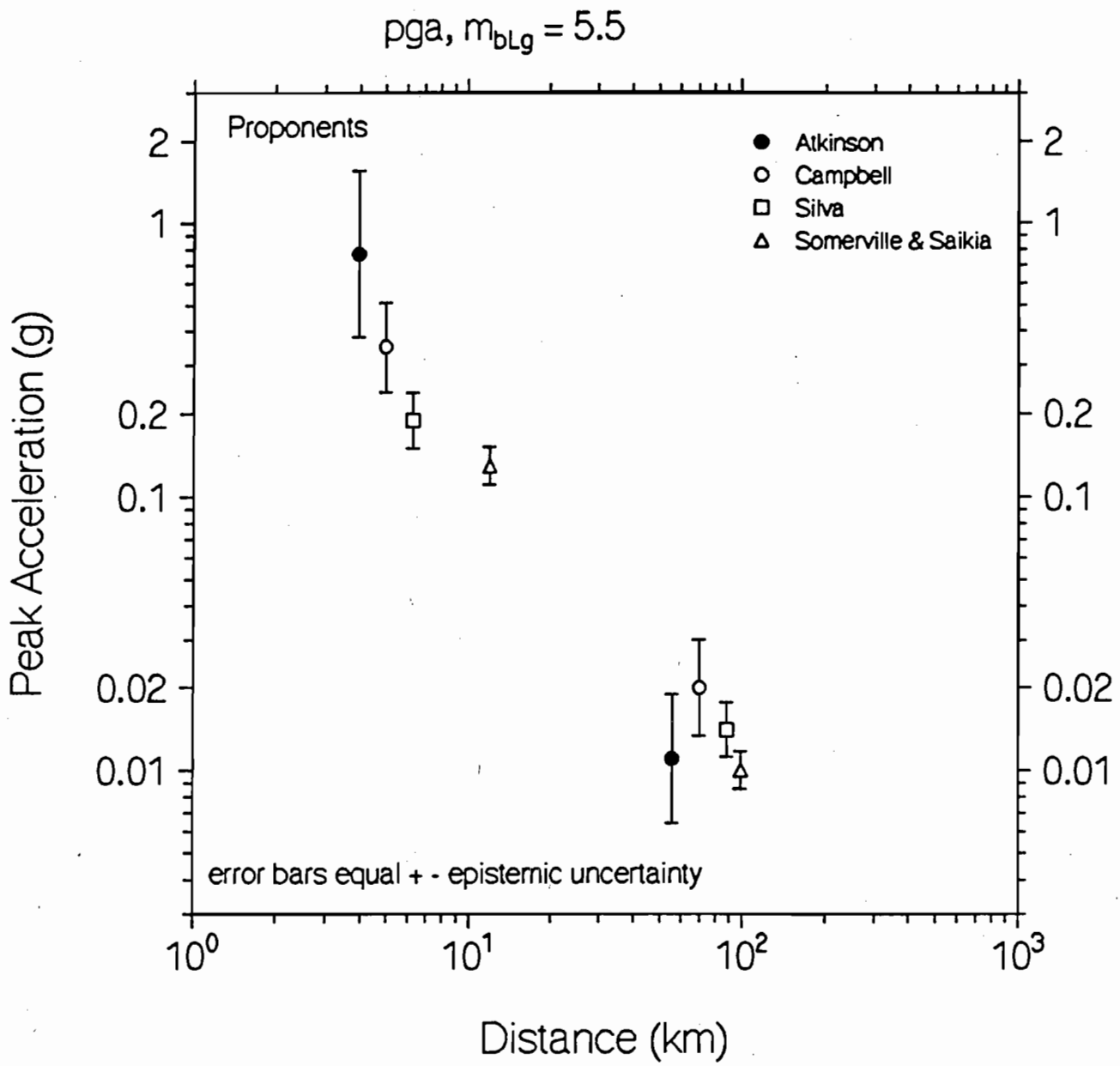

F = 2.5 Hz, mbLg = 7.0
Proponents
Atkinson
Campbell
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty
Spectral Acceleration (g)
2
1
0.2
0.1
0.02
0.01
0.002
10^0
10^1
10^2
10^3
Distance (km)

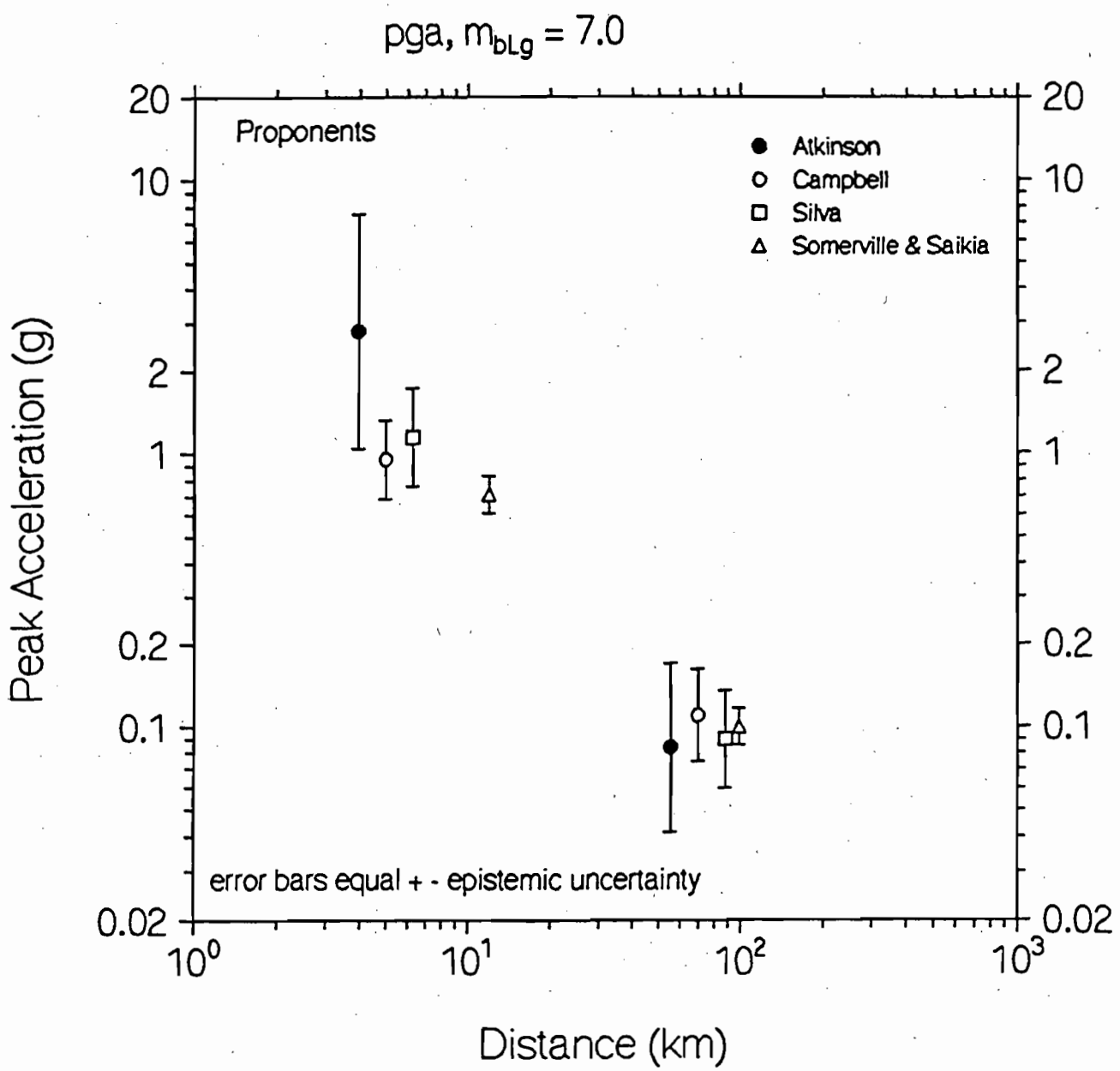

F = 10 Hz, m_{bLg} = 5.5
Proponents
Atkinson
Campbell
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty
Spectral Acceleration (g)
2
1
0.2
0.1
0.02
0.01
10^0
10^1
10^2
10^3
Distance (km)


F = 10 Hz, m_{bLg} = 7.0
Proponents
Atkinson
Campbell
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty
Spectral Acceleration (g)
Distance (km)
20
10
2
1
0.2
0.1
0.02
10^0
10^1
10^2
10^3


F = 25 Hz, m_{bLg} = 5.5
Proponents
Atkinson
Campbell
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty
Spectral Acceleration (g)
2
1
0.2
0.1
0.02
0.01
10^0
10^1
10^2
10^3
Distance (km)


F = 25 Hz, m_{bLg} = 7.0
Proponents
Atkinson
Campbell
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty
Spectral Acceleration (g)
20
10
2
1
0.2
0.1
10^0
10^1
10^2
10^3
Distance (km)


pga, m_{bLg} = 5.5
Proponents
Atkinson
Campbell
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty
Peak Acceleration (g)
2
1
0.2
0.1
0.02
0.01
10^0
10^1
10^2
10^3
Distance (km)


pga, m_{bLg} = 7.0
Proponents
Atkinson
Campbell
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty
Peak Acceleration (g)
Distance (km)
20
10
2
1
0.2
0.1
0.02
10^0
10^1
10^2
10^3

ATTACHMENT B-2

EXPERTS 1 (PRE-WORKSHOP) RESULTS

a. Instructions B-224
b. Results and documentation B-242
c. Plots of median ± epistemic uncertainty B-362
d. Plots of median ± total uncertainty B-372
e. Plots of epistemic uncertainty B-378
f. Plots of aleatory uncertainty B-388
g. Plots of total uncertainty B-398

SSHAC SECOND GROUND-MOTION WORKSHOP

INSTRUCTIONS AND QUESTIONNAIRE FOR EXPERTS

Gabriel R. Toro
Risk Engineering, Inc.
July 8, 1994

As part of your participation in the second SSHAC Ground Motion Workshop, we are asking you to prepare and document ground-motion estimates for a specific tectonic province and for a suite of magnitudes, distances, and frequencies of engineering interest. We are testing a format for these estimates that is somewhat different from those used in past ground-motion elicitation efforts. Your estimates, and the data and arguments supporting these estimates, will be important inputs in the development of a composite ground-motion model. Please return your estimates and documentation so that I receive them by July 20, 1994. We need this material for a meeting on July 21.

The definition of the problem is as follows:

- Site location: northeastern United States or southeastern Canada
- Site conditions Eastern United States Rock (2800 m/s average shear-wave velocity over the top 30 m)
- Magnitudes, distances (to closest point on rupture), and oscillator frequencies as given below:

Distance to closest point on rupture (km)	m_{Lg} 5.5	m_{Lg} 7
5	1 Hz, 10 Hz, PGA	1 Hz*, 10 Hz*, PGA
20	1 Hz*, 2.5 Hz*, 10 Hz*, 25 Hz*	1 Hz*, 2.5 Hz, 10 Hz*, 25 Hz*
70	1 Hz, 10 Hz, PGA	1 Hz, 10 Hz, PGA
200	1 Hz	1 Hz*

where the asterisks denote debating points (i.e., predictions on which we will focus the comparisons and discussions).

For each magnitude-distance-frequency combination, you are asked to provide the following information (ordered by priority):

1a an estimate of the median ground-motion amplitude (5% damped spectral acceleration or PGA),

1b a central estimate of the aleatory uncertainty (about the true median) anticipated in future observations of ground motions under the same conditions (i.e., same magnitude, distance, geographic region, and site conditions; this aleatory uncertainty is typically represented by the standard deviation σ, which we will call $\sigma_{\ln[\text{amplitude}],\ \text{aleatory}}$ for the sake of clarity),

2a an estimate of the epistemic uncertainty associated with your estimate of the median,

2b epistemic uncertainty associated with the aleatory uncertainty (i.e., uncertainty about the true value of $\sigma_{\ln[\text{amplitude}],\ \text{aleatory}}$),

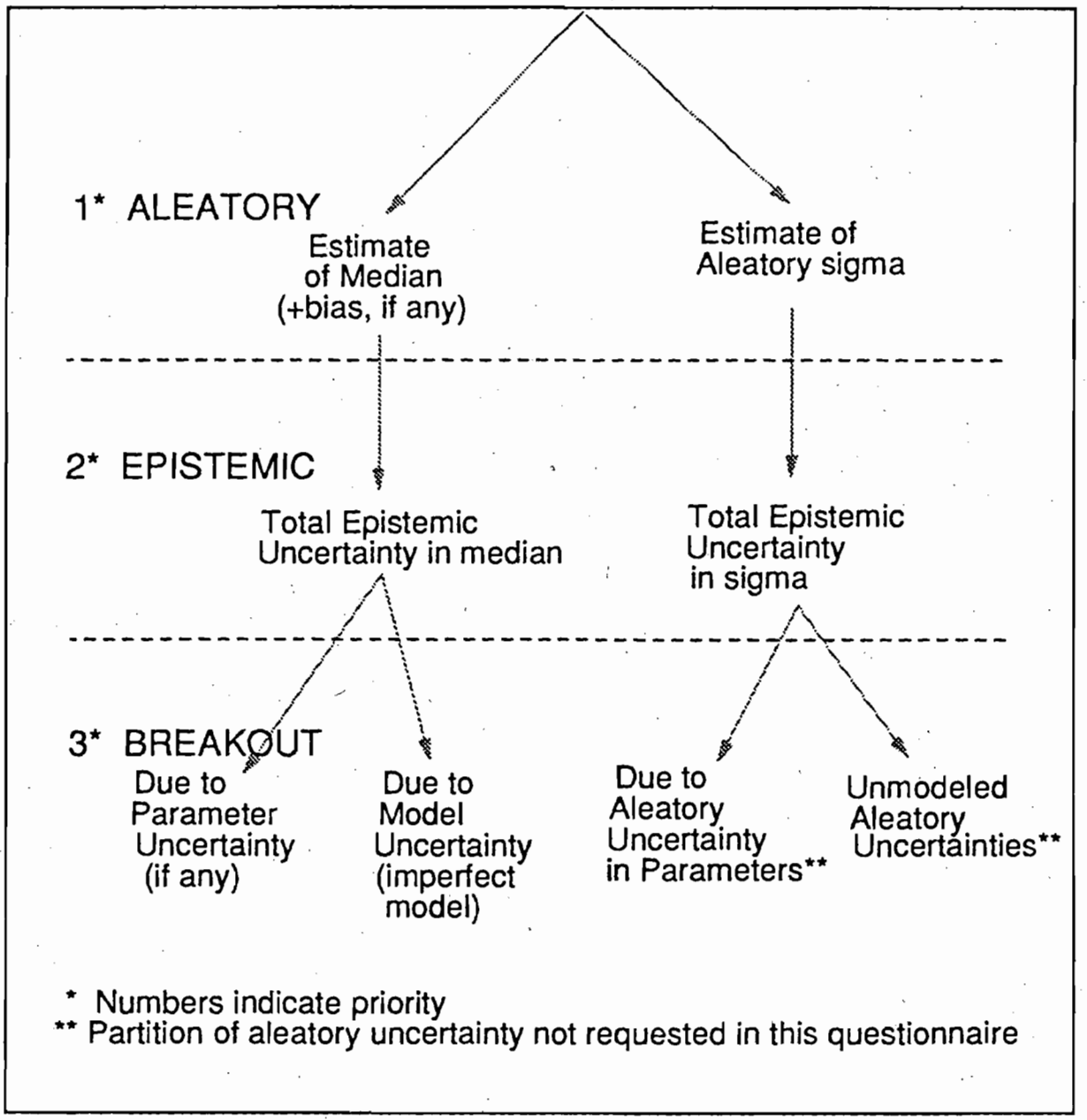
3 partitioning of the epistemic uncertainty into its parametric and modeling components, if applicable.

The definition of epistemic and aleatory uncertainties follows the "white paper" distributed prior to the first workshop, and are repeated below:

> Epistemic Uncertainty. Uncertainty that is due to incomplete knowledge and data about the physics of the earthquake process. In principle, epistemic uncertainty can be reduced by the collection of additional information.
>
> Aleatory Uncertainty. Uncertainty that is inherent to the unpredictable nature of future events. It represents unique details of source, path, and site response that cannot be quantified before the earthquake occurs. Given a model, one cannot reduce the aleatory uncertainty by collection of additional information.

The epistemic uncertainty about the median amplitude is further sub-divided into two components: parametric and modeling. The parametric component represents, for example, uncertainty about the median amplitude due to uncertainty about the median stress drop for the eastern U.S. (e.g., is it 120 bars?, does it increase with seismic moment?). The modeling component relates to uncertainty about the model's systematic bias (i.e., $\ln[\text{Amplitude}]_{\text{true}} - \ln[\text{Amplitude}]_{\text{predicted}}$). Such bias may be introduced by the model's functional form or by parameters that are not treated explicitly as uncertain. Uncertainty about the size of the bias arises because the data available for model validation are few and are often outside the magnitude-distance range of engineering interest. The Appendix to these instructions, and the white paper distributed prior to the first workshop, contain examples on these distinctions. In addition, you may contact David Boore, Allin Cornell, or myself, if you have any question about these distinctions or if you wish to discuss their validity or usefulness.

In the evaluation of epistemic and aleatory uncertainties, you should use whichever method you think is appropriate (e.g., propagation of parameter and modeling uncertainties, use of empirical data from ENA or other regions, and/or direct subjective assessments). Your assessment of aleatory uncertainty should be conditional on the independent variables given (i.e., m_{Lg}, closest distance, geographic region, and site conditions). If your model contains additional independent variables (e.g., stress drop, focal depth, rupture dimensions, depth to basement), you should incorporate the effect of uncertainty in these variables on the total aleatory uncertainty requested above.The following graph illustrates the relationships among the quantities that you are asked to provide, and their relative priorities.



Enclosed with these instructions are the ground-motion estimates and documentation prepared by four "model proponents." The four models represented by the proponents were selected as the four models more appropriate for ground-motion prediction in the CEUS, based on the feedback received during the first Workshop. You should use these estimates and documentation as background information when preparing your estimates. You are not required to (1) choose from among the proponent's estimates, or (2) submit your estimate as a weighted sum of the proponent's estimates. You are free to use any approach or combination of approaches, including the proponents', to arrive at your estimates. Also, the sensitivity results provided by the proponents should also help you if you would like to use a proponent's model but do not agree with the median values or parametric uncertainties used by that proponent.

You should take the broader perspective of an integrator rather than that of a scientist defending his or her preferred model. If you think that a model other than your preferred model is a credible model, you should consider that model's estimates when arriving at your estimates of median values and uncertainties.

Format of Results and Documentation

Estimates of Median and Uncertainties. Your results for the prescribed magnitudes, distances, and frequencies should be provided in the attached forms 1 through 5. Debating points are identified by thick rectangles; magnitude-distance-frequency combinations for which no input is required are shaded. You may wish to submit, in addition, graphical results, tables, and/or equations that cover a wider magnitude-distance-frequency range; we encourage but do not require such results. The functional forms you provide may prove helpful because, ultimately, we shall have to provide predictions over a continuous range of magnitude and distance.

The aleatory uncertainty may be represented adequately by a lognormal distribution (so, you would simply specify $\sigma_{\ln[Amp],aleatory}$). If you feel that this is not the case, provide an alternative distribution. You should also specify truncation, if appropriate. We encourage you to concentrate your attention on the extent of the spread (as measured, for example, by the logarithmic standard deviation of the median; i.e., $\sigma_{\ln[Amp]aleatory}$), rather than on the fine details of the distribution shape (i.e., lognormal vs. triangular).

Each component of the epistemic uncertainty may also be represented adequately by lognormal distributions (in which case you would enter the logarithmic standard deviation [using natural logs]), or by discrete, triangular, uniform, or other distributions. If you do not think that the partitioning of epistemic uncertainty into parametric and modeling components is not appropriate or practical, enter your estimate of the total epistemic uncertainty in the box labeled "uncert. in bias (ln)."[1]

---

[1]We left the format of the tables unchanged for the sake of consistency between the tables used by the proponents and those used by the larger group of experts. We recognize that it may not always be practical to break-up the epistemic uncertainty into its modeling and parametric components. It is more important that you concentrate on the median estimate and on the total aleatory and epistemic uncertainties.

To specify the epistemic uncertainty about the proper value of $\sigma_{\ln[Amp],aleatory}$, you may use multiple values of $\sigma_{\ln[Amp],aleatory}$ with associated weights or, again, any other simple measure of "spread" such as the epistemic standard deviation of $\sigma_{\ln[Amp],aleatory}$.

Documentation. Please provide three to ten pages of documentation, summarizing and justifying the approach (or approaches) and parameters used to generate your estimates, including how the two uncertainty estimates were obtained. In addition, you should briefly discuss the following three topics:

1. strengths and weaknesses of the approach (or approaches) used or considered, and applicability to each of the magnitude-distance-frequency ranges of interest;

2. qualitative discussion of whether the hard-rock site considered here is representative of rock sites in CEUS

3. qualitative discussion of how your results would be different for other regions within CEUS.

Your discussion of the various approaches used should consider the inner elements and parameters in each approach used or considered. If you like one element of a certain approach but think other elements of that approach are weak, you should state that.

You may wish to include relevant papers and reports as appendices to your documentation.

Expert: _____

Ground Motion Measure: 1-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

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Expert: _____

Ground Motion Measure: 2.5-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

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Expert: _____

Ground Motion Measure: 10-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

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Expert: _____

Ground Motion Measure: 25-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

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Expert: _____

Ground Motion Measure: Peak Ground Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

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APPENDIX

THE PARTITION AND ESTIMATION OF UNCERTAINTY

(rev. July 11, 1994)

In the "white paper" on uncertainty, we developed a two-way partition of uncertainty, as follows:

a) Is this uncertainty that can be reduced with the collection of additional data? (epistemic vs. aleatory)

b) Is this uncertainty due to a parameter of the model that is explicitly treated as uncertain? (parametric vs. modeling)

The table that follows contains examples of the four types of uncertainty resulting from this partitioning.

	Epistemic	Aleatory
Modeling	Uncertainty about the true model bias (i.e, to what extent model has a tendency to over- or under-predict observations)	Unexplained scatter due to physical processes not included in the model
Parametric	Uncertainty about median stress drop for ENA, depth distribution, etc.	Event-to-event variation in stress drop or focal depth, etc

In this exercise, we are asking you to report the two components of epistemic uncertainty and the combined (parametric+modeling) aleatory uncertainty. The example that follows should clarify these definitions.

Consider first the hypothetical situation in which there are thousands of records from earthquakes in the region of interest, all having the magnitude (m_x), same distance (r_x), and

same site category (s_x) for the prediction at hand. Given these data, we can compute the true value of the median[2] ground-motion amplitude at a certain frequency as

$$\ln[Amplitude]_{\text{true median}} = \frac{1}{N}\sum_{i=1}^{N} \ln[Amplitude]_{\text{observed},\, i} \tag{1}$$

where N is the number of records. One can also compute the true standard deviation associated with aleatory uncertainty (which is due to aleatory variations in all source, path, and site factors other than region, magnitude, distance, and site category) from the observed scatter as

$$\sigma_{\ln[Amplitude],\text{aleatory}} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} \left(\ln[Amplitude]_{\text{observed},\, i} - \ln[Amplitude]_{\text{true median}}\right)^2} \tag{2}$$

Assume also that we have a deterministic predictive model (e.g., a physical model, a stochastic model, or an empirical attenuation function) of the form:

$$\ln[Amplitude]_{\text{pred}} = f(m, r, \text{ site category; } \boldsymbol{P}) \tag{3}$$

where $\boldsymbol{P}$ is a vector of explicit model parameters (e.g., stress drop, focal depth, slip distribution, etc.) and that we know the parameter values $\boldsymbol{P}_i$ for each record. This model can be used to predict the amplitude for a given set of parameters $\boldsymbol{P}_0$, as

$$\ln[Amplitude]_{\text{pred},\boldsymbol{P}_0} = f(m, r, \text{ site category; } \boldsymbol{P}_0) \tag{4}$$

The predictive model can also be used to predict the median amplitude for the magnitude, distance and site conditions of interest as

$$\ln[\text{Ampl.}]_{\text{pred. median}} = \frac{1}{N}\sum_{i=1}^{N} f(m_x, r_x, s_x;\ \boldsymbol{P}_i) \tag{5}$$

which is equivalent to

[2]We are using the term median in a loose sense. Strictly speaking, the quantity in Equation 1 is the logarithmic-mean amplitude, which is equal to the median amplitude only if the amplitude follows a log-normal distribution.

$$\ln[\text{Ampl.}]_{\text{pred. median}} = E_P\left[f(m_x, r_x, s_x;\ P)\right] \tag{6}$$

where E_P denotes expected value (i.e., averaging) over the distribution of the parameter vector P. In the hypothetical situation considered here, we know the probability distribution of the parameters in P (i.e., we know the median, mean, standard deviation, distribution type, etc, for all parameters in P) because we have a very large number of records and we know the parameter values P_i for each record.

Because the predictive model does not include all physical processes and parameters affecting ground motions, the predicted median value is likely to differ from the true median value. The bias in the predictive model can be evaluated by comparing observations and predictions for the available recordings for the same magnitude, distance, and site category of interest; i.e.,

$$\mu = \frac{1}{N}\sum_{i=1}^{N}\left(\ln[Amplitude]_{\text{observed, } i} - f(m_x, r_x, s_x;\ P_i)\right) \tag{7}$$

or

$$\mu = \ln[Amplitude]_{\text{true median}} - \frac{1}{N}\sum_{i=1}^{N} f(m_x, r_x, s_x;\ P_i) \tag{8}$$

Because we know the model bias for the magnitude, distance, and site conditions of interest, we can use bias-corrected model predictions of the true median amplitude.

The aleatory uncertainty defined in Equation 3 can be decomposed into uncertainty due to uncertainty in the parameter vector P (aleatory parametric uncertainty) and uncertainty due to un-modeled physical processes and missing parameters (aleatory modeling uncertainty). Equation 2 is re-written as[3],

$$\sigma_{\ln[Amplitude],\text{aleatory}} = \sqrt{\begin{array}{l} \frac{1}{N}\sum_{i=1}^{N}\left(f(m_x, r_x, s_x; P_i) + \mu - \ln[Amplitude]_{\text{true median}}\right)^2 + \\ \frac{1}{N}\sum_{i=1}^{N}\left(\ln[Amplitude]_{\text{observed, } i} - f(m_x, r_x, s_x; P_i) - \mu\right)^2 \end{array}} \tag{9}$$

[4]where the first summation represents aleatory parametric uncertainty and the second summation represents aleatory modeling uncertainty. In a manner analogous to the step of

[3]We assume that the predictive model's dependence on the parameters in vector P is correct.

4

going from Equation 5 to Equation 6, the parametric term may be written as an expectation over the parameter values, obtaining

$$\sigma_{\ln[Amplitude],\text{aleatory}} = \sqrt{\begin{array}{l} E_P\left[\left(f(m_x, r_x, s_x; \boldsymbol{P}) + \mu - \ln[Amplitude]_{\text{true median}}\right)^2\right] + \\ \frac{1}{N}\sum_{i=1}^{N}\left(\ln[Amplitude]_{\text{observed},\,i} - f(m_x, r_x, s_x; \boldsymbol{P}_i) - \mu\right)^2 \end{array}} \tag{10}$$

This partitioning of aleatory uncertainty is not necessary, but some investigators consider it useful when applying models with physically based parameters.

In reality, the number of available records for the desired magnitude, distance, and site category is small at best. Assume, for the moment, that we have a small number n of records with the magnitude, distance, and site conditions of interest. We can apply an equation analogous to Equation 7 (but with the smaller sample size) to estimate the model bias; i.e.,

$$\hat{\mu} = \frac{1}{n}\sum_{i=1}^{n}\left(\ln[Amplitude]_{\text{observed},\,i} - f(m_x, r_x, s_x;\ \boldsymbol{P}_i)\right) \tag{11}$$

but this estimate of the bias has statistical uncertainty because n is small. This uncertainty is epistemic modeling uncertainty.

Limitations in the data also introduce a parametric component of epistemic uncertainty in physical ground-motion models. This uncertainty is due to uncertainty about the true distributions of model parameters. Thus, epistemic parametric uncertainty arises when we apply Equation 6 to predict the median amplitude $\ln[\text{Amplitude}]_{\text{est.,median}}$, being uncertain about the distribution of the parameters (particularly about their central tendencies, i.e., median or mean). Returning to the example of stress drop, the extent of this uncertainty depends on the uncertainty in the median stress drop and on the sensitivity of $f(m_x, r_x, s_x;\ \boldsymbol{P})$ to stress drop.

The aleatory uncertainty may be estimated using equations analogous to Equations 2 or 9; i.e.,

$$\hat{\sigma}_{\ln[Amplitude],\text{aleatory}} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\ln[Amplitude]_{\text{observed},\,i} - \ln[Amplitude]_{\text{est. median}} - \hat{\mu}\right)^2} \tag{12}$$

or

$$\hat{\sigma}_{\ln[Amplitude],\text{aleatory}} = \sqrt{\begin{array}{l} E_P\left[\left(f(m_x, r_x, s_x; \boldsymbol{P}) + \hat{\mu} - \ln[Amplitude]_{\text{est. median}}\right)^2\right] + \\ \frac{1}{n}\sum_{i=1}^{n}\left(\ln[Amplitude]_{\text{observed},\,i} - f(m_x, r_x, s_x; \boldsymbol{P}_i) - \hat{\mu}\right)^2 \end{array}} \tag{13}$$

There is also epistemic uncertainty associated with the estimated $\sigma_{\ln[\text{Ampl.}],\text{aleatory}}$ because of the limited sample size and uncertainty in the distribution of $\boldsymbol{P}$.

In practice, the data are so limited that one is required to use data from other magnitudes, distances, and site categories to estimate the bias, epistemic uncertainty, and aleatory uncertainty. In doing this, there is the implicit assumption that the predictive model $f(m,r,\text{site category}; \boldsymbol{P})$ is equally good, and has the same bias, for (m_x, r_x, s_x) as for the magnitudes, distances, and site categories represented in the data. This assumption introduces additional epistemic uncertainty, which may quantified by considering alternative models.

Some Possible Approaches

The following is a brief description of some of the techniques available for the estimation of bias, epistemic uncertainty, and aleatory uncertainty. Additional details are found in the White Paper on Uncertainty that was distributed prior to the first workshop.

Physical and Stochastic Models. The 1993 EPRI study provides an example of the Abrahamson et al. (1991) formulation of uncertainty. Modeling uncertainty is calculated by comparing observed spectral accelerations to predictions obtained using parameters $\boldsymbol{P}_i$ appropriate to each event and site. These comparisons yield estimates of the bias

$$\hat{\mu} = \frac{1}{n}\sum_{i=1}^{n}\left(\ln[Amplitude]_{\text{observed},\,i} - f(m_i, r_i, s_i;\ \boldsymbol{P}_i)\right) \tag{14}$$

and the standard error

$$\text{std. error} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(\ln[Amplitude]_{\text{observed},\,i} - f(m_i, r_i, c_i; \boldsymbol{P}_i) - \mu\right)^2} \tag{15}$$

The standard error serves as an estimate of the aleatory modeling uncertainty (i.e., physical process and parameters not included in the predictive model, which cause seemingly random scatter). The epistemic modeling uncertainty (i.e., uncertainty in the bias) should be estimated as (std. error)/$(n')^{1/2}$, where n' is the equivalent number of independent observations (this number is smaller than n because of correlation among records from the same event). In the EPRI study, additional epistemic modeling uncertainty was introduced by site-specific correction terms. Additional epistemic modeling uncertainty may arise due to the existence of competing models.

The epistemic and aleatory uncertainty in the model parameters P_i (e.g., uncertainty in the median stress drop and uncertainty in the stress drop for the next event) introduce epistemic parametric and aleatory parametric uncertainties in the predictions. The contributions of stress drop to the epistemic parametric and aleatory parametric uncertainties are approximately[5] equal to

$$\left[\frac{\partial f(m,r,\text{site category};\ P)}{\partial \ln\Delta\sigma}\right]_{P=P_{\text{median}}} \times \sigma_{\overline{\ln\Delta\sigma}} \tag{16}$$

and

$$\left[\frac{\partial f(m,r,\text{site category};\ P)}{\partial \ln\Delta\sigma}\right]_{P=P_{\text{median}}} \times \sigma_{\ln\Delta\sigma} \tag{17}$$

where $\sigma_{\overline{\ln\Delta\sigma}}$ is the logarithmic standard deviation representing epistemic uncertainty in the median stress drop (i.e., how well do we know the median stress drop that we would observe if we studied earthquakes in the region for thousands of years) and $\sigma_{\ln\Delta\sigma}$ is the logarithmic standard deviation representing aleatory uncertainty (i.e., the event-to-event scatter in $\ln[\Delta\sigma]$ that we would observe if we studied earthquakes in the region for thousands of years). Assuming that the uncertainties about all explicit model parameters in P are independent (i.e., no trade-offs), the total epistemic parametric and aleatory parametric uncertainties are approximately equal to

$$\sqrt{\sum_j \left\{\left[\frac{\partial f(m,r,\text{site category};\ P)}{\partial \ln p_j}\right]_{P=P_{\text{median}}} \times \sigma_{\overline{p_j}}\right\}^2} \tag{18}$$

and

$$\sqrt{\sum_j \left\{\left[\frac{\partial f(m,r,\text{site category};\ P)}{\partial \ln p_j}\right]_{P=P_{\text{median}}} \times \sigma_{p_j}\right\}^2} \tag{19}$$

where the summations extend over all model parameters. Alternatively, one may use logic-trees to calculate the parametric uncertainties, as was done in the EPRI study.

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[5] The result is approximate because it involves linearization of f(m,r, site category; P) with respect to one of the parameters in P.

The aleatory uncertainty (modeling+parametric) may also be calculated directly using records from the same region or from other regions (i.e., using Eq. 12). If the magnitudes and distances in the differ substantially from the magnitude and distance for which a prediction is being made, there is a problem with different sensitivity to a parameter (such as Q) at different magnitudes and distances. If residual standard deviations from another region are being used to estimate the aleatory uncertainty in a region with limited data, one should keep in mind the following considerations: (1) if the regression contained additional explanatory variables (e.g., focal depth, style of faulting), these variables should be treated as uncertain parameters and integrated over in order to obtain a revised estimate of aleatory uncertainty; and (2) the residual standard deviation may contain some effects other than aleatory uncertainty (e.g., lack of fit, undetected regional variations in the data set).

Empirical Attenuation Equations. In empirical attenuation equations, the empirically derived coefficients take the role of parameters. These coefficients have no aleatory uncertainty (i.e., they are assumed to be the same for all events and sites). The calculated statistical uncertainty in these coefficients is typically very small and not representative of the true epistemic uncertainty. Differences among empirical models developed by different investigators (using somewhat different data sets and functional forms) is a better representation of epistemic uncertainty.

Modeling uncertainty is characterized by the residual standard deviation σ. This standard deviation contains both aleatory and epistemic components, but it is typically taken as all aleatory.

If empirical attenuation equations are used in a hybrid mode (i.e., the empirical attenuation equations are modified to account for regional differences in source scaling, magnitude definition, path effects, or site effects), such corrections introduce epistemic parametric uncertainty, which should be considered.

If the attenuation equations contain explanatory variables other than magnitude, distance, and site category, one must treat these explanatory variables as uncertain parameters (as was done with physical models). Thus, one must integrate over these parameters, considering the appropriate distribution of the parameter in the region of interest. For instance, if parameter Z represents faulting style in the attenuation equation

$$\ln[\text{Amplitude}]=g(m,r,\text{site category},Z) \tag{20}$$

and the probability of distribution of faulting styles in the region of interest is given by $p_Z(z_1)$, $p_Z(z_2)$, ... $p_Z(z_m)$, then the attenuation equation without Z is equal to

$$g^*(m_x,r_x,s_x)=\sum_{k=1}^{m} p_Z(z_k)\, g(m_x,r_x,s_x,z_k) \tag{21}$$

and the aleatory parametric uncertainty due to Z is characterized by a standard deviation equal to

$$\sqrt{\sum_{k=1}^{m} p_Z(z_k)\left(g(m_x, r_x, s_x, z_k) - g^*(m_x, r_x, s_x)\right)^2} \tag{22}$$

This standard deviation, and other parametric standard deviations, should be combined with the residual standard deviation (using a square root of the sum of the squares formula), to obtain the total aleatory uncertainty associated with g*(m,r,s) (i.e., for predictions in terms of magnitude, distance, and site category).

The distribution of Z above may be magnitude and distance dependent (e.g., the distribution of style of faulting and focal depth may depend on magnitude; the distribution of azimuth may be magnitude and distance dependent). In those cases, distributions of Z for the appropriate values of m_x and r_x must be used.

Changes in the definition of magnitude or distance can be treated in a similar manner. For instance, if the original attenuation equation uses distance definition R_1 and one wants to change to R_2, one may perform calculations similar to those in Equations 12 and 13 (but in integral form), using the conditional probability density function $f_{R_1|R_2,m,r}(r_1;\ r_2,m,r)$. Even if distance definition R_2 is superior to R_1, this approach will yield a higher residual standard deviation for R_2, because it ignores dependence between the regression residuals and $R_1|R_2,m,r$.

Ground Motion Estimates by N. Abrahamson

Distance Definition:

There is a discrepancy in the distance definitions for the models provided to the experts. The instructions specify that rupture distance is used, but Walt's model (the EPRI model) uses a horizontal distance (e.g. Joyner and Boore type distance). This creates a problem for the 5 km distance estimate for both the median value and the aleatory uncertainty (the focal depth variability increases the aleatory uncertainty).

In addition, Gail's model uses a point source. She has located the point source at the rupture distance. As pointed out by Gail, this is not appropriate for a magnitude 7 at 5 km.

In interpreting these models, I made a rough correction to the distances for the 5 km case. For Walt's model I based the correction on the depth distribution used in the EPRI model. The median depth is about 12 km. Therefore for M=5.5, I used 13 km. For the large magnitude event, I also considered the depth of the asperity since the point source model has been validated against WUS large event data by putting the point source at the closest point of the fault but at the depth of the asperity. In the EPRI model, the mean asperity depth is located at 60% down dip. Using a weighting of 2/3 for 45 degree dips and 1/3 for 90 degree dips, I computed a rupture distance of 8.5 km for Walt's 5 km distance estimates.

For Gail's model, I also assumed that the point source should be located at the closest distance but at the depth of the asperity. If the asperity is at a depth of 5 km, then I assumed that the rupture reaches the surface. Again using a weighting of 2/3 for 45 degree dips and 1/3 for 90 degree dips, I computed a closest distance of 2.5 km for Gail' model. I should note that I don't think that an event with an asperity disatance of 5 km is likely to occurr.

Additional Models

In making the ground motion estimates, I considered some additional models.

First, I developed estimates for a new model that is a modification of the EPRI model but using a magnitude dependent high-frequency stress-parameter for M>6 (see Figure V.5-5). I did this to account for variability in a more rational way.

In the EPRI model, a constant median high-frequency stress-parameter was used (120 bars). However, this constant value exceeds the stress-parameter for M>6. Therefore, the model has a bias (although with a large uncertainty). The median stress-parameter for large magnitude earthquakes has more uncertainty than the median stress-parameter for moderate earthquakes. Therefore, the epistemic uncertainty for the larger magnitude events should be higher. Having a negative bias coupled with a larger epistemic uncertainty would overestimate the ground motions for large magnitude events at the 84th percentile. To avoid this, the aleatory uncertainty for the large magnitude events was reduced. This reduction is consistent with the trend magnitude dependent aleatory uncertainty observed in WUS data.

As an alternative model, I've used a magnitude dependent stress-parameter model that removes the bias at large magnitude and coupled this with a larger epistemic uncertainty. The ground motions for the new model were estimated using Walt's sensitivity of 60% change in ground motion for a 100% change in stress-parameter. I estimated that the epistemic uncertainty due to the magnitude dependent stress-parameter is 0.25 natural log units for a magnitude 7 event. (I assume that moment magnitude 7 and MLG 7 are the same)

In addition, I've considered the empirical data for rock sites shown in the EPRI report (Figures 2-3, 2-5, 2-7,and 2-9). This is not a formal regression, but rather a rough estimate of the median ground motions. I also considered a WUS rock empirical ground motion model (Geomatrix, 1991) for reference. For the WUS attenuation relation, I used a moment magnitude of 5 for the MLG 5.5 event and a moment magnitude of 7.0 for the MLG 7.0 event.

Approach Used to Develop Ground Motion Estimates

My approach to developing the ground motion estimates was to first plot up the various model predictions (using a consistent distance). I then looked at the

discrepancies and evaluated the models based on my estimate of their strengths and weaknesses for the particular magnitude, distance, frequency combination.

Separating modeling uncertainty and parametric uncertainty

I have assumed that the difference between the one-corner and two-corner models for the stochastic approaches is a difference in the model parameters and not in the models. Therefore, I have put the uncertainty associated with the one vs two corner models under parametric epistemic uncertainty. I'm not sure this is right and I need to think about it some more.

I have not had time to develop a formal procedure for computing the uncertainties, so I just estimated the uncertainties based on the plotted results. The partitioning of the epistemic uncertainty into parametric and modeling used the following guidelines:

Variability of the median of the median predictions is combined with the specified parametric epistemic uncertainties to estimate the composite parametric epistemic uncertainty. That is, I increased the average parametric epistemic uncertainty to account for variability between the median predictions for the alternative models. This assumes that the models could be made to give the same predictions if the parameter distributions in the models were modified.

The modeling epistemic uncertainty is based on validation of the models to previous earthquake recordings. For this, I used the listed values. The modeling epistemic uncertainty should be increased as the model is applied to events outside of the magnitude and distance range used in the validation. For the specified events, (MLG=5.5 and MLG=7.0) the models have been validated for this magnitude range. As a result, I have not increased the modeling epistemic uncertainties.

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 1: Page __ of __

Expert: N. Abrahamson

Ground Motion Measure: 1-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.040	0.50
	epistemic uncertainty	parametric (ln)	0.30	0.35
		median bias	0	0
		uncert. in bias (ln)	0.20	0.20
	aleatory uncertainty	median σ	0.80	0.75
		uncertainty in σ	0.10	0.15
20 km	median amplitude		0.010	0.15
	epistemic uncertainty	parametric (ln)	0.30	0.35
		median bias	0	0
		uncert. in bias (ln)	0.20	0.20
	aleatory uncertainty	median σ	0.84	0.75
		uncertainty in σ	0.10	0.15
70 km	median amplitude		0.0025	0.038
	epistemic uncertainty	parametric (ln)	0.30	0.35
		median bias	0	0
		uncert. in bias (ln)	0.20	0.20
	aleatory uncertainty	median σ	0.85	0.77
		uncertainty in σ	0.10	0.18
200 km	median amplitude		0.0009	0.018
	epistemic uncertainty	parametric (ln)	0.25	0.40
		median bias	0	0
		uncert. in bias (ln)	0.20	0.20
	aleatory uncertainty	median σ	0.85	0.80
		uncertainty in σ	0.10	0.18

Comments/footnotes:

Expert: N. Abrahamson

Ground Motion Measure: 2.5-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.040	0.36
	epistemic uncertainty	parametric (ln)	0.25	0.30
		median bias	0	0
		uncert. in bias (ln)	0.20	0.20
	aleatory uncertainty	median σ	0.73	0.65
		uncertainty in σ	0.10	0.15
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

Expert: N. Abrahamson

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Ground Motion Measure: 10-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.16	2.2
	epistemic uncertainty	parametric (ln)	0.25	0.35
		median bias	0	0
		uncert. in bias (ln)	0.15	0.15
	aleatory uncertainty	median σ	0.72	0.65
		uncertainty in σ	0.10	0.15
20 km	median amplitude		0.16	0.75
	epistemic uncertainty	parametric (ln)	0.20	0.30
		median bias	0	0
		uncert. in bias (ln)	0.15	0.15
	aleatory uncertainty	median σ	0.72	0.65
		uncertainty in σ	0.10	0.15
70 km	median amplitude		0.030	0.18
	epistemic uncertainty	parametric (ln)	0.25	0.25
		median bias	0	0
		uncert. in bias (ln)	0.15	0.15
	aleatory uncertainty	median σ	0.72	0.65
		uncertainty in σ	0.10	0.15
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND GROUND MOTION WORKSHOP

Form 4: Page __ of __

Expert: N. Abrahamson

Ground Motion Measure: 25-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.18	1.0
	epistemic uncertainty	parametric (ln)	0.25	0.25
		median bias	0	0
		uncert. in bias (ln)	0.15	0.15
	aleatory uncertainty	median σ	0.72	0.60
		uncertainty in σ	0.10	0.15
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND GROUND MOTION WORKSHOP

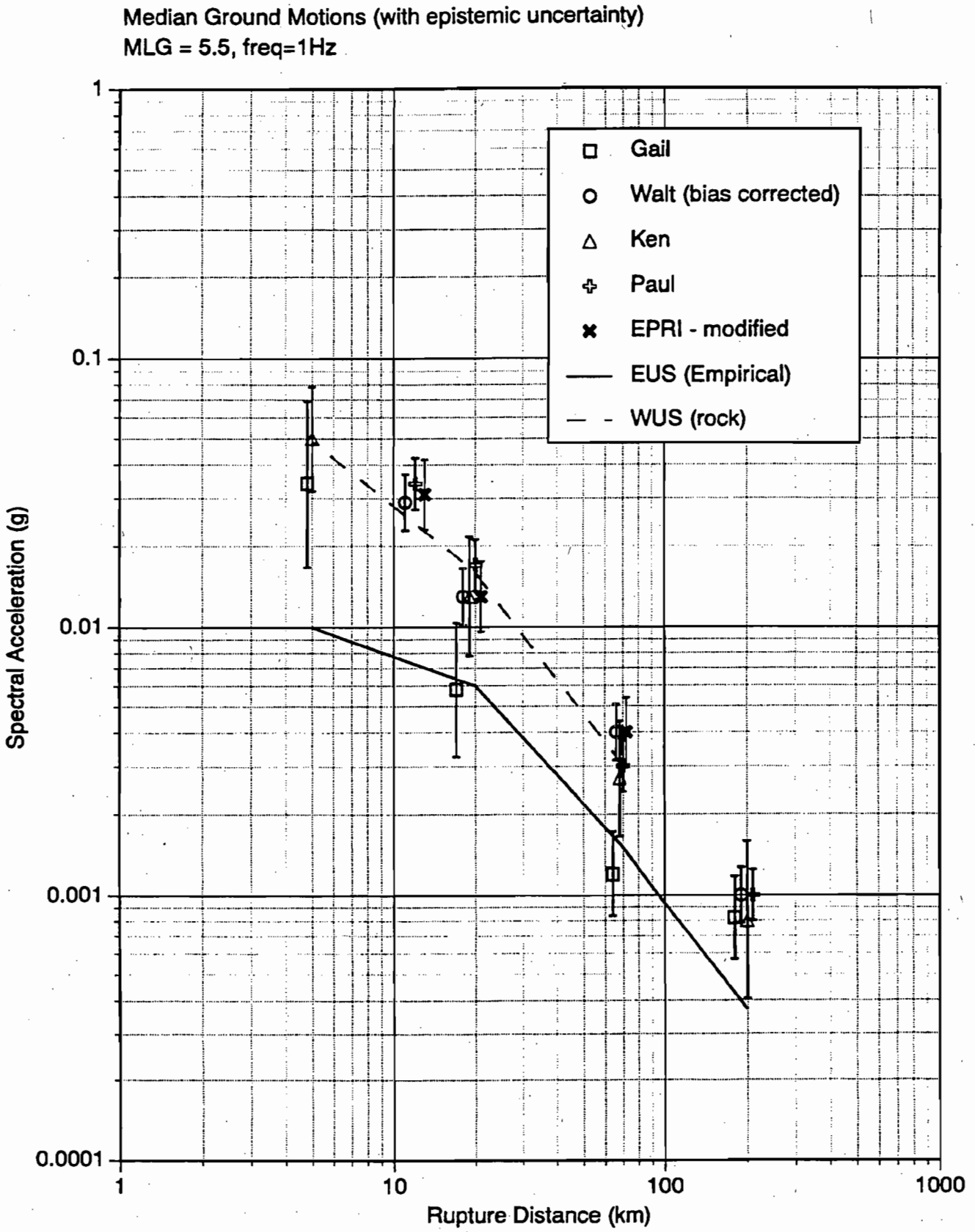
Form 5: Page __ of __

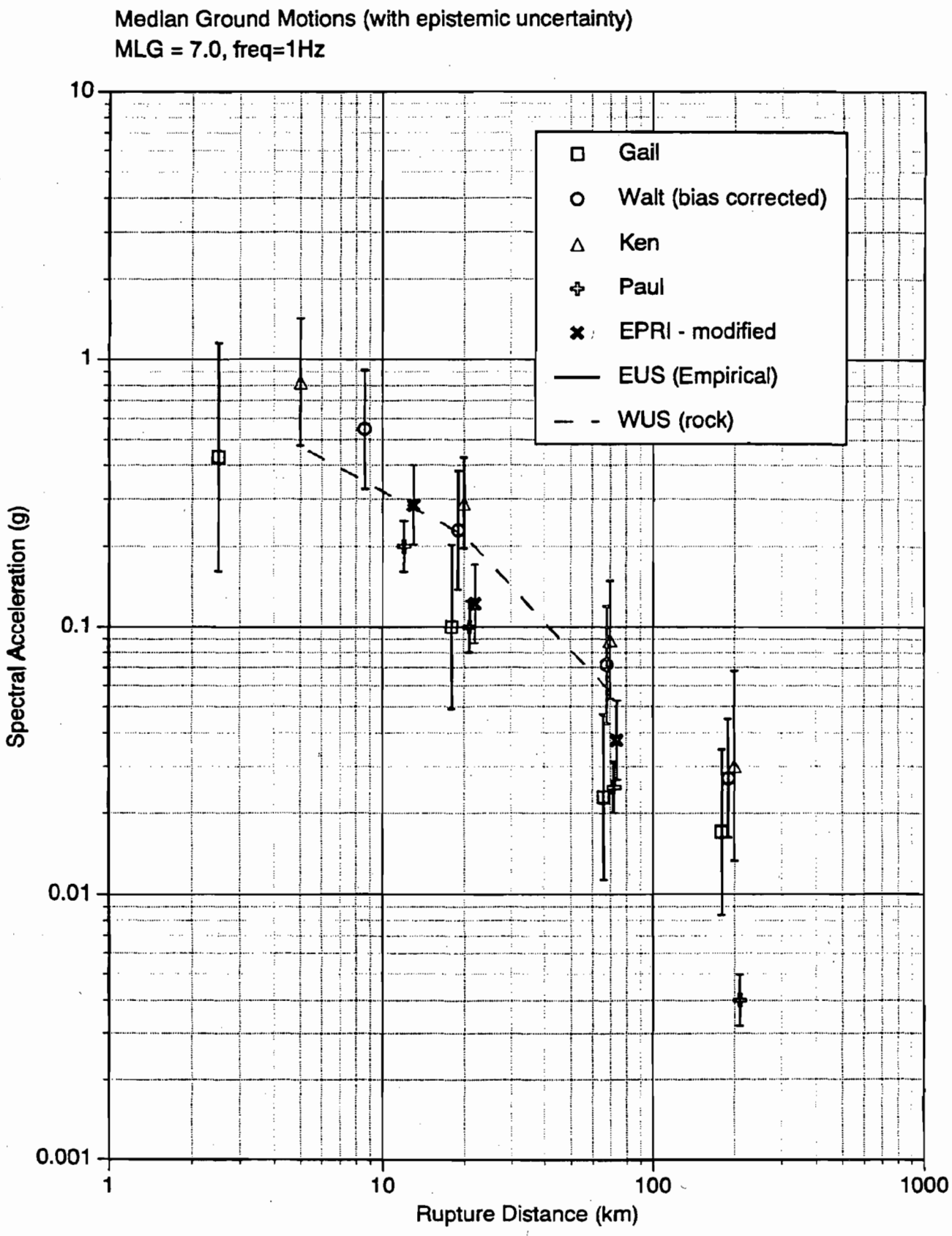
Expert: N. Abrahamson

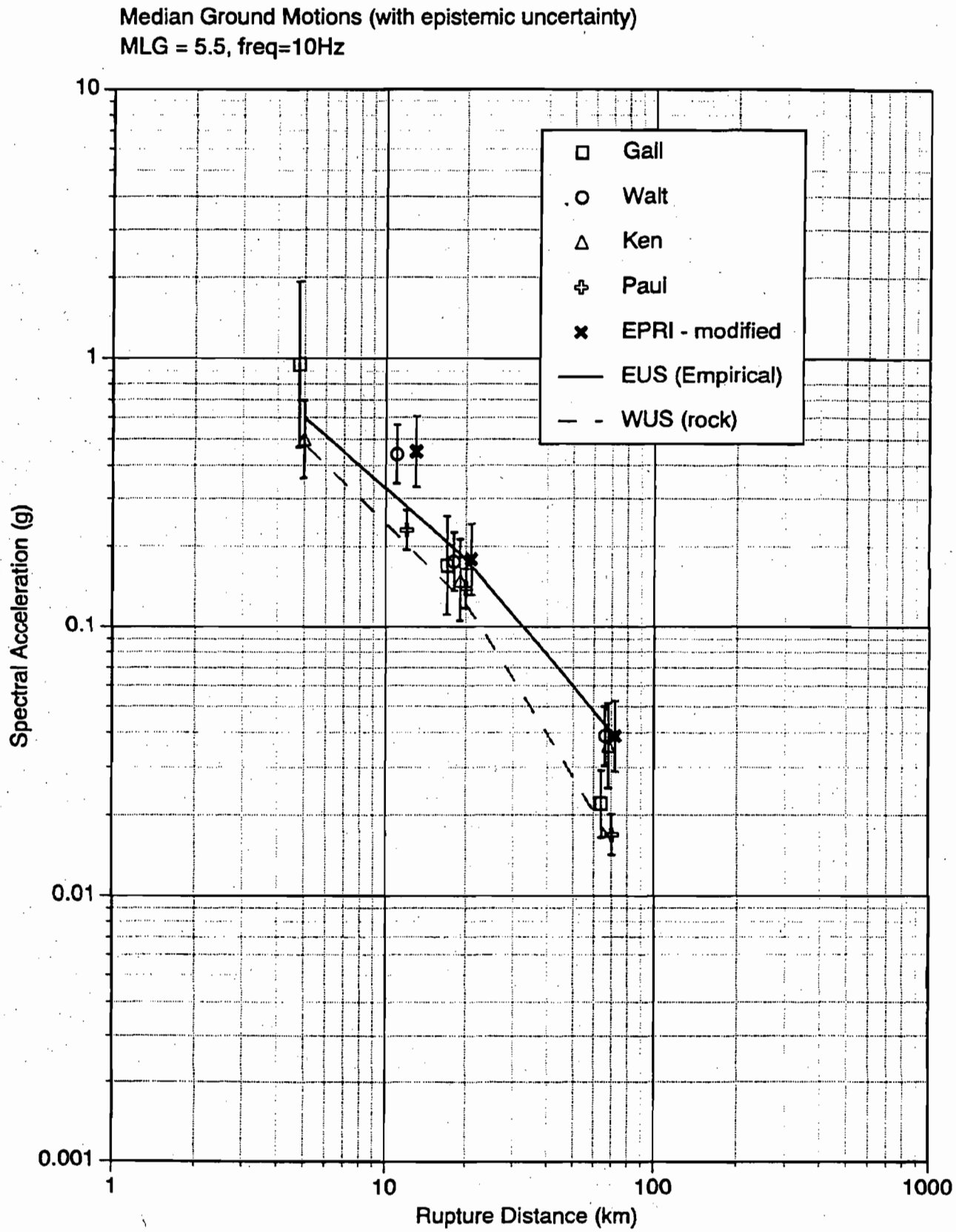
Ground Motion Measure: Peak Ground Acceleration (g)

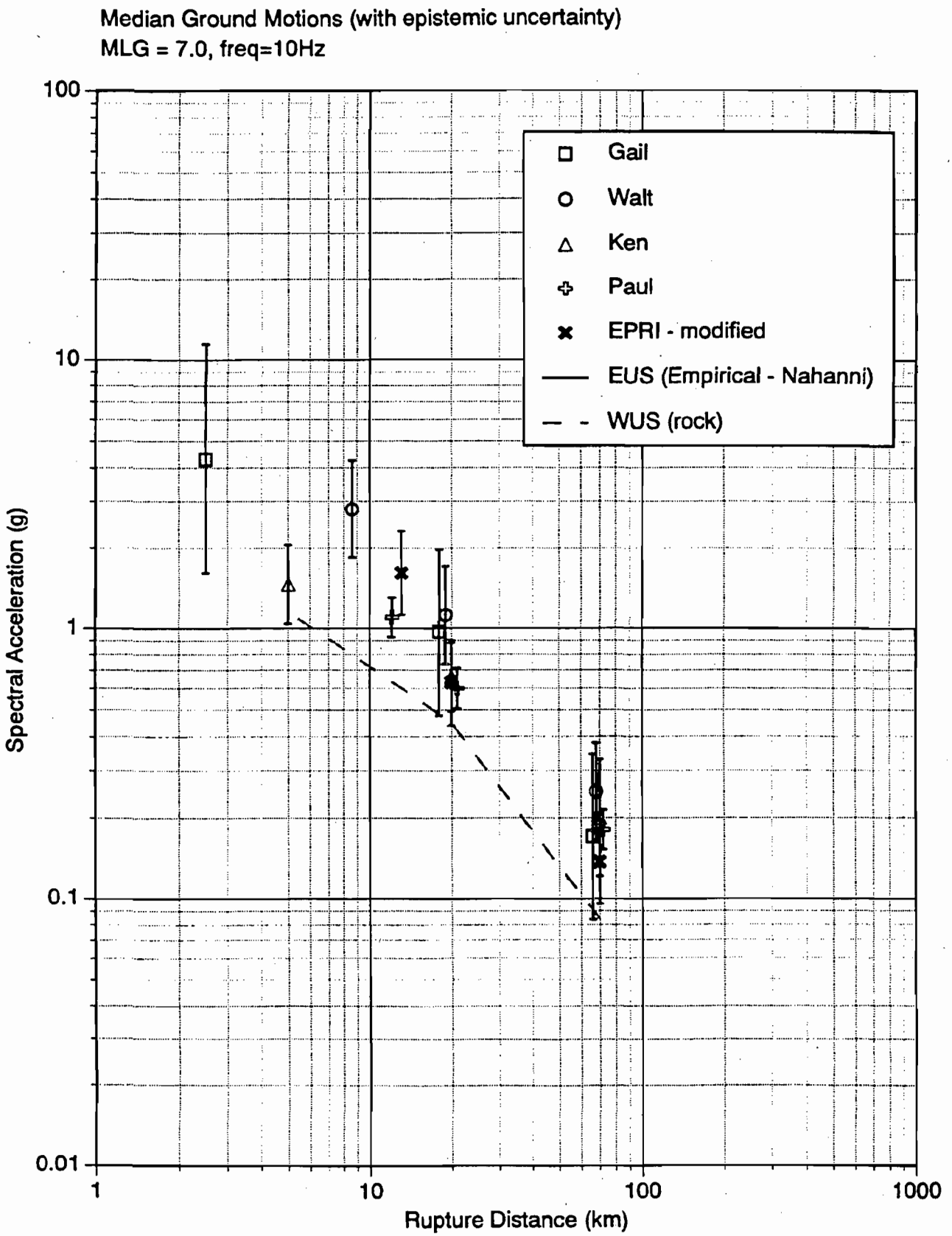
Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.52	1.7
	epistemic uncertainty	parametric (ln)	0.30	0.35
		median bias	0	0
		uncert. in bias (ln)	0.15	0.15
	aleatory uncertainty	median σ	0.72	0.60
		uncertainty in σ	0.10	0.15
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude		0.013	0.090
	epistemic uncertainty	parametric (ln)	0.25	0.20
		median bias	0	0
		uncert. in bias (ln)	0.15	0.15
	aleatory uncertainty	median σ	0.75	0.60
		uncertainty in σ	0.10	0.15
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

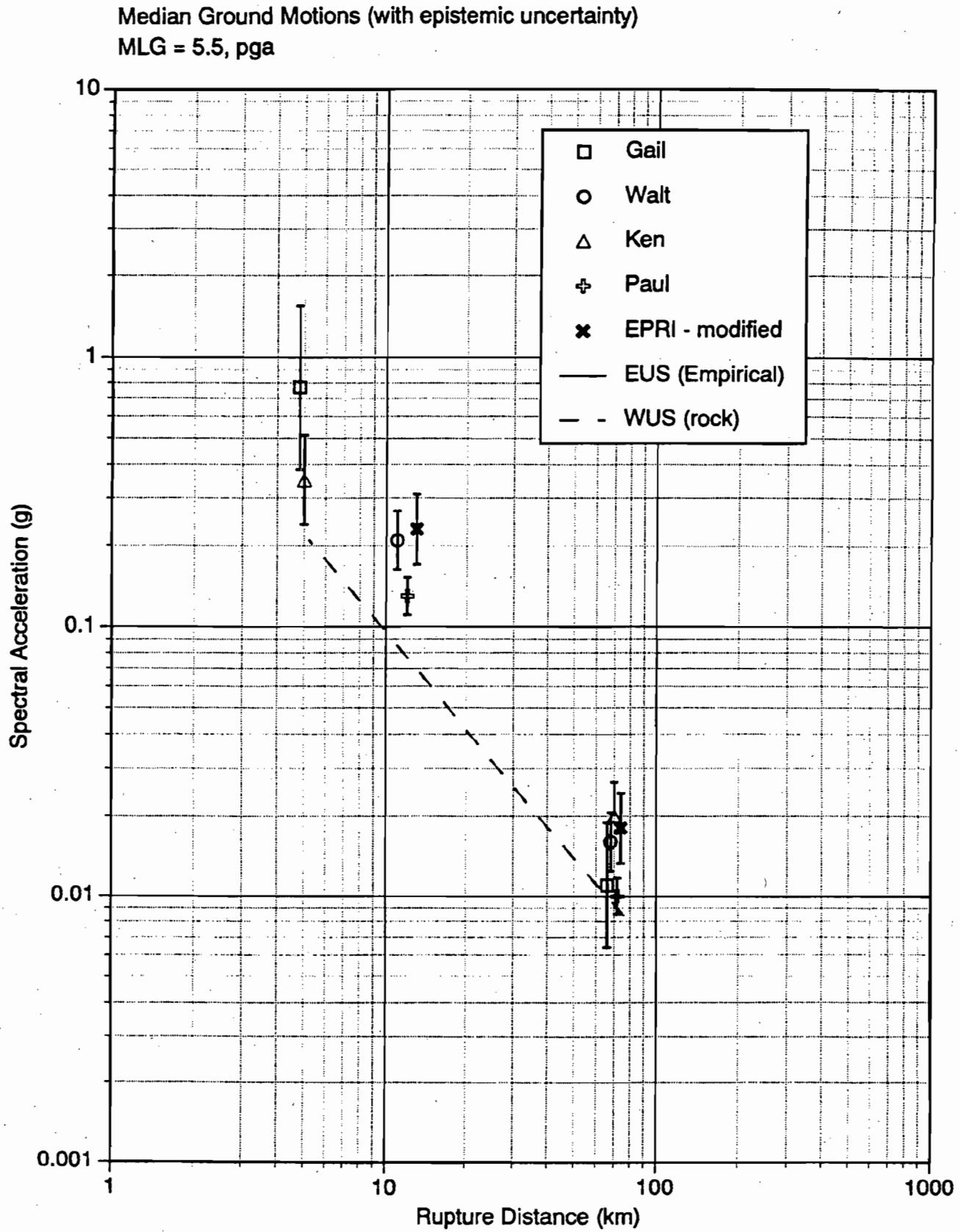
Comments/footnotes:

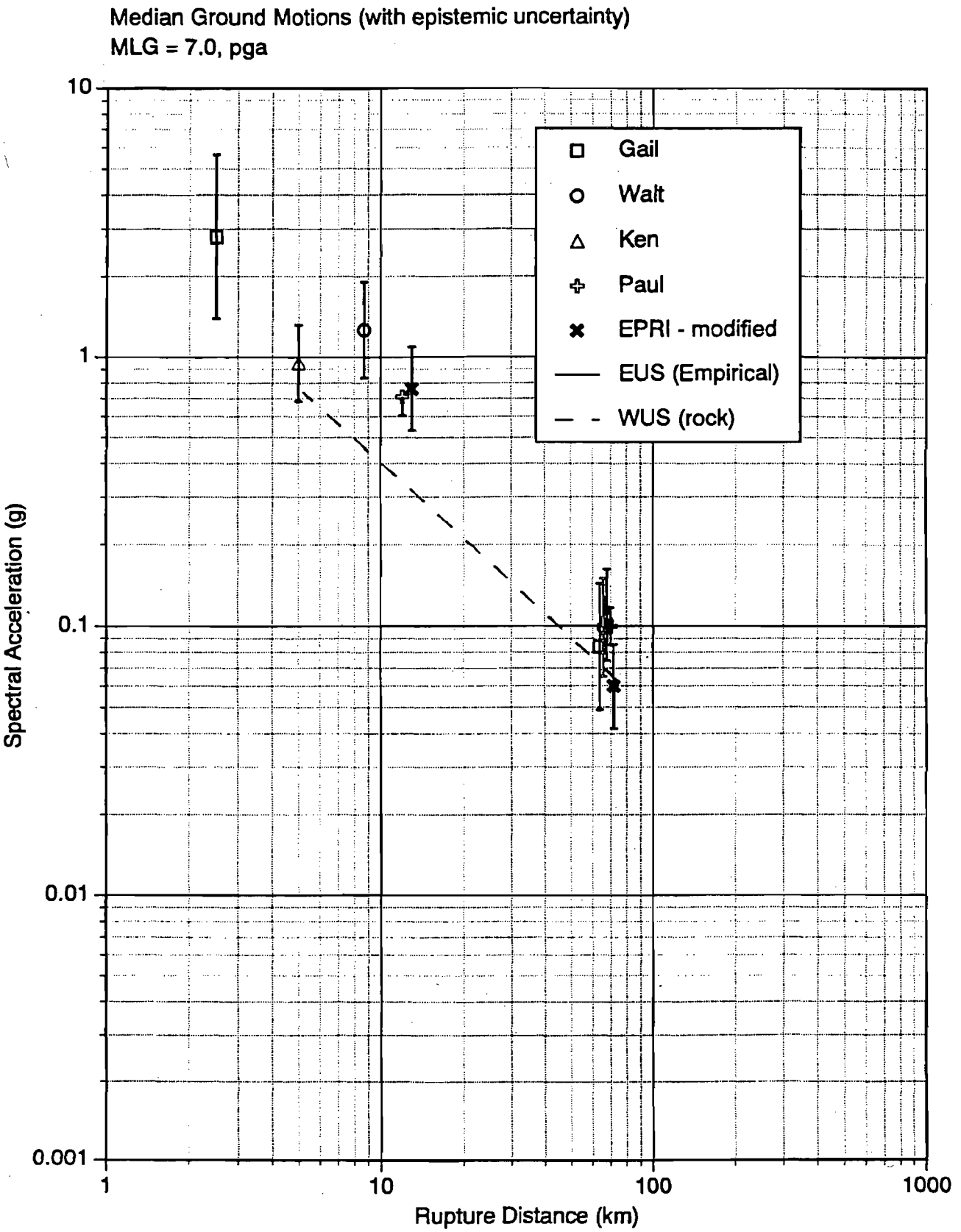

Median Ground Motions (with epistemic uncertainty)
MLG = 5.5, freq=1Hz
Gail
Walt (bias corrected)
Ken
Paul
EPRI - modified
EUS (Empirical)
WUS (rock)
Spectral Acceleration (g)
1
0.1
0.01
0.001
0.0001
1
10
100
1000
Rupture Distance (km)

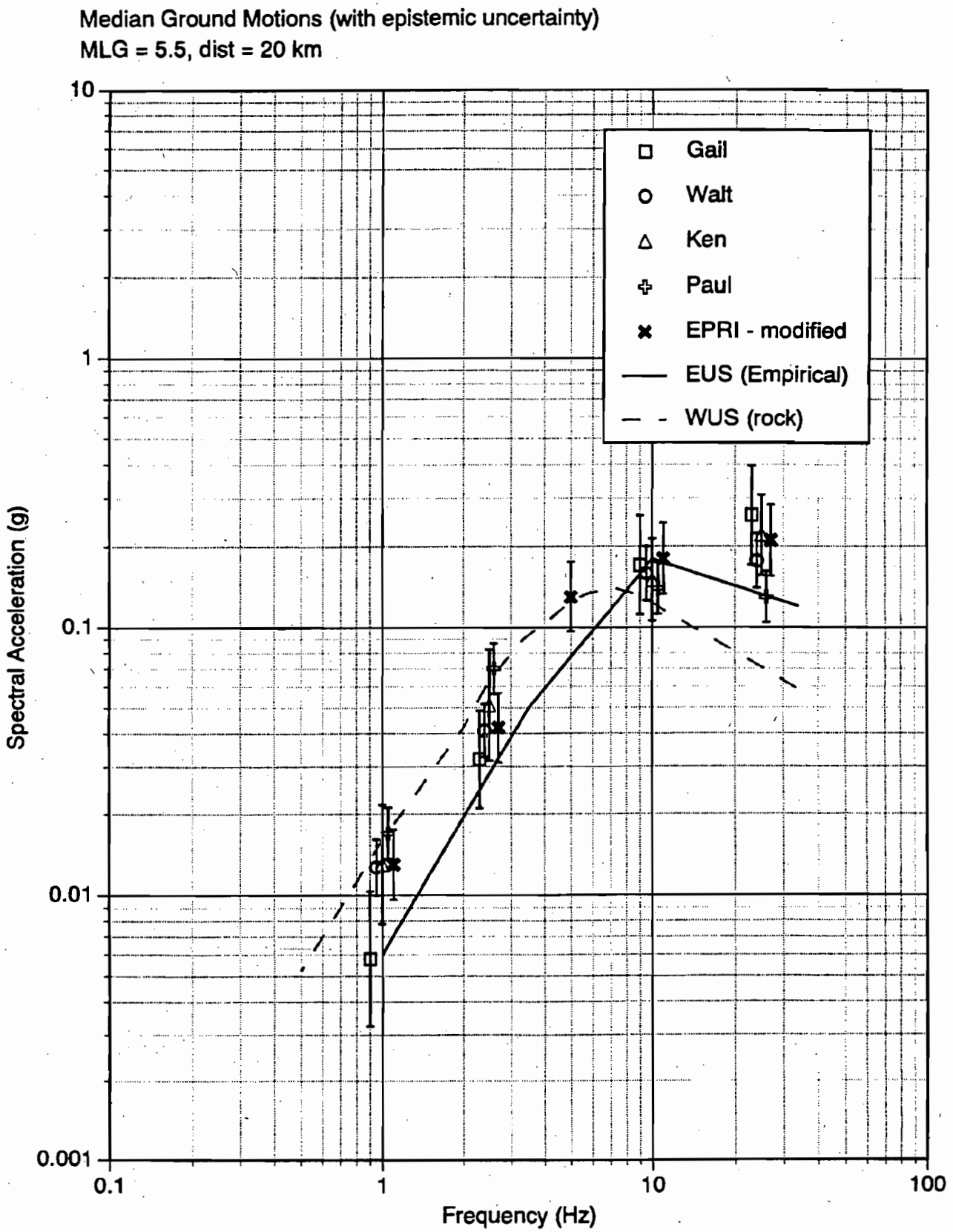

Median Ground Motions (with epistemic uncertainty)
MLG = 7.0, freq=1Hz
Gail
Walt (bias corrected)
Ken
Paul
EPRI - modified
EUS (Empirical)
WUS (rock)
Spectral Acceleration (g)
10
1
0.1
0.01
0.001
1
10
100
1000
Rupture Distance (km)

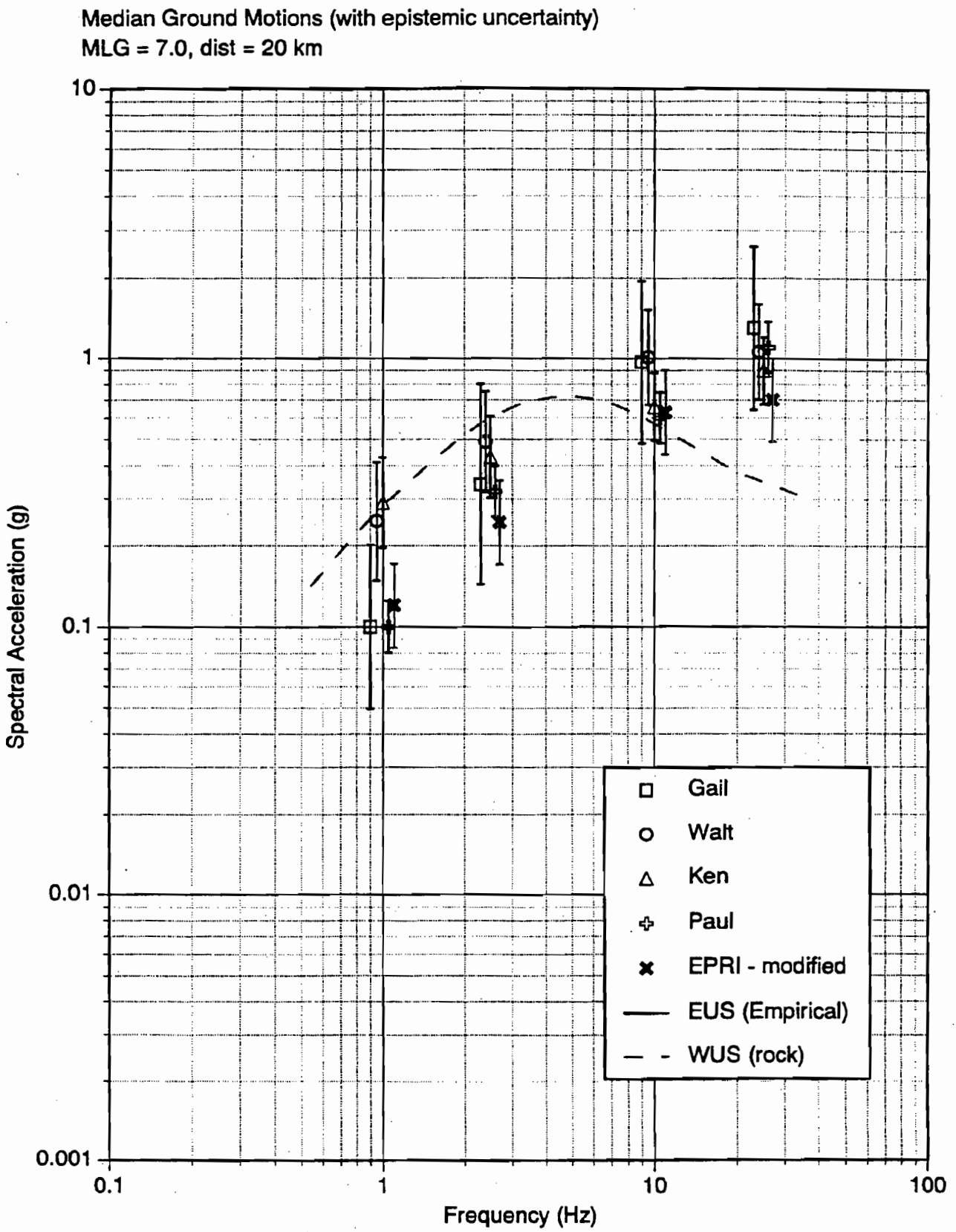

Median Ground Motions (with epistemic uncertainty)
MLG = 5.5, freq=10Hz
Gall
Walt
Ken
Paul
EPRI - modified
EUS (Empirical)
WUS (rock)
Spectral Acceleration (g)
10
1
0.1
0.01
0.001
1
10
100
1000
Rupture Distance (km)

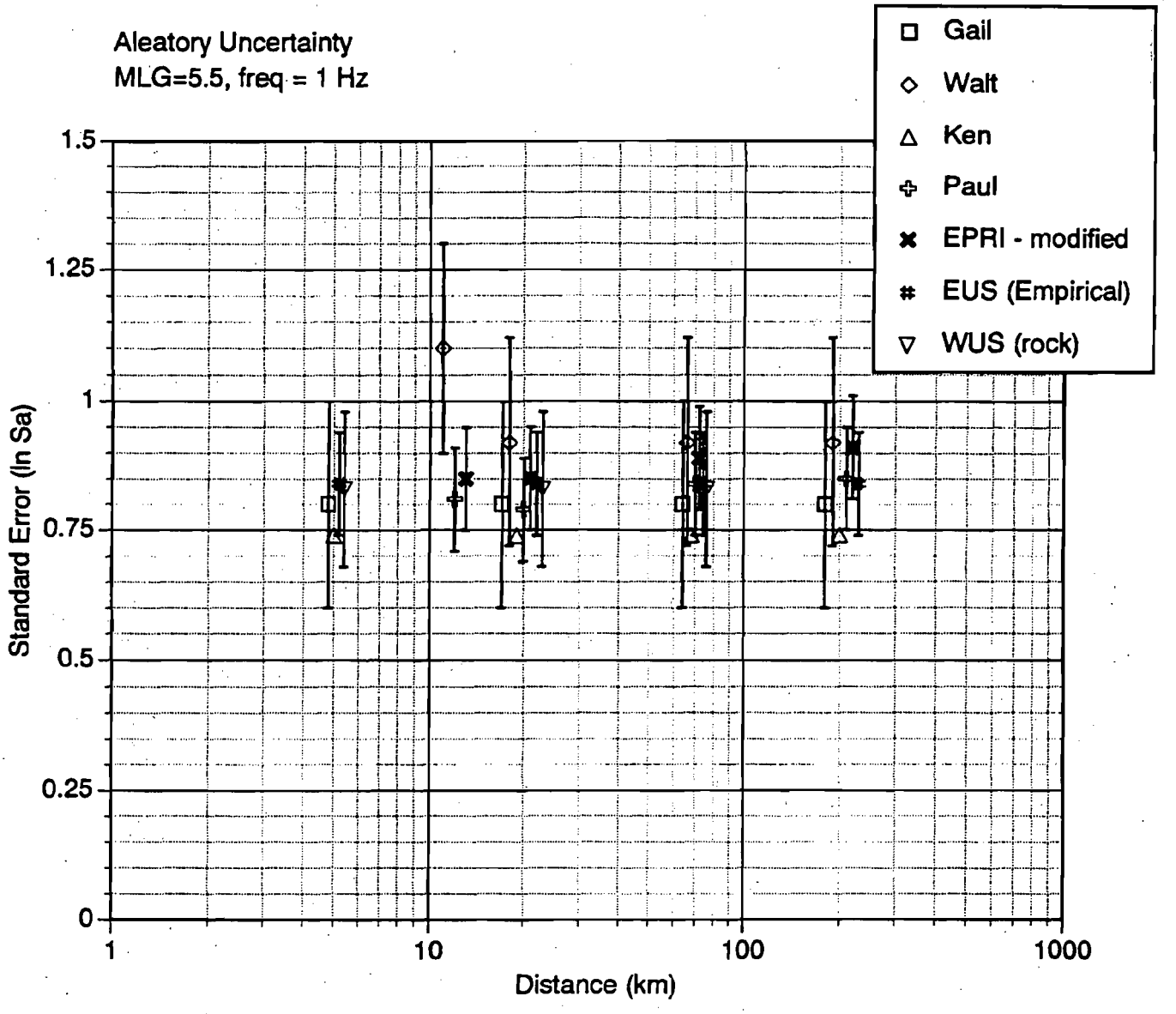

Median Ground Motions (with epistemic uncertainty)
MLG = 7.0, freq=10Hz
Gail
Walt
Ken
Paul
EPRI - modified
EUS (Empirical - Nahanni)
WUS (rock)
Spectral Acceleration (g)
100
10
1
0.1
0.01
1
10
100
1000
Rupture Distance (km)

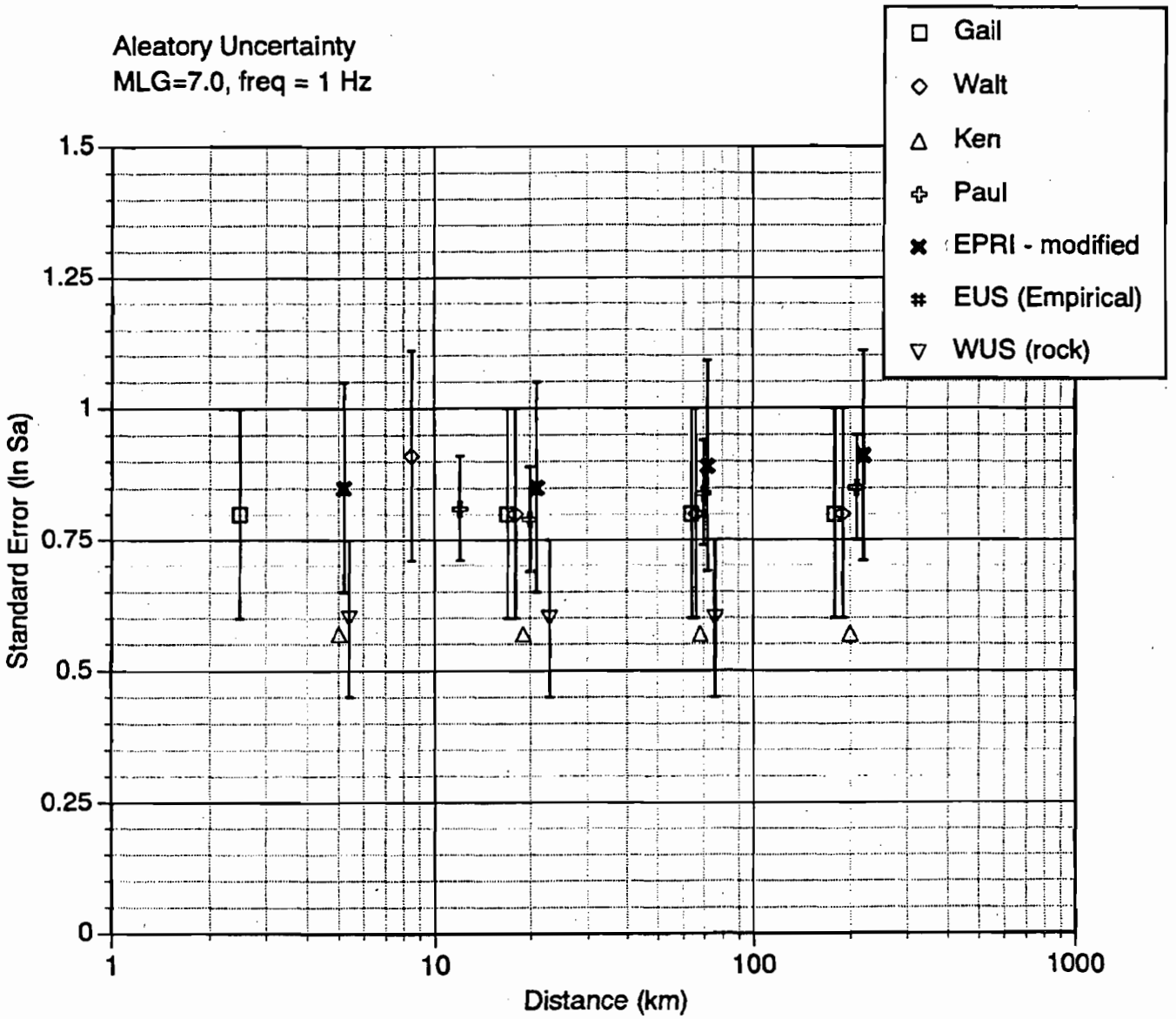

Median Ground Motions (with epistemic uncertainty)
MLG = 5.5, pga
Gail
Walt
Ken
Paul
EPRI - modified
EUS (Empirical)
WUS (rock)
Spectral Acceleration (g)
10
1
0.1
0.01
0.001
1
10
100
1000
Rupture Distance (km)

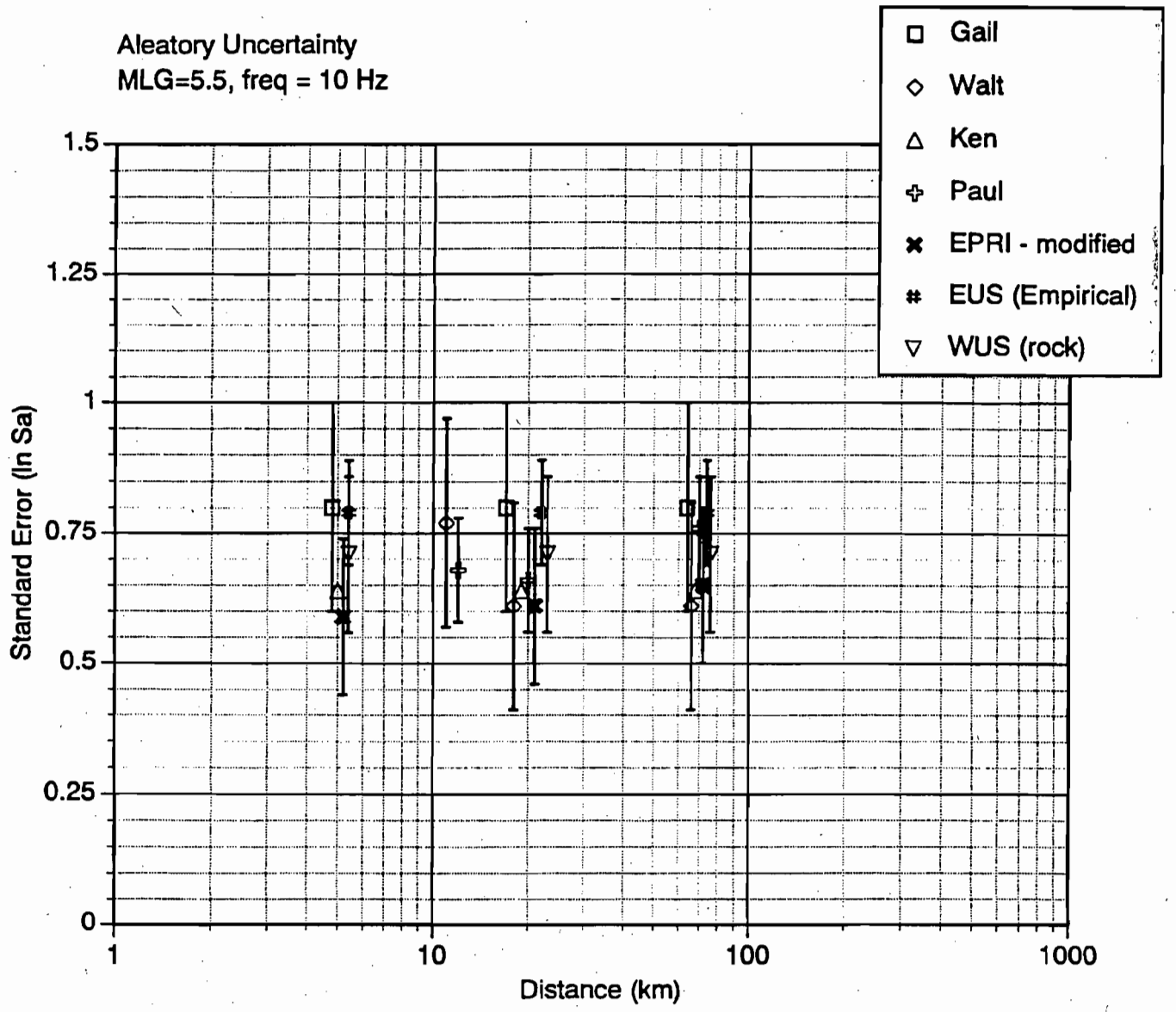

Median Ground Motions (with epistemic uncertainty)
MLG = 7.0, pga
Gail
Walt
Ken
Paul
EPRI - modified
EUS (Empirical)
WUS (rock)
Spectral Acceleration (g)
10
1
0.1
0.01
0.001
1
10
100
1000
Rupture Distance (km)

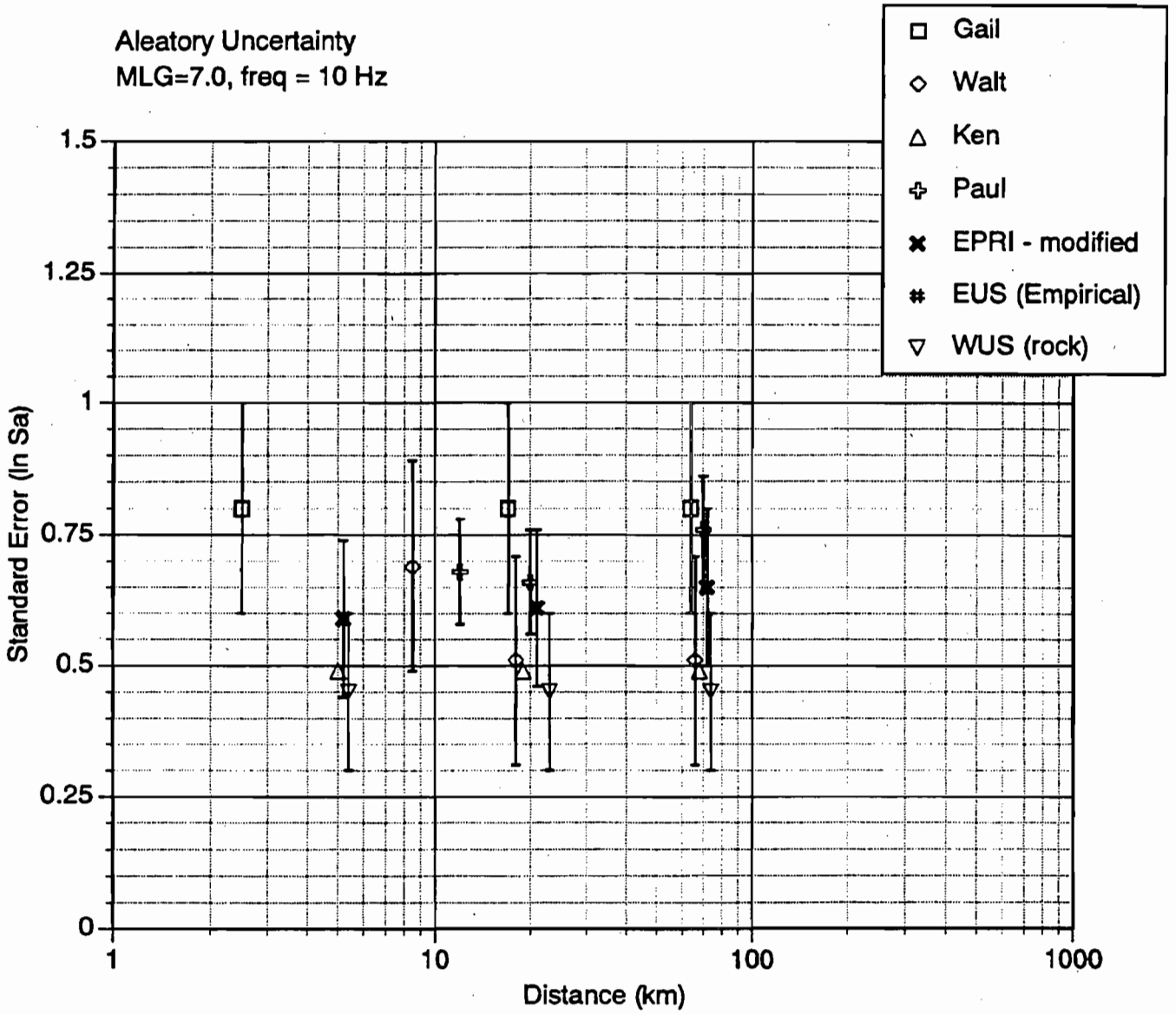

Median Ground Motions (with epistemic uncertainty)
MLG = 5.5, dist = 20 km
Gail
Walt
Ken
Paul
EPRI - modified
EUS (Empirical)
WUS (rock)
Spectral Acceleration (g)
10
1
0.1
0.01
0.001
0.1
1
10
100
Frequency (Hz)

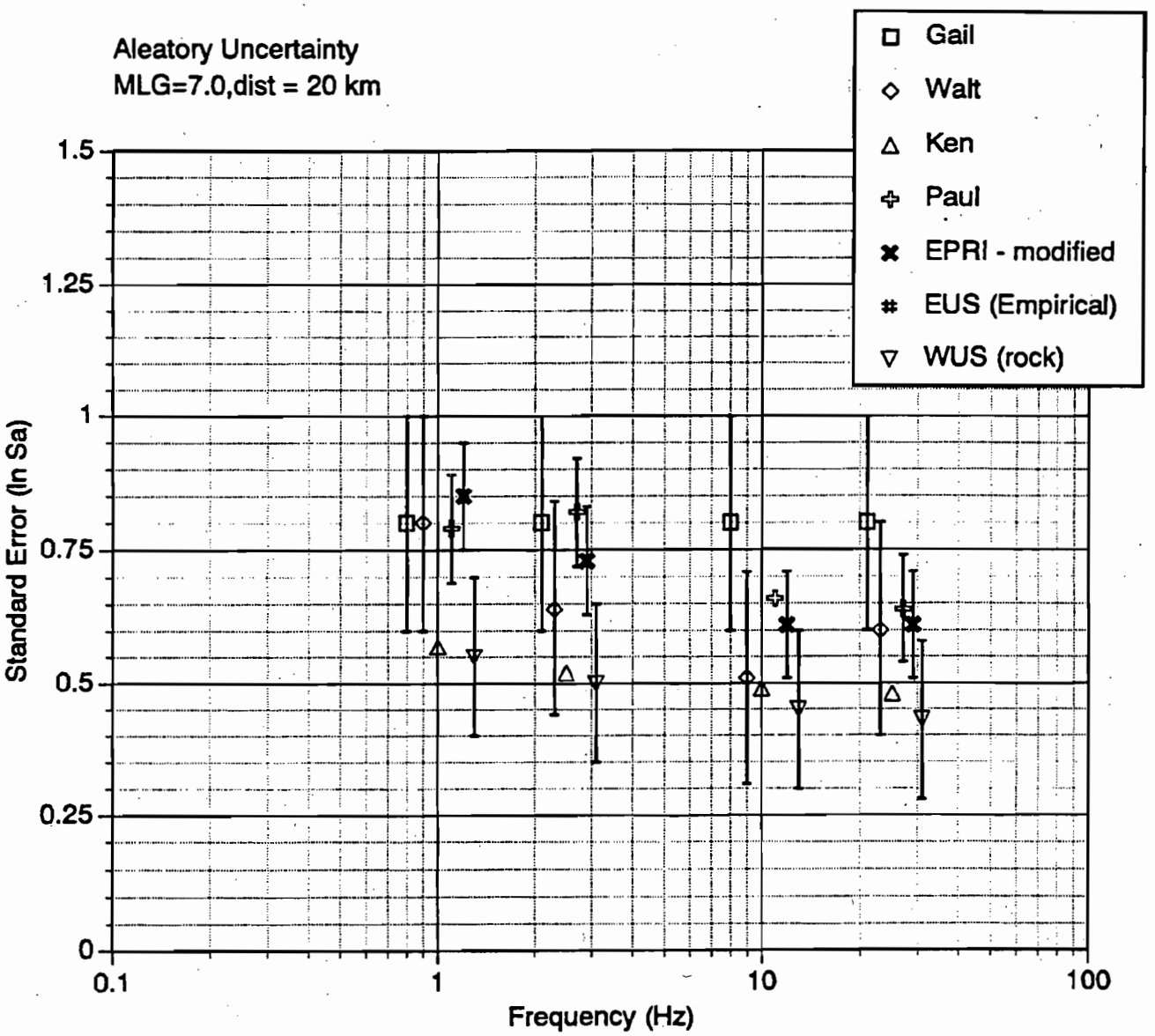

Median Ground Motions (with epistemic uncertainty)
MLG = 7.0, dist = 20 km
Spectral Acceleration (g)
10
1
0.1
0.01
0.001
0.1
1
10
100
Frequency (Hz)
Gail
Walt
Ken
Paul
EPRI - modified
EUS (Empirical)
WUS (rock)

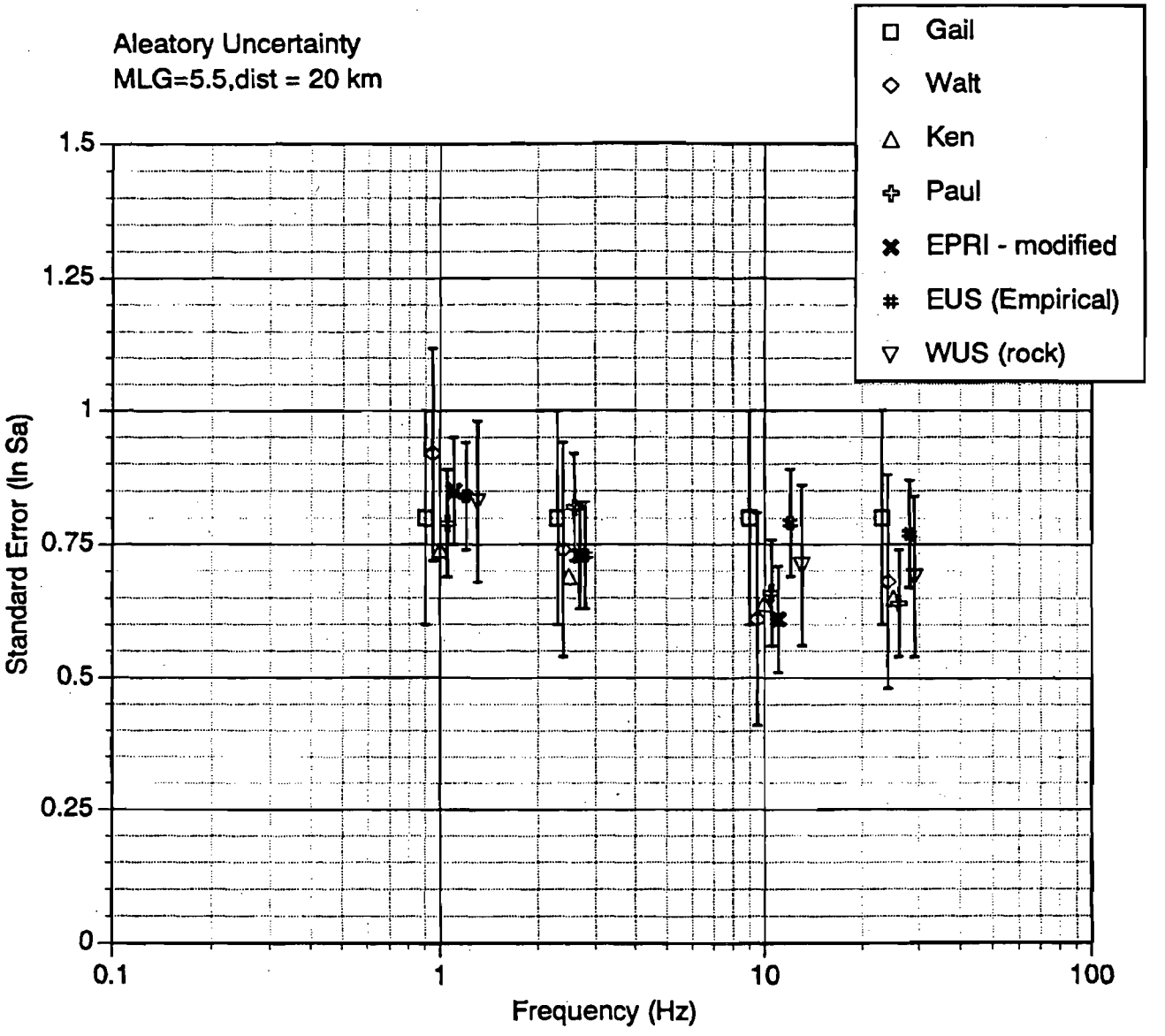

Aleatory Uncertainty
MLG=5.5, freq = 1 Hz
Gail
Walt
Ken
Paul
EPRI - modified
EUS (Empirical)
WUS (rock)
Standard Error (ln Sa)
1.5
1.25
1
0.75
0.5
0.25
0
1
10
100
1000
Distance (km)


Aleatory Uncertainty
MLG=7.0, freq = 1 Hz
Gail
Walt
Ken
Paul
EPRI - modified
EUS (Empirical)
WUS (rock)
Standard Error (ln Sa)
1.5
1.25
1
0.75
0.5
0.25
0
1
10
100
1000
Distance (km)


Aleatory Uncertainty
MLG=5.5, freq = 10 Hz
Gail
Walt
Ken
Paul
EPRI - modified
EUS (Empirical)
WUS (rock)
Standard Error (ln Sa)
1.5
1.25
1
0.75
0.5
0.25
0
1
10
100
1000
Distance (km)


Aleatory Uncertainty
MLG=7.0, freq = 10 Hz
Gail
Walt
Ken
Paul
EPRI - modified
EUS (Empirical)
WUS (rock)
Standard Error (ln Sa)
1.5
1.25
1
0.75
0.5
0.25
0
1
10
100
1000
Distance (km)


Aleatory Uncertainty
MLG=7.0,dist = 20 km
Gail
Walt
Ken
Paul
EPRI - modified
EUS (Empirical)
WUS (rock)
Standard Error (ln Sa)
1.5
1.25
1
0.75
0.5
0.25
0
0.1
1
10
100
Frequency (Hz)


Aleatory Uncertainty
MLG=5.5,dist = 20 km
Gail
Walt
Ken
Paul
EPRI - modified
EUS (Empirical)
WUS (rock)
Standard Error (ln Sa)
1.5
1.25
1
0.75
0.5
0.25
0
0.1
1
10
100
Frequency (Hz)

because Atkinson assumed a shear wave velocity at the source that is different from the Mid-continent model used in the study. For example, at a depth of 10 km Atkinson used a shear wave velocity of 3.8 km/s, whereas the Mid-continent model has 3.5 km/s. To account for this difference, Atkinson's stress parameter for this focal depth is divided by the factor $(3.8^3/3.5^3)^{1.5}$ which is about 1.45. With this modification, these stress parameters can be used in the stochastic model with the Mid-continent velocity structure to yield high frequency spectral levels that are consistent with the empirical data base.

These high frequency stress parameters are plotted versus moment magnitude in Figure V.5-5. These data show a decrease of stress parameter for magnitudes greater than 6.0; however, a linear least-squares fit of log stress parameter versus magnitude is not statistically significant at the 95% confidence level. The stress parameters range from 37 to 488 bars. The mean natural log stress parameter is 4.79±0.16 (120 bars) with a standard error of a single observation of 0.71 on the natural logarithm of stress parameter.

V.5.2.2 Estimation of Brune Stress Drops

Brune stress drops may be estimated either in the time domain, by measuring the source duration and seismic moment, or in the frequency domain by measuring corner frequency and seismic moment. In a previous study sponsored by EPRI, Somerville et al. (1987) used the time domain approach to estimate median stress drops of 120 bars and 90 bars for large earthquakes in eastern and western North America respectively based on teleseismic data. Comparable values have been estimated in the present study by fitting the Fourier amplitude spectrum of near-source recordings to the omega-square spectral model given in Equation 3.1. The methodology, described below, was applied to both stable continental interiors and tectonically active regions.

V.5.2.2.1 Methodology

In the inversion scheme, earthquake source, path, and site parameters are obtained by using a nonlinear least-squares inversion of Fourier amplitude spectra for the stochastic model parameters in Equation 3.1 (Silva and Stark, 1992). The bandwidth for each amplitude

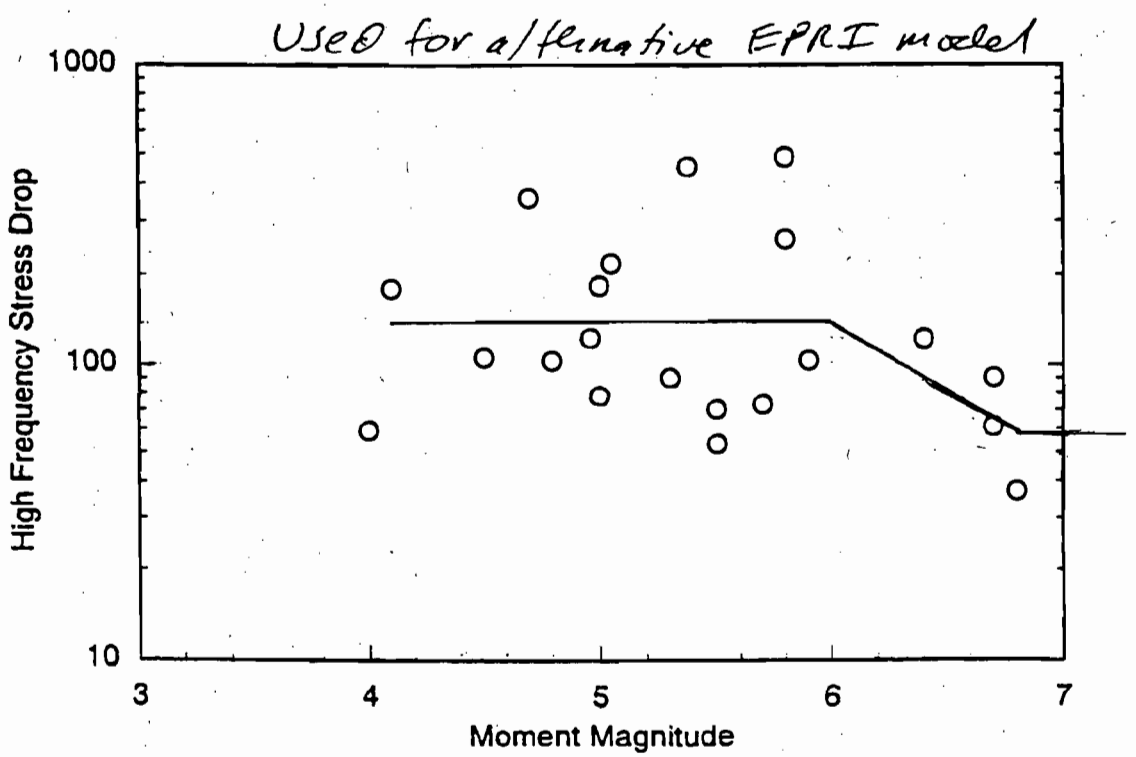


Figure V.5-5. High-frequency stress parameters modified from Atkinson (1993) to be consistent with the Mid-continent velocity structure.

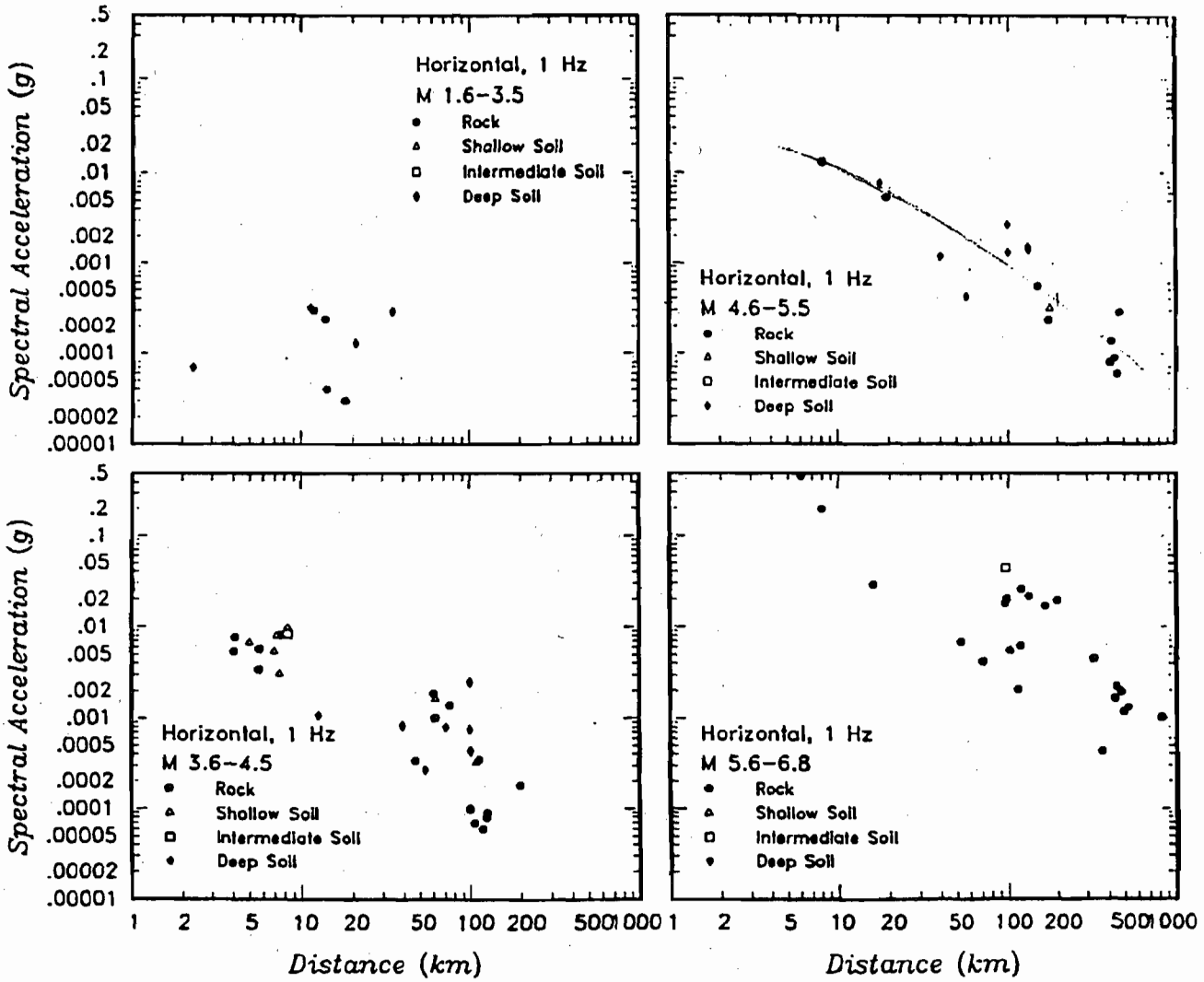


Figure 2-9. Peak horizontal spectral acceleration data for 1 Hz frequency from ENA ground motion data base.

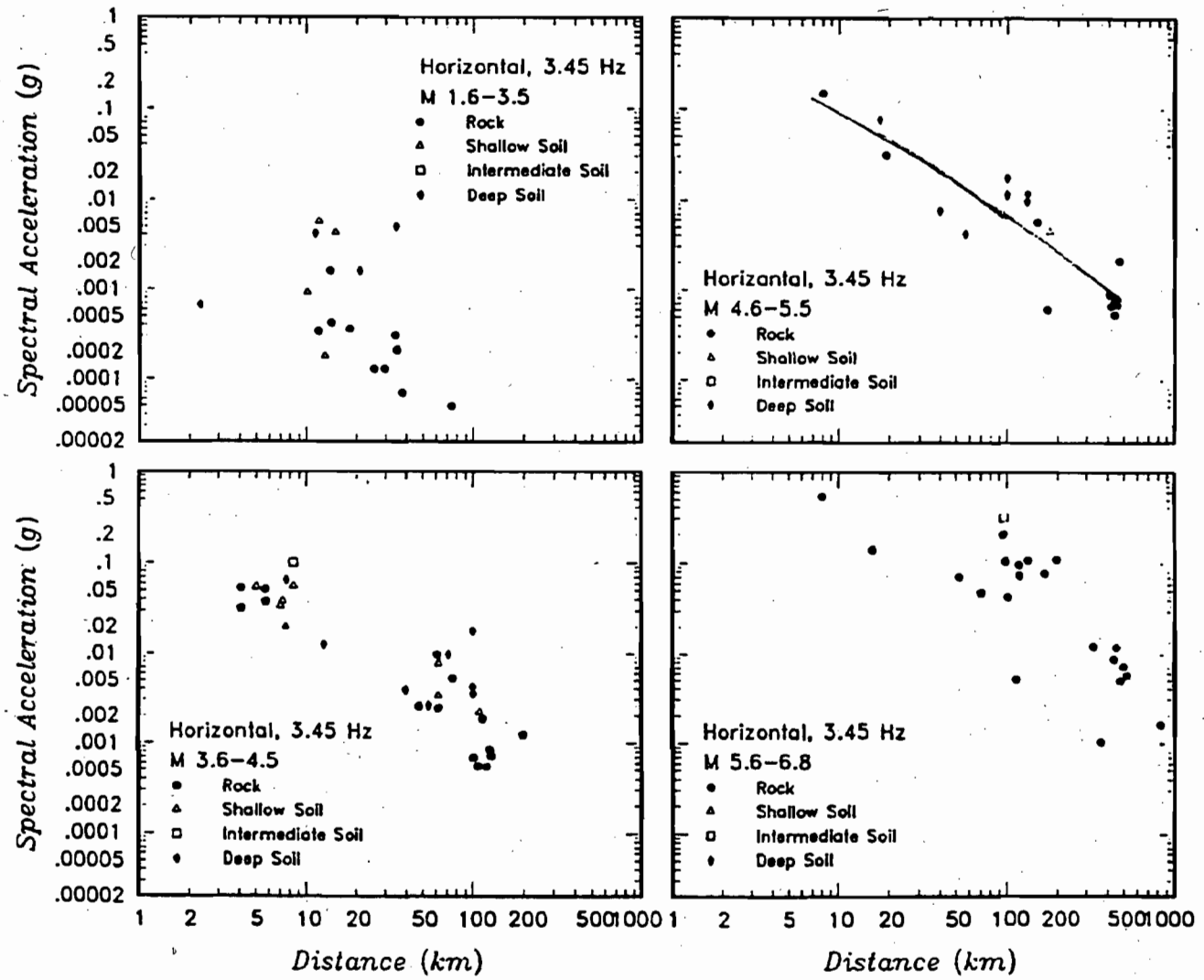


Figure 2-7. Peak horizontal spectral acceleration data for 3.45 Hz frequency from ENA ground motion data base.

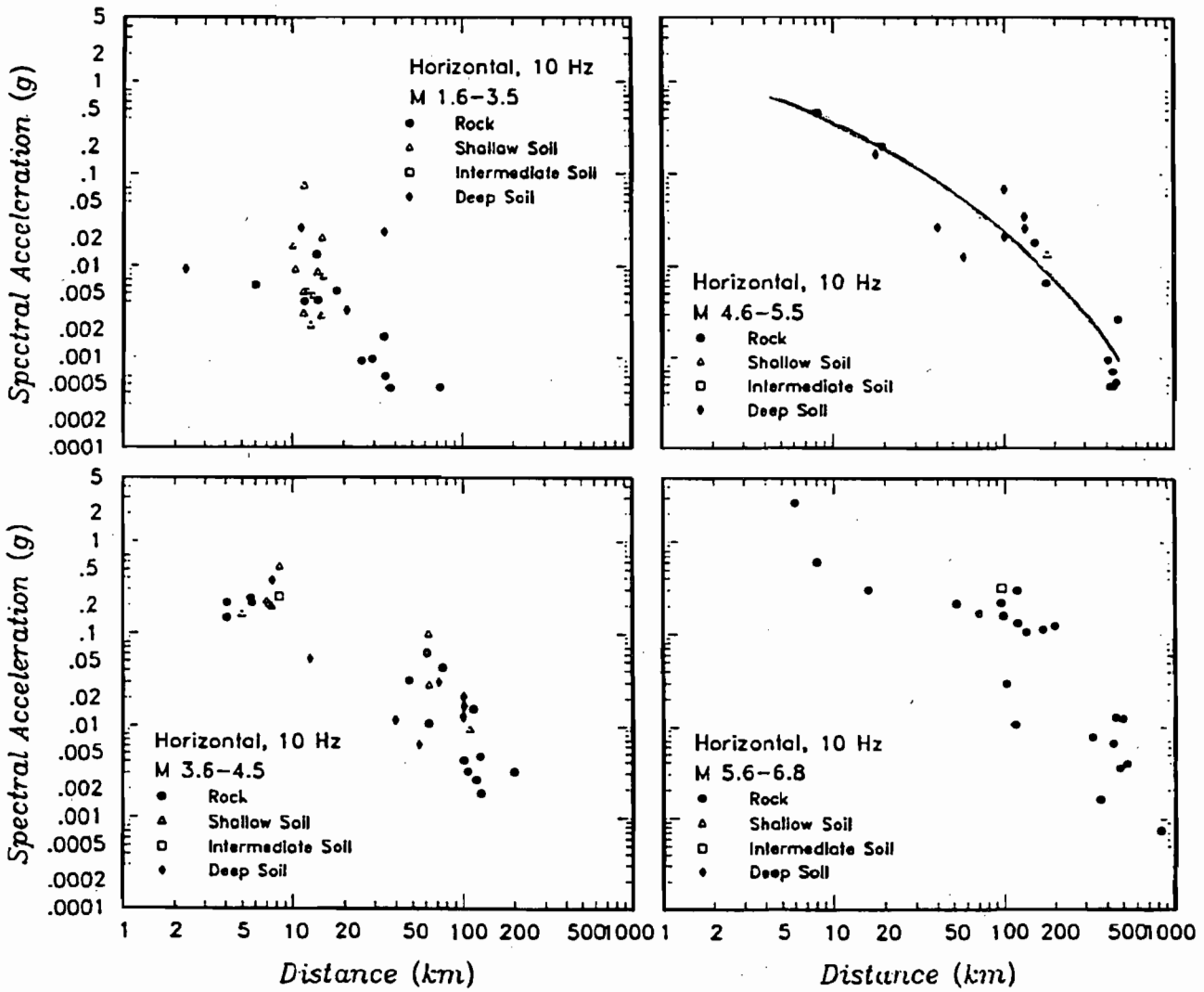


Figure 2-5. Peak horizontal spectral acceleration data for 10 Hz frequency from ENA ground motion data base.

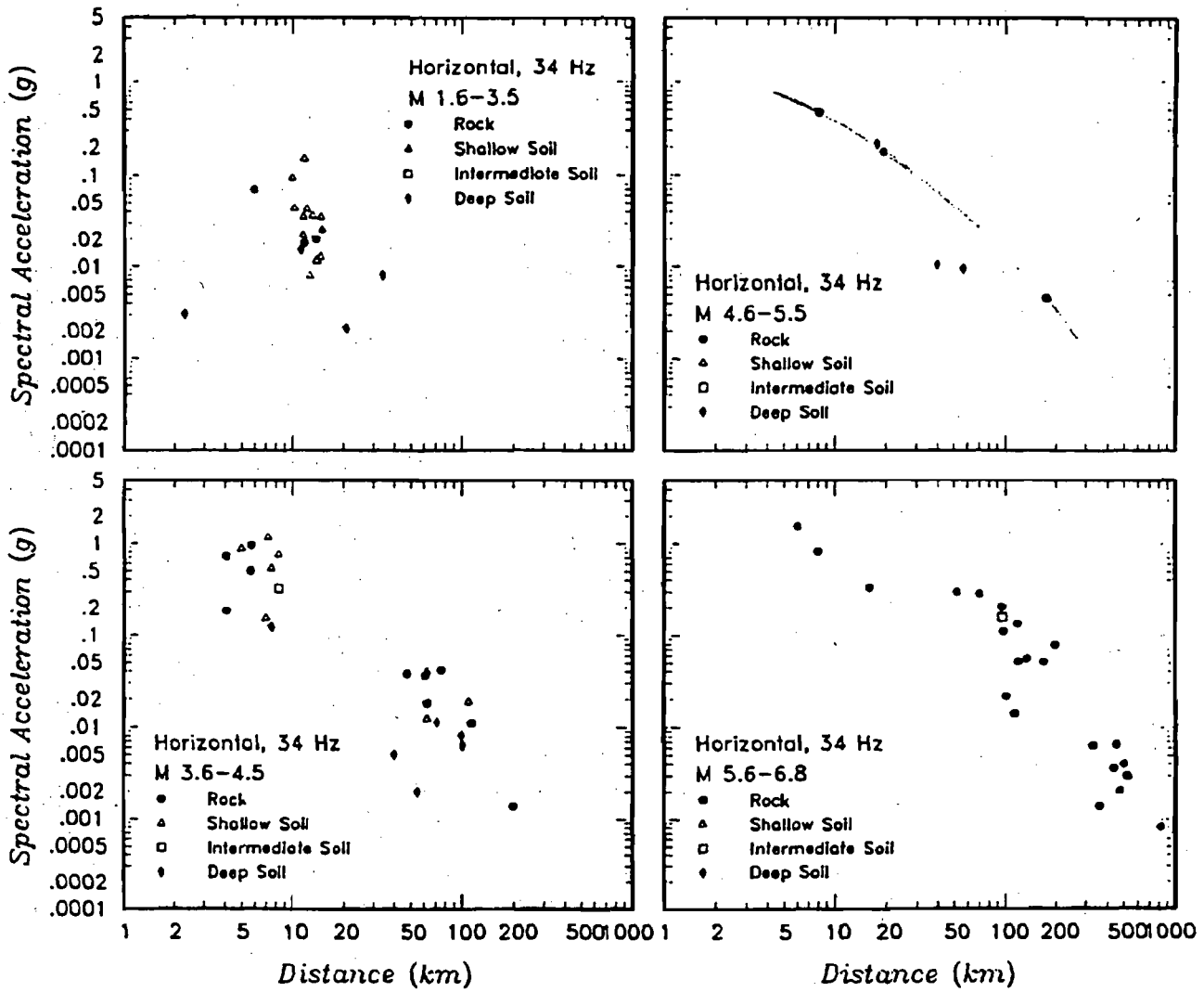


Figure 2-3. Peak horizontal spectral acceleration data for 34 Hz frequency from ENA ground motion data base.

Trouble points:
The magnitude of the events is not consistent between the proponents. In all of the models, the magnitude used in the model is not m_{Lg}, but moment magnitude. The conversion from m_{Lg} to moment magnitude is not consistent.

	Moment Magnitude			
m_{Lg}	Gail	Walt	Ken	Paul
5.5	5.0	5.0		5.2
7.0	7.0	7.0		6.4

I don't know what was used for Ken's model.

Strengths and Weaknesses of Each Model

1. Gall: Stochastic model w/empirical attenuation

Strengths:
The attenuation of the Fourier amplitude spectrum is modelled emprically. This avoids the need for assuming a wave propagation model. This is particulary helpful for the larger distances (100-200 km) for which they may be significant reflected waves.

The site condition is for ENA rock since that is the empirical data base. This avoids the problem of selecting a kappa value.

Weaknesses:
The source is modelled by a point source and it is unclear how this model should be applied to large events at short distances.

The rock sites are assumed to be hard rock (e.g. 2800 ft/sec shear wave velocity) but its not clear to me that they are this hard.

Does not include region specific deterministic crustal effects that may vary in ENA. This is a consquence of the strength of using emprical attenuation. If it is modelled empirically, then the empirical data (whereever it is collected) it assumed to apply to a specific site.

2. Walt: Stochastic model w/ray theory attenuation

Strengths:
Based on a standard model that is well understood by the profession. The small number of source parameters can be evaluated by others.

Attenuation of the Fourier spectrum includes deterministic effects of the crustal structure that can be modeled by 1-D ray theory results.

The model has been tested against earthquake recordings for the magnitude range of interest, including estimates of the modeling uncertainty (often missing in the uncertainty given for numerical simulations)

Weaknesses:
The ray theory results are senstive to source depth location if the source is located near a layer. This makes the attenuation less robust.

The source is modelled by a point source which may not apply to large events at short distances.

Overestimates the ground motion at 1-second by 50%. Forces me to correct for bias (assuming that the model will be wrong for future earthquakes as well) or have a potential significant overprediction. This is most likely a consequence of using a simple source model (e.g. one-corner model) vs a more complex model (e.g. two-corner).

3. Ken: Hybrid empirical

Strengths:
The main strength of this method is that is allows the near-source effects observed in WUS empirical data to be transported to the EUS. Since the modifications are all scale factors, the models used to modifiy the ground motion only need to be accurate in a relative sense (not absolute).

Weaknesses:
The main weakness of this method is the additional transformations that are needed. The WUS soil ground motion is transformed to WUS rock ground motion which is then modified for EUS crustal effects.

The uncertainty of the median values of these transformations was estimated as part of the modeling epistemic uncertainty, but there should be an increase in the aleatriy uncertainty as well due to the aleatory uncertainty of estimating rock ground motions from soil ground motions. I think that this additional aleatory uncertainty is quite large.

No validation of the method is given. How well does this method work for small magnitude (e.g. M=5) events?

Documentation not complete.

4. Paul: Advanced numerical modeling (reduced empirical GF)

Strengths:
The strength of this approach is that it provides a method for transporting empirical Green's functions from a specific site and source to other sites and sources.

The model accounts for deterministic effects of the crustal structure that can be accounted for by 1-D models of the crust.

The model has been tested against earthquake recordings for the magnitude range of interest, including estimates of the modeling uncertainty (often missing in the uncertainty given for numerical simulations)

The radiation pattern is represented empirically so that if the radiation pattern is coherent, then it is included implicity in the model, but if it is not coherent then it excluded implicity. This gets around arguements about whether or not the radiation pattern should be included in the numerical simulation.

The model uses a finite fault source so it should be applicable to large events at short distances (e.g. M=7, R=5 km)

Weaknesses:
The complications in wave propagation (e.g. scattering, 2-D and 3-D structure effects) for the new site are assumed to be captured in the selected empirical source functions, regardless of distance. Since the empirical source functions are from nearby events (< 15 km), scattering effects along a longer distance are not included.

The predicted ground motions depend critically on the selected source functions. The variability of the ground motion due to different source functions is not considered.

This method is more difficult to use and therefore harder to perform independent checks. The main difficulty is in setting up the empirical source functions.

The model has more parameters than the stochastic model. Many of the additional source parameters are fixed, but

The model is also more numerical intensive (e.g. computing the Green's functions).

The model uses a finite fault source so it should be applicable to large events at short distances (e.g. M=7, R=5 km)

Weaknesses:
The complications in wave propagation (e.g. scattering, 2-D and 3-D structure effects) for the new site are assumed to be captured in the selected empirical source functions, regardless of distance. Since the empirical source functions are from nearby events (< 15 km), scattering effects along a longer distance are not included.

The predicted ground motions depend critically on the selected source functions. The variability of the ground motion due to different source functions is not considered.

This method is more difficult to use and therefore harder to perform independent checks. The main difficulty is in setting up the empirical source functions.

The model has more parameters than the stochastic model. Many of the additional source parameters are fixed, but

The model is also more numerical intensive (e.g. computing the Green's functions).

Use of hard Rock

Using hard rock (2800 ft/sec) is reasonable for this comparison, but I think that a better value would be the 2000 ft/sec since this seems to be a better average of the top 30m of rock at nuclear sites in the EUS as noted by Walt.

I would like to know what the velocities are at the sites which recorded the data in Gail's data set. She has assumed that that are applicable to 2800 ft/sec. Are they really that hard?

Applicability to other regions

Based on the EPRI study, the ground motion attenuation in the Gulf coast (region 4 i Figure 5-14) is significantly different from the rest of the EUS. At distances of 80-150 km, there are also some differences in other regions: Central and Western Tennessee, Lake Superior, and Northern Great Plains (regions 6, 7, 11, and 13 in FIgure 5-14). The ground motion may be a factor of 1.5-2 lower at these distances for these regions.

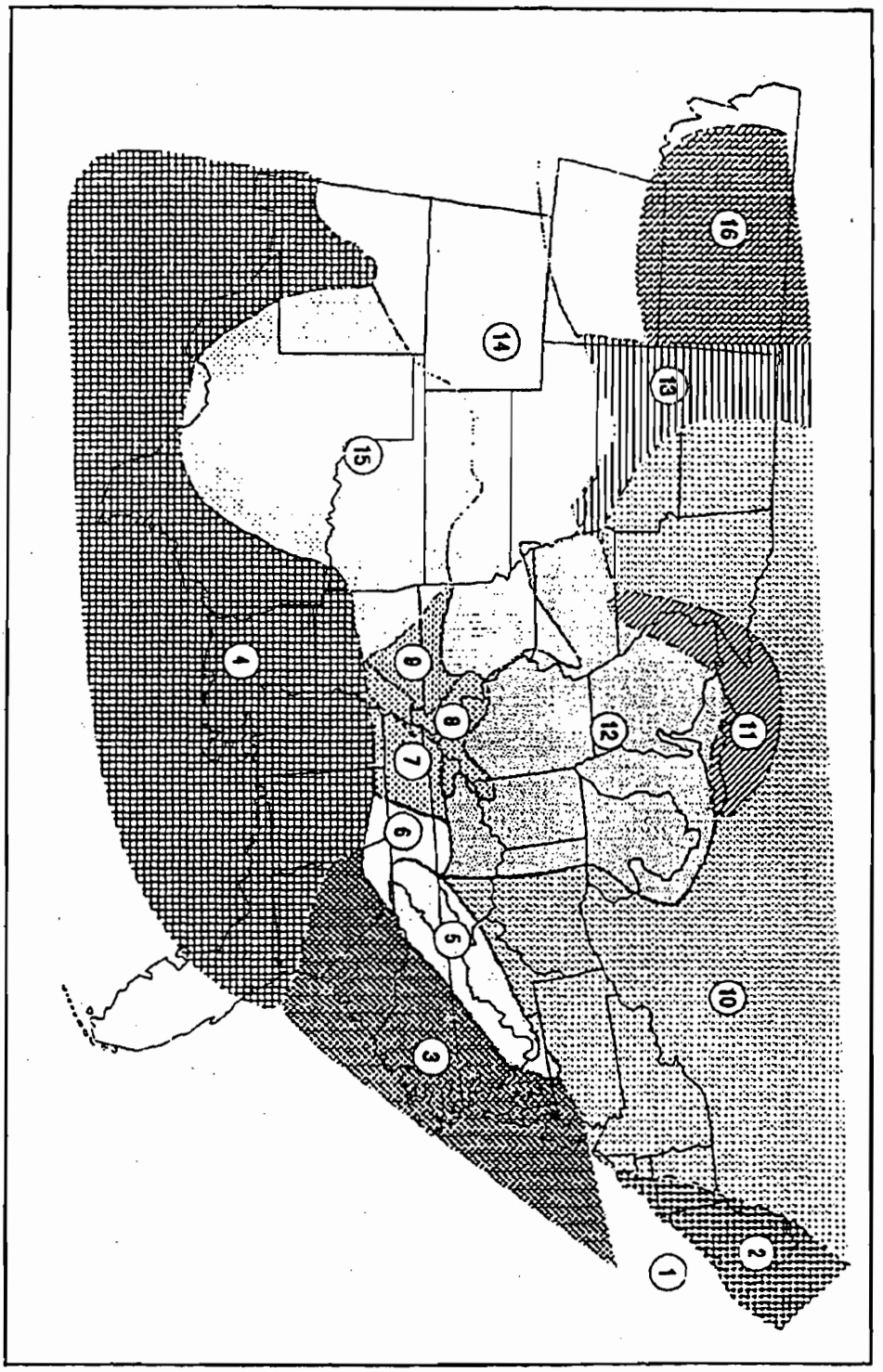


Figure 5-14. Crustal structure regionalizations for the EUS (Woodward-Clyde, 1991).

MEMORANDUM

TO: Dave Boore
Gabriel Toro

FROM: Gail Atkinson

DATE: July 21, 1994

RE: Revised SSHAC ground motion estimates

I have reviewed the ENA ground motion estimates submitted by the four model proponents (Atkinson, Campbell, Silva, Somerville/Saikia). Attempting to balance these estimates in some way and arrive at an opinion on the 'correct' values was an exercise in frustration. The approach I would like to take is something like this:

1. 'Calibrate' the various methods for a fixed set of input parameters, so we could first determine if the methods are equivalent. (Based on some comparisons that Somerville and I did, and a bit of blind faith in the other two methods, I am making the assumption that each of these methods will give the right answer if the inputs to the method are correct.)
2. Have each proponent provide brief but systematic (and quantitative) documentation of the data or reasoning behind each input to their model. Do an initial feedback loop on just these inputs, to arrive at appropriate alternative values and weights for the input parameters.
3. Then do ground motion predictions for various required alternatives and weight appropriately.

This approach is not possible with the information at hand. The obvious approach given simply the four sets of ground motion estimates is to weight the values in some way. Assuming that all methods have the potential to give correct answers, and all proponents have the potential to use their favorite method correctly, one might be tempted to use equal weights for the four sets of estimates. I am certain that this would be a mistake. The reason is that the estimates do not each contain independent evaluations of each of the required input parameters.

For example, a major difference in the 1-Hz estimates amongst proponents stems from the source model. My proposed two-corner source model is the wildcard here. The Silva estimates, following EPRI, use the traditional Brune model assumption. The Campbell estimates simply quote the EPRI model. From involvement with the EPRI project, I know that an examination of the shape of the source spectrum was beyond its scope. What I don't know from this material is what Silva or Campbell's opinion on source shape would be, had they specifically examined this issue in the course of developing their estimates. If I had such information, I might be more inclined to change my own opinion. Somerville's source model in not very transparent, in that it has an implicit

California shape, whatever that may be, adjusted for eastern fault dimensions. It may well be closer to my source spectrum, but it is difficult to say.

Another example of overlap between the estimates is the attenuation. The Atkinson attenuation is empirical, while both the Silva and Somerville attenuation, taken from the EPRI study, are based on detailed modeling with a common set of crustal models and focal depths; the Campbell estimates again quote the EPRI study. For kappa values, Silva, Somerville and Campbell all quote the values that Silva derived for the EPRI study.

In my revised estimates, I have tried to weight the alternative input parameters, rather than the proponents. This gets complicated, especially since there are also significant differences in the moments associated with the estimates of the various proponents (Somerville's moments differ significantly from those of Atkinson, Silva, and Campbell (I assume Campbell used the EPRI relations between moment and mLg)). Given the time available, I tried to balance the estimates based on judgement of the merits of their input parameters, using the infamous 'by eye' method. No doubt the results are nauseatingly subjective.

The considerations that went into the attached 'best-guess' ground motions, as derived from the four proponent sets, were as follows:

1. The 'truth' about the source model may lie somewhere in between my source model and the Brune model.
2. The Silva and Somerville models give a robust estimate of the decay of Fourier amplitudes with distance. The corresponding attenuation of response spectral amplitudes is less robust since their duration model does not account for the well-documented effects of scattering on duration, within the first 50 km. These effects are probably important for f>2 Hz. By comparison, the Atkinson attenuation of Fourier amplitudes is not as general, and may not be as applicable over the broader ENA region; however the Atkinson duration model is more appropriate, especially for f>2 Hz, so the time-domain attenuation may be more realistic for high-frequencies, at least within the first 50 km.
3. Based on ECTN records, a kappa of 0.006 is probably too high for truly hard-rock sites.
4. Campbell's use of NEHRP (ie. political) correction factors to de-amplify WUS soil to obtain WUS rock has probably resulted in overestimation of WUS rock. I hope Silva will enlighten us on this point, but my understanding of the NEHRP factors is that they represent the general reluctance of the engineering community to accept the realities of soil amplification. I also think Campbell's uncertainties in the median amplifications used to adjust WUS soil to WUS rock are too low if they are based only on uncertainties in classification.

5. I do not believe that stochastic point-source estimates should be made for distances less than 10 km (median focal depth for ENA), particularly for large magnitudes. Since I see other proponents have taken liberties with the 5 km estimates, I have too. My new 5 km estimates are closer to the 10 km stochastic values.
6. I think some of the proponents (I wouldn't name names, of course, but their initials are PS, WS and KC) have been overly optimistic about our epistemic uncertainties, particularly for large ENA events at close distances.
7. Somerville's mLg 7 event had a much smaller moment than that used by the other proponents.
8. Overall, many of the input assumptions shared by the other proponents, taken from the EPRI study, might be considered more of a 'consensus' view than my own opinions. However my estimates, taken from the Atkinson-Boore study, contain more extensive empirical validation of both input parameters and predictions than does the EPRI study. So I think I have most of the data in my corner, although one might argue with my interpretation of those data.

I look forward to a lively debate at the workshop.

Gail Atkinson

SSHAC SECOND GROUND MOTION WORKSHOP

Form 1: Page __ of __

Expert: Gail Atkinson

Ground Motion Measure: 1-Hz Spectral Acceleration (g)

Distance	Quantity		m_{L_g} 5.5	m_{L_g} 7.0
5 km	median amplitude		0.05	0.5
	epistemic uncertainty	parametric (ln)	0.3	0.7
		median bias	0.0	0.0
		uncert. in bias (ln)	0.5	0.7
	aleatory uncertainty	median σ	0.9	0.9
		uncertainty in σ	0.2	0.2
20 km	median amplitude		0.01	0.15
	epistemic uncertainty	parametric (ln)	0.5	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.3	0.5
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
70 km	median amplitude		0.005	0.04
	epistemic uncertainty	parametric (ln)	0.2	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.2	0.5
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
200 km	median amplitude		0.001	0.025
	epistemic uncertainty	parametric (ln)	0.2	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.2	0.5
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2

Comments/footnotes:

SSHAC SECOND GROUND MOTION WORKSHOP

Form 2: Page __ of __

Expert: Gail Atkinson

Ground Motion Measure: 2.5-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.045	0.4
	epistemic uncertainty	parametric (ln)	0.2	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.3	0.7
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 3: Page __ of __

Expert: Gail Atkinson

Ground Motion Measure: 10-Hz Spectral Acceleration (g)

Distance	Quantity		m_{L_g} 5.5	m_{L_g} 7.0
5 km	median amplitude		0.6	2.2
	epistemic uncertainty	parametric (ln)	0.3	0.7
		median bias	0.0	0.0
		uncert. in bias (ln)	0.5	0.7
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
20 km	median amplitude		0.17	0.97
	epistemic uncertainty	parametric (ln)	0.2	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.3	0.5
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
70 km	median amplitude		0.025	0.2
	epistemic uncertainty	parametric (ln)	0.2	0.4
		median bias	0.0	0.0
		uncert. in bias (ln)	0.2	0.5
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND GROUND MOTION WORKSHOP

Form 4: Page __ of __

Expert: Gail Atkinson

Ground Motion Measure: 25-Hz Spectral Acceleration (g)

Distance	Quantity		m_{L_g} 5.5	m_{L_g} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.25	1.2
	epistemic uncertainty	parametric (ln)	0.2	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.3	0.5
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 5: Page __ of __

Expert: Gail Atkinson

Ground Motion Measure: Peak Ground Acceleration (g)

Distance	Quantity		m_{L_g} 5.5	m_{L_g} 7.0
5 km	median amplitude		0.38	1.4
	epistemic uncertainty	parametric (ln)	0.3	0.7
		median bias	0.0	0.0
		uncert. in bias (ln)	0.5	0.7
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude		0.014	0.1
	epistemic uncertainty	parametric (ln)	0.3	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.2	0.5
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

GROUND MOTION ESTIMATES

Don Bernreuter

Epistemic Uncertainty

My epistemic uncertainty is large, for a number of reasons:

1. Uncertainty about which is the correct source model.

   Generally, I think that the ω^2 model is better than other models, but there are a number of possible variations of ω^2 models. For example:

   i. Brune model (single low frequency corner).

   ii. New model of two corner frequencies proposed by Atkinson & Boore. Seems to have a significant impact on both high and mid-range spectral amplitudes.

   iii. The Joyner two-corner model is also a possibility, but its main impact is to strongly saturate the GM at some critical M.

   iv. For larger events, M>6 and certainly for M>6.75 none of the simple source models (i, ii, or even iii) appear very viable. These all assume only one large dislocation with constant properties, etc. For large events, I see several small strong regions of energy release superimposed on a larger region of lower energy release. I suppose actually model (ii) might represent such a case, but it's not clear how f_A, f_B, and c should be chosen and what is the sensitivity of the GM to variations in these parameters.

   For larger events, the advanced numerical modeling approach is attractive. However, in my view, there is still considerable uncertainty about the source function Somerville uses, how it is distributed over

the fault surface, rupture velocities, etc. None of these are discussed by Somerville.

In general, I would expect the results from a simple Brune-like model to be too high for large events. The new Atkinson double-corner model might better represent the complexity of large earthquakes. The problem here for me is that it appears to give even higher spectral amplitudes in the 2 — 50 Hz range than the simpler Brune single-corner model and certainty much higher than Somerville's model.

v. Uncertainty as to the relation between seismic moment and corner frequency — Mo $f_c^a = c$. a is often taken as 3 leading to a constant $\Delta\sigma$ with increasing magnitude. Nuttli and others suggest that a = 3.75 to 4 fits the data better, and leads to an increase in $\Delta\sigma$ with Mo. This can have a significant impact on scaling with magnitude or increasing Mo. Intensity data models suggest a strong scaling with increase Mo. If one includes the data given in Atkinson's for m_{Lg} down to 3.5, which seem to have fc less than 10 Hz, one certainly sees a Mo $f_c^{3.75} = c$ scaling. This relation Mo $f_c^a = c$ implies a strong similarity between earthquakes of increasing size as a result of the simple Brune model. As I noted in (iv), I do not think that this is the true state of nature and the scaling by such a simple law breaks down for larger earthquakes.

2. Uncertainty about the true median value of stress drop.

Its not at all clear to me that $\Delta\sigma$ obtained by different approaches is giving estimates of the parameter needed to compute strong ground motion. In the far-field, we see an averaged scaling parameter. For small earthquakes, this might be okay, but for larger earthquakes, I do not see a uniform release of energy. Thus, closer to the fault we will see considerable variation

depending upon the details of the rupture process and energy release. These details control the high-frequency strong ground motion.

In addition, I ask myself if $\Delta\sigma$ has a continuous distribution. Or, are we seeing a bi-modal or tri-modal behavior? Maybe we have a class of earthquakes with $\Delta\sigma$ centered around 100 — 200 bars and a class of earthquakes in an area where the faults are well healed in the 500 bar range. These are two very different models for $\Delta\sigma$.

In Somerville's model, $\Delta\sigma$ is not directly used and is a function of the structure of the dislocation rise time and complexity of the function used to represent the dislocation.

3. Relation between m_{Lg} and Mo.

This leads to a significant uncertainty. I have a problem with the approach of using a body wave spectra to compute a m_{Lg} to relate to Mo. In addition, there is significant differences between m_{Lg} and Mo used by Atkinson, Somerville and Silva. For m_{Lg} of 7, Atkinson has a log Mo = 26.6, whereas Somerville has log Mo = 25.6, or a factor of 10 lower corresponding to a M = 6.4 as compared to M = 7 used by Atkinson. Nuttli developed an empirical relation which would give log Mo = 27.2 for m_{Lg} = 7. Silva appears to have a larger Mo for m_{Lg} = 7 than Atkinson's approximately M = 7.3. At m_{Lg} = 5.5, the estimates for Mo are closer.

4. Uncertainty geometric attenuation and layering effects.

   Some models include layering, etc. in them, in particular Somerville's estimates. Atkinson uses a strong term for geometric attenuation in the first 70 km as —1.1 log r compared to —log r for others. Including layering, or not including it, can have a large impact on the estimates. Personally, I think the models with structure greatly over estimate this effect as compared to the real world.

Values for Sigma

I think the above list covers the most important elements of my epistemic uncertainty. The problem is how to quantify the above. Some of the above uncertainties are related. I will try and factor out this, but naturally, it is hard to do. The various comparisons provided really are not too much help in sorting out the individual factors because they are not for the same case. It would have been nice if Silva, Atkinson and Somerville each modeled the same small Mo and the same large Mo earthquakes, rather than having different Mo's, etc. so we could see the impact of the three different "source" models.

The largest source of epistemic uncertainty appears to be in the Mo — m_{Lg} relation at larger magnitudes. As I look at the various relations, it would appear to lead to about a factor of 10 — 15 in the estimate of Mo, say from low to high or approximately a factor of 3 — 5 or ground motion. This would lead to a σ_M. ~ 0.8. The uncertainty is larger for $m_{Lg} = 7$ than for 5.5 at 5.5 $\sigma_M \sim 0.4$.

The Atkinson two-corner model appears about 20% higher in the 10 Hz PGA range than the Brune model and about 20% lower at 1 Hz. It's hard to tell how much difference Somerville's model makes compared to the others. As noted my uncertainty is larger for large events than for smaller events. Variations in the

the definition of duration also adds some uncertainty along with the other parameters (other than stress drop) also add a little uncertainty. Overall I would estimate $\sigma_{SM} \sim 0.25$ excluding stress drop and Mo $f_c^a = c$ for $m_{Lg} \sim 5.5$. For $m_{Lg} \sim 7$ mu uncertainty is much larger because I think all of the models are a poor representation of nature. A factor of 2 or so seems reasonable here but with little justification as it is hard to come by. Hence $\sigma_{SM} = 0.7$ for $m_{Lg} \sim 7$.

How the corner frequency or stress drop scales with Mo is a large potential source of uncertainty for $m_{Lg} \sim 7$. At $m_{Lg} = 7$ it could introduce a factor of 5 difference. However, as I noted I discount this because I do not think the source model is applicable. At $m_{Lg} = 5.5$ the effect is less important — but more real. Yet much of this — at least at $m_{Lg} = 5.5$ may be related to the two corner model or what-have-you.

If I start combining the above sigmas the resultant is much too large. Clearly, they are not all independent. Thus the final ~~numbers~~ Numbers given are based on the above considerations and my judgment as to what seems reasonable. I am also influenced by Campbell and Silva's values for the aleatory uncertainty estimates. My estimates are larger for 1 hz than 10 Hz or PGA because the models are not very good at 1 Hz and for large events.

Aleatory Uncertainty

Based on what I know about WUS data with some increase due to a wider range of stress drops in the EUS. As noted I am also influenced by EPRI's work (Silva) and Campbell's WUS work.

SSHAC SECOND GROUND MOTION WORKSHOP

Form 1: Page __ of __

Expert: BERNREUTER

Ground Motion Measure: 1-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.036	0.8
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.6	1.0
	aleatory uncertainty	median σ	0.7	0.8
		uncertainty in σ	0.4	0.4
20 km	median amplitude		0.015	0.3
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.6	0.9
	aleatory uncertainty	median σ	0.7	0.8
		uncertainty in σ	0.3	0.4
70 km	median amplitude		0.003	0.09
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.6	0.9
	aleatory uncertainty	median σ	0.7	0.8
		uncertainty in σ	0.2	0.4
200 km	median amplitude		0.001	0.03
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.6	0.9
	aleatory uncertainty	median σ	0.7	0.8
		uncertainty in σ	0.2	0.2

Comments/footnotes:

SSHAC SECOND GROUND MOTION WORKSHOP

Form 3: Page __ of __

Expert: BERNREUTER

Ground Motion Measure: 10-Hz Spectral Acceleration (g)

Distance	Quantity		m_{L_R} 5.5	m_{L_R} 7.0
5 km	median amplitude		0.5	2.0
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.6	0.9
	aleatory uncertainty	median σ	0.7	0.7
		uncertainty in σ	0.3	0.3
20 km	median amplitude		0.16	0.98
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.6	0.8
	aleatory uncertainty	median σ	0.6	0.6
		uncertainty in σ	0.2	0.3
70 km	median amplitude		0.039	0.3
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.6	0.8
	aleatory uncertainty	median σ	0.6	0.6
		uncertainty in σ	0.2	0.3
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND GROUND MOTION WORKSHOP

Form 4: Page __ of __

Expert: BERNREUTER

Ground Motion Measure: 25-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.25	1.15
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.6	0.8
	aleatory uncertainty	median σ	0.65	0.6
		uncertainty in σ	0.2	0.3
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND GROUND MOTION WORKSHOP

Form 5: Page __ of __

Expert: BERNREUTER

Ground Motion Measure: Peak Ground Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.34	1.0
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.6	0.9
	aleatory uncertainty	median σ	0.7	0.7
		uncertainty in σ	0.2	0.3
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude		0.02	0.11
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.6	0.8
	aleatory uncertainty	median σ	0.6	0.6
		uncertainty in σ	0.2	0.2
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

EXPERT EVALUATION OF GROUND MOTIONS IN THE CENTRAL AND EASTERN UNITED STATES

SECOND SSHAC GROUND-MOTION WORKSHOP
Palo Alto, California
July 27-28, 1994

Kenneth W. Campbell
EQE *International*, Inc.
Evergreen, Colorado

INTRODUCTION

I used a weighted estimate of ground motions derived from the Hybrid Empirical Model, the Stochastic Simulation (EPRI) Model, the Stochastic Simulation (Atkinson) Model, and the Advance Numerical Model to produce the recommended median values of PGA and PSA and their associated uncertainty for the Central and Eastern United States (CEUS).

As stated in the instructions for the second SSHAC Ground Motion Workshop, the estimates were made for a hypothetical site located in the northeastern United States and southeastern Canada. The site conditions are described as Eastern United States Rock (i.e., a site having an average shear-wave velocity of 2800 m/sec over the top 30 m). The magnitudes, distances, and ground-motion parameters for which estimates were provided are given in Table 1.

METHODOLOGY

A description of the methodology used to develop the ground-motion and uncertainty estimates is given below.

Weights

I assigned relative weights to each set of models, magnitudes, and distances based on the proponents' and my own opinion on the strengths and weaknesses of each model. A brief explanation of how these weights were assigned is given below. Because of the limited amount of time that was available, these assignments are rather crude and are meant to indicate the general process by

which these weights should be determined. The actual weights that I used to develop the estimates are presented in Table 1.

Hybrid Empirical Model

1. I gave this model relatively more weight at 5 km because it is well constrained by near-source recordings. All of the other models were based on a point-source representation of the earthquake, which is not valid at close distances, especially for the larger magnitudes. Relatively more weight was given to this model for the magnitude 7 event than for the magnitude 5.5 event, since the point-source representation is particularly poor for an earthquake of this size.

2. I would have given even more weight to this model at close distances, except that it may have a tendency to underestimate high-amplitude ground motions because of inherent nonlinear soil and soft-rock responses that may have not been completely removed from the original predictions.

3. I gave this model zero weight at 200 km, since the Western United States (WUS) attenuation relationships on which it is based are not reliable beyond about 100 km. Note, however, that the predicted values at this distance are not all that inconsistent with those derived from the other models.

Stochastic Simulation (EPRI) Model

1. I gave relatively less weight to this model at 5 km, especially for the magnitude 7 event, because it is based on a point-source representation of the earthquake.

2. I gave relatively less weight to this model at 200 km because it uses a simplified model to account for enhanced ground motions due to critical reflections that are important at this distance.

Stochastic Simulation (Atkinson) Model

1. I gave relatively less weight to this model at 5 km, especially for the magnitude 7 event, because it is based on a point-source representation of the earthquake.

2. I gave relatively more weight to this model at 200 km because it is based on observed attenuation characteristics at this distance.

Advance Numerical Model

1. Although this model incorporated finite fault effects, I gave it relatively less weight at 5 km, especially for the magnitude 5.5 event, because it appears to have been applied in such a manner that the median closest distance is larger than this target value.

2. I gave this model relatively less weight at magnitude 7 because it used a moment magnitude that was 0.6 to 0.8 units lower than was used by the other proponents and, hence, may be unconservative.

3. I gave this model relatively more weight at 200 km because it incorporates the most comprehensive modeling of the critical reflections that are important at this distance.

Median Ground Motion

I estimated median ground-motions by taking a weighted average of the logarithms of the median estimates (i.e., the geometric mean) provided by the four models. These estimates are summarized on the accompanying forms.

Epistemic Uncertainty

I did not attempt to separate the parametric and modeling components of the epistemic uncertainty. When separate estimates for these two components were provided by the proponents, I simply combined them by adding their variances. I estimated the total epistemic uncertainty by adding the weighted average of the epistemic variances provided by the four models to the weighted average of the variances of the logarithms of the median predictions derived from the four models. These estimates are summarized on the accompanying forms.

Aleatory Uncertainty

I estimated aleatory uncertainty by taking a weighted average of the aleatory variances provided by the four models. These estimates are summarized on the accompanying forms.

Epistemic Uncertainty on the Aleatory Uncertainty

I estimated the epistemic uncertainty on the aleatory uncertainty by adding an estimate of the variance of this uncertainty to the weighted average of the

calculated variances of the aleatory variances provided by the four models. The former was estimated to be 0.01 (i.e., a standard deviation of 0.1) based on estimates provided by empirical attenuation relationships for the WUS. These estimates are summarized on the accompanying forms.

DISCUSSION

The hard rock site for which estimates were made in this study is not typical of sites in the CEUS that are located on sediments (e.g., the Mississippi Valley), and may not even be typical of the majority of hard-rock sites in the CEUS based on results given by Walt Silva in his submission. For more typical sites, the ground motions on very hard rock provided in this study should be adjusted for the response of local site conditions.

All of the models depend to some extent on specific source and propagation models. To the extent that these source and propagation models vary significantly from region to region in the CEUS, the results will change accordingly. To accommodate these differences, the models would either have to be applied to a specific region, or sensitivity studies would have to be performed in order to show that the models are appropriate for the region of interest.

TABLE 1
WEIGHTS USED IN THE ANALYSES

Parameter	m_{LG}	Closest Dist. (km)	Hybrid Empirical	Stochastic (EPRI)	Stochastic (Atkinson)	Advance Numerical
PGA	5.5	5	0.6	0.2	0.2	0
	5.5	70	0.25	0.25	0.25	0.25
	7.0	5	0.5	0.2	0.2	0.1
	7.0	70	0.3	0.3	0.3	0.1
PSA (25 Hz)	5.5	20	0.25	0.25	0.25	0.25
	7.0	20	0.3	0.3	0.3	0.1
PSA (10 Hz)	5.5	5	0.6	0.2	0.2	0
	5.5	20	0.25	0.25	0.25	0.25
	5.5	70	0.25	0.25	0.25	0.25
	7.0	5	0.5	0.2	0.2	0.1
	7.0	20	0.3	0.3	0.3	0.1
	7.0	70	0.3	0.3	0.3	0.1
PSA (2.5 Hz)	5.5	20	0.25	0.25	0.25	0.25
	7.0	20	0.3	0.3	0.3	0.1
PSA (1 Hz)	5.5	5	0.6	0.2	0.2	0
	5.5	20	0.25	0.25	0.25	0.25
	5.5	70	0.25	0.25	0.25	0.25
	5.5	200	0	0.2	0.4	0.4
	7.0	5	0.5	0.2	0.2	0.1
	7.0	20	0.3	0.3	0.3	0.1
	7.0	70	0.3	0.3	0.3	0.1
	7.0	200	0	0.2	0.4	0.4

SSHAC SECOND
GROUND MOTION WORKSHOP

Expert: KEN CAMPBELL

Ground Motion Measure: 1-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.045	0.62
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.51	0.78
	aleatory uncertainty	median σ	0.84	0.72
		uncertainty in σ	0.15	0.15
20 km	median amplitude		0.013	0.20
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.63	0.78
	aleatory uncertainty	median σ	0.82	0.74
		uncertainty in σ	0.15	0.15
70 km	median amplitude		0.0028	0.056
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.67	0.90
	aleatory uncertainty	median σ	0.83	0.74
		uncertainty in σ	0.15	0.15
200 km	median amplitude		0.0011	0.011
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.44	1.05
	aleatory uncertainty	median σ	0.85	0.80
		uncertainty in σ	0.15	0.15

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Expert: KEN CAMPBELL

Ground Motion Measure: 2.5-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.050	0.44
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.46	0.56
	aleatory uncertainty	median σ	0.76	0.68
		uncertainty in σ	0.15	0.15
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Expert: KEN CAMPBELL

Ground Motion Measure: 10-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.55	2.0
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.50	0.72
	aleatory uncertainty	median σ	0.70	0.62
		uncertainty in σ	0.15	0.15
20 km	median amplitude		0.16	0.86
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.32	0.54
	aleatory uncertainty	median σ	0.68	0.62
		uncertainty in σ	0.15	0.15
70 km	median amplitude		0.027	0.20
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.44	0.55
	aleatory uncertainty	median σ	0.71	0.63
		uncertainty in σ	0.15	0.15
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Expert: KEN CAMPBELL

Ground Motion Measure: 25-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.20	1.1
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.40	0.50
	aleatory uncertainty	median σ	0.70	0.64
		uncertainty in σ	0.15	0.15
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Expert: KEN CAMPBELL

Ground Motion Measure: Peak Ground Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.37	1.2
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.61	0.70
	aleatory uncertainty	median σ	0.67	0.62
		uncertainty in σ	0.15	0.15
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude		0.014	0.097
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.46	0.51
	aleatory uncertainty	median σ	0.69	0.63
		uncertainty in σ	0.15	0.15
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

GROUND-MOTION ESTIMATES FOR THE NORTHEASTERN U.S. OR SOUTHEASTERN CANADA

W. B. Joyner

The attached estimates were made using a stochastic model based on recent work by Atkinson (1993) and Boatwright and Choy (1992) on source spectra and work by Atkinson and Mereu (1992) on distance attenuation in eastern North America. The principal difference between the model I used and the one described by Atkinson and Boore (1994) is that their two-corner source model is made up of two additive components whereas mine has two multiplicative components. The multiplicative model has fewer free parameters, and the corresponding spectra do not have the prominent sag at 2 to 3 s period that is characteristic of the additive model for large magnitudes. I am not claiming at this stage, however, that the multiplicative model is superior.

I have developed two variations of the multiplicative model. The one I prefer and have used in making the attached estimates is the self-similar model in which both corner frequencies scale as moment to the minus one-third power. The other is the empirical model in which the scaling of the corner frequencies with moment is adjusted to fit the spectral data, subject to the constraint that the high-frequency spectral level scale as moment to the one-third power.

The spectrum for the self-similar model is given by

$$A(f) = CM_0(2\pi f)^2/([1+(f/f_A)^2]^{3/4}[1+(f/f_B)^2]^{1/4}), \tag{1}$$

where $C = \mathcal{R}_{\mathcal{P}}FV/(4\pi\rho\beta^3 R)$, $\mathcal{R}_{\mathcal{P}}$ is the factor for average radiation pattern (0.55), F is the free-surface amplification factor (2.0), V is the factor for partition into two horizontal components (0.707), ρ is the crustal density (2.8 gm/cc), β is the source-region shear-wave velocity (3.8 km/s), M_0 is the seismic moment (dyne-cm) and R is distance (km). The corner frequencies are given by

$$f_A = 2.272 - 0.5\mathrm{M} \tag{2}$$

and

$$f_B = 3.389 - 0.5\mathrm{M}, \tag{3}$$

where M is moment magnitude ($= \frac{2}{3}\log M_0 - 10.7$). The constant terms in equations (2) and (3) were chosen so tha the high-frequency spectral levels and 1-Hz spectral amplitudes would fit the values given by Atkinson [1993, equations (4) and (5)]. The spectrum of equation (1) has an intermediate slope of $\omega^{1/2}$. A spectrum with an intermediate slope of ω can be developed that fits Atkinson's high-frequency spectral levels and 1-Hz spectral amplitudes, but it calls for f_A values that differ more from hers than the model with the $\omega^{1/2}$ intermediate slope.

There are other, minor, differences between my model and Atkinson and Boore (1994). I have used a κ filter (Anderson and Hough (1984) with a κ value of 0.002 instead of a sharp high-frequency cutoff at $f_{max} = 50Hz$. The choice of 0.002 for κ was governed by

the records of Miramichi events that showed flat spectra out to 100 Hz. The use of a κ filter with such a small value of κ required the use of a time step of 0.002 s. At D. M. Boore's suggestion suggestion I have changed the geometric spreading decay so that it is R^{-1} from $R = 0$ to $R = 70$ km, flat from $R = 70$ to $R = 130$ km, and $R^{-1/2}$ beyond $R = 130$ km. The associated Q model is $Q = 680f^{0.36}$. I have introduced a site-amplification filter based on the quarter-wavelength approximation (Boore and Joyner, 1991) and an assumed linear increase in velocity with depth from 2.8 km/s at the surface to 3.8 km/s at a depth of 3.6 km, which is the depth at which the overburden pressure reaches the value of 1 kbar, necessary to close the pores (Press, 1966).

I did not have time for an analysis of uncertainty, so I took as my estimates the values Gail Atkinson gave in her submission as "proponent." This should be appropriate in view of the similarity in the models.

In my view the point-source stochastic model makes the optimum use of available data while retaining simplicity, and I believe that the point-source stochastic model should be used exclusively for estimating ground motion in eastern North America (with possible exceptions in areas such as New Madrid and Charleston). Admittedly, estimates at 5 km for a moment magnitude 7 earthquake do strain the point-source assumption. I am not concerned with changes in magnitude scaling at short distance. We have examined that question with western U.S. empirical data (Boore *et al.*, 1994) and have found no effect. Directivity effects, however, may be preferentially higher at short distances and the point-source estimates thereby too low, but even if that is the case we need not be concerned, because the contribution of moment magnitude 7 earthquakes at 5 km to the hazard in Eastern North America is negligible except perhaps in areas such as New Madrid or Charleston.

The hard-rock site described in the instructions, with the surface shear-wave velocity of 2.8 km, is probably representative of rock sites in eastern North America that were affected by Wisconsin glaciation. Such sites probably require κ values of 0.002 or less. South of the southern limit of Wisconsin glaciation somewhat lower values of shear-wave velocity and higher values of κ would probably be appropriate for rock sites.

The geometric-spreading and Q functions used were obtained from data recorded in southeastern Canada on the Eastern Canada Telemetered Network. Data from the U.S. National Seismic Network suggest that there may be some reconizable differences in geometric-spreading and Q functions over the eastern and central U.S. (Harley Benz, oral communication, 1994).

In closing I wish to register my agreement with Gail Atkinson that moment magnitude (or better still high-frequency magnitude) is preferable to m_{Lg} for purposes of ground-motion estimation.

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SSHAC SECOND GROUND MOTION WORKSHOP

Expert: W. B. Joyner

Ground Motion Measure: 1-Hz Spectral Acceleration (g)

Distance	Quantity		m_{L_R} 5.5	m_{L_R} 7.0
5 km	median amplitude		0.028	0.671
	epistemic uncertainty	parametric (ln)	0.5	0.7
		median bias	0.0	0.0
		uncert. in bias (ln)	0.5	0.7
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
20 km	median amplitude		0.0072	0.163
	epistemic uncertainty	parametric (ln)	0.5	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.3	0.5
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
70 km	median amplitude		0.0014	0.036
	epistemic uncertainty	parametric (ln)	0.3	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.2	0.5
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
200 km	median amplitude		0.00091	0.024
	epistemic uncertainty	parametric (ln)	0.3	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.2	0.5
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2

Comments/footnotes:

SSHAC SECOND GROUND MOTION WORKSHOP

Expert: W. B. Joyner

Ground Motion Measure: 2.5-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.025 ✓	0.315 ✓
	epistemic uncertainty	parametric (ln)	0.3	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.3	0.7
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND GROUND MOTION WORKSHOP

Expert: W. B. Joyner

Ground Motion Measure: 10-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.618 ✓	3.40 ✓
	epistemic uncertainty	parametric (ln)	0.5	0.7
		median bias	0.0	0.0
		uncert. in bias (ln)	0.5	0.7
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
20 km	median amplitude		0.104 ✓	0.731 ✓
	epistemic uncertainty	parametric (ln)	0.3	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.3	0.5
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
70 km	median amplitude		0.014 ✓	0.130 ✓
	epistemic uncertainty	parametric (ln)	0.2	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.2	0.5
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND GROUND MOTION WORKSHOP

Expert: W. B. Joyner

Ground Motion Measure: 25-Hz Spectral Acceleration (g)

Distance	Quantity		m_{L_g} 5.5	m_{L_g} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.180 ✓	1.06 ✓
	epistemic uncertainty	parametric (ln)	0.3	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.3	0.5
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND GROUND MOTION WORKSHOP

Form 5: Page 5 of 5

Expert: W. B. Joyner

Ground Motion Measure: Peak Ground Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.700	2.83
	epistemic uncertainty	parametric (ln)	0.5	0.7
		median bias	0.0	0.0
		uncert. in bias (ln)	0.5	0.7
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude		0.0074	0.067
	epistemic uncertainty	parametric (ln)	0.5	0.5
		median bias	0.0	0.0
		uncert. in bias (ln)	0.2	0.5
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND

GROUND MOTION WORKSHOP

SECOND GROUND MOTION ESTIMATES AND DOCUMENTATION

by

Walt Silva

Pacific Engineering and analysis

July 20, 1994

The current ground motion estimates are developed from the viewpoint of a reasonably knowledgeable practitioner rather than proponent. I have included other models but retain a large weight on the EPRI model. In this regard perhaps the proponent lingers although in projects for WNA, I generally weight site specific (using the stochastic model) 0.5-0.6 and 0.5-0.4 weight to WNA empirical or hybrid empirical. Additionally, the EPRI model as implemented here is bias corrected. In my experience with the model in comparisons to data and finite fault modeling, the point source appears to have a stable overprediction of average motions at low frequencies (about 1 Hz and below). This bias results in a large reduction (50%) of motions at low frequencies (1 Hz). On further reflection, I would probably have done this in the initial estimates although I am always sensitive to the task of supporting a reduction in motion to a regulatory panel.

I am curious why PGA is not emphasized since it is used to pin shapes and this procedure is currently and will continue to be used? Also PGV is important because 0098 spectra are used in CENA and V/A ratios are different for CENA and WNA rock motions. Additionally DOE is becoming interested in motions at 2 sec. How would this affect the models being considered?

The specific models and weights are as follows:

Model	Weight
EPRI (1993) bias corrected	0.4
Atkinson (adjusted)	0.3
Advanced Numerical Modeling	0.2
Stochastic 1/R ($1/\sqrt{R}$, R > 100 km)	0.1

The following capricious logic documents the choice of models and respective weights.

1) EPRI (1993) with 40% weight: This models represents the most intensive and comprehensive development in terms of parameters and uncertainties as well as validation of all the models considered. It considers effects of source finiteness and observed source depth distributions. It is simplest model with the fewest parameters and when using WNA parameters its predictions compare very favorably with the WNA empirical (see discussion on stochastic model).

2) Atkinson (adjusted) with a 30% weight: I am concerned about the empirical attenuation applied to large magnitudes and was uncertain about the 5 km results (Atkinson has only 1 event within 20 km). To accommodate the closest distance, I ran the point source with the specified parameters but using the Atkinson 2-corner source model (h = 10 km). Figure Set 2 shows the resulting spectra and Table 1 lists the ground motions. To adjust my runs to what Gail might have gotten, I scaled my 2-corner runs down by 1.5. This factor results from correcting R^{-1} to $R^{-1.1}$ at R = 11 km $\approx$ 1.3 and taking out the amplification in the Midcontinent crustal structure $\approx$ 1.2. The net result is 1.3 times 1.2 $\approx$ 1.5. It should be noted my motivation for including this model is primarily the 2-corner source, the attenuation is similar to EPRI (1993) as Figure 3 suggests.

3) Advanced Numerical Modeling was given 20% weight: This model apparently has very similar attenuation characteristics as the Atkinson empirical model for small magnitude earthquakes (Atkinson and Somerville, 1994). It also gave values close to Atkinson's for m_{Lg}

7.0. It seems the epistemic uncertainty is very low for a model with many parameters applied in a region with few opportunities to constrain the parameters. I would not associate such a low epistemic uncertainty with the stochastic finite fault applied in ENA. I am concerned with the large disagreement between the bias corrected EPRI and advanced numerical modeling results. In validation exercises EPRI (1993) both models showed similar values for modeling uncertainty plus randomness for the same earthquakes and nearly the same sites ?

4) Stochastic with 10 % weight: The simple 1/R geometrical attenuation single corner frequency stochastic model predicts WNA ground motions reasonably well. Figure Set 1 shows PGA attenuation for M 5.5, 6.0, 6.5, 7.0, and 7.5 using a point source with 1/R and a stochastic finite source with 1/R compared to WNA empirical attenuation. The point source depth used is 8 km and is taken from Joyner and Boore's (1981) factious depth for PGA attenuation. For all magnitudes, the comparisons between the point source (dashed lines) and the empirical (solid lines) are good. At M 7.5, the point source overpredicts as it does not include saturation effects (log PGA ~ 0.3 M) but up to M 7.0 the point source is not overpredicting. The EPRI 1993 model incorporates this effect of source finiteness. These results suggest that a point source using 1/R is a reasonable model for ground motions due to a finite source in a realistic earth structure. Much of this logic reflects my feelings about the difference between using rigorous wave propagation methods in idealized 1-dimensional earth models and trying to predict strong ground motions in the real earth for engineering design. When all the variabilities are considered, 1/R with a flattening beyond some distance (70-100 km) does a good job on average.

Interestingly, and worth note, the stochastic finite source overpredicts at distance using 1/R and the degree of overprediction is smallest for the M 5.5. For M 6.5 (the best constrained empirical), the stochastic finite source was run using the Ou and Herrmann formulation for direct plus post-critical rays. The results show larger motions than 1/R in close and a slightly faster attenuation rate at distance and then a change at about 70 km. A plausible interpretation of these results is that a finite source suitably averaged over slip models, nucleation points, crustal structure (not done here), and site azimuth attenuates about like 1/R (compare the dashed line and the crosses for M 6.5) out to some distance defined by an average crustal thickness where the slope changes. In other words, a finite source comprised of patches with each patch attenuating with direct waves greater then 1/R has a net effect which attenuates about as 1/R (before the critical distance). This is why the point source works. A finite source with each patch attenuating as 1/R falls off more slowly than 1/R, as Figure Set 1 suggest. Note the attenuation for M 5.5 for point and finite sources both using 1/R are nearly identical and match the empirical very well. In this case, the M 5.5 source size is essentially a point. The point in all of this is that the EPRI (1993) model used a point source with the Ou and Herrmann formulation and may, as a result, tend to be high in-close and fall off too fast at intermediate distances. I do feel that the point source should be run with 1/R ($1/\sqrt{R}$, $R>R_0$) to emulate a finite fault. These results also suggest that empirical attenuation models based largely on small magnitude data may show more structure in attenuation with distance than would be shown with larger sources. To capture an aspect of the 1/R results and to have some contribution of the stochastic model to the specific magnitudes and distances (rather than the EPRI regression model) I ran the point source with the give parameters with a depth of 10 km (Table 1). The depth was based on the average C_7 terms in the EPRI (1993) midcontinent attenuation model and

the hypocenter distribution (EPRI, 1993). These results were bias corrected using the bias estimates listed in the tables from the initial ground motion estimates and given a 10% weight.

5) Hybrid Empirical was given a weight of 0%: Based on comparisons between the stochastic point source and empirical relations for WNA (such as Figure Set 1) I would expect the adjusted empirical to be similar to the stochastic model predictions. The fact that they are support the stochastic model's validity. Weighting it higher would essentially dilute the 2-corner contribution. I suppose the converse argument could be made in giving EPRI 0% weight and the Hybrid Empirical 40%. I don't know what to say about that.

The accompanying reduction in epistemic uncertainty by combining models was assumed to be:

1) 100% reduction in bias uncertainty from 0.2 to 0.1

2) the parametric was left unchanged for m_{L_ϕ} 5 and reduced by 50% for m_{L_ϕ} 7.

For application, the advanced numerical modeling (or an equivalent such as Toro's model, Hutchings' model, or NCEER'S model which is well validated) representing finite fault and more rigorous wave propagation than 1/R and $1/\sqrt{R}$ with larger epistemic uncertainties (reflecting source function variabilities, magnitude area relations, asperity characteristics (size and depth), rise time scaling, etc) needs to be in the form of an attenuation model. I would also feel more comfortable with a demonstration that the Atkinson empirical attenuation form is appropriate for large magnitudes, for higher frequencies, and for PGA, and adjusted for magnitude saturation effects. If EPRI (1993) we redone using 1/R my weights would be revised

specific stochastic point source 50-60%, Atkinson 30% (primarily for the 2-corner contribution), and finite fault 20%. For the finite fault, I would use the stochastic finite fault with Ou and Herrmann geometrical spreading. I believe the finite fault is most appropriate for deterministic studies in site-specific cases where you are dealing with a dominate structure with M>6.5 and with the site within about 10 km.

Table 1

1.0 Hz Spectral Acceleration (g)			R (km)
	M 5.0	M 7.1	
Atkinson	0.0169 (0.011)*	0.3820 (0.255)	11
Stochastic	0.0243 (0.0163)**	0.5209 (0.3492)	11
	0.0083	0.1856	22
	0.0119 (0.008)	0.2533 (0.169)	22
	0.00231	0.0521	71
	0.00337 (0.0023)	0.0713 (0.048)	71
	0.00081	0.0194	200
	0.00186 (0.0012)	0.0268 (0.0179)	200
2.5 Hz Spectral Acceleration (g)			**R (km)**
	0.04712	0.5810	22
	0.04924 (0.036)	0.4471 (0.3312)	22

*Corrected for $R/R^{1.1}$ where R = 11 km and amplification in Midcontinent crust of about 1.2

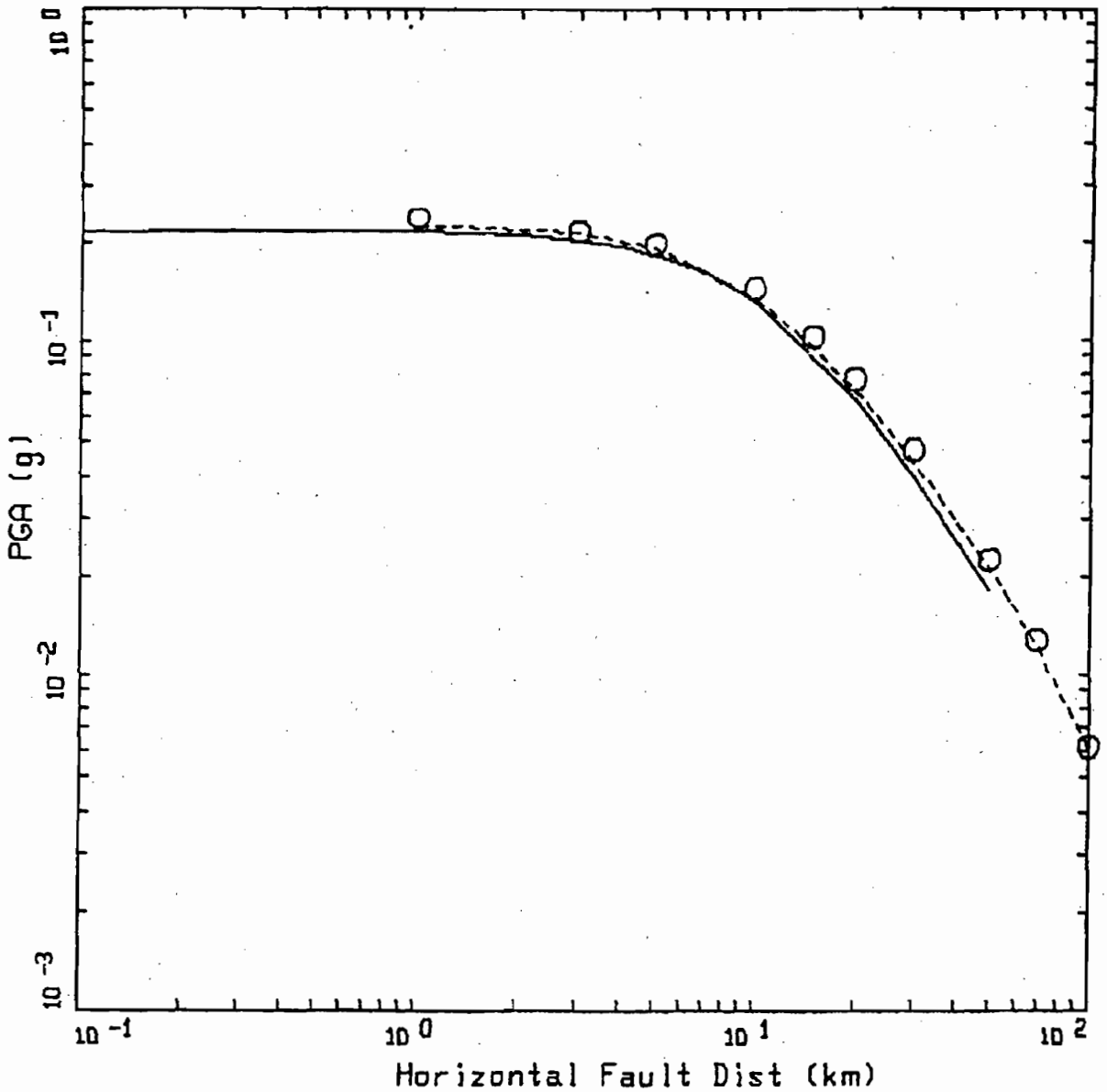
**Corrected for bias

Model Parameters: h = 10 km, $\Delta\sigma$ = 120 bars, κ = 0.006 sec, $Q(f) = 670\ f^{0.33}$, Midcontinent Crust, Atkinson = 2-corner source, Stochastic = 1-corner source

Table 1 (cont.)

10 Hz Spectral Acceleration (g)		R (km)
M 5.0	M 7.1	
		11
0.5214 (0.3342)	2.646 (1.69)	
0.3274 (0.2959)	1.867 (1.689)	11
0.2204	1.350	22
0.1385 (0.1253)	0.8550 (0.7736)	22
0.0394	0.2942	22
0.0249 (0.0225)	0.1873 (0.1695)	22

25 Hz Spectral Acceleration (g)		R (km)
0.3009	1.638	22
0.1783 (0.1613)	1.024 (0.9266)	22
ap (g)		
0.2741 (0.183)	1.378 (0.919)	11
0.1713 (0.155)	0.8989 (0.8133)	11
0.0160	0.1206	71
0.0105 (0.0095)	0.0841 (0.0761)	71



M=5.5 SLIP VARIATION
AVERAGE PGA ATTENUATION

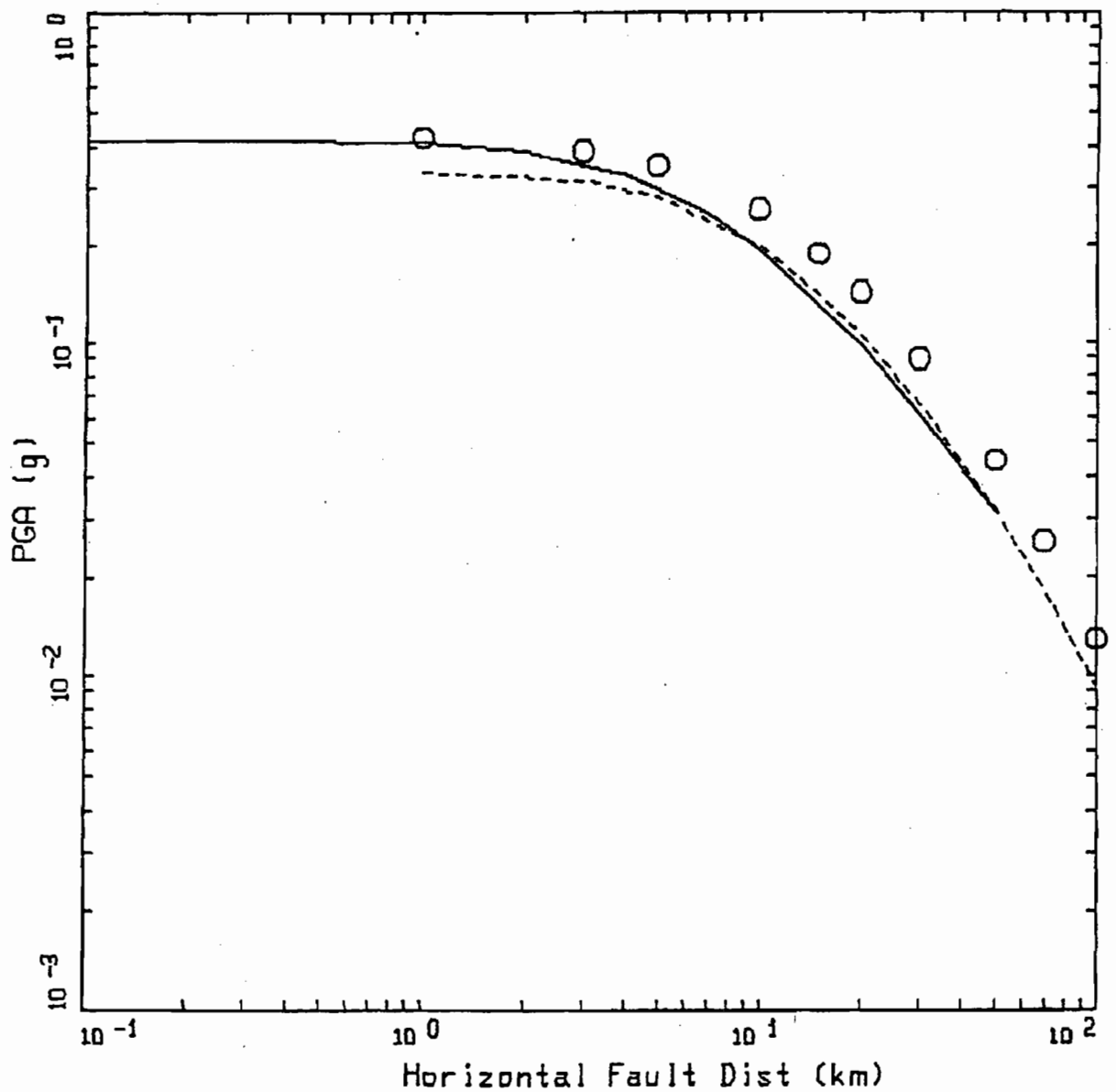
LEGEND

O FINITE SOURCE: AVG OVER 11 SLIPS, 11 SITES, NEW RT, RAND FOC, NEW AMPS

----- POINT SOURCE

——— AVERAGE EMPIRICAL (PG&E)

Figure Set 1.



M=6.0 SLIP VARIATION
AVERAGE PGA ATTENUATION

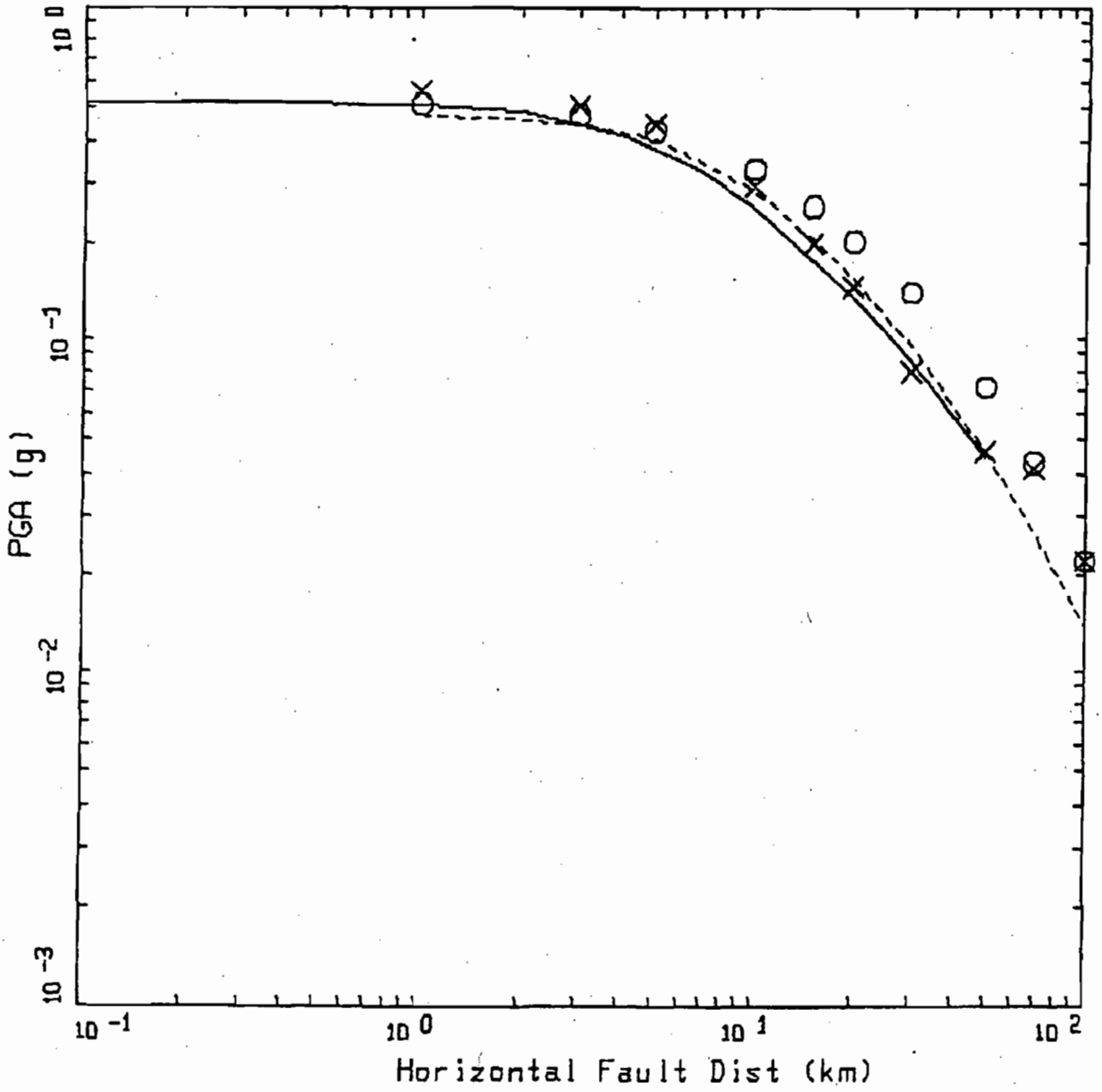
LEGEND

O FINITE SOURCE: AVG OVER 11 SLIPS, 11 SITES, NEW RT, RAND FOC, NEW AMPS

----- POINT SOURCE

——— AVERAGE EMPIRICAL (PG&E, AB-SIL)

Figure Set 1. (Continued)



M=6.5 SLIP VARIATION
AVERAGE PGA ATTENUATION

LEGEND

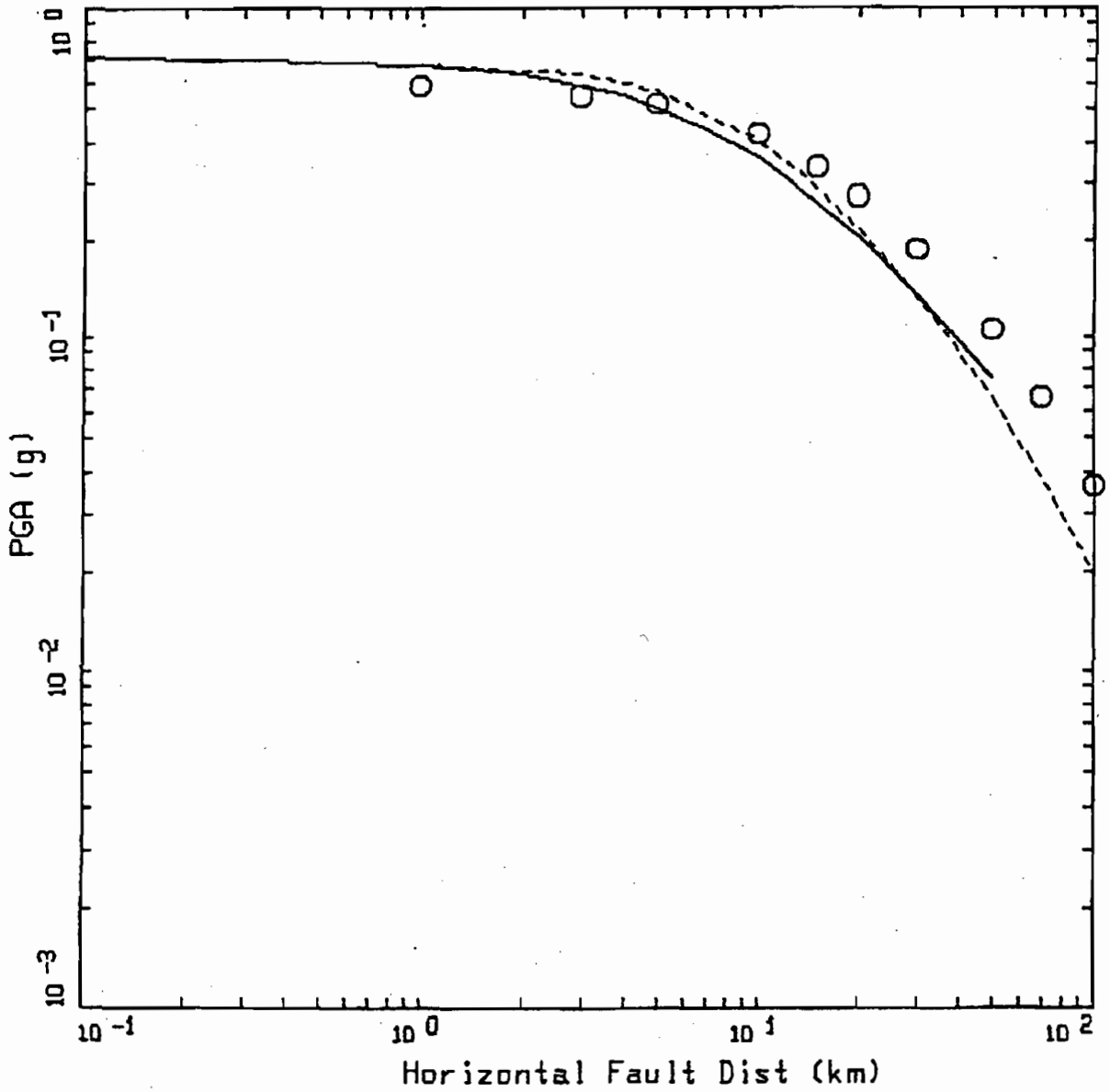
O FINITE SOURCE: AVG OVER 11 SLIPS, 11 SITES, NEW RT, RAND FOC, BOORE AMPS

X FINITE SOURCE: AVG OVER 11 SLIPS, 11 SITES, NEW RT, RANFOC, WALD/OH, NEW AMPS

----- POINT SOURCE

——— AVERAGE EMPIRICAL

Figure Set 1. (Continued)



M=7.0 SLIP VARIATION
AVERAGE PGA ATTENUATION

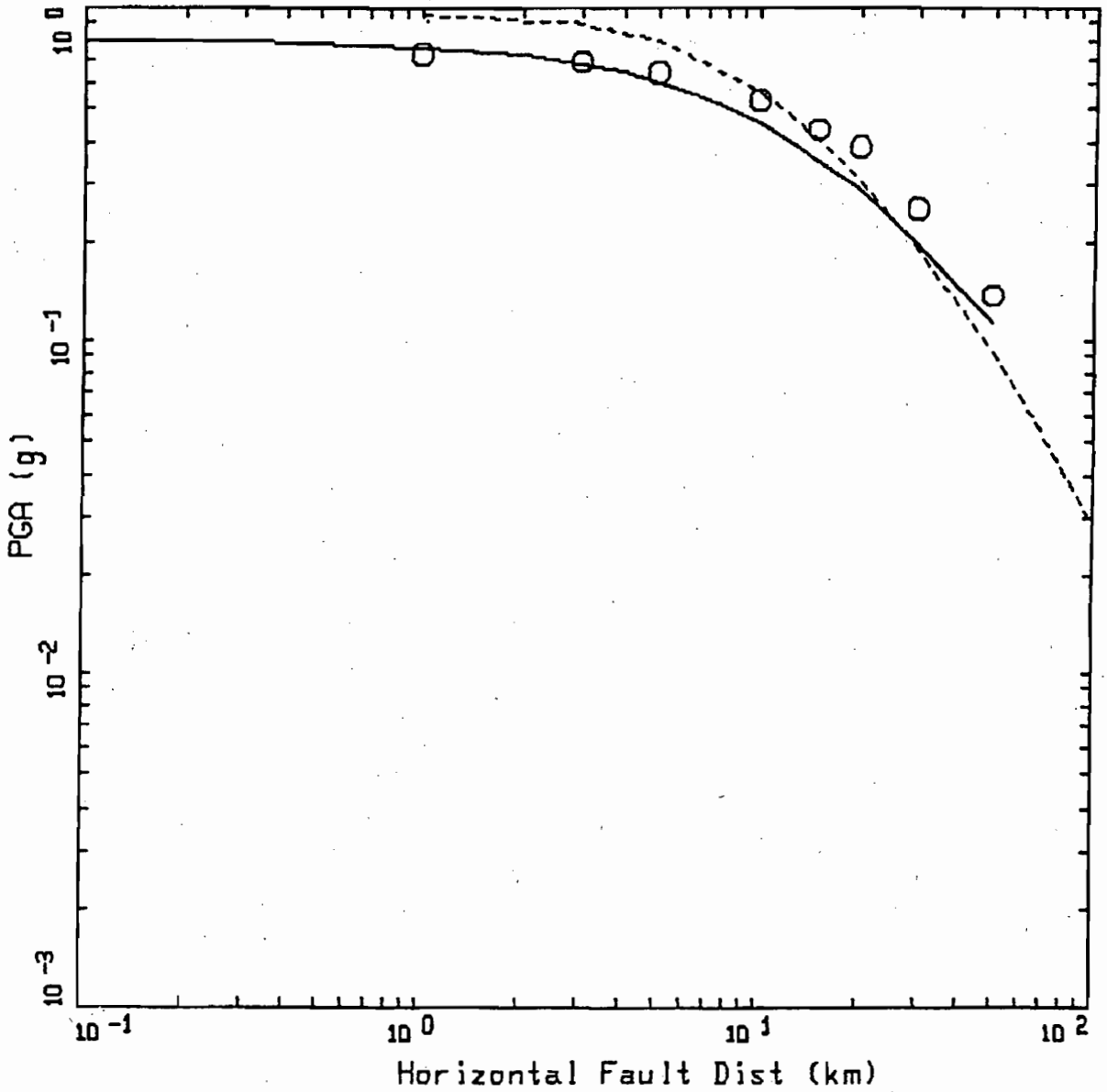
LEGEND

O FINITE SOURCE: AVG OVER 11 SLIPS, 11 SITES, NEW RT, RAND FOC, NEW AMPS

----- POINT SOURCE

——— AVERAGE EMPIRICAL (PG&E, AB-SIL)

Figure Set 1. (Continued)



M=7.5 SLIP VARIATION
AVERAGE PGA ATTENUATION

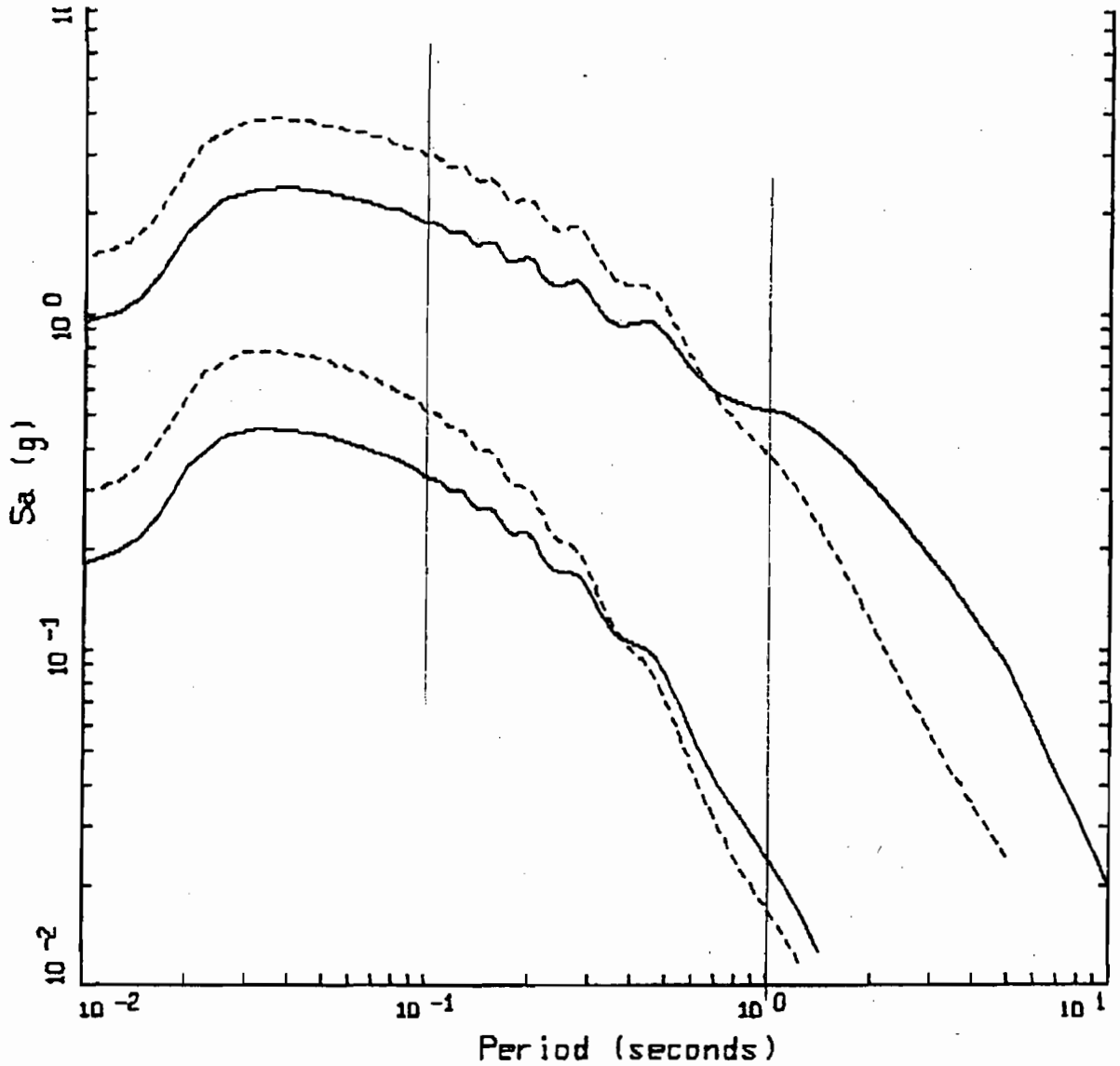
LEGEND

O FINITE SOURCE: AVG OVER 11 SLIPS, 11 SITES, NEW RT, RAND FOC, NEW AMPS, NEW AREA

----- POINT SOURCE

——— AVERAGE EMPIRICAL (PG&E, AB-SIL)

Figure Set 1. (Continued)

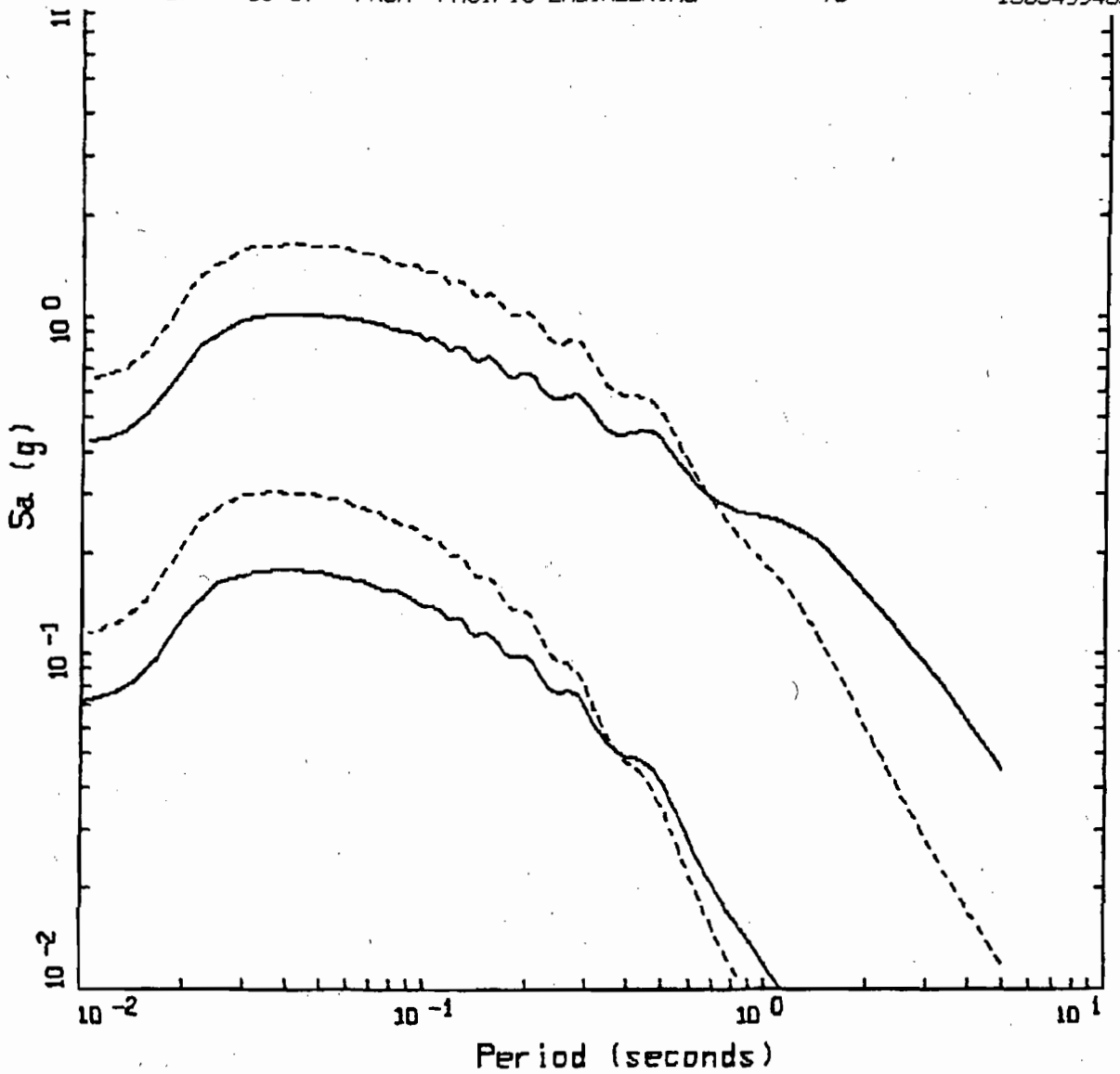


SSHAC RESPONSE SPECTRA
MIDCONT CRUST, D=5 KM

LEGEND

——— 5 %, M=5.0, SD=120 BARS; PGA=0.171 G
----- 5 %, M=5.0, ATKINSON SOURCE; PGA=0.274 G
——— 5 %, M=7.1, SD=120 BARS; PGA=0.899 G
----- 5 %, M=7.1, ATKINSON SOURCE; PGA=1.378 G

Figure Set 2.

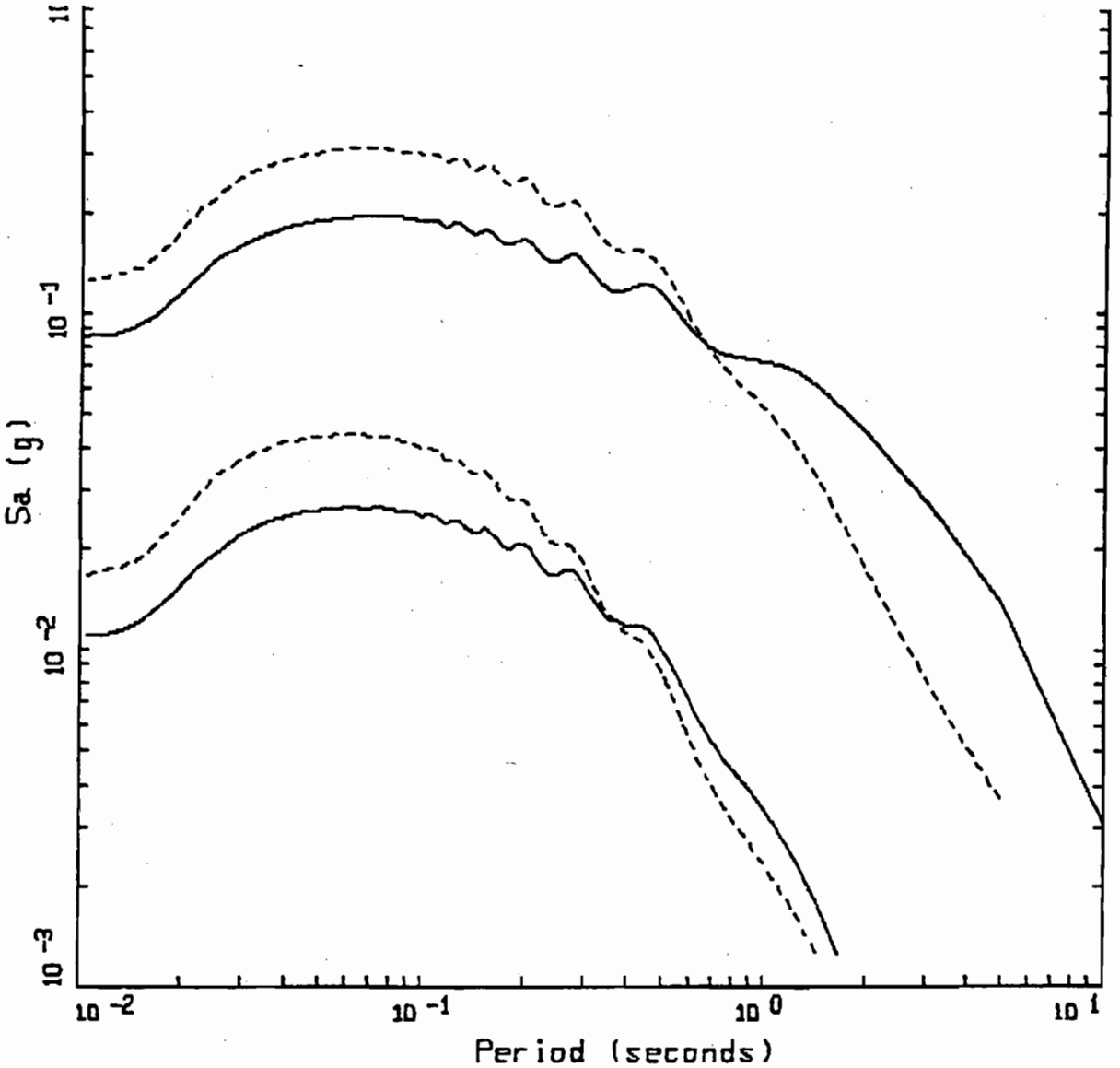


SSHAC RESPONSE SPECTRA
MIDCONT CRUST, D=20 KM

LEGEND

———	5 %, M=5.0, SD=120 BARS; PGA=0.069 G
- - - - -	5 %, M=5.0, ATKINSON SOURCE; PGA=0.108 G
———	5 %, M=7.1, SD=120 BARS; PGA=0.401 G
- - - - -	5 %, M=7.1, ATKINSON SOURCE; PGA=0.610 G

Figure Set 2. (Continued)



SSHAC RESPONSE SPECTRA
MIDCONT CRUST, D=70 KM

LEGEND

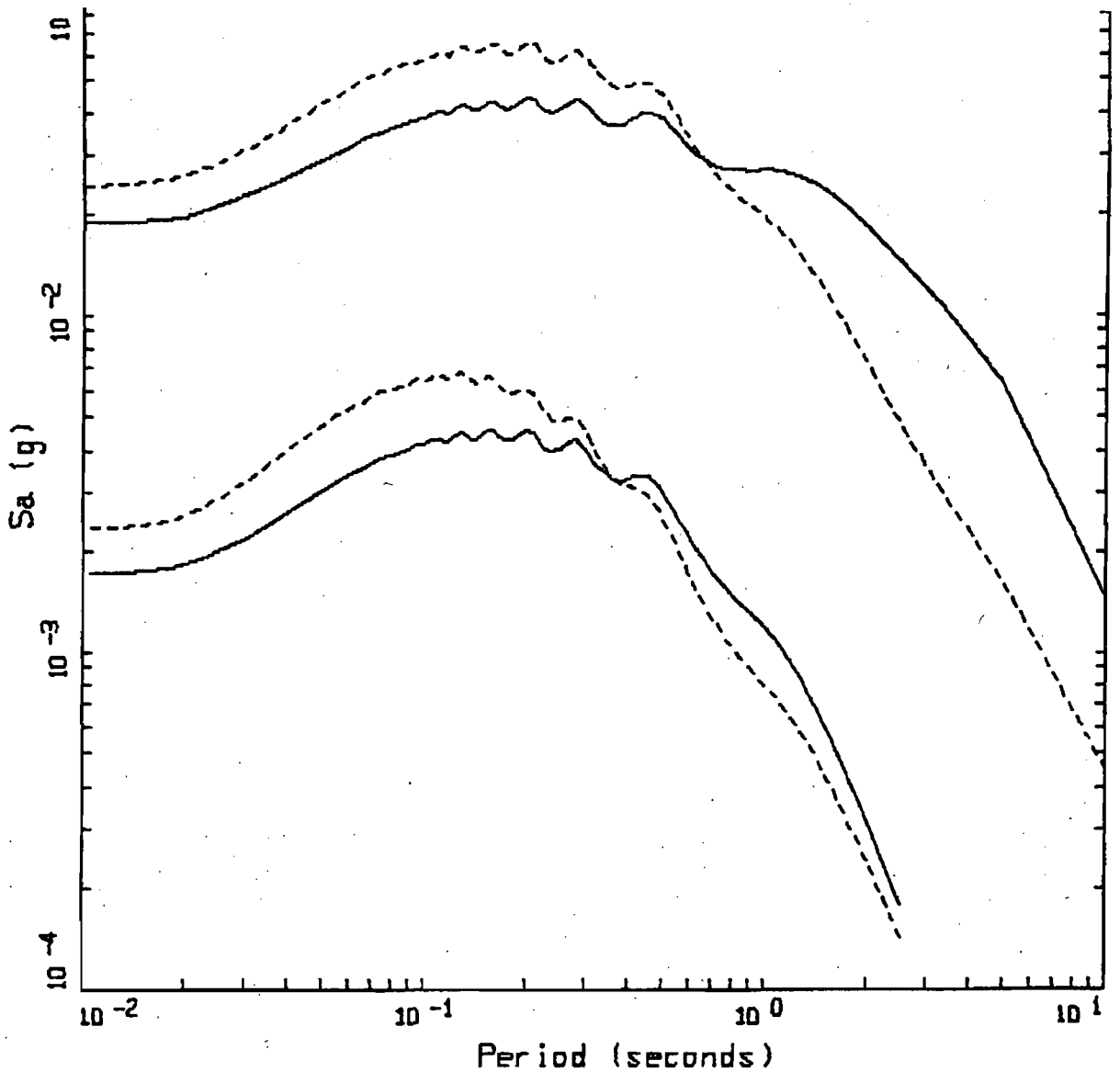
——— 5 %, M=5.0, SD=120 BARS; PGA=0.011 G

----- 5 %, M=5.0, ATKINSON SOURCE; PGA=0.016 G

——— 5 %, M=7.1, SD=120 BARS; PGA=0.082 G

----- 5 %, M=7.1, ATKINSON SOURCE; PGA=0.121 G

Figure Set 2. (Continued)



SSHAC RESPONSE SPECTRA
MIDCONT CRUST, D=200 KM

LEGEND

———	5 %, M=5.0, SD=120 BARS; PGA=0.002 G
-----	5 %, M=5.0, ATKINSON SOURCE; PGA=0.002 G
———	5 %, M=7.1, SD=120 BARS; PGA=0.019 G
-----	5 %, M=7.1, ATKINSON SOURCE; PGA=0.024 G

Figure Set 2. (Continued)

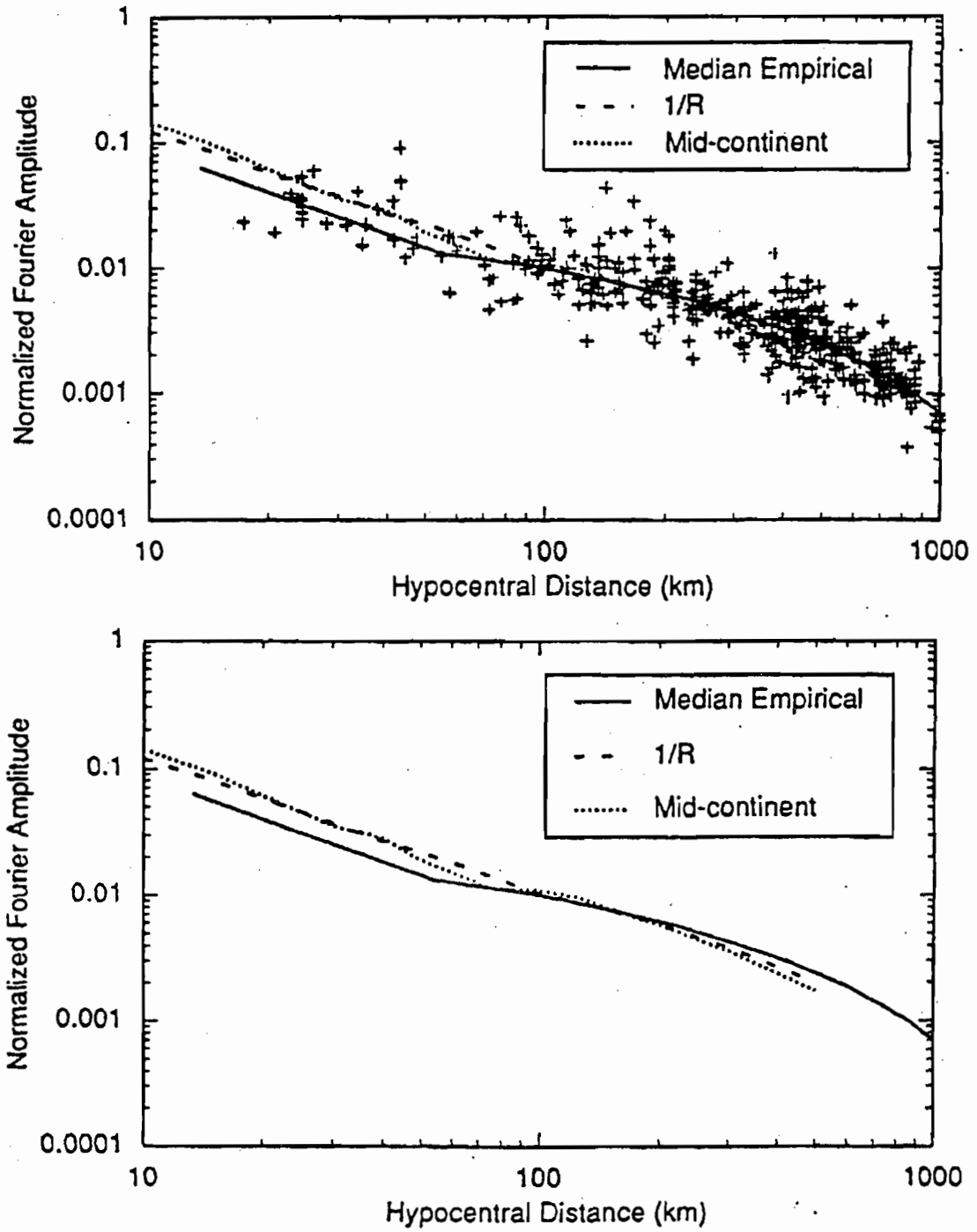


Figure 5-2a. Top frame: Empirical attenuation in southeastern Canada for Fourier amplitude at 2 Hz from Atkinson and Mereu (1992). Station corrections and source corrections have been applied. The solid curve is the regression fit to these data. The dashed and dotted lines are based on the stochastic model described in Section 3.2. Bottom frame: Without data.

Figure 3.

SSHAC SECOND GROUND MOTION WORKSHOP

Expert: WALT SILVA

Ground Motion Measure: 1-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.023	0.370
	epistemic uncertainty	parametric (ln)	0.14	0.31
		median bias	0	0
		uncert. in bias (ln)	0.1	0.1
	aleatory uncertainty	median σ	1.11	0.91
		uncertainty in σ	0.2	0.2
20 km	median amplitude		0.015	0.160
	epistemic uncertainty	parametric (ln)	0.14	0.31
		median bias	0	0
		uncert. in bias (ln)	0.1	0.1
	aleatory uncertainty	median σ	0.92	0.8
		uncertainty in σ	0.2	0.2
70 km	median amplitude		0.003	0.046
	epistemic uncertainty	parametric (ln)	0.14	0.31
		median bias	0	0
		uncert. in bias (ln)	0.1	0.1
	aleatory uncertainty	median σ	0.92	0.8
		uncertainty in σ	0.2	0.2
200 km	median amplitude		0.001	0.018
	epistemic uncertainty	parametric (ln)	0.14	0.31
		median bias	0	0
		uncert. in bias (ln)	0.1	0.1
	aleatory uncertainty	median σ	0.92	0.8
		uncertainty in σ	0.2	0.2

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Expert: WALT SILVA

Ground Motion Measure: 2.5-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.044	0.400
	epistemic uncertainty	parametric (ln)	0.12	0.25
		median bias	0	0
		uncert. in bias (ln)	0.1	0.1
	aleatory uncertainty	median σ	0.74	0.64
		uncertainty in σ	0.2	0.2
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND GROUND MOTION WORKSHOP

Expert: WALT SILVA

Ground Motion Measure: 10-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.322	1.910
	epistemic uncertainty	parametric (ln)	0.11	0.24
		median bias	0	0
		uncert. in bias (ln)	0.1	0.1
	aleatory uncertainty	median σ	0.77	0.69
		uncertainty in σ	0.2	0.2
20 km	median amplitude		0.155	0.892
	epistemic uncertainty	parametric (ln)	0.11	0.24
		median bias	0	0
		uncert. in bias (ln)	0.1	0.1
	aleatory uncertainty	median σ	0.61	0.51
		uncertainty in σ	0.2	0.2
70 km	median amplitude		0.026	0.194
	epistemic uncertainty	parametric (ln)	0.11	0.24
		median bias	0	0
		uncert. in bias (ln)	0.1	0.1
	aleatory uncertainty	median σ	0.61	0.51
		uncertainty in σ	0.2	0.2
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Expert: WALT SILVA

Ground Motion Measure: 25-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.190	1.13
	epistemic uncertainty	parametric (ln)	0.11	0.24
		median bias	0	0
		uncert. in bias (ln)	0.1	0.1
	aleatory uncertainty	median σ	0.68	0.60
		uncertainty in σ	0.2	0.2
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Expert: WALT SILVA

Ground Motion Measure: Peak Ground Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.172	0.96
	epistemic uncertainty	parametric (ln)	0.11	0.24
		median bias	0	0
		uncert. in bias (ln)	0.1	0.1
	aleatory uncertainty	median σ	0.79	0.72
		uncertainty in σ	0.2	0.2
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude		0.011	0.089
	epistemic uncertainty	parametric (ln)	0.11	0.24
		median bias	0	0
		uncert. in bias (ln)	0.1	0.1
	aleatory uncertainty	median σ	0.62	0.52
		uncertainty in σ	0.2	0.2
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND GROUND MOTION WORKSHOP

Menlo Park July 28-29 1994

DOCUMENTATION OF GROUND MOTION ESTIMATES DERIVED FROM THE ESTIMATES OF FOUR PROPONENTS

GROUND-MOTION EXPERTS: Paul Somerville and Chandan Saikia, Woodward-Clyde

Prepared July 18, 1994

DERIVATION OF GROUND MOTION ESTIMATES FROM THE ESTIMATES OF FOUR PROPONENTS

PART 1. MEDIAN AMPLITUDES (Topic 1a)

1.1. Magnitude Dependence; Conversion of m_{blg} - M_w

We think that the M_w values of 7.23 used by Campbell and Silva and the M_w value of 7.0 used by Atkinson are inappropriate representations of an m_{blg} 7 earthquake, for the reasons described in Appendix 1. In order to use their estimates for m_{blg} 7, we have adjusted them to represent motions for M_w 6.4. When this is done, the differences among the ground estimates by the different proponents are greatly reduced, as shown in Figures 1-1 through 1-3. We have similarly adjusted the estimates for the m_{blg} 5.5 earthquake by Atkinson, Campbell and Silva, converting their estimates for M_w 5.0 to estimates for M_w 5.2.

1.2. Period Dependence

We think that the source model of Atkinson underpredicts the motions at a period of one second. We assign low weights to these estimates in deriving our best estimates. The predictions of m_{blg} 5.5 motions by Somerville and Saikia have high frequency levels that seem inconsistent with those for m_{blg} 7 motions, suggesting that kappa may have not been treated consistently between these two sets of calculations. Accordingly, the high frequency estimates of Somerville and Saikia for m_{blg} 5.5 are assigned low weights in deriving our best estimates.

1.3. Distance Dependence

We think that the point source stochastic models of Atkinson and Silva overpredict the near fault motions (distances of 5 and 12 km) for magnitude 7.0. We assign low weights to these estimates in deriving our best estimates.

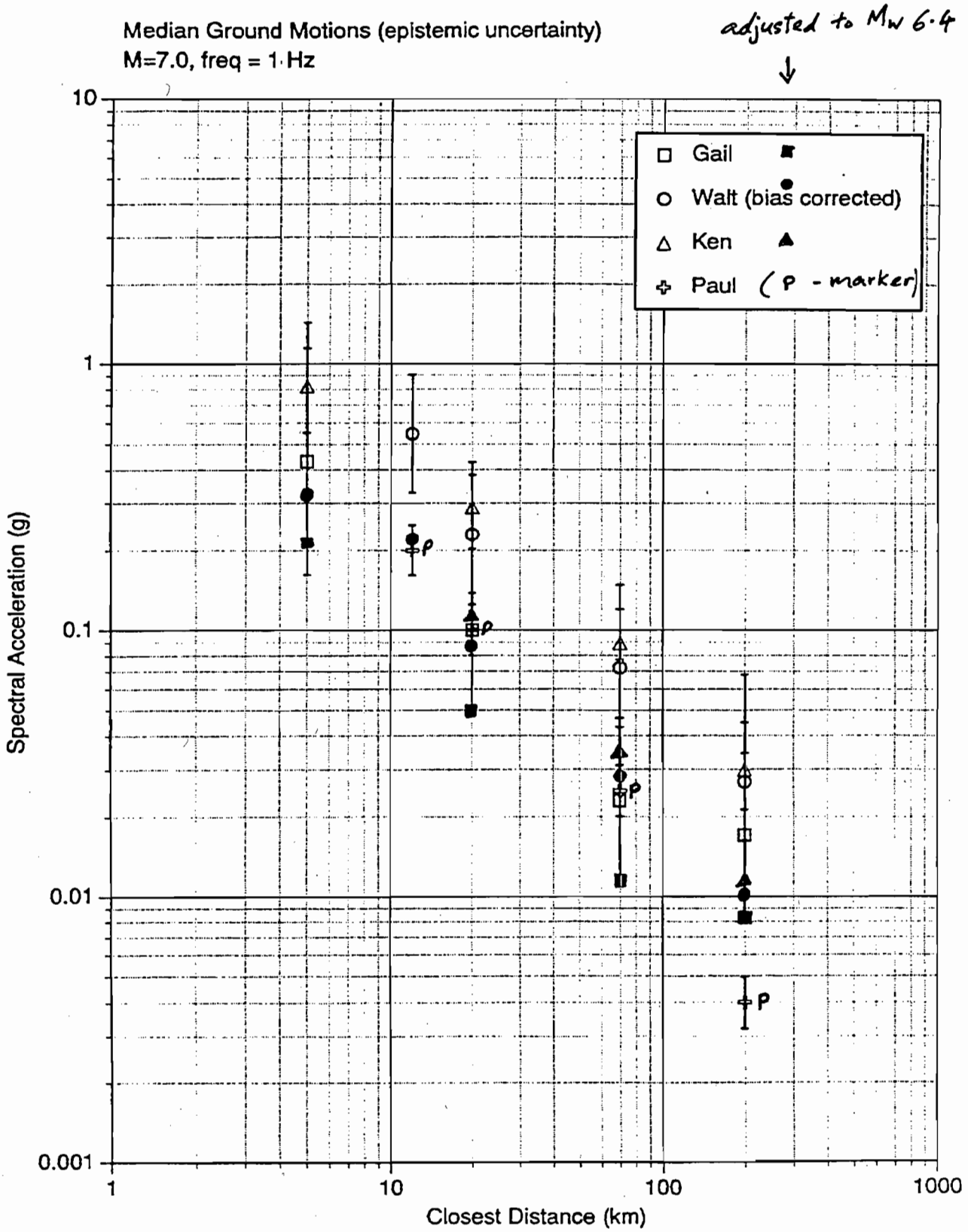

Median Ground Motions (epistemic uncertainty)
M=7.0, freq = 1 Hz
adjusted to Mw 6.4
Gail
Walt (bias corrected)
Ken
Paul (P - marker)
Spectral Acceleration (g)
Closest Distance (km)
10
1
0.1
0.01
0.001
1
10
100
1000
P

Fig. 1-1

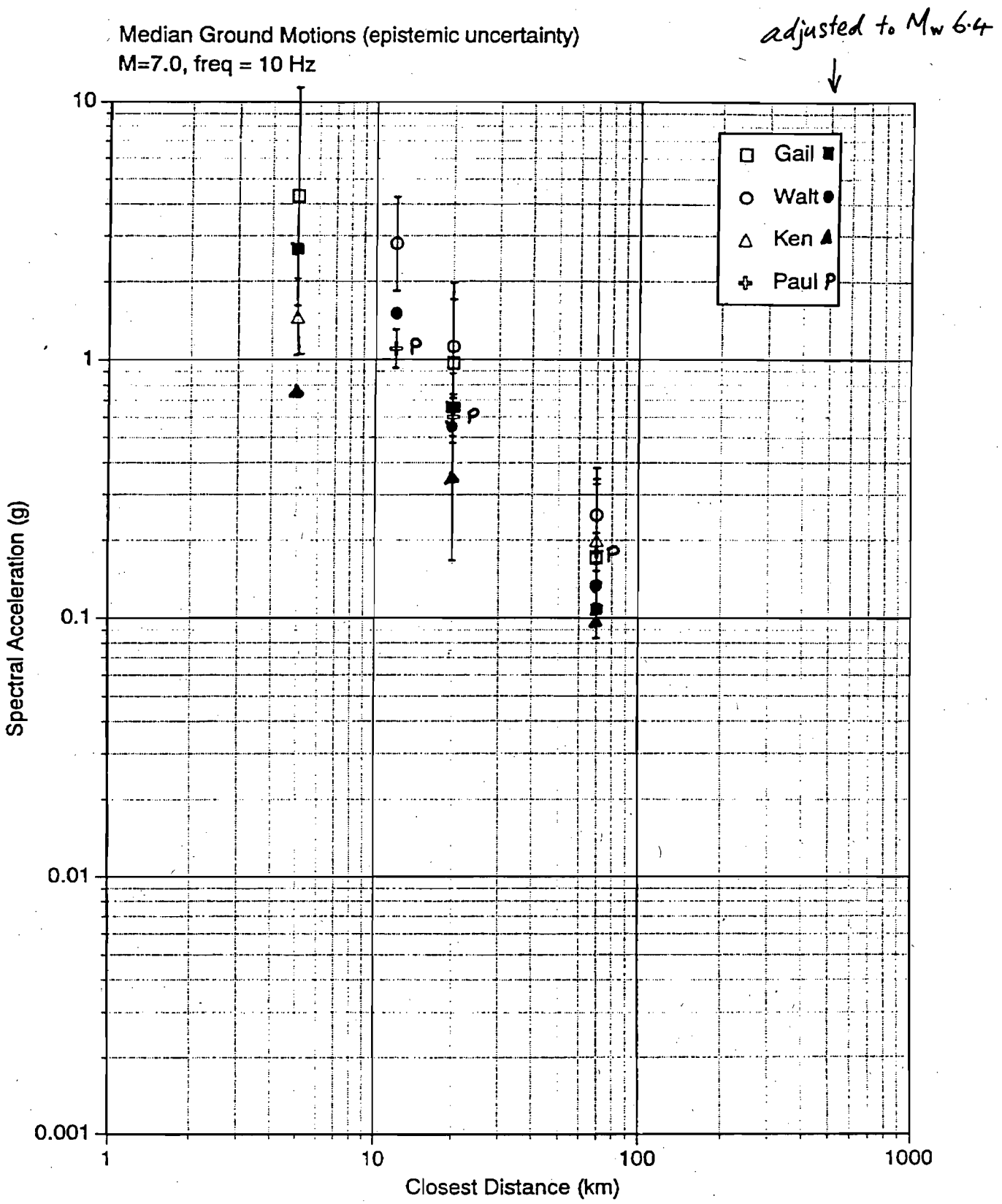

Median Ground Motions (epistemic uncertainty)
M=7.0, freq = 10 Hz
adjusted to Mw 6.4
Gail
Walt
Ken
Paul
P
Spectral Acceleration (g)
10
1
0.1
0.01
0.001
1
10
100
1000
Closest Distance (km)

Fig 1-2

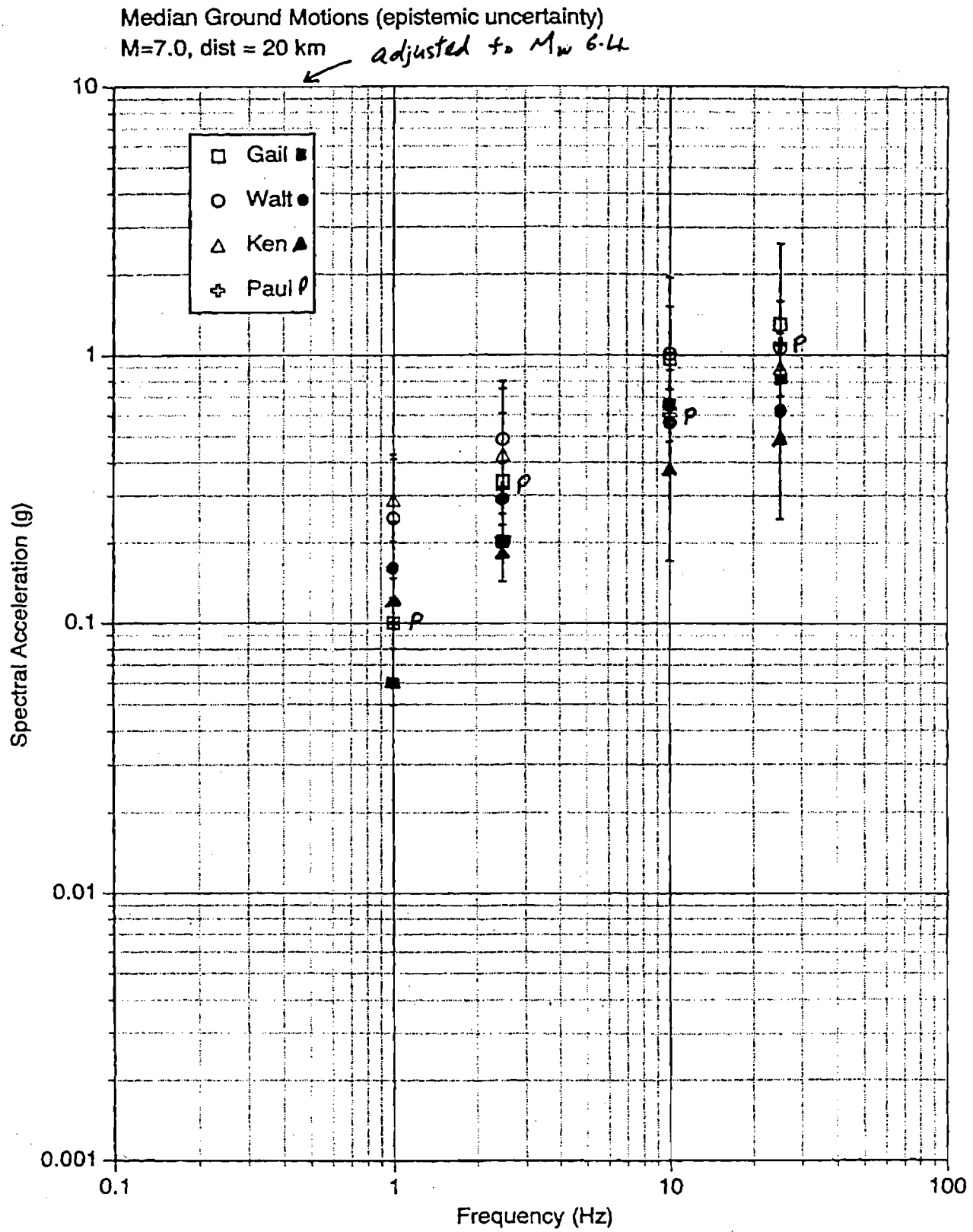

Median Ground Motions (epistemic uncertainty)
M=7.0, dist = 20 km
adjusted to Mw 6.4
Gail
Walt
Ken
Paul
P
Spectral Acceleration (g)
Frequency (Hz)
10
1
0.1
0.01
0.001
0.1
1
10
100

Fig 1-3.

PART 2. ALEATORY UNCERTAINTY (Topics 1b, 2b)

2.1 Specific Comments on Estimates by Individual Proponents.

Atkinson assumed an aleatory uncertainty of 0.8, independent of magnitude, distance and period. However, the values given in Table 2 of her Appendix B range from 0.99 at 1 Hz to 0.67 at 10 Hz. This strong period dependence is compatible with the estimates of other proponents. She does not estimate total aleatory uncertainty by combining parametric and modeling components following the Abrahamson et al. (1990) procedure, as was done by Silva and by Somerville and Saikia. Consequently, we are unable to compare the contribution of parametric uncertainty due to the stress parameter in her model with that of Silva's model.

The aleatory uncertainty in the Silva model shows a higher frequency dependence than that of the other proponents for m_{blg}5.5, and is very large for the longer periods. His aleatory uncertainty is generally less than that of the other proponents (except Campbell) for m_{blg} 7 because most of the uncertainty in the stress parameter is treated as epistemic parametric uncertainty for magnitude 7. As indicated in the preceding paragraph, we do not have an estimate of parametric uncertainty due to the stress parameter in another version of the stochastic model (Atkinson's model) to evaluate the appropriateness of the Silva estimate.

Somerville and Saikia seem to have overestimated their aleatory uncertainty by double counting the contributions from Q and kappa. Since they used fixed assumptions about Q and kappa values in the calculations that were compared with recorded data to estimate modeling uncertainty, it is inappropriate to include parametric uncertainties in Q and kappa in the overall aleatory uncertainty. The practical results of this double counting are not large, and are only significant for the estimates of aleatory uncertainty for 25 Hz and PGA.

The aleatory uncertainty in the Campbell model is lower than that of the other models, especially for m_{blg} 7. Campbell assumed that the strong magnitude dependence of aleatory uncertainty that is observed in strong motion data in the western United States is also applicable in the northeastern United States and southeastern Canada. One issue that he did not address is whether the aleatory uncertainty that he derives from attenuation relations for soil is also appropriate for attenuation relations for rock.

2.2 Magnitude Dependence.

As described above, Campbell assumed that the strong magnitude dependence of aleatory uncertainty that is observed in strong motion data in the western United States is also applicable in the northeastern United States and southeastern Canada. We consider this to be a reasonable assumption, but would prefer that it be supported by some kind of evidence from ground motion data from the northeastern United States and southeastern Canada. Unpublished results of analyses of the empirical data that were performed during the EPRI project may shed light on this. All of the other three proponents use models which have large parametric uncertainties. We think that there is considerable overlap between the parametric uncertainty and the modeling uncertainty (derived from goodness of fit to recorded data), because of the imperfection of the models. The combined aleatory uncertainty in these models therefore probably overestimates the

variability that we will see in recorded data. Based on these considerations, we have adopted an intermediate position. We have introduced a magnitude dependence into the aleatory uncertainty that is not present in the estimates derived from the three modeling approaches, giving estimates for m_{blg} 7 that are intermediate between the low values extrapolated from the western United States by Campbell and the high values that come from the three modeling approaches.

2.3 Period Dependence.

There is a tendency for the aleatory uncertainty to decrease with increasing frequency in all of the four proponents' models for both magnitudes evaluated. We think that this is a realistic feature of aleatory uncertainty in ground motions, and have introduced a monotonic decrease in aleatory uncertainty with increasing frequency into our best estimate of the ground motions.

2.4 Distance Dependence.

Taken together, the aleatory uncertainty of the four models does not show a dependence on distance for either magnitude. However, for the Somerville and Saikia calculations for the higher frequencies, there is a pronounced increase in aleatory uncertainty at a distance of 70 km. This results from variations in the critical distance for lower crustal reflections due to variability in crustal structure. There is evidence for this kind of distance dependence in the residuals between recorded motions and those calculated by ray theory in Atkinson and Somerville, 1994 (Figures 10 and 11). We have chosen to reflect this kind of distance dependence in the aleatory uncertainty for the higher frequencies. We also expect it to be present in the aleatory uncertainty for the lower frequencies, but this uncertainty is so large because of the large modeling uncertainty component at the lower frequencies that the distance dependence is not resolved. With the distance measure defined as closest distance to the fault rupture, we do not understand why the uncertainties in the estimates of Silva at close distances are so large.

2.5 Epistemic uncertainty associated with aleatory uncertainty

Two of the proponents (Atkinson and Silva) estimated this to be 0.2, one (Somerville and Saikia) estimated it to be 0.1, and one (Campbell) did not provide an estimate. In our minds, the largest source of this uncertainty is due to uncertainty in whether the aleatory uncertainty decreases with magnitude in northeastern United States and adjacent southeastern Canada, as it does in the western United States. Accordingly, we assign this parameter a value of 0.1 for m_{blg} 5.5 and 0.15 for m_{blg} 7.

PART 3. EPISTEMIC UNCERTAINTY (Topics 2a, 3)

We think that it is appropriate to separate epistemic uncertainty into its parametric and modeling components, and have provided our estimates in this form. The parametric component is entered in the box labelled "parametric," and the modeling component is entered in the box labelled "uncertainty in bias." We consider our best estimate ground motions to be unbiassed and so we report zero bias.

Two of the proponents (Atkinson and Campbell) have very large epistemic uncertainties for both magnitudes, and another (Silva) has large epistemic uncertainites for m_{blg} 7. Atkinson uses "guestimates" of parametric uncertainty that are not documented or justified in detail. In the hybrid approach used by Campbell, there are large modeling uncertainties involved in the conversion from soil to rock conditions in the WUS, and from WUS to CEUS rock conditions, but their sizes are not identified individually or separated from the component due to differences among empirical attenuation relations. Silva's large parametric uncertainty for m_{blg} 7, which is clearly documented in the EPRI report, comes from assigning most of the variability in stress drop for large magnitudes to epistemic uncertainty.

In contrast with these large (and in some cases poorly documented) epistemic uncertainties, the estimates of epistemic uncertainty by Somerville and Saikia are rigorously documented and are quite small. Based on a review of the parametric and modeling uncertainties considered by the other proponents in estimating epistemic uncertainty, we have not identified any aspects that were not taken into account by Somerville and Saikia. This should justify giving larger weights (as amended by weights based on the other considerations discussed in Part 1) to the median ground motion amplitude estimates of Somerville and Saikia than to those of Atkinson and Campbell for m_{blg} 5.5, and to all three of the other proponents for m_{blg} 7, in deriving best estimates for the ground motion amplitudes.

In estimating epistemic uncertainty in the best estimates of ground motions provided here, we consider that the relatively low values of modeling and parametric uncertainty documented by Somerville and Saikia are more realistic than those of the other proponents, and have adopted them as representing the epistemic uncertainty in the best estimates of the ground motion amplitudes.

PART 4. DISCUSSION

4.1 General discussion of strengths and weaknesses of the approaches used

We consider the approaches of all four proponents to be relevant in a general sense for estimating ground motions in northeastern North America. Specific qualifiers to this general statement are discussed in Part 1 above and Part 4.2 below. The approaches are related to physical models and incorporate empirical data in differing ways and to differing degrees, and produce differing estimates of ground motions and their uncertainties.

4.1.1 Considerations based on estimates of uncertainty by the different models

The variations in aleatory uncertainty between the different proponents are fairly well documented and understood. The largest sources of differences relate to the large uncertainty in the stress parameter in the stochastic model for m_{blg} 5.5, and to the assumption of magnitude dependent aleatory uncertainty in the hybrid empirical method for m_{blg} 7. However, there are large differences among the four proponents' estimates of epistemic uncertainty, as described above in Part 3. These estimates are significantly larger for the Atkinson, Campbell and Silva models than they are for the Somerville and Saikia model. Based on a review of the parametric and modeling uncertainties considered by these three proponents in estimating epistemic uncertainty, we have not identified any aspects that were not taken into account by Somerville and Saikia. This may justify giving larger weights to the median ground motion amplitude estimates of Somerville and Saikia than to those of Atkinson and Campbell for m_{blg} 5.5, and to all three of the other proponents for m_{blg} 7, in deriving best estimates for the ground motion amplitudes.

4.1.2 Considerations based on the nature of the different models

The stochastic models used by the proponents are all based on a point source model having a uniform radiation pattern and a random phase spectrum. The assignment of a Brune source spectrum (or two-cornered spectrum) having a finite corner frequency and finite stress parameter to a point source is, strictly speaking, inconsistent since a true point source has infinite corner frequency and infinite stress drop. Obviously, the point source representation is being used as a convenience, but in this mode, the stochastic model is more like a mathematical analog of a physical model than a physically plausible model. Similarly, the approximate methods that are used to represent geometrial spreading in the stochastic model are more like mathematical analogs than true physical models. In the stochastic approach used by Atkinson, all three of the inputs (the source model, the geometrical spreading function, and the ground motion duration model) are estimated from empirical data. Her model is more like a hybrid empirical model than a theoretical model which predicts ground motions from a set of physical laws, but has the flexibility of incorporating empirically based inputs.

The advanced numerical modeling approach used by Somerville and Saikia, in comparison, has a corner frequency that results from finite source dimensions (as in the Brune model), and uses Green's functions (which are a rigorous representation of wave propagation in simplified crustal models) to represent geometrical spreading. While the approach used by Somerville and Saikia

contains simplifications and approximations, it is a more physically-based model than the point-source stochastic model. It has more predictive power in regions where data are sparse than does a hybrid empirical model that relies on regional data for the constraint of its input parameters. The advanced numerical modeling method is compatible with methods that are used routinely in the estimation of earthquake source parameters and wave propagation characteristics based on the calculation of synthetic seismograms, and should be comprehensible to this large community of seismologists. The Green's functions used by the method need only be calculated once for a given crustal structure. They can then be archived on the INTERNET for use by multiple investigators in ground motion modeling and seismic source inversion.

One of the features of the stochastic model is its dependence on a key parameter, the stress parameter, that directly scales the ground motion amplitude at frequencies above the corner frequency. This simple model should have an advantage over more complex models in that it is subject to uncertainty in the median values and variabilities of fewer parameters. However, there appears to be considerable epistemic uncertainty in the median value of the stress parameter (Atkinson most recently used 180 bars, while Silva used 120 bars). Moreover, as we saw in the discussion of aleatory uncertainty in Part 2, the variability in the stress parameter gives rise to very large uncertainties in predicted ground motions.

It is possible that this variability in stress parameter is really caused by other factors, such as the inadequate sampling of azimuthal variability in source radiation. Complexities such as this may cause the over-estimation of variability in the stress parameter, as well as contribute to the modeling uncertainty when azimuthally invariant ground motion predictions are compared with data having real azimuthal variation in source radiation. Thus inadequate parameterizations of source and path models, instead of yielding the benefit of minimizing parametric uncertainty, may give rise to the double counting of certain effects in parametric and modeling uncertainty and result in larger overall aleatory uncertainty than more adequate parameterizations of source and path models.

The source radiation strength in the advanced numerical model used by Somerville and Saikia is controlled by the radiation contained in empirical source functions. As implemented in their calculations, a fixed set of empirical source functions is used and so they do not treat the source radiation as a variable. Any inadequacies in this representation of source radiation strength appear as modeling uncertainty derived from goodness of fit to a suite of different earthquakes, and there is no parametric uncertainty involved with the prediction of ground motions for future events. In this sense, the advanced numerical modeling approach is free of a source strength parameter that is difficult to constrain, and is thus simpler to use. However, the empirical source functions that it uses need to be appropriate to the region in which the method is applied. To date, the available evidence indicates that the stress drops of magnitude 5 events (which are used for empirical source functions) are about 100 bars in both eastern and western North America, justifying the use of empirical source functions in the eastern United States that are derived from western United States earthquakes.

In the hybrid empirical approach used by Campbell, there are large modeling uncertainties involved in the conversion from soil to rock conditions in the WUS, and from WUS to CEUS rock conditions. We think that this parametric uncertainty could be reduced, and the hybrid

empirical method improved, by starting with empirical attenuation relations for hard rock, even allowing for the difficulties associated with the hard rock data.

4.2 Applicability to magnitude/distance/frequency ranges

For predictions for a specified M_w, we consider the hybrid empirical method of Campbell and the advanced numerical modeling method of Somerville and Silva to be applicable for all of the combinations of magnitude, distance and frequency values specified in the Instructions to Proponents. The point source stochastic models of Atkinson and Silva may not be appropriate at close distances to large earthquakes, and the Atkinson model may not be appropriate for periods around 1 second. For predictions for a specified m_{blg}, the Atkinson, Campbell and Silva methods are not applicable for the larger magnitudes unless corrections (described in Appendix 1) are applied to the relationships between M_w and m_{blg}.

4.3 Representativeness of hard rock site

The hard rock site (2.8 km/sec average shear wave velocity over the top 30 m) is probably representative of unweathered crystalline rock sites in the northeastern United States and southeastern Canada. It may not be representative of sedimentary rock sites in the Central and Eastern United States.

4.4 How results would differ in other regions within the Central and Eastern United States

The ground motion estimates presented here are for the northeastern United States or southeastern Canada (region 10 in the EPRI regionalization of crustal structure). The variability of median ground motions (5 Hz response spectral acceleration at 5% damping) for a moment magnitude 6.5 earthquake calculated using the crustal structure models for all 16 regions of eastern North America is illustrated in Figure 5-46 from EPRI TR-102293-V1, which is reproduced as Figure 4.1. The intra-region variability about the median ground motions due to uncertainty in crustal structure may be different in different regions. This is illustrated in Figures 4.2 through 4.4, where the intra-region variability for the Grenville and New Madrid regions are compared. The variability in the Grenville region is largest for distances around 100 km and is produced by variability in the depth of the Moho. In contrast, the variability in the New Madrid region is largest for distances around 60 km, and is produced by variability in the depth of the Conrad.

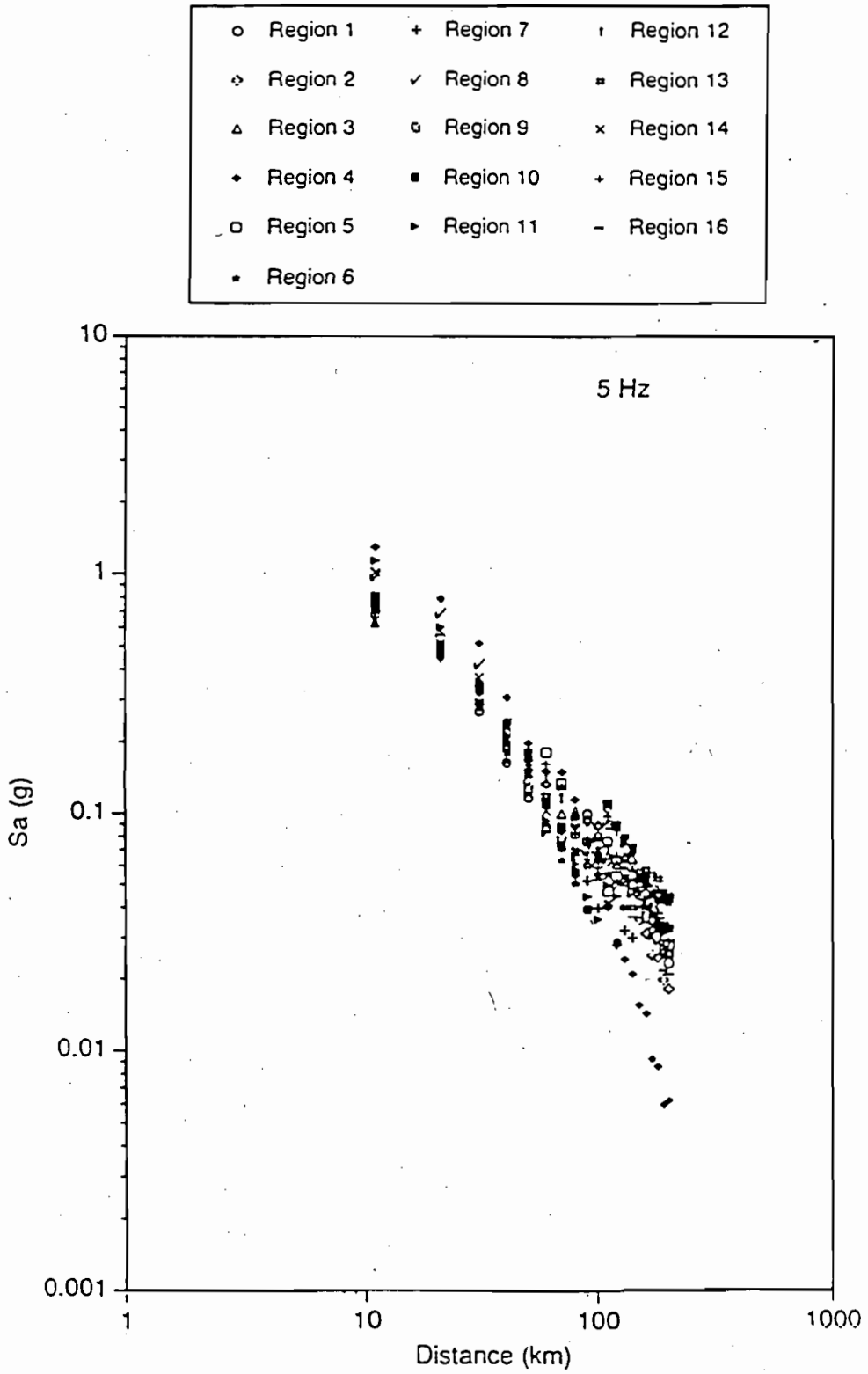


Figure 5-46. Comparison of median ground motion attenuation of spectral acceleration at 5 Hz for the 16 regions.

Fig. 4-1

the maximum standard error is shifted to distances of 80 to 120 km again associated with the variation in Moho depth. The depth of the Moho affects the distance range at which the maximum standard error occurs. In general, the deeper the Moho, the larger the distance at which the maximum occurs.

In Figures 5-25 and 5-26 the variation of ground motion for a given crustal structure is shown for three depths. To account for the variability in focal depth, the ground motion variability is computed using a weighted average over focal depths where the weights are given by the EAA generic depth distribution (Table 5-9). The standard errors of the mean spectral acceleration are shown in Figures 5-27a,b,c for 1, 5, and 15 Hz.

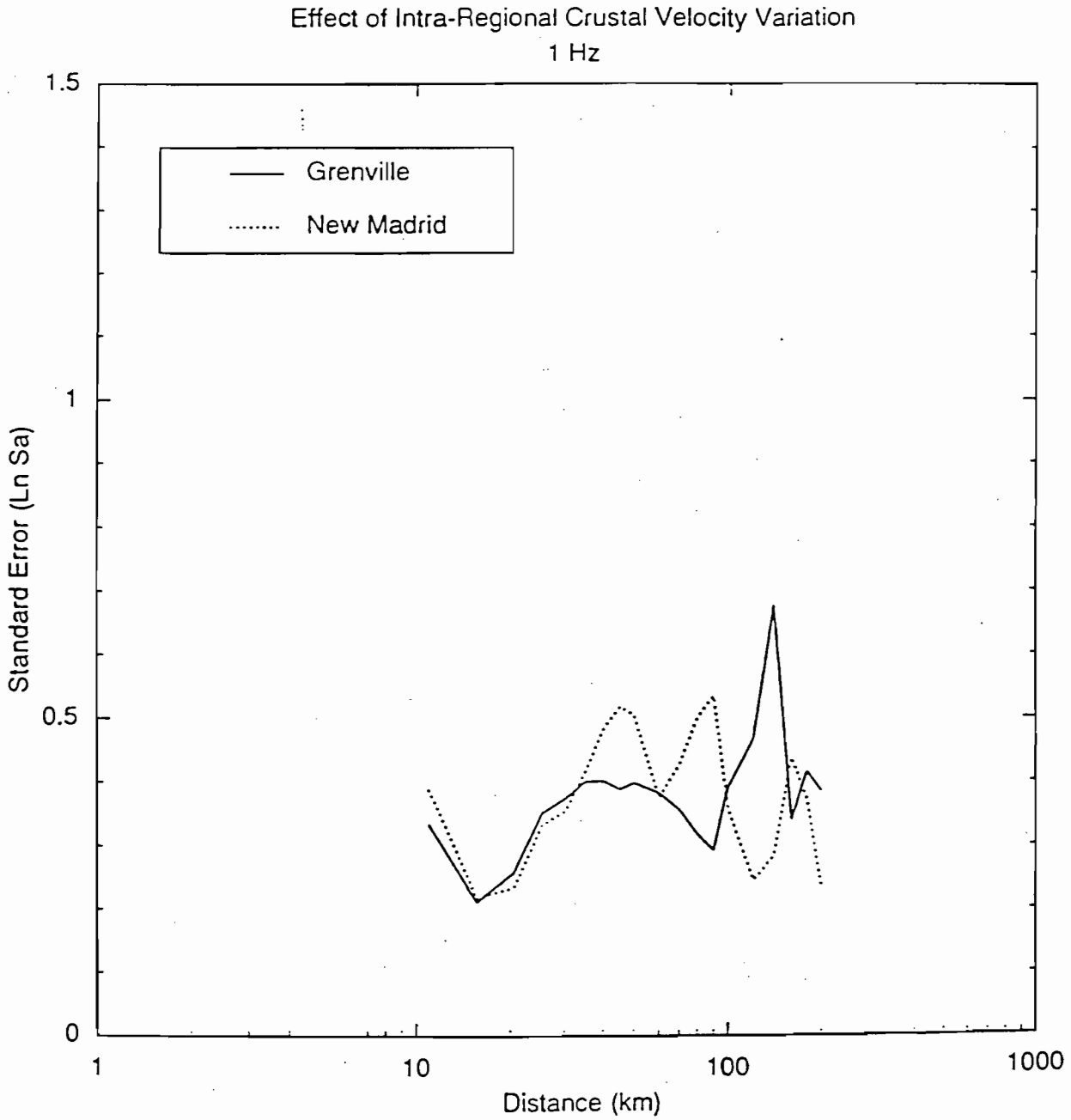


Figure 5-27a. Variability of spectral acceleration at 1 Hz due to crustal velocity uncertainty within the Grenville and New Madrid region. The variability includes variability in focal depth.

Fig. 4·2

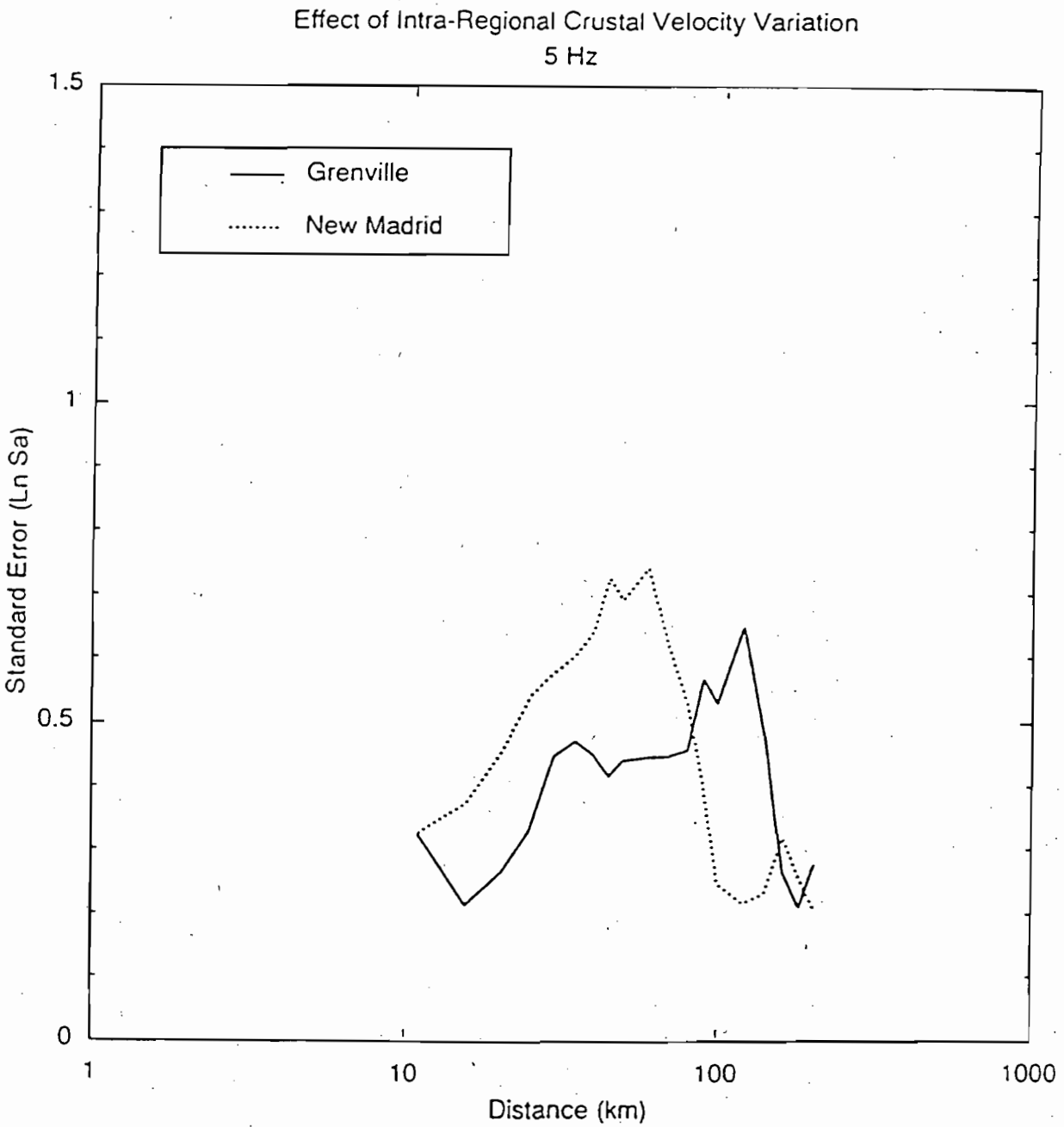


Figure 5-27b. Variability of spectral acceleration at 5 Hz due to crustal velocity uncertainty within the Grenville and New Madrid region. The variability includes variability in focal depth.

Fig. 4-3

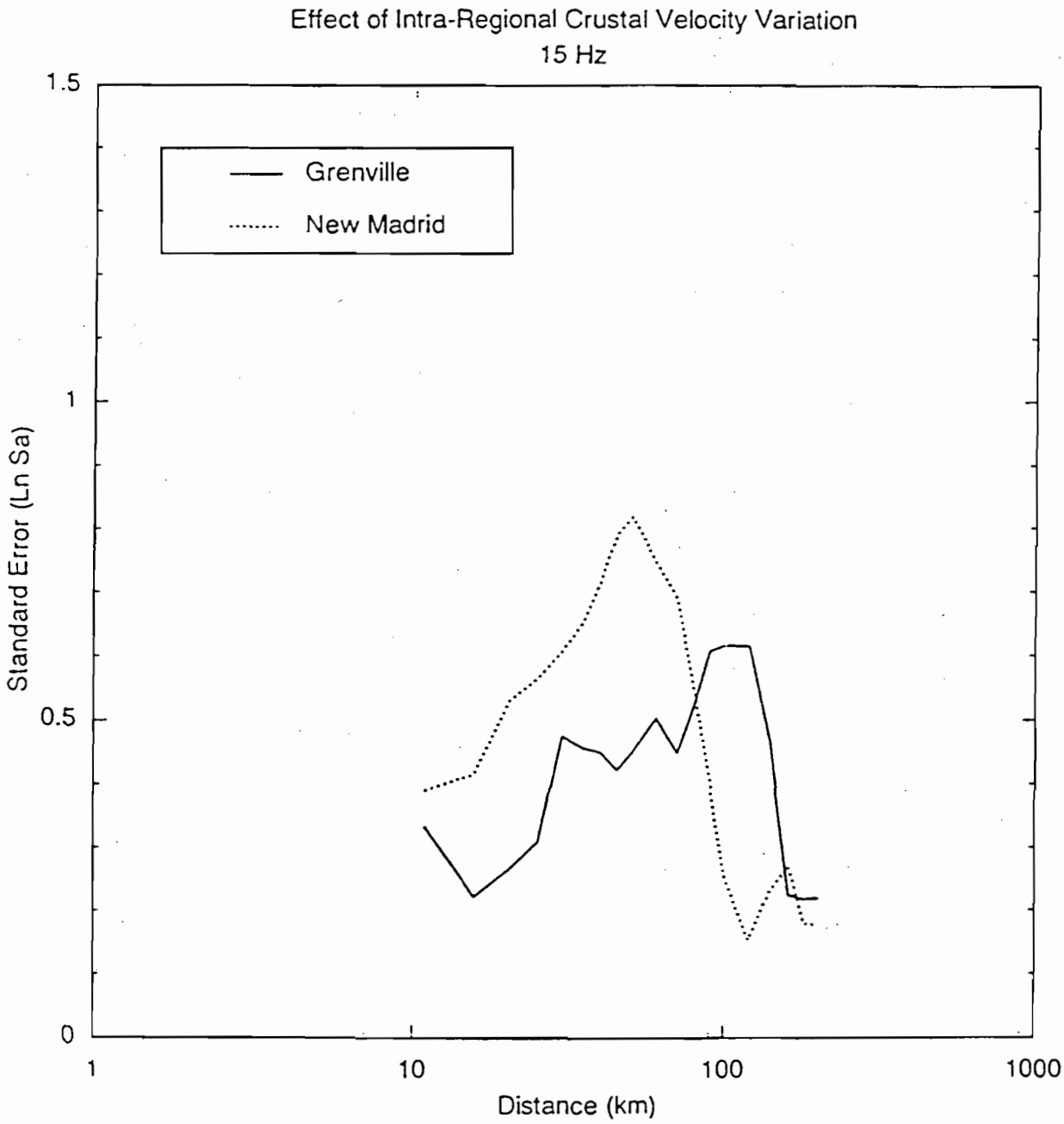


Figure 5-27c. Variability of spectral acceleration at 15 Hz due to crustal velocity uncertainty within the Grenville and New Madrid region. The variability includes variability in focal depth.

Fig. 4

PART 5. BIBLIOGRAPHY

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PART 6. ESTIMATES OF MEDIAN AND UNCERTAINTIES

Estimates of median ground motion values and their uncertainties are given in Tables 1 through 5 that follow. The reported aleatory uncertainty is for predicting ground motions given an earthquake size expressed as m_{blg}. The uncertainty due to seismic moment should be removed from the aleatory uncertainty when predicting ground motions from seismic moment M_o or moment magnitude M_w.

Expert: Somerville / Saikia

Ground Motion Measure: 1-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.06	0.3
	epistemic uncertainty	parametric (ln)	0.15	0.15
		median bias	–	–
		uncert. in bias (ln)	0.2	0.2
	aleatory uncertainty	median σ	0.8	0.7
		uncertainty in σ	0.1	0.15
20 km	median amplitude		0.17	0.1
	epistemic uncertainty	parametric (ln)	0.15	0.15
		median bias	–	–
		uncert. in bias (ln)	0.2	0.2
	aleatory uncertainty	median σ	0.8	0.7
		uncertainty in σ	0.1	0.15
70 km	median amplitude		0.003	0.03
	epistemic uncertainty	parametric (ln)	0.15	0.15
		median bias	–	–
		uncert. in bias (ln)	0.2	0.2
	aleatory uncertainty	median σ	0.8	0.7
		uncertainty in σ	0.1	0.15
200 km	median amplitude		0.001	0.01
	epistemic uncertainty	parametric (ln)	0.15	0.15
		median bias	–	–
		uncert. in bias (ln)	0.2	0.2
	aleatory uncertainty	median σ	0.8	0.7
		uncertainty in σ	0.1	0.15

Comments/footnotes:

Expert: Somerville / Saikia

Ground Motion Measure: 2.5-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.07	0.25
	epistemic uncertainty	parametric (ln)	0.1	0.1
		median bias	-	-
		uncert. in bias (ln)	0.2	0.2
	aleatory uncertainty	median σ	0.7	0.6
		uncertainty in σ	0.1	0.15
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

Expert: Somerville / Saikia

Ground Motion Measure: 10-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.6	1.5
	epistemic uncertainty	parametric (ln)	0.1	0.1
		median bias	–	–
		uncert. in bias (ln)	0.15	0.15
	aleatory uncertainty	median σ	0.65	0.55
		uncertainty in σ	0.1	0.15
20 km	median amplitude		0.17	0.6
	epistemic uncertainty	parametric (ln)	0.1	0.1
		median bias	–	–
		uncert. in bias (ln)	0.15	0.15
	aleatory uncertainty	median σ	0.65	0.55
		uncertainty in σ	0.1	0.15
70 km	median amplitude		0.03	0.15
	epistemic uncertainty	parametric (ln)	0.1	0.1
		median bias	–	–
		uncert. in bias (ln)	0.15	0.15
	aleatory uncertainty	median σ	0.75	0.65
		uncertainty in σ	0.1	0.15
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

Expert: Somerville / Saikia

Ground Motion Measure: 25-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.25	0.75
	epistemic uncertainty	parametric (ln)	0.1	0.1
		median bias	-	-
		uncert. in bias (ln)	0.12	0.12
	aleatory uncertainty	median σ	0.60	0.55
		uncertainty in σ	0.1	0.15
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

Expert: Somerville / Saikia

Ground Motion Measure: Peak Ground Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.3	0.9
	epistemic uncertainty	parametric (ln)	0.1	0.1
		median bias	-	-
		uncert. in bias (ln)	0.12	0.12
	aleatory uncertainty	median σ	0.6	0.55
		uncertainty in σ	0.1	0.15
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude		0.015	0.09
	epistemic uncertainty	parametric (ln)	0.1	0.1
		median bias	-	-
		uncert. in bias (ln)	0.12	0.12
	aleatory uncertainty	median σ	0.7	0.6
		uncertainty in σ	0.1	0.15
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

APPENDIX 1.

REVIEW OF m_{blg} - M_w RELATIONSHIPS USED BY THE FOUR PROPONENTS

The ground motion estimates provided by the four model proponents for specified m_{blg} values of 5.5 and 7.0 were all generated using M_w (moment magnitude) estimates. The relationships between M_w and m_{blg} that were used differ widely, especially for m_{blg} 7. The M_w values used by each proponent are given in Table 1.

Table 1. M_w values used by proponents to represent m_{blg} values

PROPONENT	M_w for m_{blg} 5.5	M_w for m_{blg} 7.0
Atkinson	5.0	7.0
Campbell	5.0	7.23
Silva	5.0	7.23
Somerville & Saikia	5.2	6.4

Most investigators who have developed empirical m_{blg} - M_w relationships have found that the data are well fit by a linear relationship. Some examples of such relationships are as follows:

$\text{Log}_{10} M_o = 1.2\ m_{blg} + 17.2$ $\quad M_w = 0.80\ m_{blg} + 0.77$ (Somerville and Saikia, 1994)

$M_w = 0.98\ m_{blg} - 0.39$ (Atkinson, 1993)

$\text{Log}_{10} M_o = 1.37\ m_{blg} + 16.22$ $\quad M_w = 0.91\ m_{blg} + 0.11$ (Patton and Walter, 1992)

These relationships are based on a set of earthquakes whose m_{blg} values range from 3 to 7 and whose M_w values range from 2.6 to 6.4.

The M_w values that they predict for m_{blg} values of 5.5 and 7.0 are listed in Table 2.

Table 2. M_w values calculated from empirical m_{blg} - M_w relationships

AUTHOR	M_w for m_{blg} 5.5	M_w for m_{blg} 7.0
Atkinson, 1993	5.00	6.47
Patton & Walter, 1992	5.12	6.48
Somerville & Saikia, 1994	5.17	6.37

Proponent Atkinson chose not to use her empirical m_{blg} - M_w relationship in converting m_{blg} 7 to M_w, because for larger magnitudes she prefers to use a non-linear relationship derived from her stochastic ground motion model. Similarly, proponents Campbell and Silva used a non-linear m_{blg} - M_w relationship based on the stochastic ground motion model (EPRI, 1993) in converting m_{blg} to M_w. The reasons for using these model-based relationships are that the empirical data are sparse and there is a desire that the relationship used be consistent with the stochastic model.

The m_{blg} - M_w relationships based on the stochastic ground motion models of Atkinson (1993) and EPRI (1993) are shown in Figures 1 and 2. Also shown on Figure 2 are revised estimates of the median values and uncertainties in the M_w and m_{blg} of the 1925 Charlevoix earthquake. This earthquake had an $m_{blg}$of 6.93 +/- 0.14, derived from five stations at less that 15 degrees (derived from Atkinson and Boore, 1987) and an M_w of 6.2 +/- 0.2 (derived from 17 observations including both regional and teleseismic stations by Bent, 1993, Table 3). While the model-based EPRI (1993) m_{blg} - M_w relationship was compatible with the previous estimates of m_{blg} and M_w of the 1925 Charlevoix earthquake, it is not compatible with the revised ones.

Proponents Somerville and Saikia prefer to use a relationship that is consistent with the empirical m_{blg} - M_w data. They do not use the stochastic model and so do not have a need to be consistent with an m_{blg} - M_w relationship based on the stochastic model. They regard the 1925 Charlevoix earthquake as representative of the m_{blg} 7 earthquake addressed in this study, and their empirical relationship is compatible with its m_{blg} of 6.93 and its M_w of 6.2, as shown in Figure 3. It had a stress drop of about 50 bars, which is about half the average of 100 bars for eastern North American events, and its source function does not exhibit any anomalous features. Although there are few events to compare it with in eastern North America, they do not view this event as an outlier in a population of m_{blg} 7 events whose average M_w is 0.6 or 0.83 units larger, i.e. M_w 7.0 or 7.23. This would correspond to seismic moments 8 to 18 times larger, and stress drops of 400 to 900 bars, if we scale up the 1925 earthquake to satisfy these M_w values.

EPRI

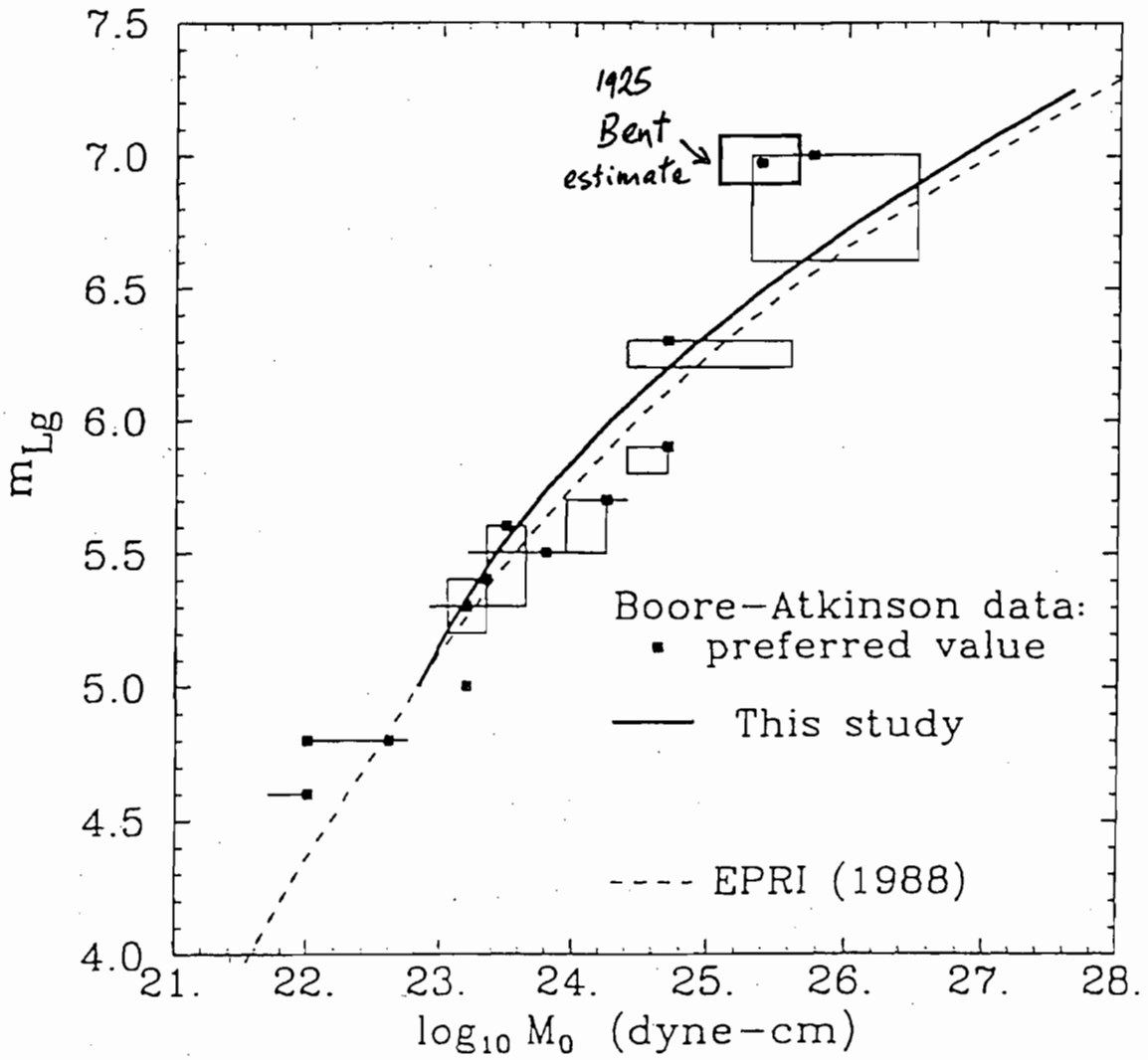


Figure V.5-1. Average predicted M_0–m_{Lg} relationship calculated using the ground-motion model in Section#3 (heavy solid line). Also shown are the relationship obtained by McGuire et al. (1988, dashed line) and the M_0–m_{Lg} data of Boore and Atkinson (1987, rectangles).

Fig A-1

Atkinson

EARTHQUAKE SOURCE SPECTRA IN ENA

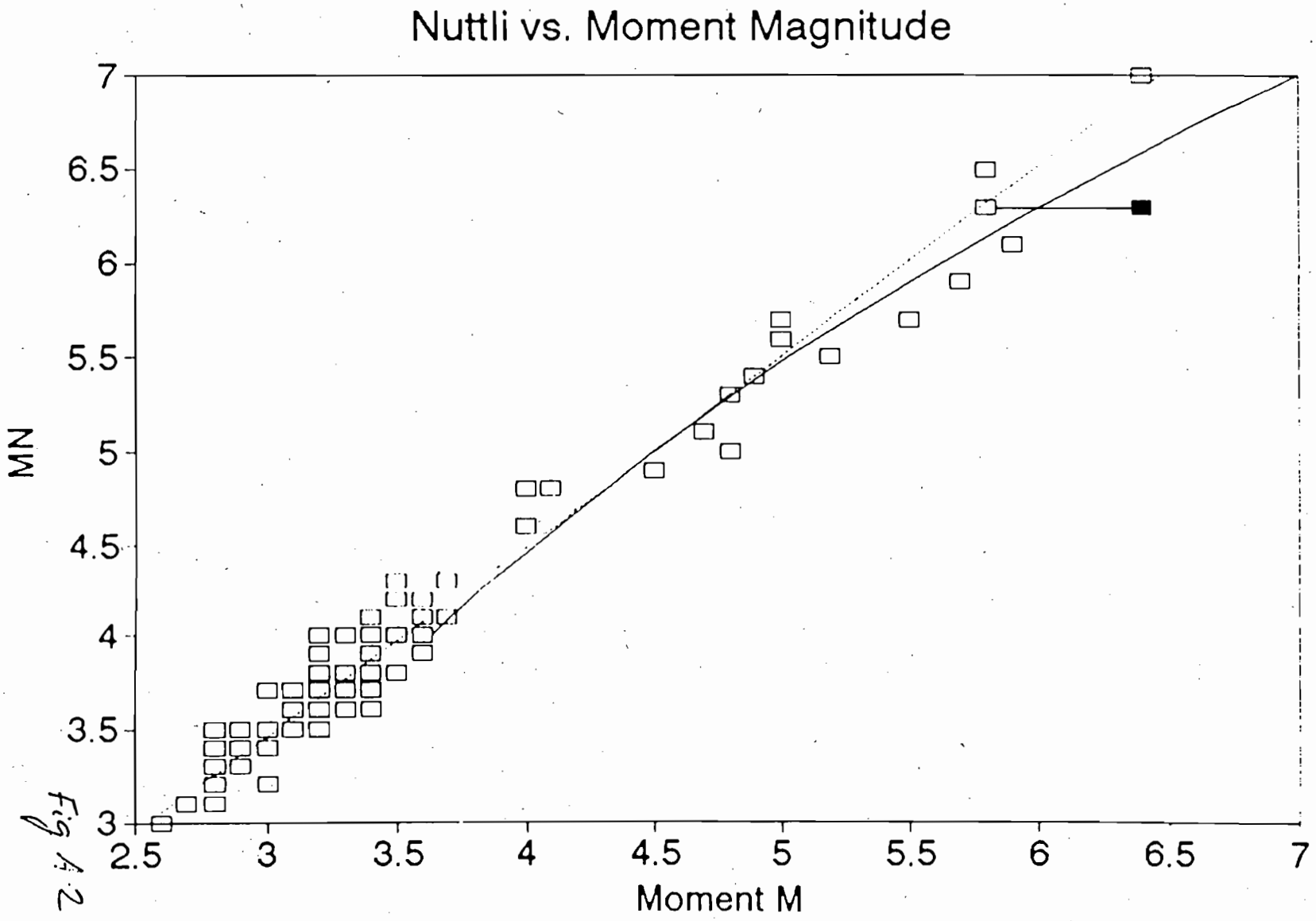


Fig 1.2

Somerville (Saikia

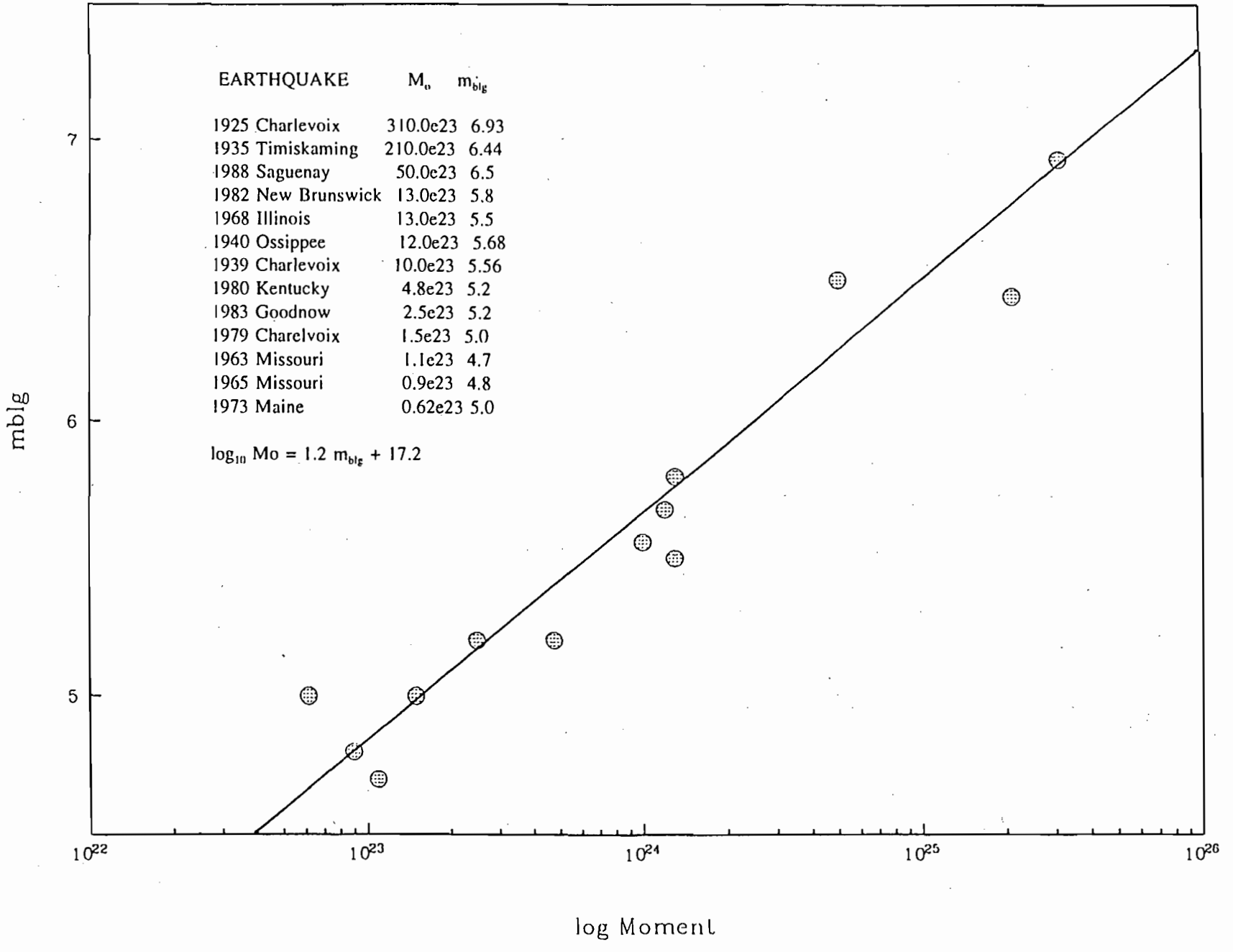
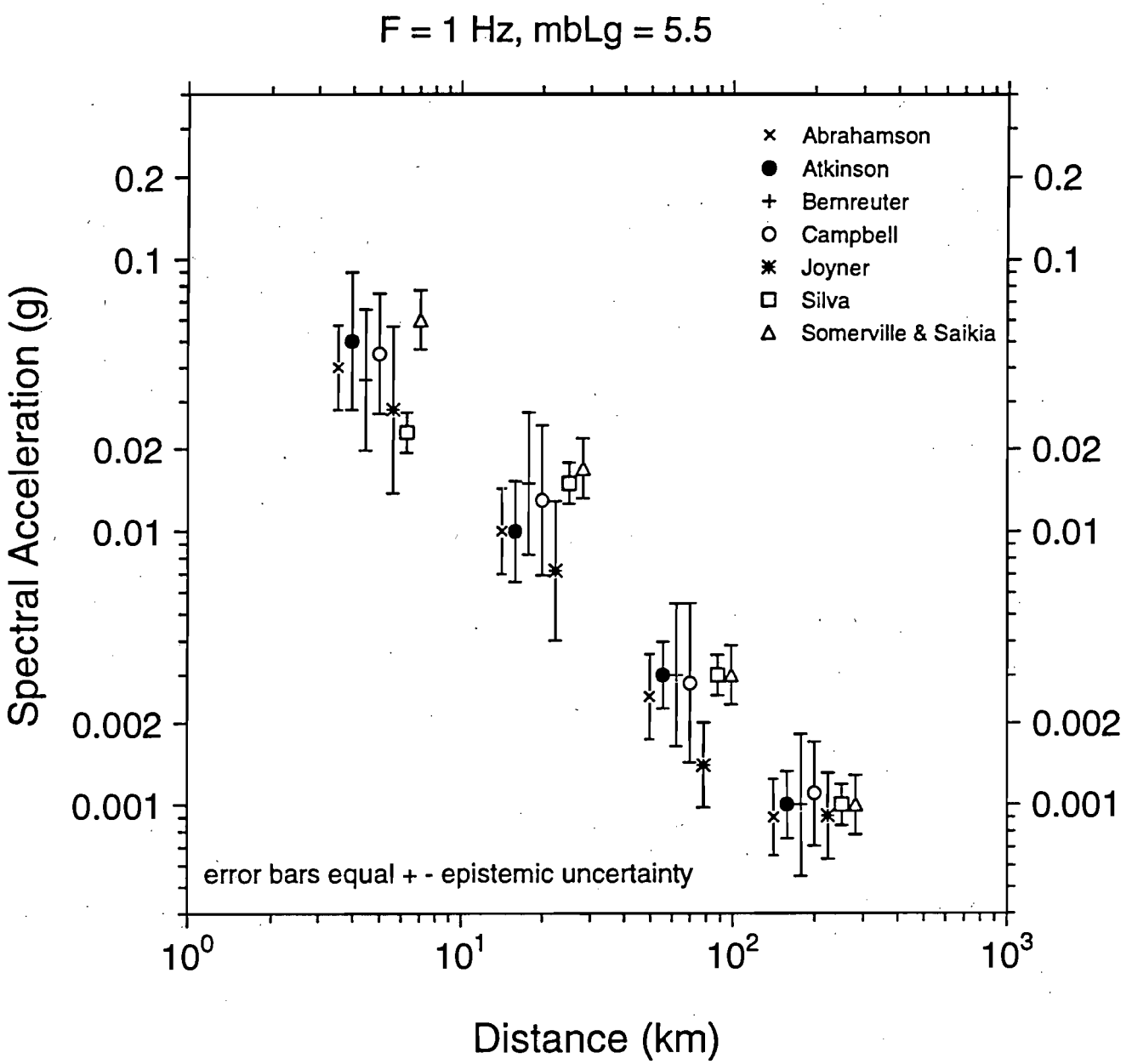
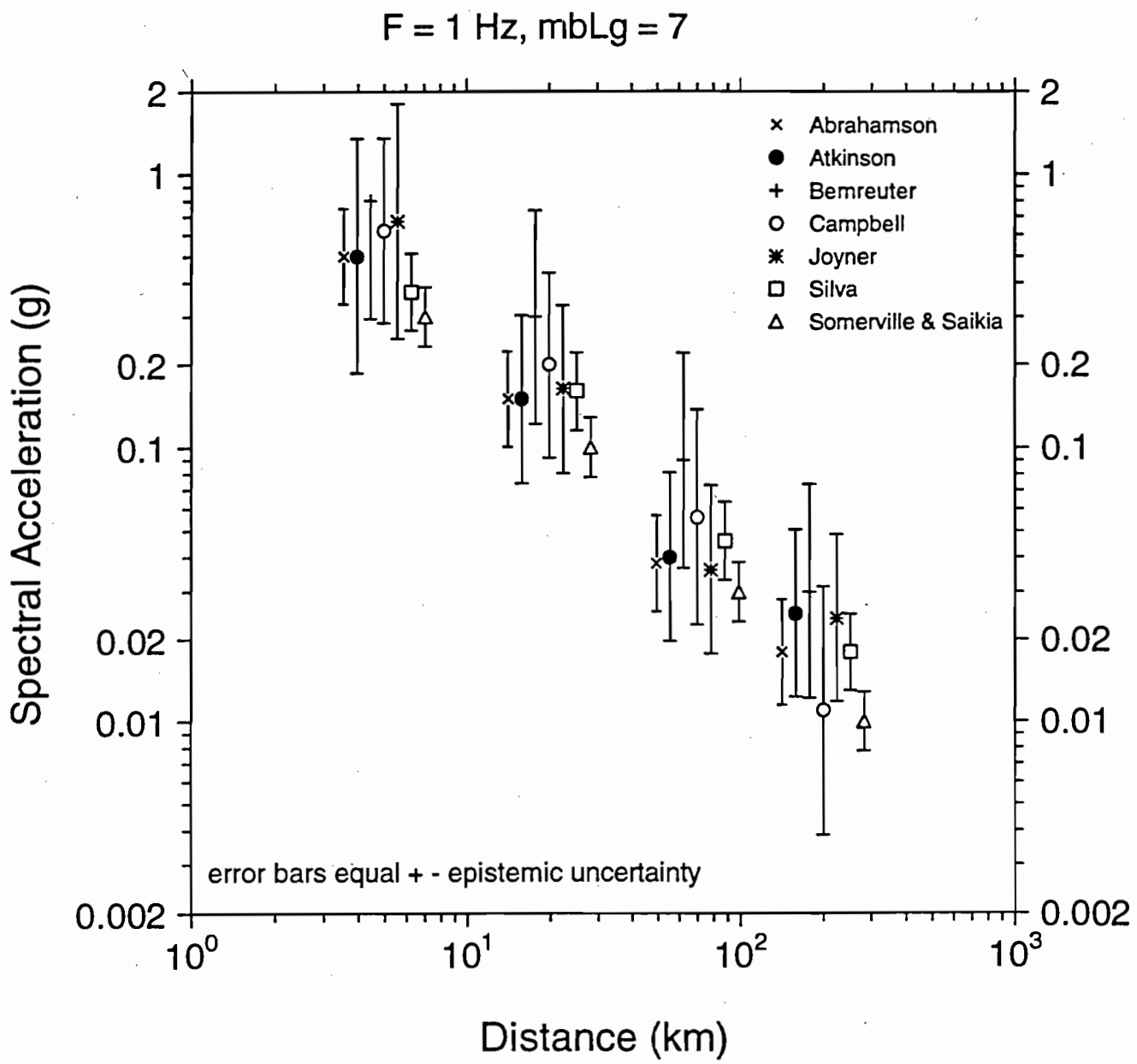


Fig A-3

pout 11 Thu Jun 23 10:42:34 1994


F = 1 Hz, mbLg = 5.5
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty
Spectral Acceleration (g)
0.2
0.1
0.02
0.01
0.002
0.001
10^0
10^1
10^2
10^3
Distance (km)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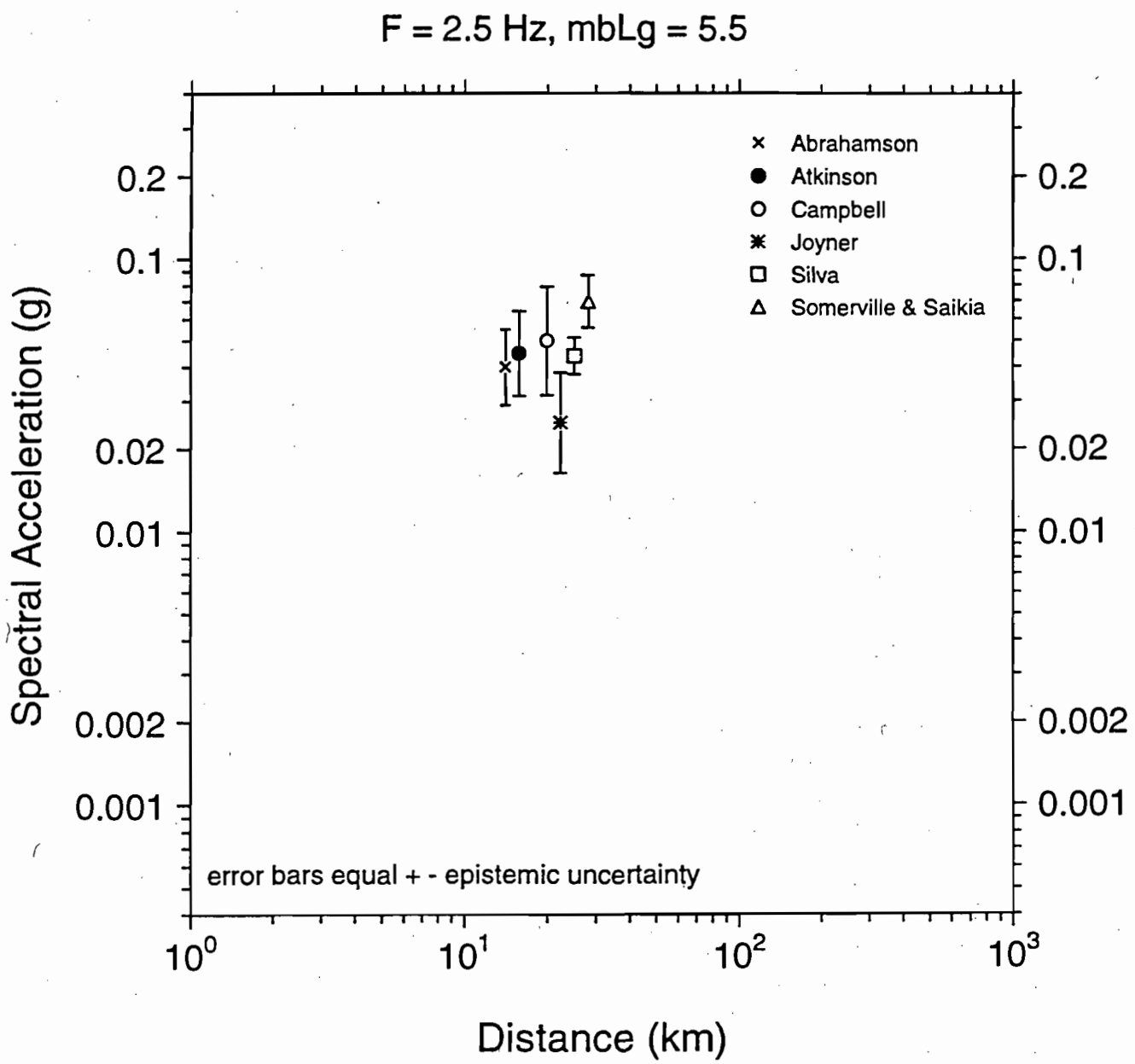
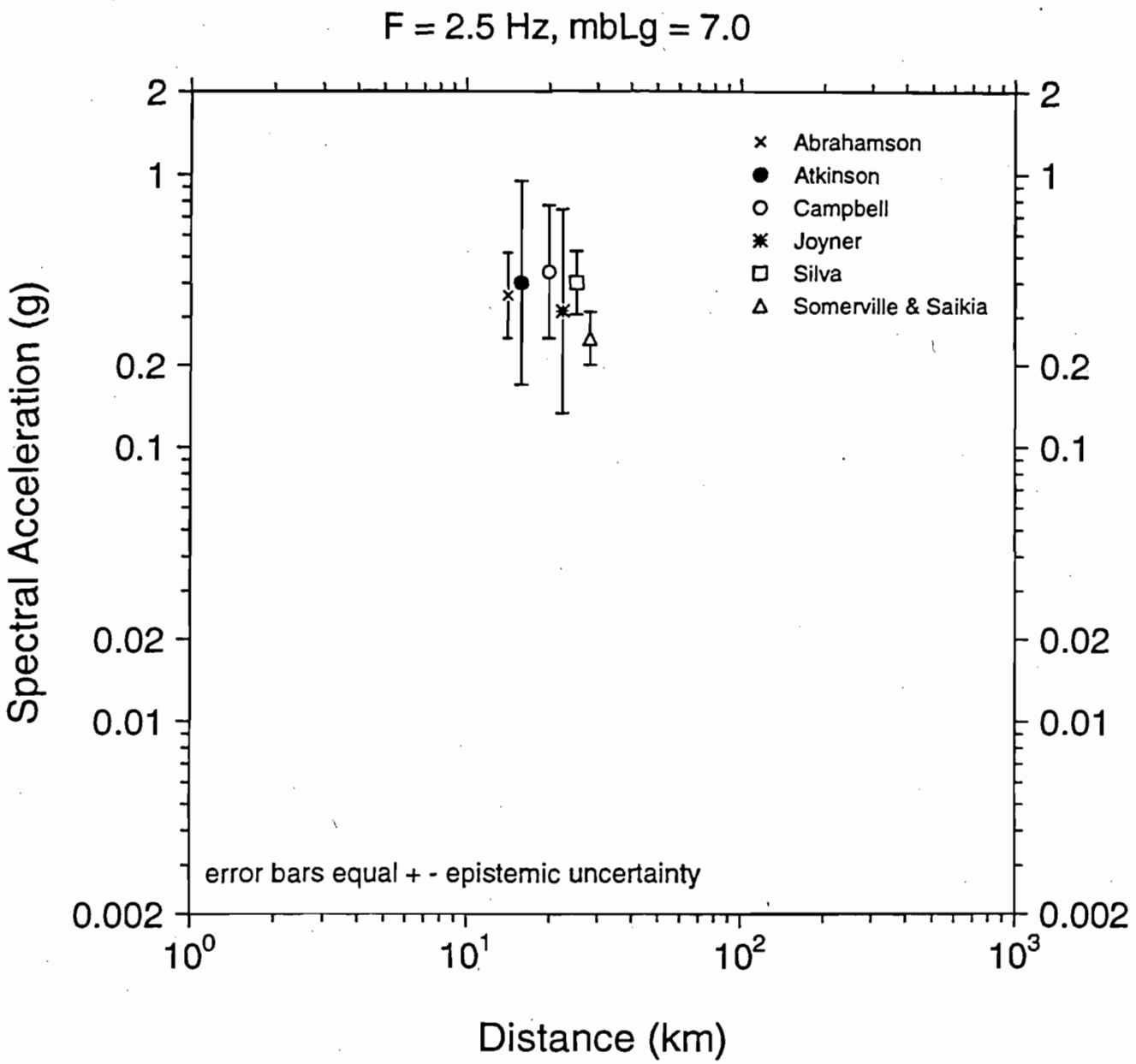
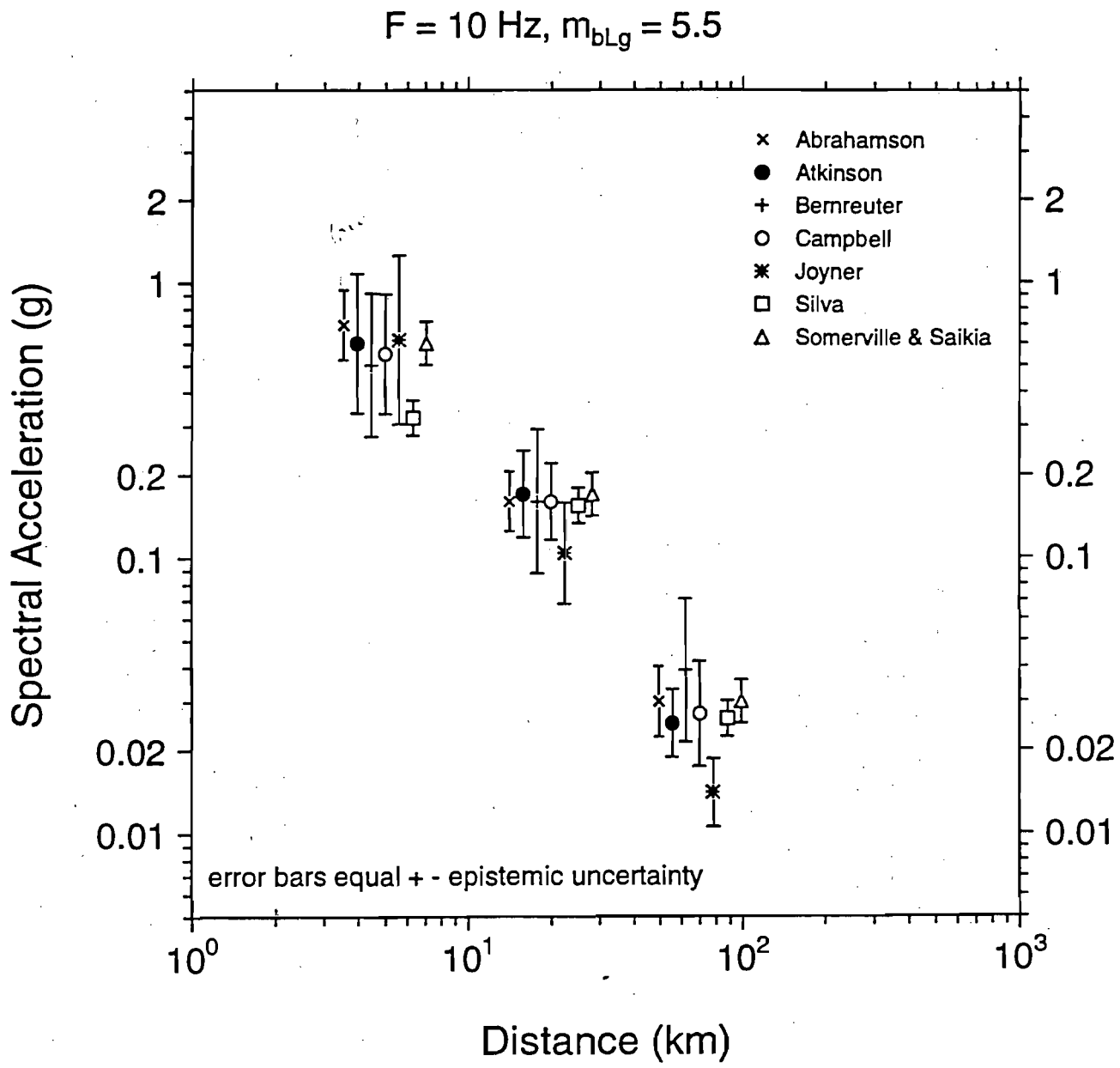
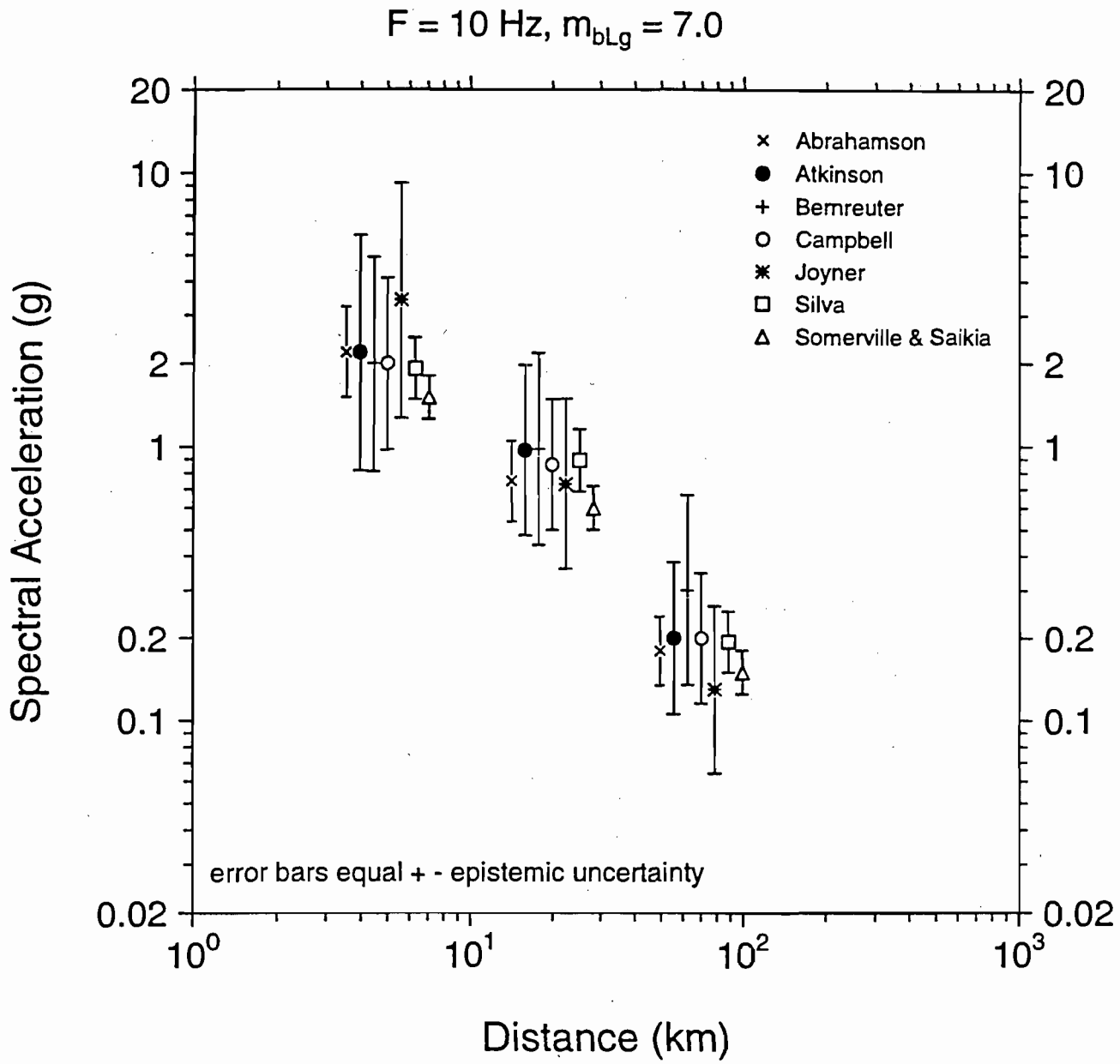
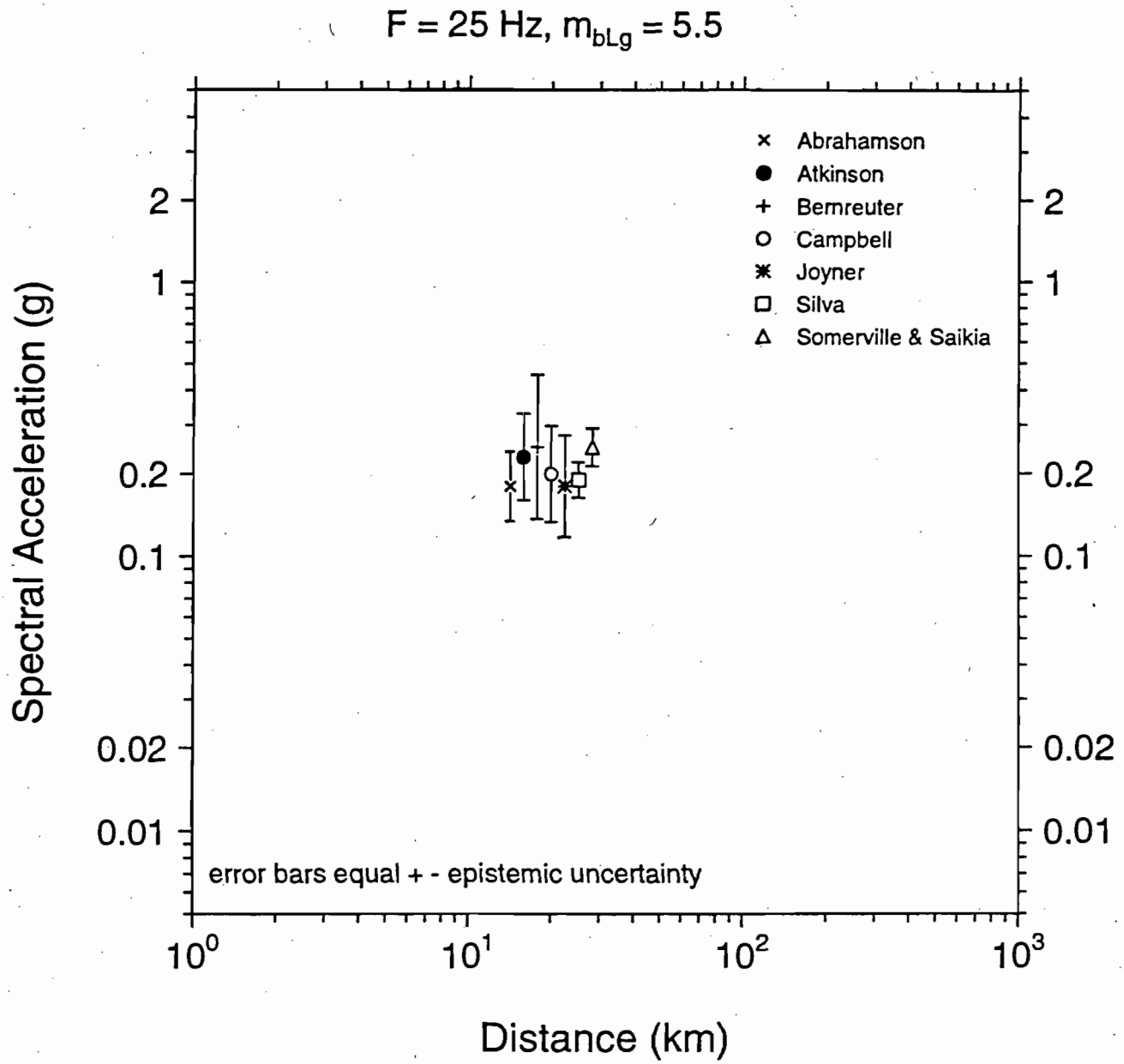
Spectral Acceleration (g)
Distance (km)
Abrahamson
Atkinson
Bemreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty
2
1
0.2
0.1
0.02
0.01
0.002
10^0
10^1
10^2
10^3

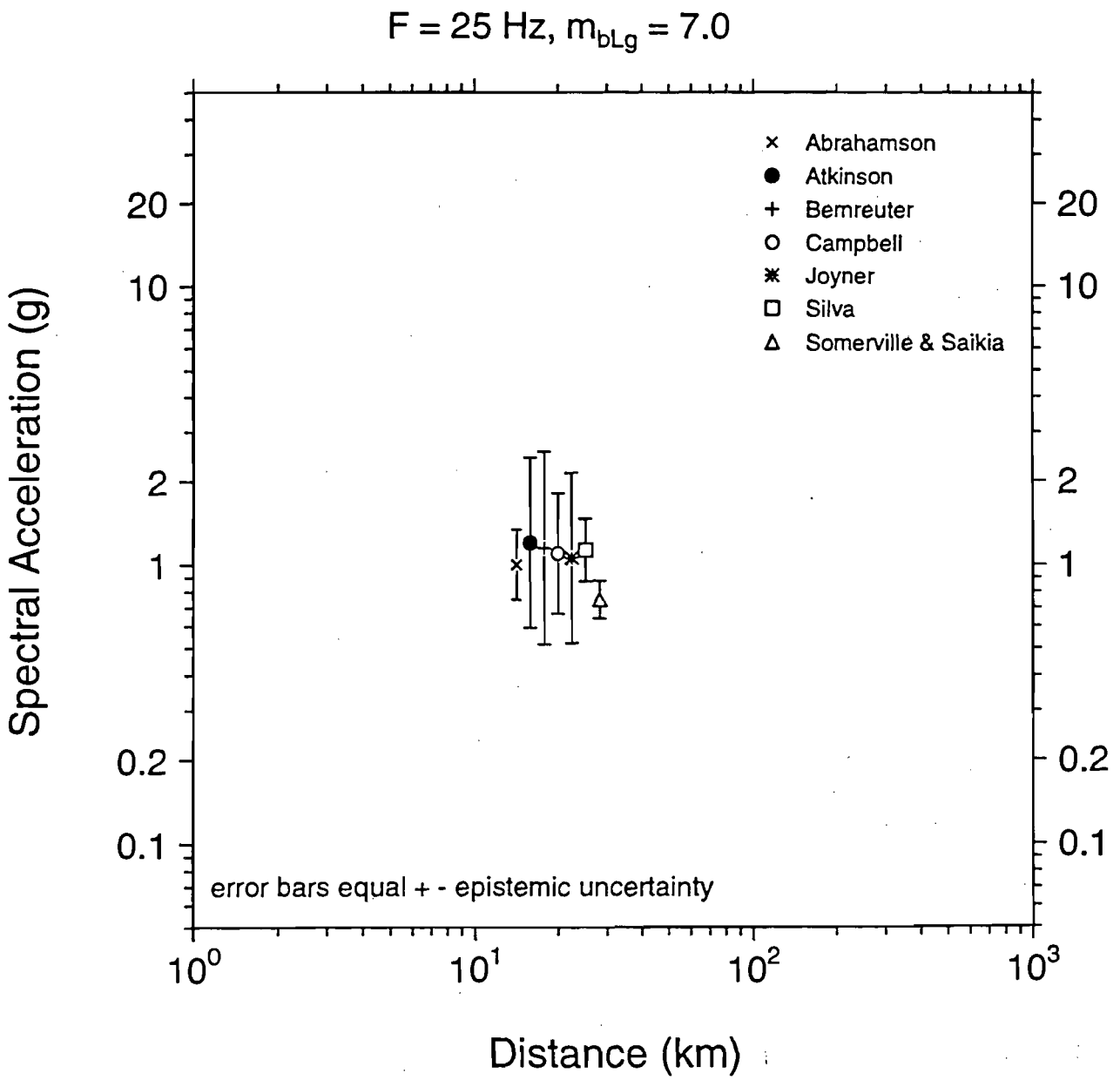

F = 2.5 Hz, mbLg = 5.5
Abrahamson
Atkinson
Campbell
Joyner
Silva
Somerville & Saikia
0.2
0.1
0.02
0.01
0.002
0.001
Spectral Acceleration (g)
error bars equal + - epistemic uncertainty
10^0
10^1
10^2
10^3
Distance (km)


F = 2.5 Hz, mbLg = 7.0
Spectral Acceleration (g)
Distance (km)
2
1
0.2
0.1
0.02
0.01
0.002
10^0
10^1
10^2
10^3
Abrahamson
Atkinson
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty


F = 10 Hz, m_{bLg} = 5.5
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty
Spectral Acceleration (g)
2
1
0.2
0.1
0.02
0.01
10^0
10^1
10^2
10^3
Distance (km)


F = 10 Hz, m_{bLg} = 7.0
Spectral Acceleration (g)
Distance (km)
20
10
2
1
0.2
0.1
0.02
10^0
10^1
10^2
10^3
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty


F = 25 Hz, m_{bLg} = 5.5
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
Spectral Acceleration (g)
2
1
0.2
0.1
0.02
0.01
error bars equal + - epistemic uncertainty
10^0
10^1
10^2
10^3
Distance (km)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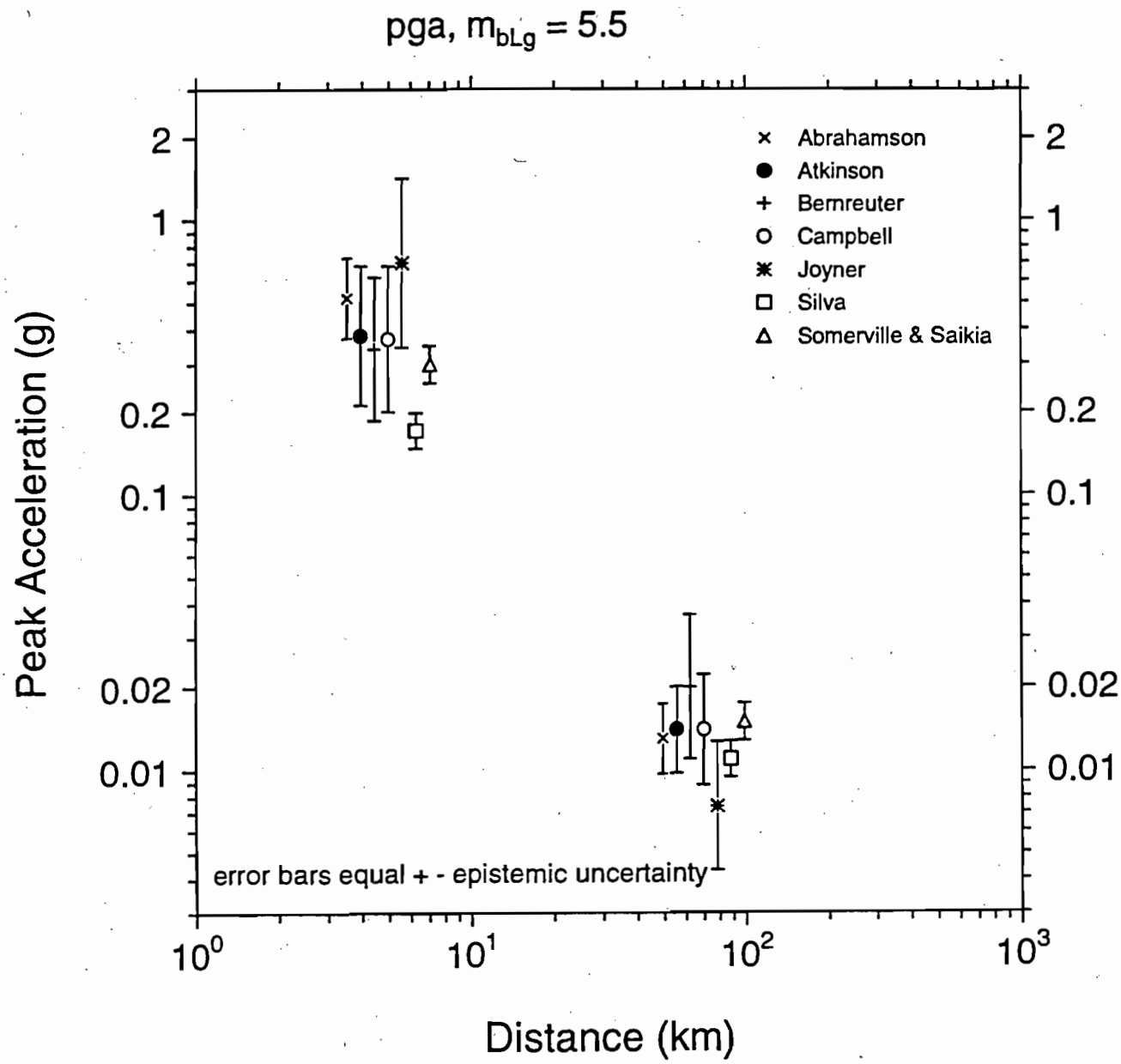
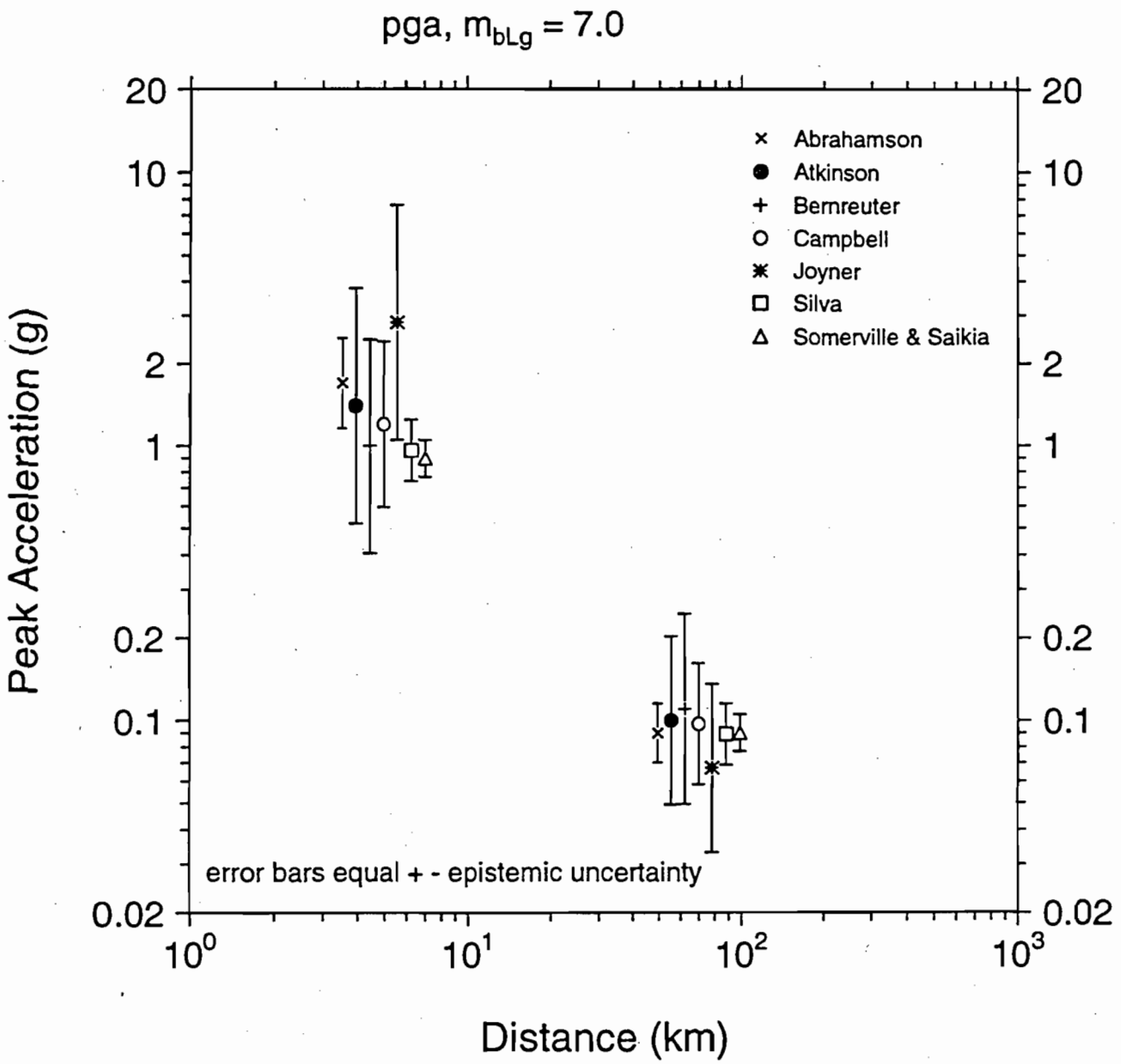
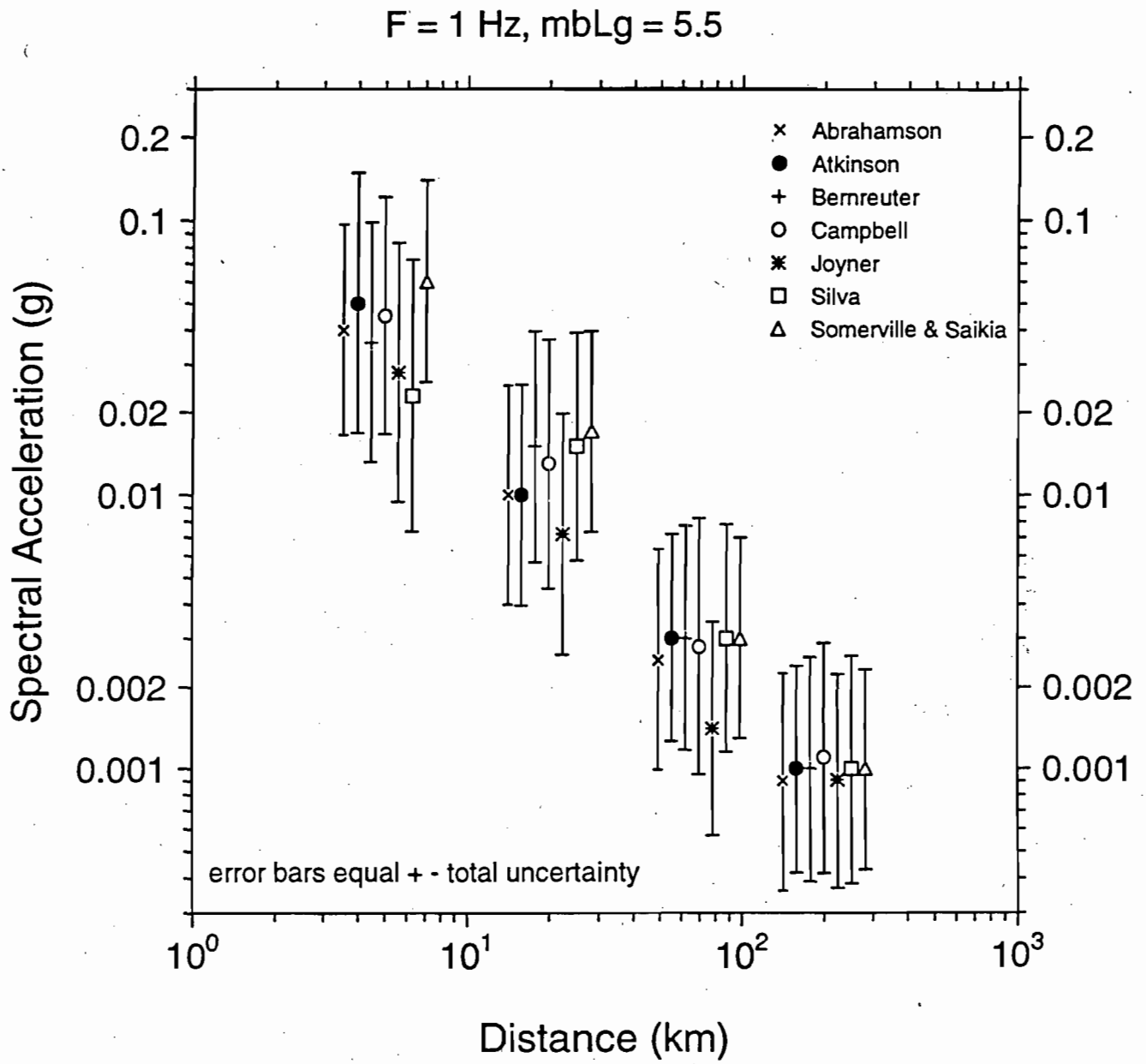
Abrahamson
Atkinson
Bemreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty
Spectral Acceleration (g)
20
10
2
1
0.2
0.1
10^0
10^1
10^2
10^3
Distance (km)


pga, m_{bLg} = 5.5
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty
Peak Acceleration (g)
Distance (km)
2
1
0.2
0.1
0.02
0.01
10^0
10^1
10^2
10^3


pga, m_{bLg} = 7.0
Peak Acceleration (g)
Distance (km)
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty
20
10
2
1
0.2
0.1
0.02
10^0
10^1
10^2
10^3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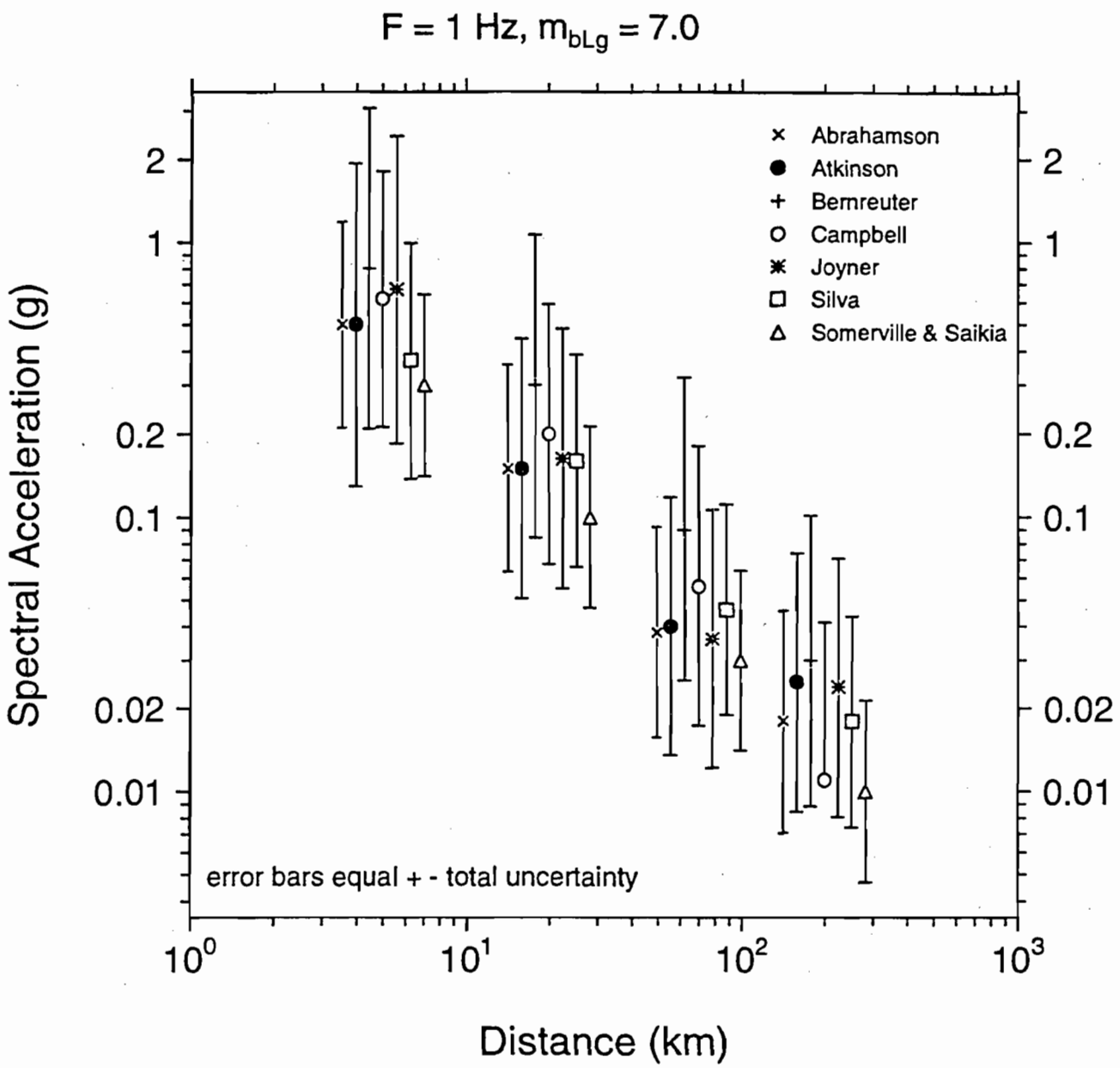
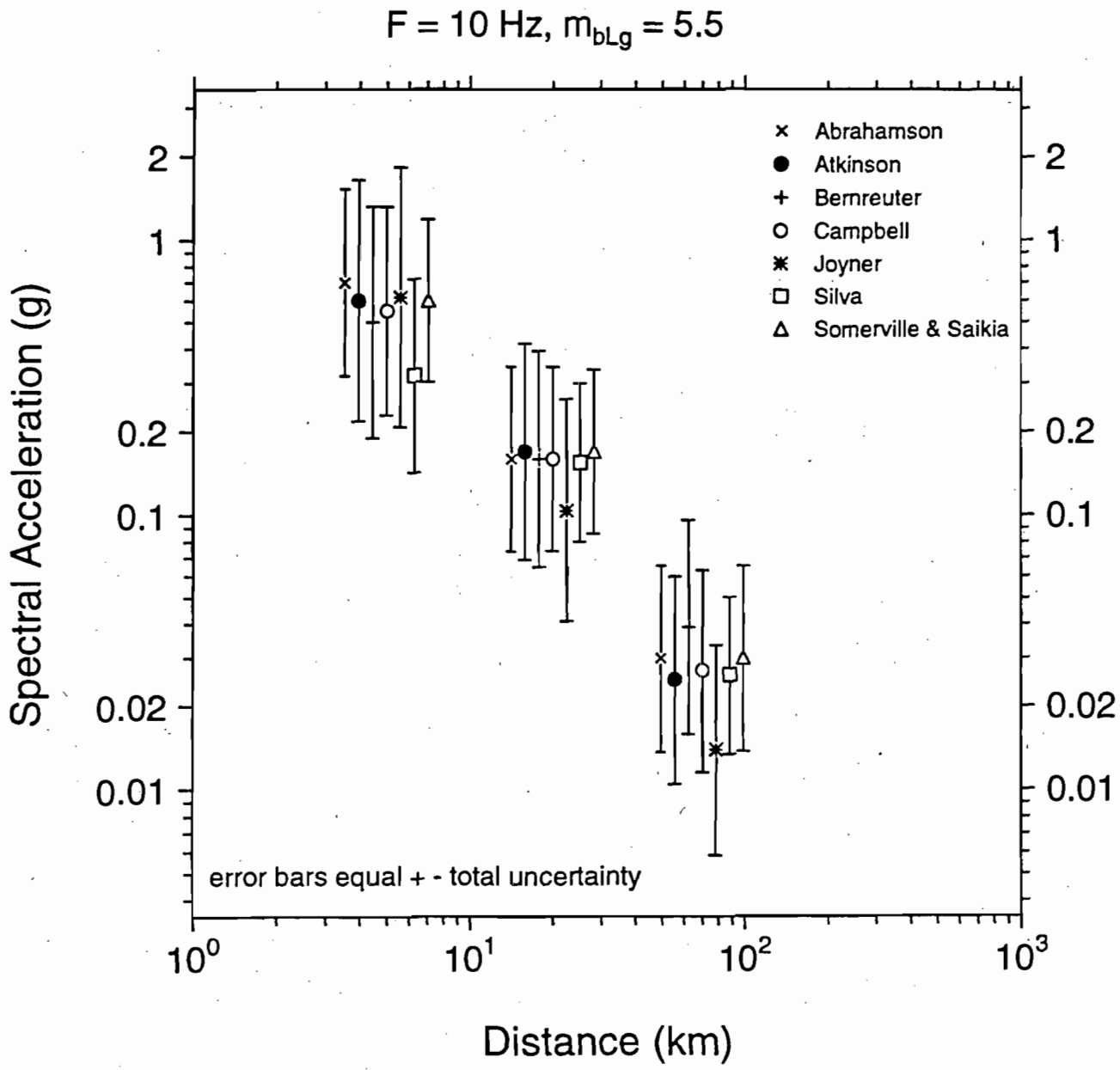
Spectral Acceleration (g)
0.2
0.1
0.02
0.01
0.002
0.001
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - total uncertainty
10^0
10^1
10^2
10^3
Distance (km)


F = 1 Hz, m_{bLg} = 7.0
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - total uncertainty
Spectral Acceleration (g)
2
1
0.2
0.1
0.02
0.01
10^0
10^1
10^2
10^3
Distance (km)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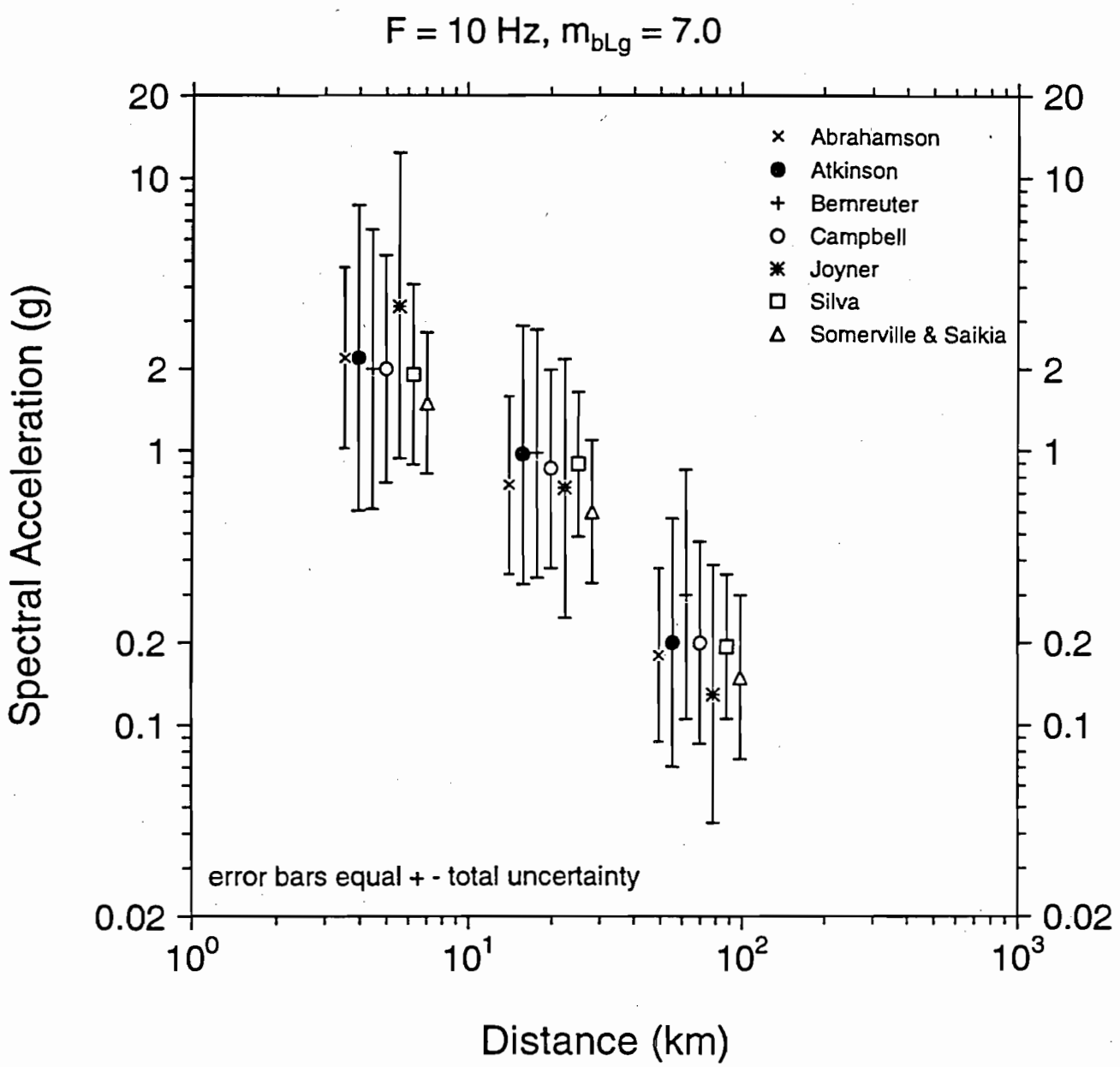
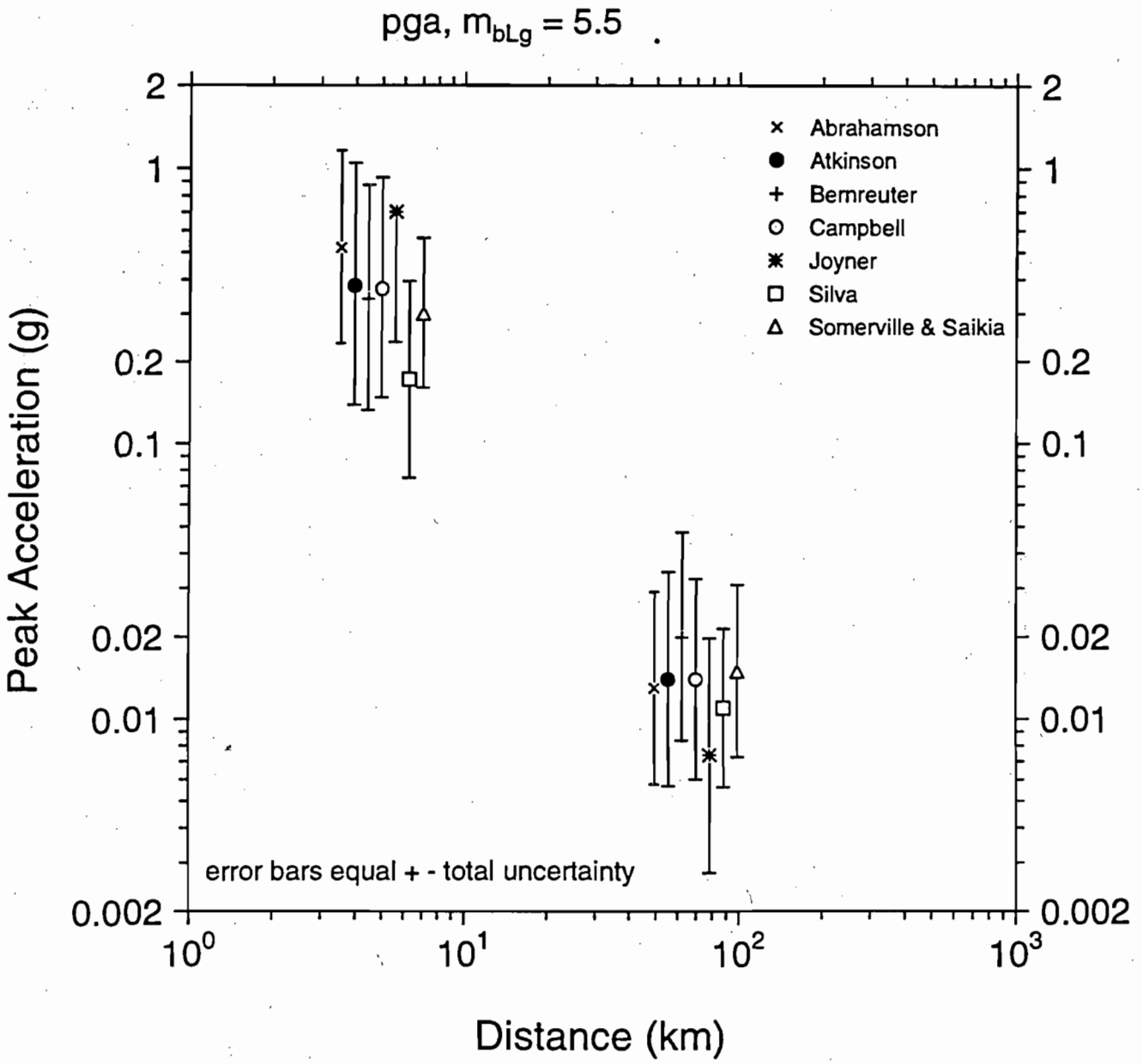
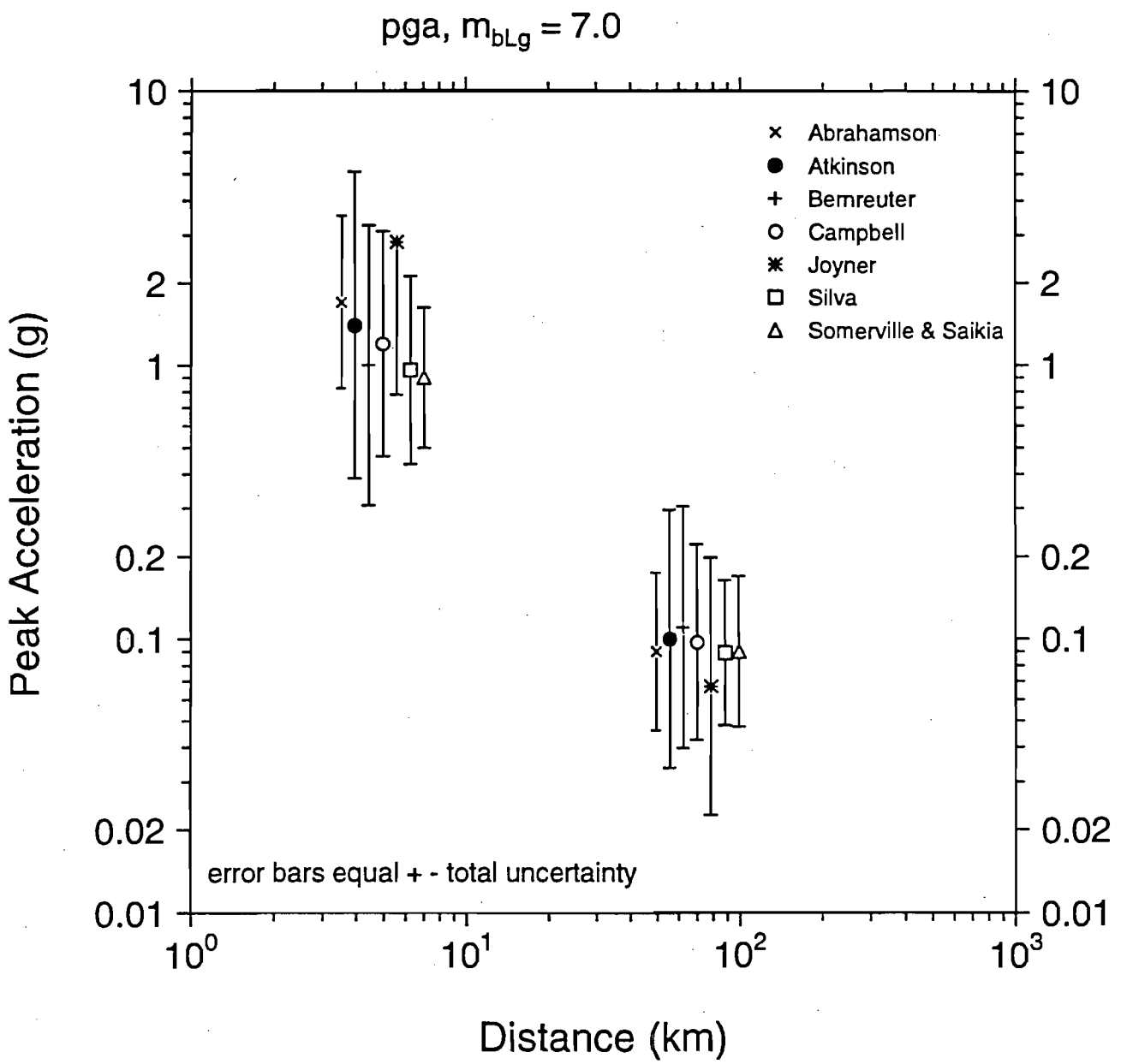
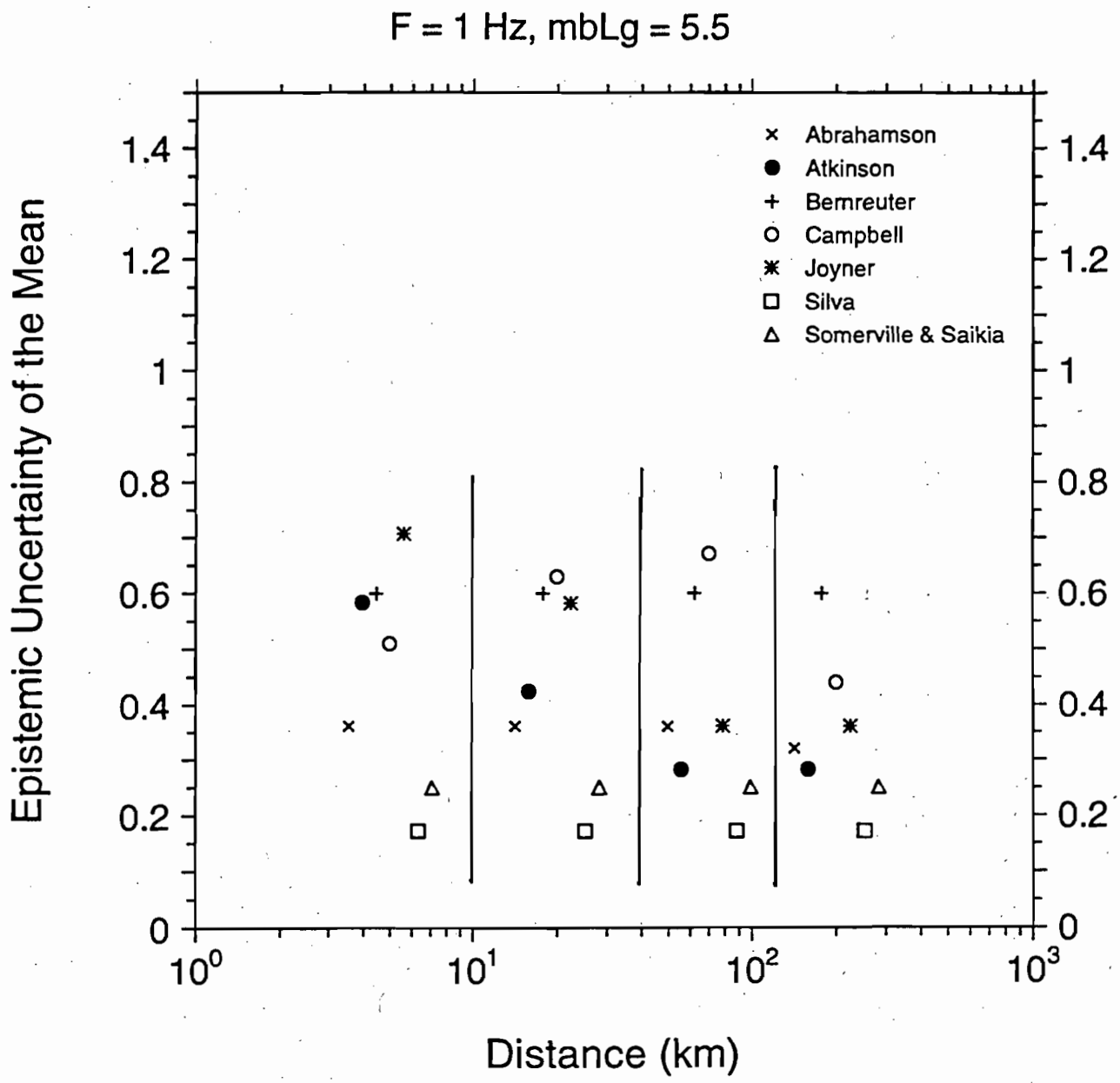
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - total uncertainty
Spectral Acceleration (g)
2
1
0.2
0.1
0.02
0.01
10^0
10^1
10^2
10^3
Distance (km)


F = 10 Hz, m_{bLg} = 7.0
Spectral Acceleration (g)
Distance (km)
20
10
2
1
0.2
0.1
0.02
10^0
10^1
10^2
10^3
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - total uncertainty


pga, m_{bLg} = 5.5
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - total uncertainty
Peak Acceleration (g)
Distance (km)
2
1
0.2
0.1
0.02
0.01
0.002
10^0
10^1
10^2
10^3


pga, m_{bLg} = 7.0
Peak Acceleration (g)
Distance (km)
10
2
1
0.2
0.1
0.02
0.01
10^0
10^1
10^2
10^3
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - total uncertainty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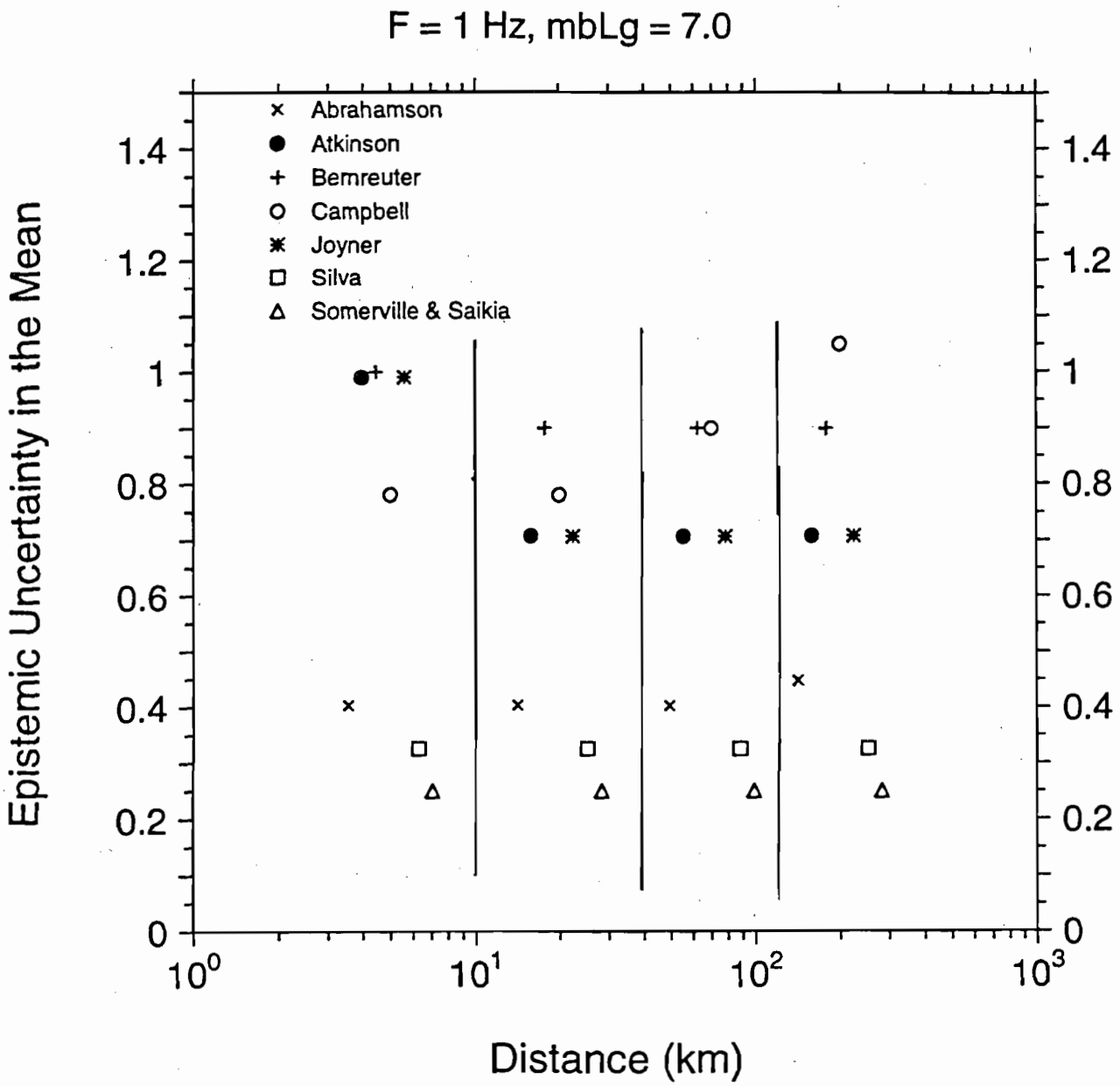
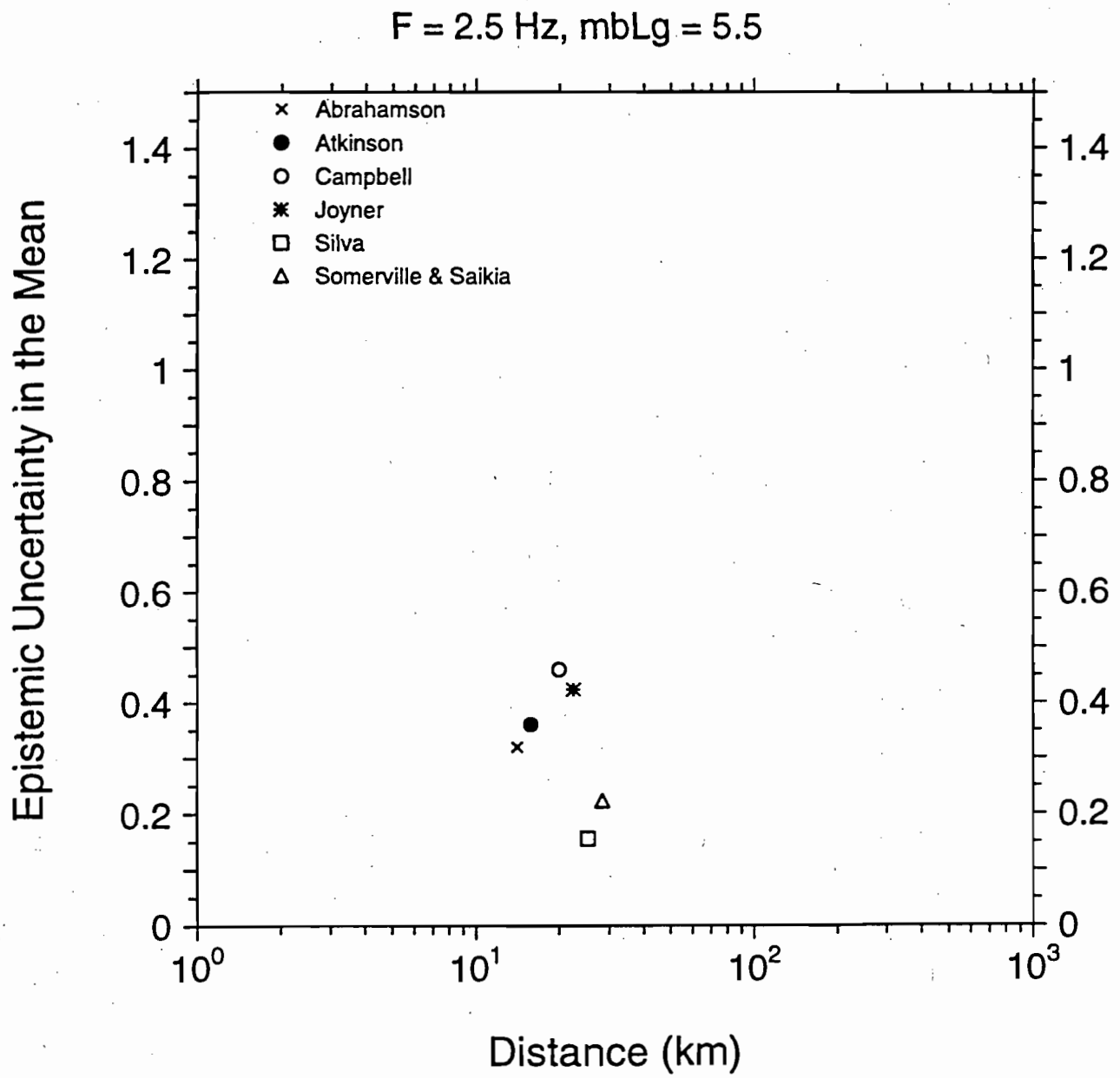
Epistemic Uncertainty of the Mean
Distance (km)
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
0
0.2
0.4
0.6
0.8
1
1.2
1.4
10^0
10^1
10^2
10^3


F = 1 Hz, mbLg = 7.0
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
Epistemic Uncertainty in the Mean
Distance (km)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
10^0
10^1
10^2
10^3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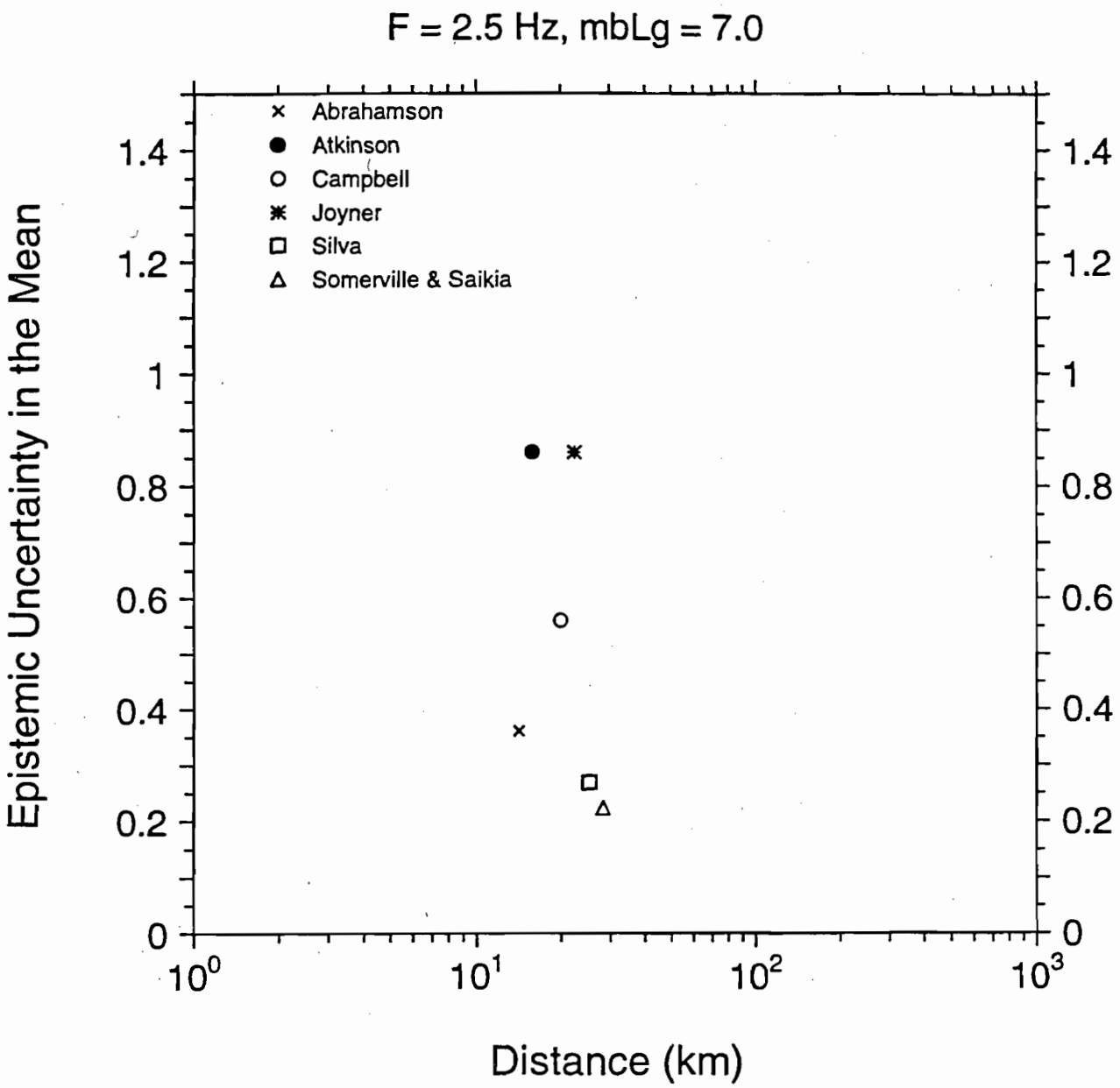
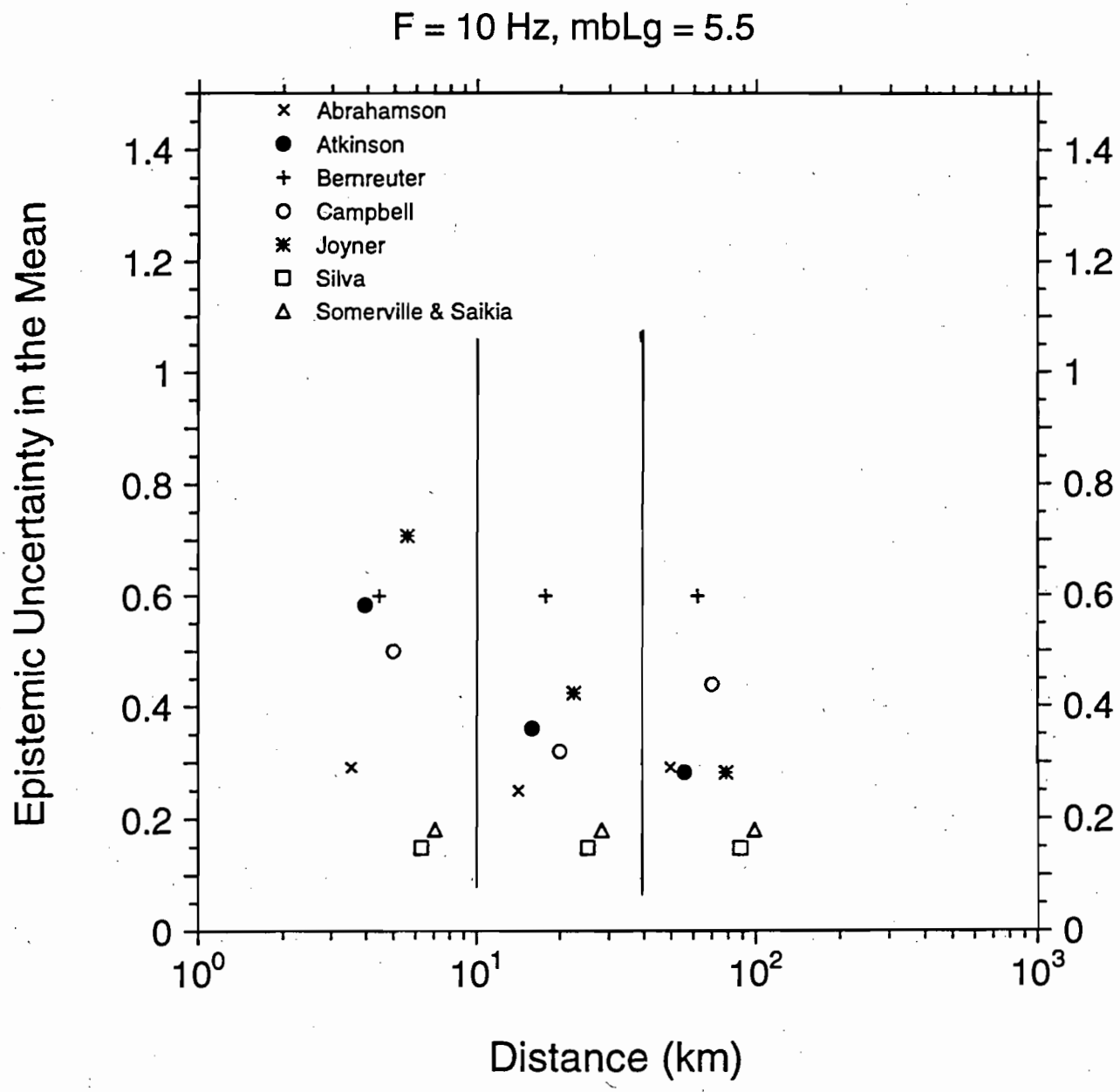
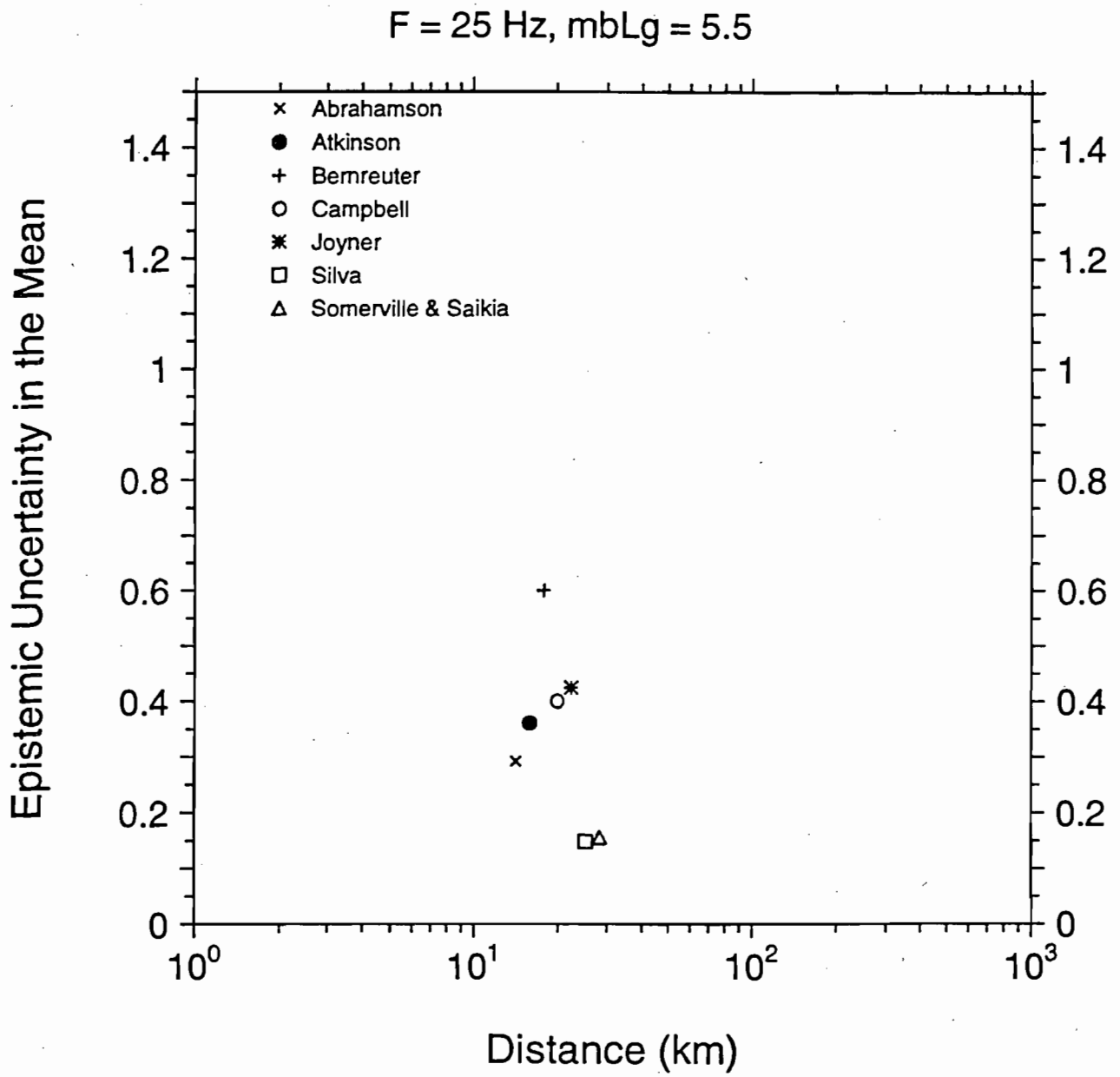
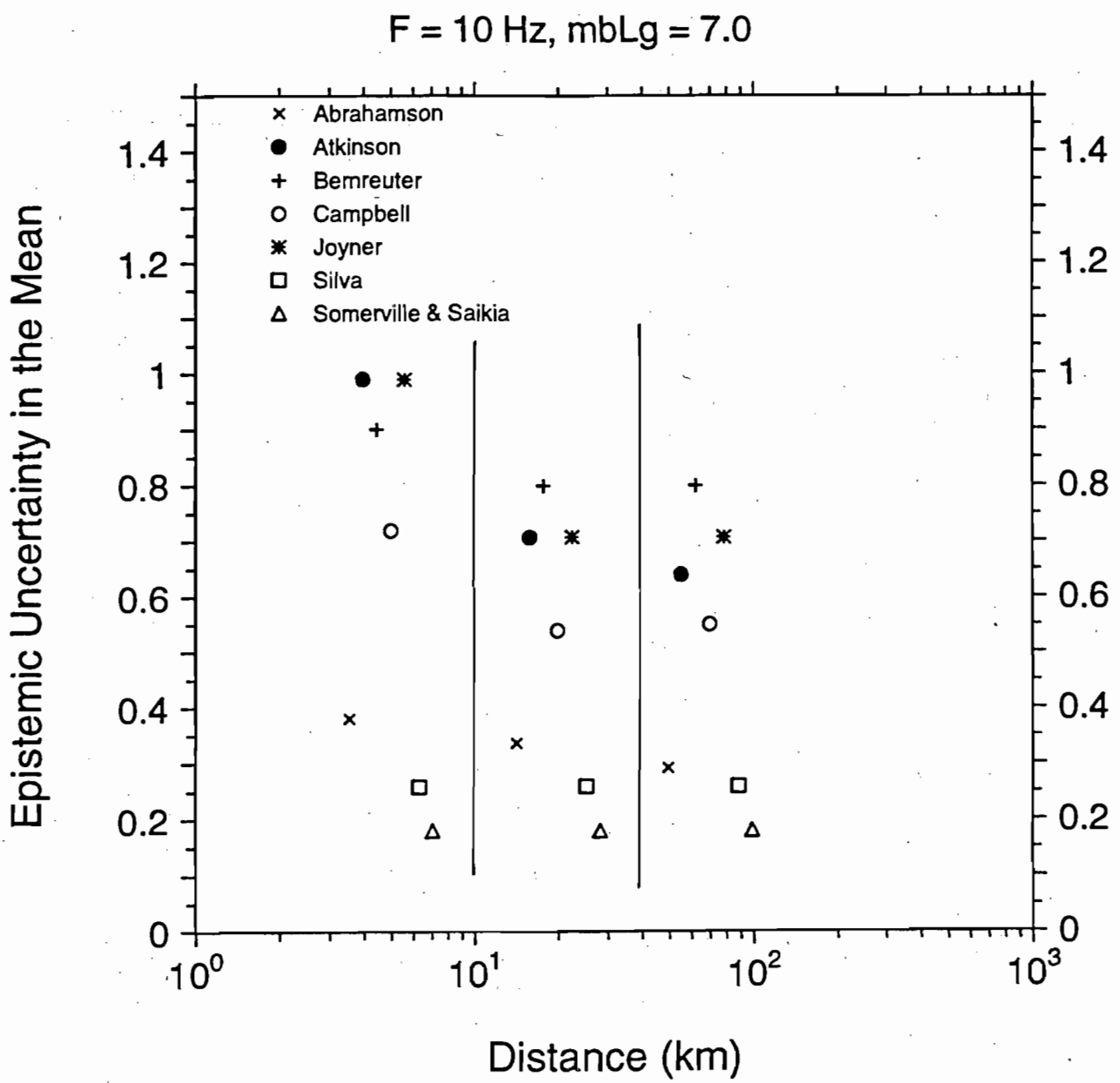
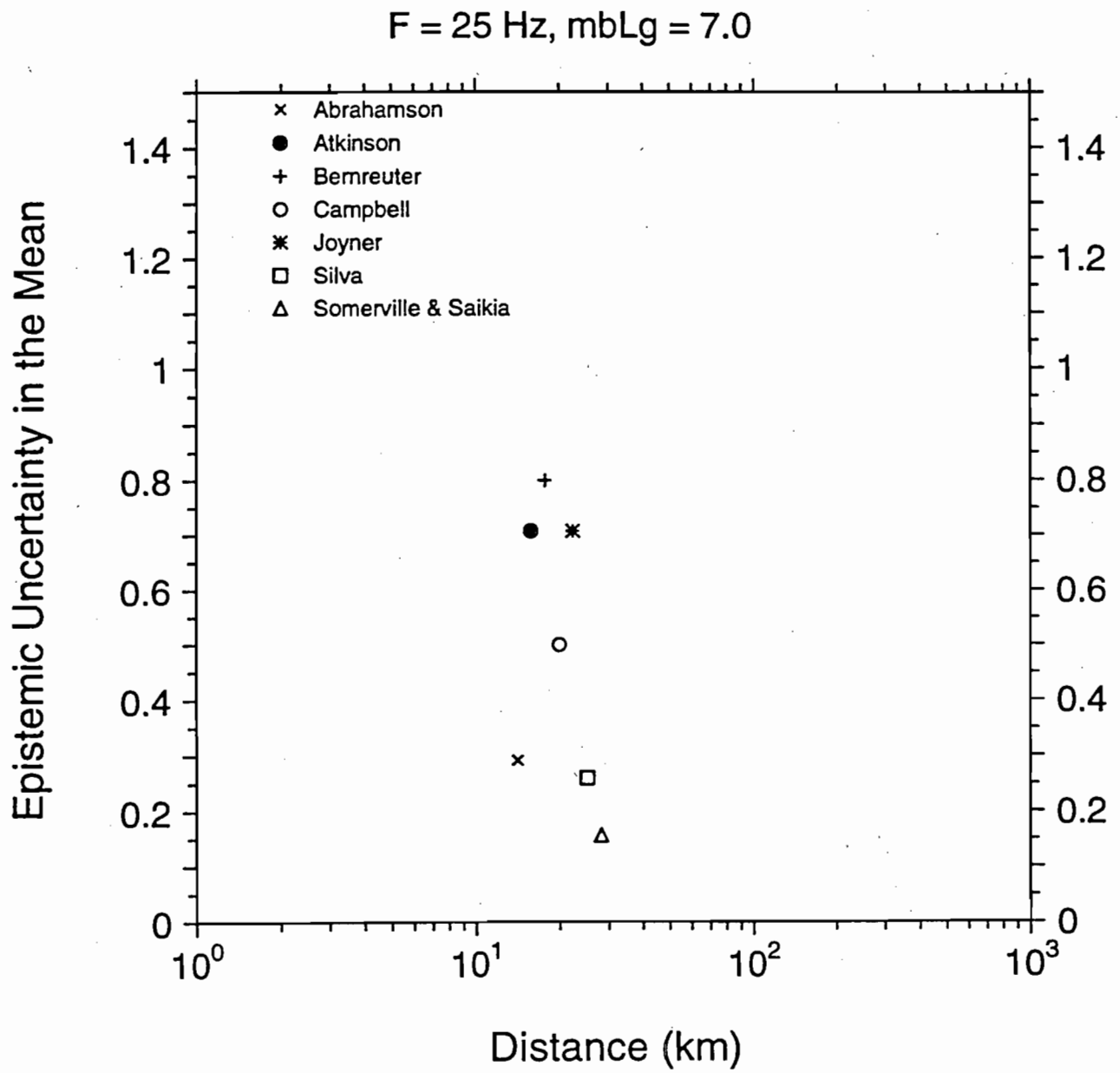
Abrahamson
Atkinson
Campbell
Joyner
Silva
Somerville & Saikia
Epistemic Uncertainty in the Mean
Distance (km)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
10^0
10^1
10^2
10^3

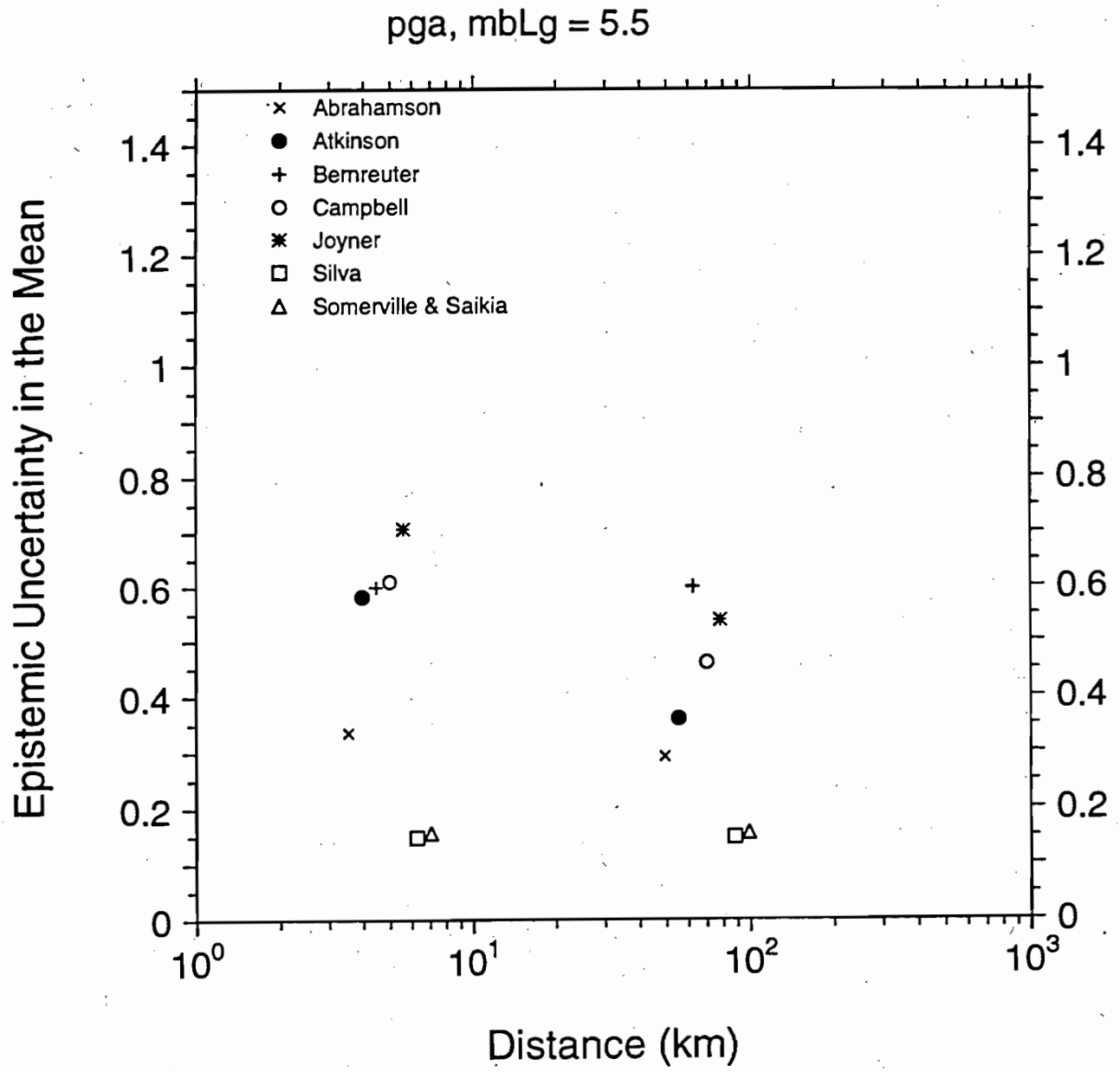

F = 2.5 Hz, mbLg = 7.0
Abrahamson
Atkinson
Campbell
Joyner
Silva
Somerville & Saikia
Epistemic Uncertainty in the Mean
Distance (km)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
10^0
10^1
10^2
10^3

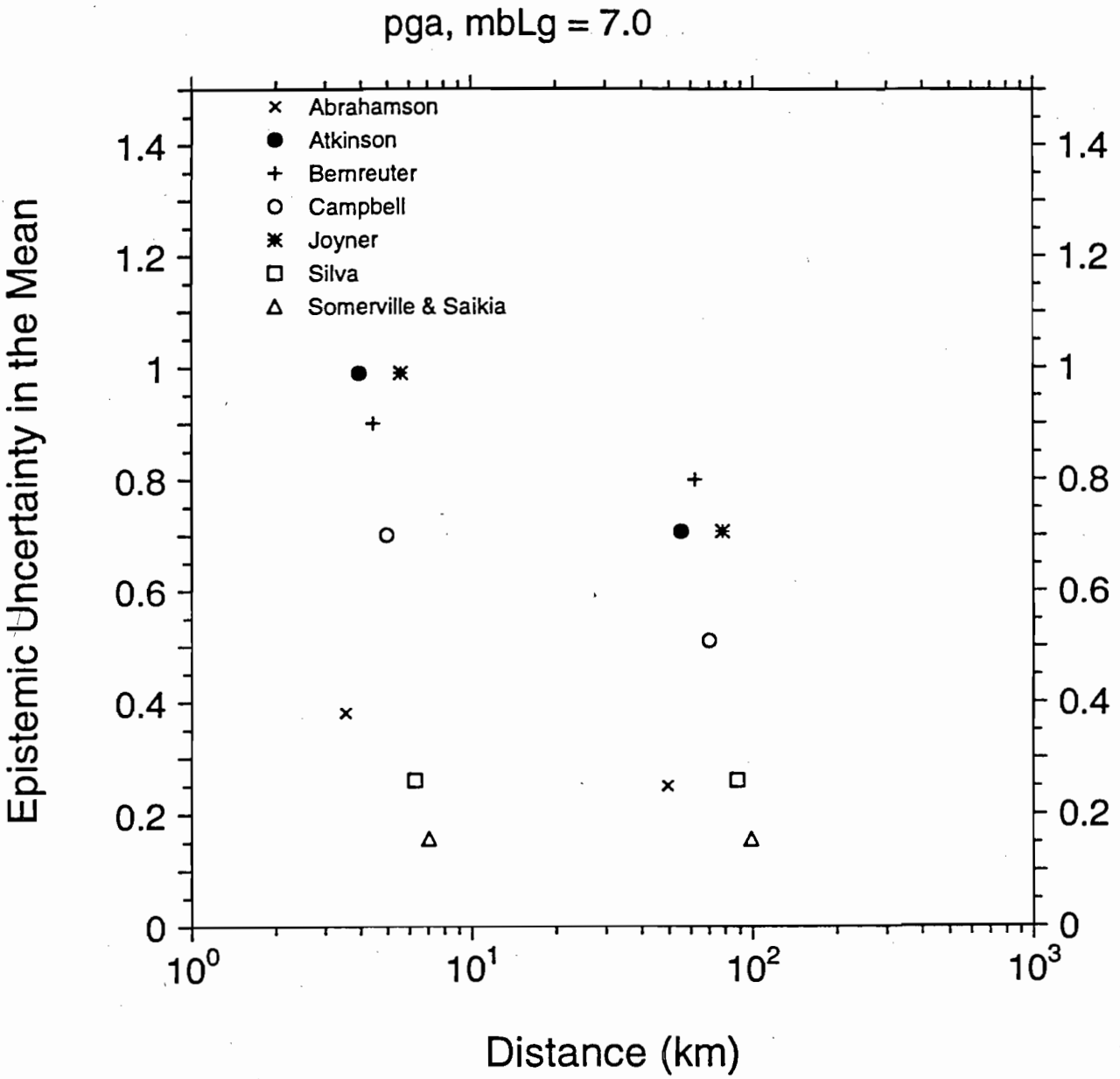

F = 10 Hz, mbLg = 5.5
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
Epistemic Uncertainty in the Mean
Distance (km)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
10^0
10^1
10^2
10^3

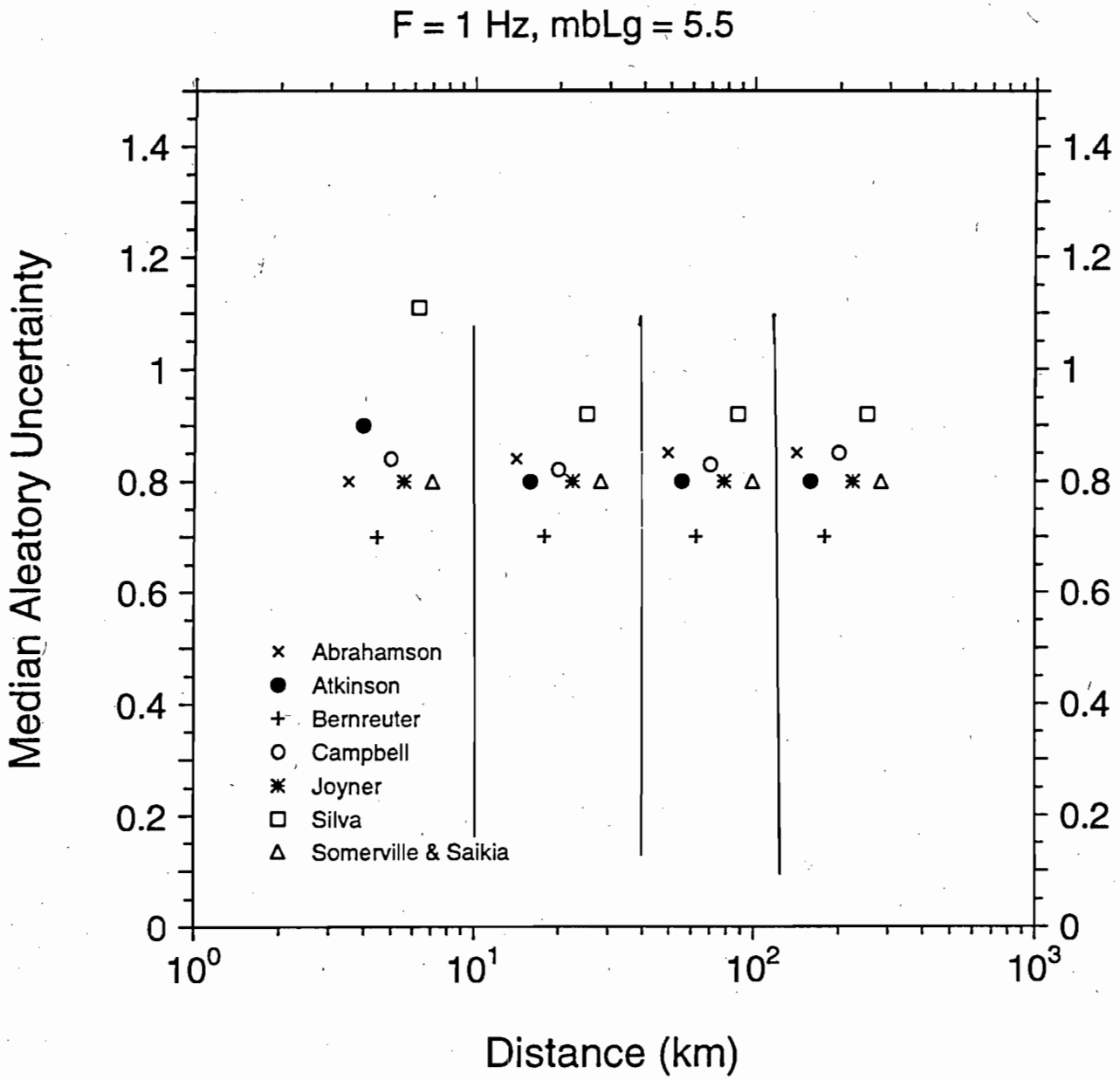

F = 25 Hz, mbLg = 5.5
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
Epistemic Uncertainty in the Mean
Distance (km)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
10^0
10^1
10^2
10^3

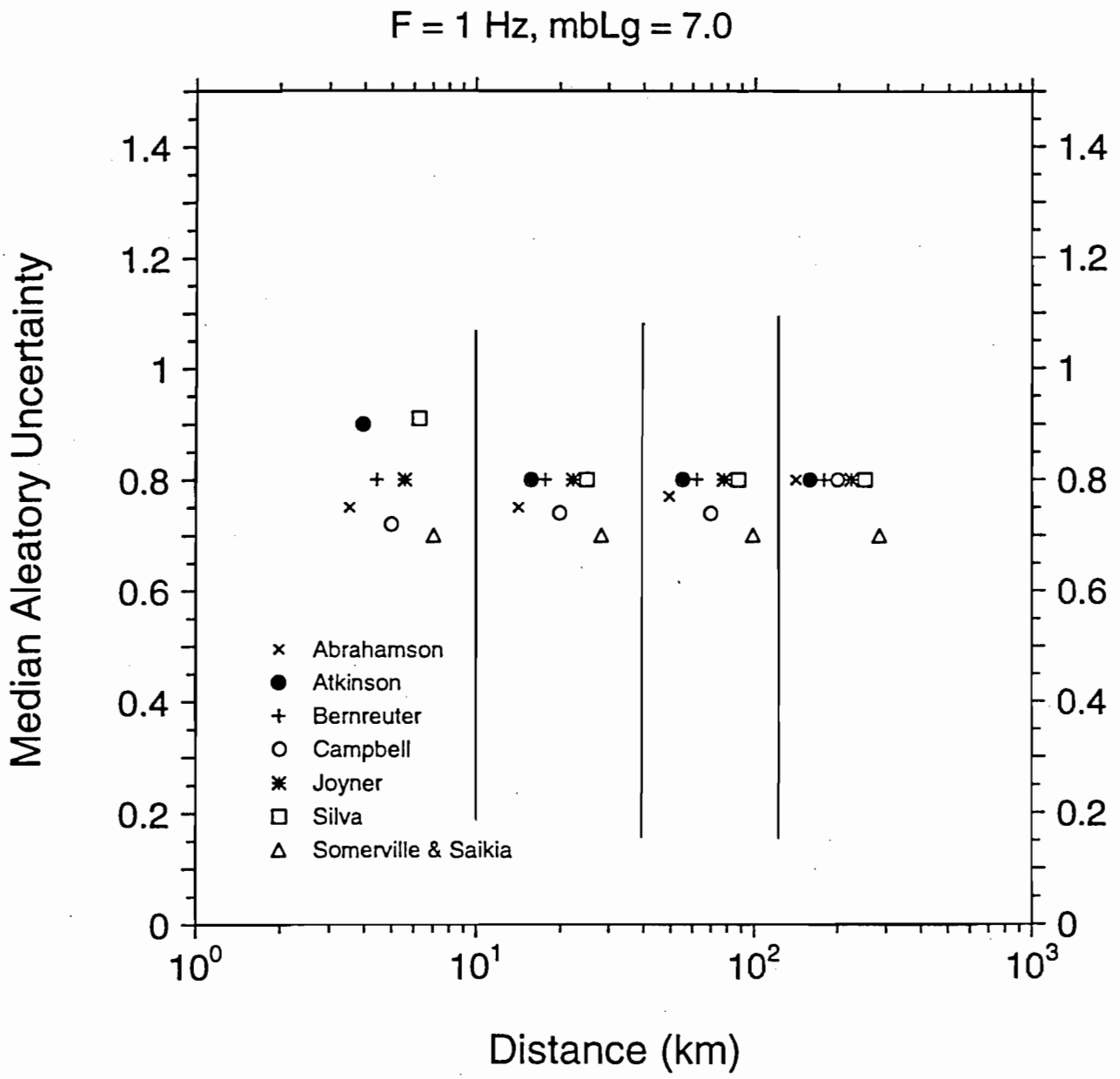

F = 10 Hz, mbLg = 7.0
Abrahamson
Atkinson
Bemreuter
Campbell
Joyner
Silva
Somerville & Saikia
Epistemic Uncertainty in the Mean
Distance (km)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
10^0
10^1
10^2
10^3

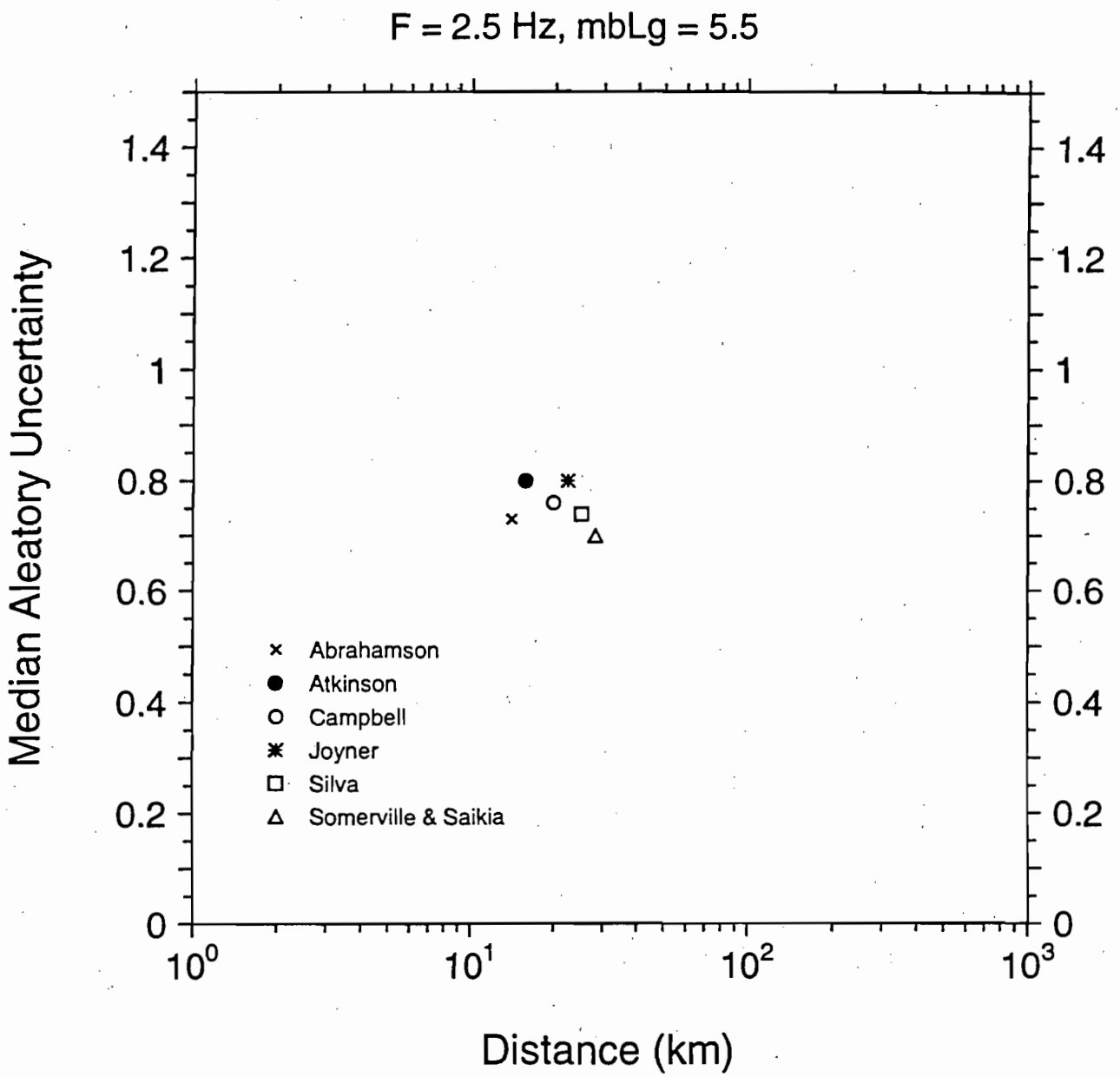

F = 25 Hz, mbLg = 7.0
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
Epistemic Uncertainty in the Mean
Distance (km)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
10^0
10^1
10^2
10^3

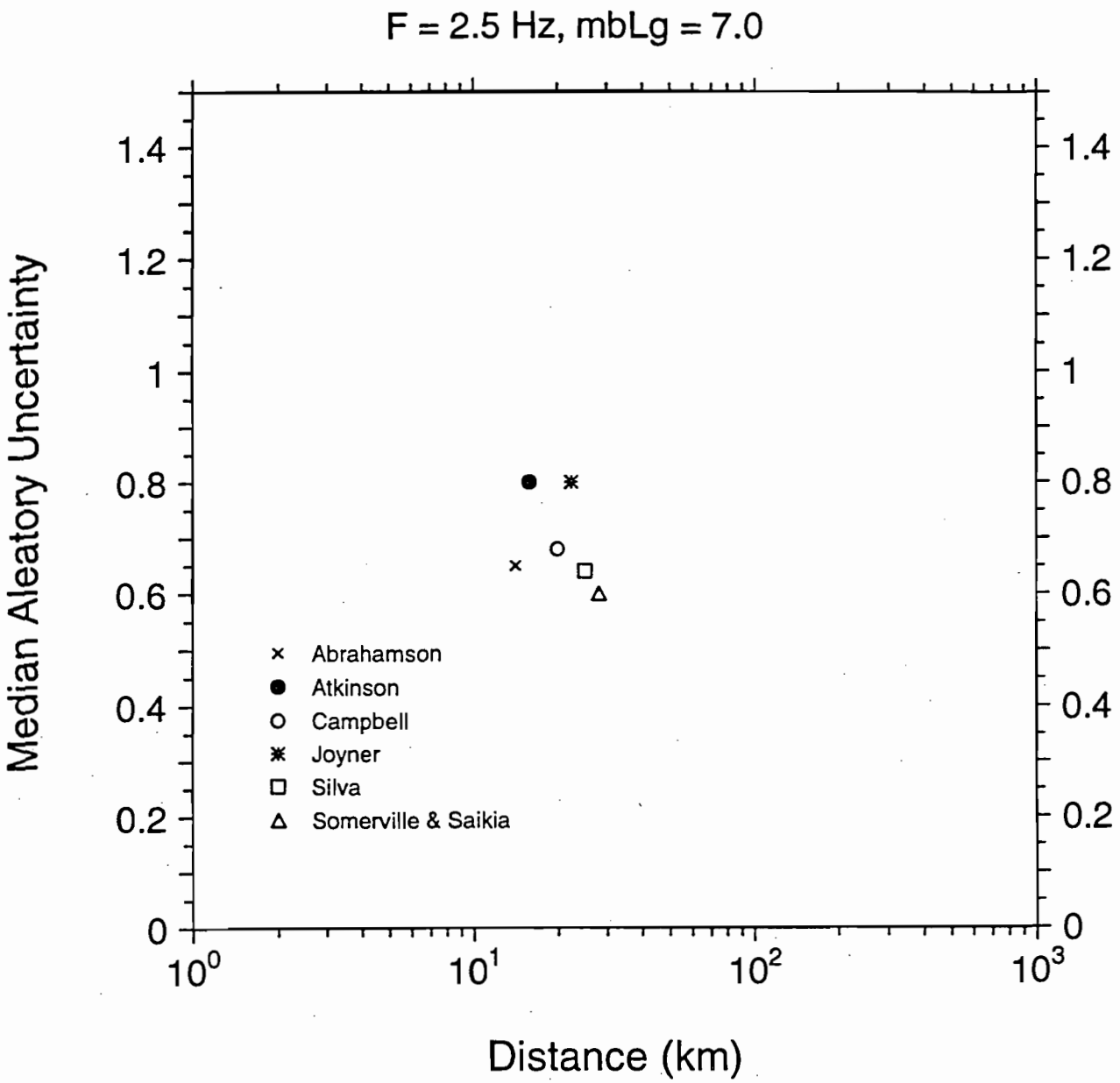

pga, mbLg = 5.5
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
Epistemic Uncertainty in the Mean
Distance (km)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
10^0
10^1
10^2
10^3

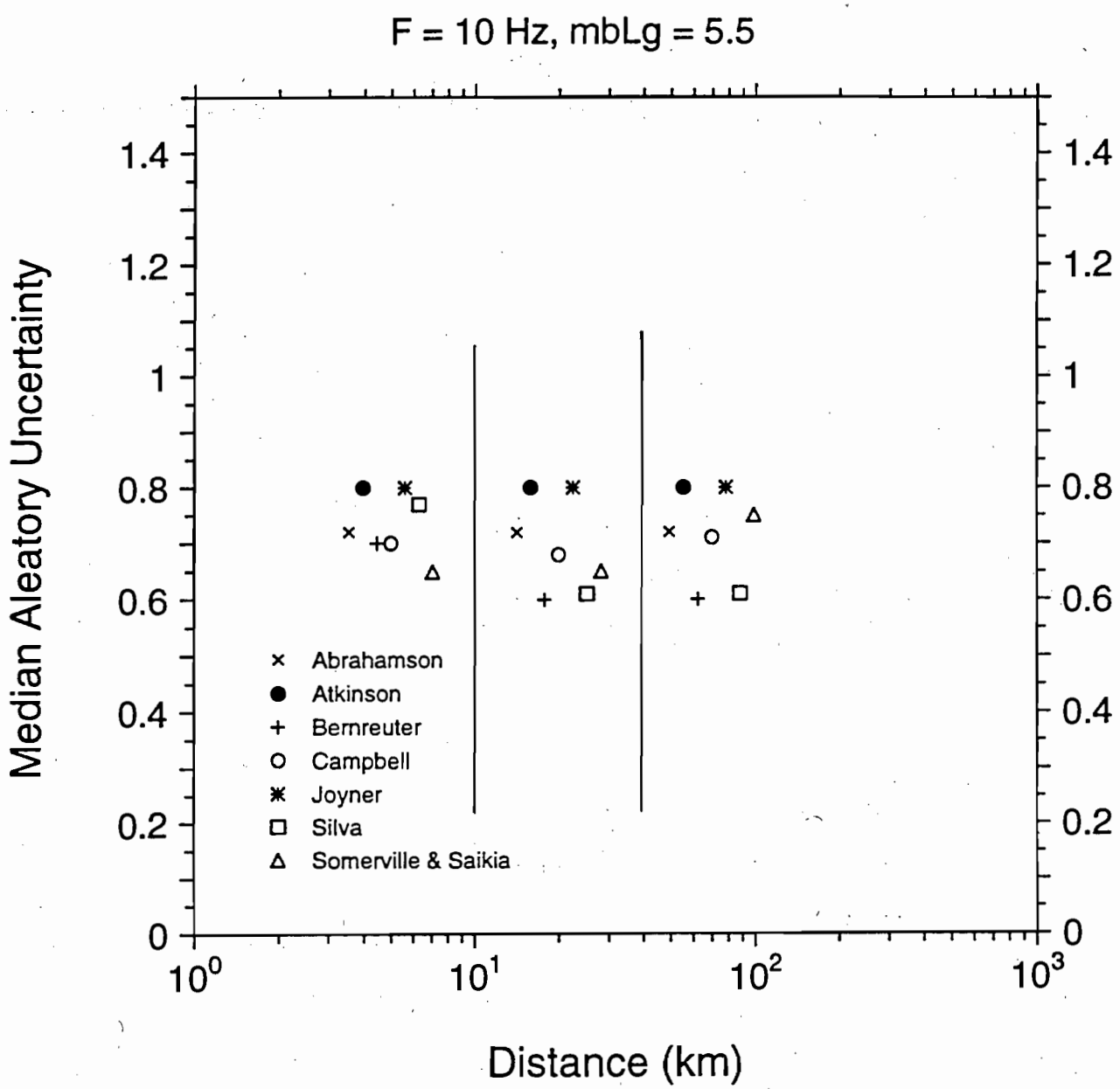

pga, mbLg = 7.0
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
Epistemic Uncertainty in the Mean
Distance (km)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
10^0
10^1
10^2
10^3

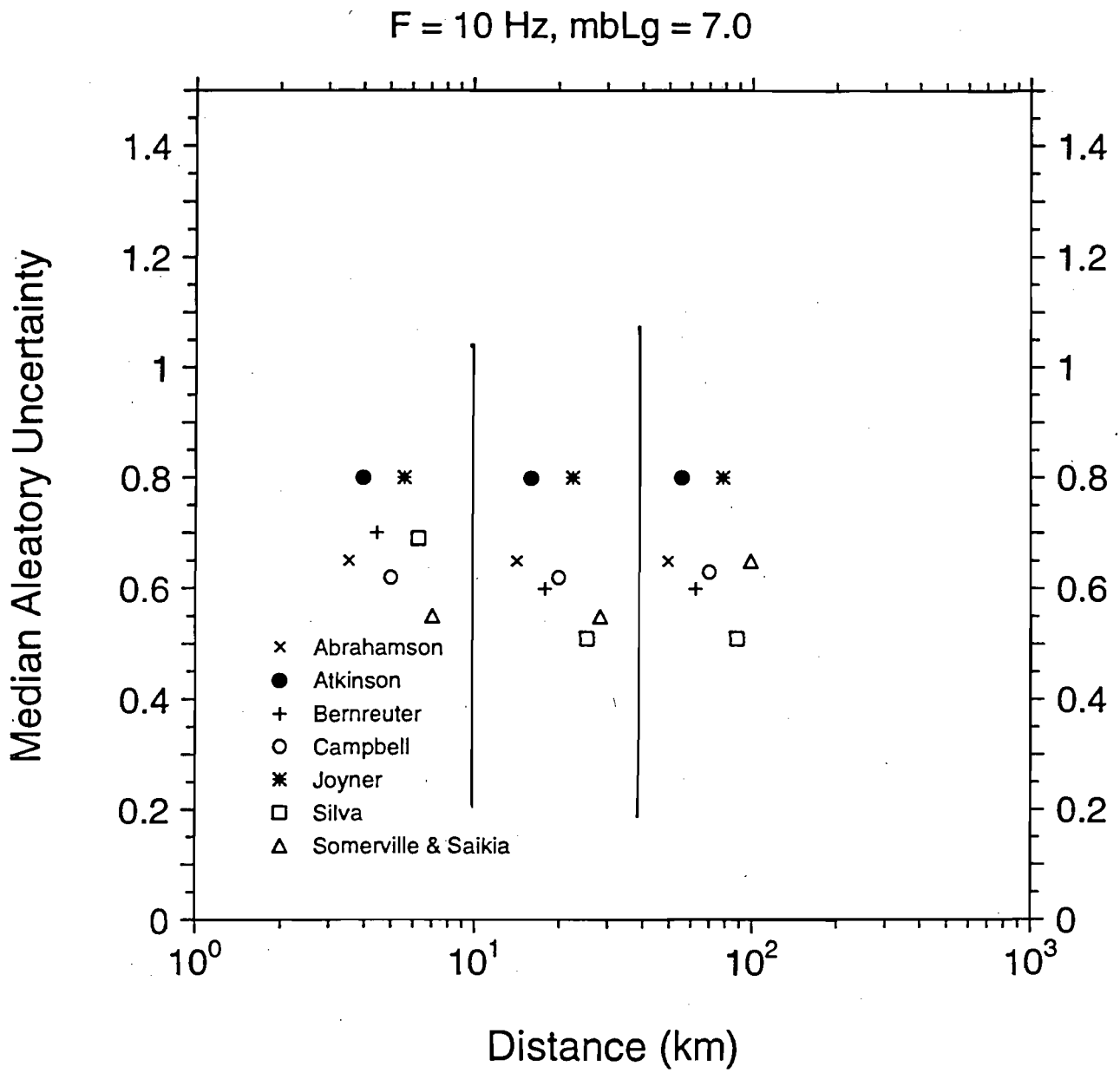

F = 1 Hz, mbLg = 5.5
Median Aleatory Uncertainty
Distance (km)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
10^0
10^1
10^2
10^3
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia

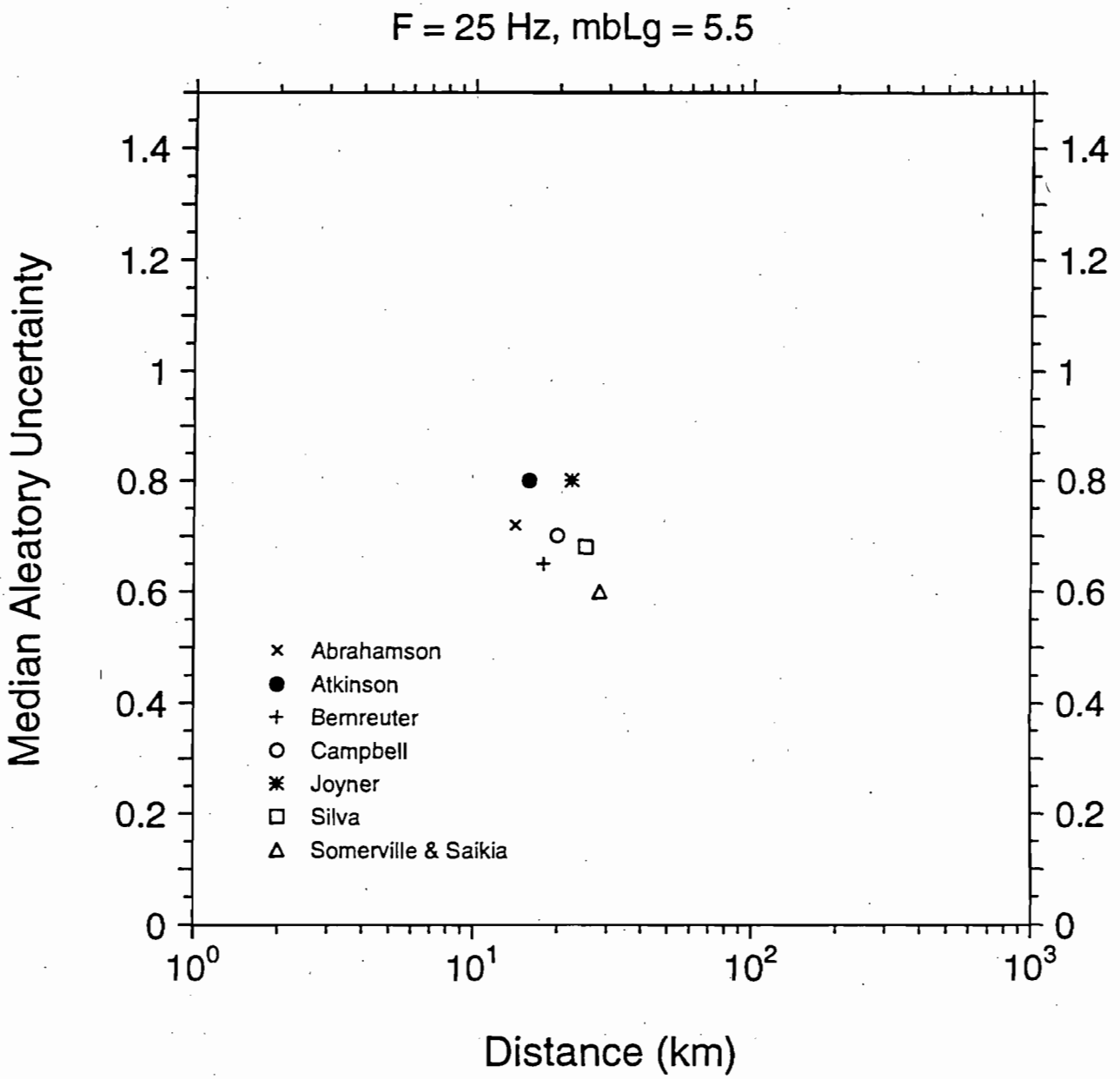

F = 1 Hz, mbLg = 7.0
Median Aleatory Uncertainty
Distance (km)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
10^0
10^1
10^2
10^3
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia

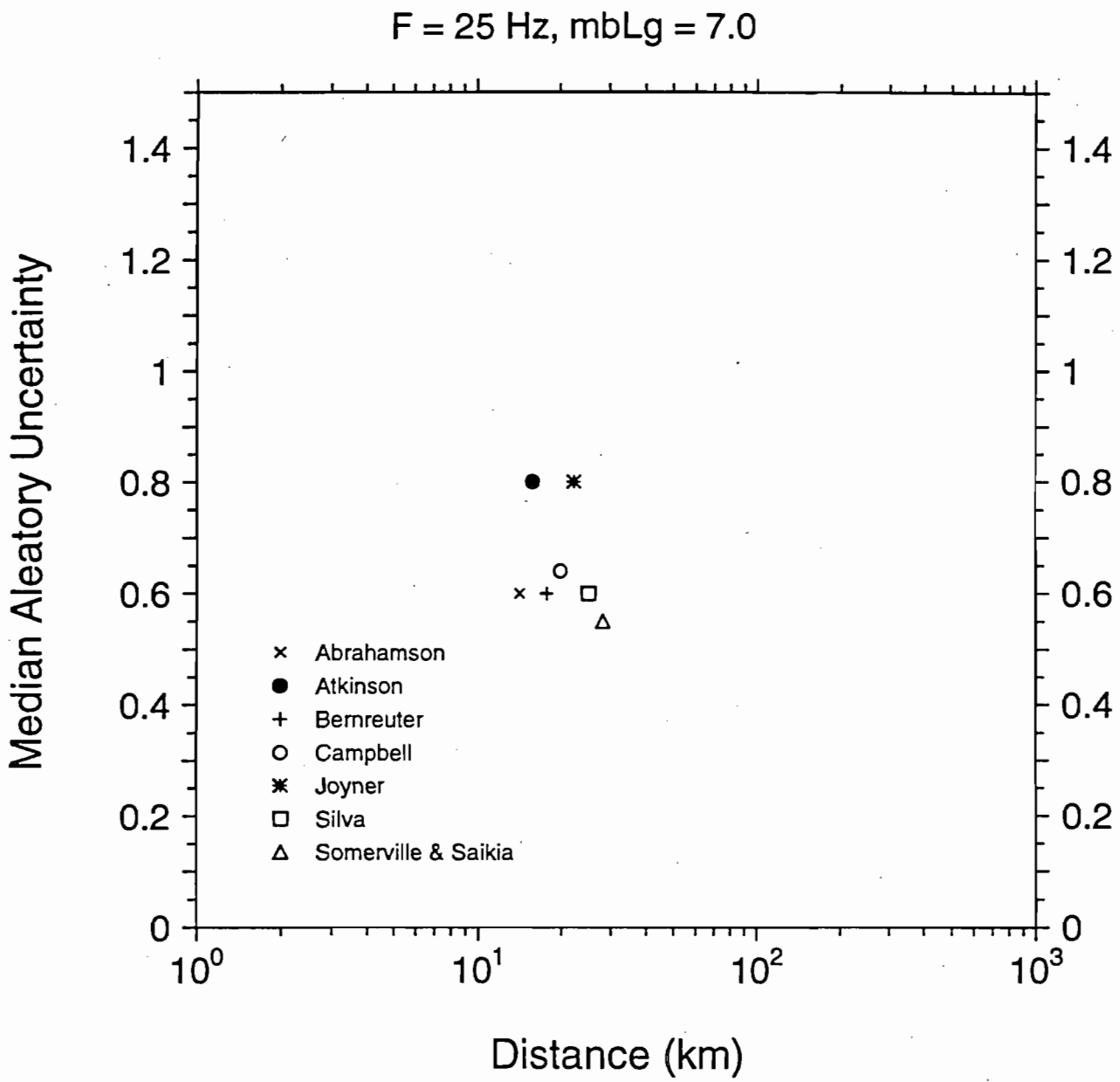

F = 2.5 Hz, mbLg = 5.5
Median Aleatory Uncertainty
Distance (km)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
10^0
10^1
10^2
10^3
Abrahamson
Atkinson
Campbell
Joyner
Silva
Somerville & Saikia

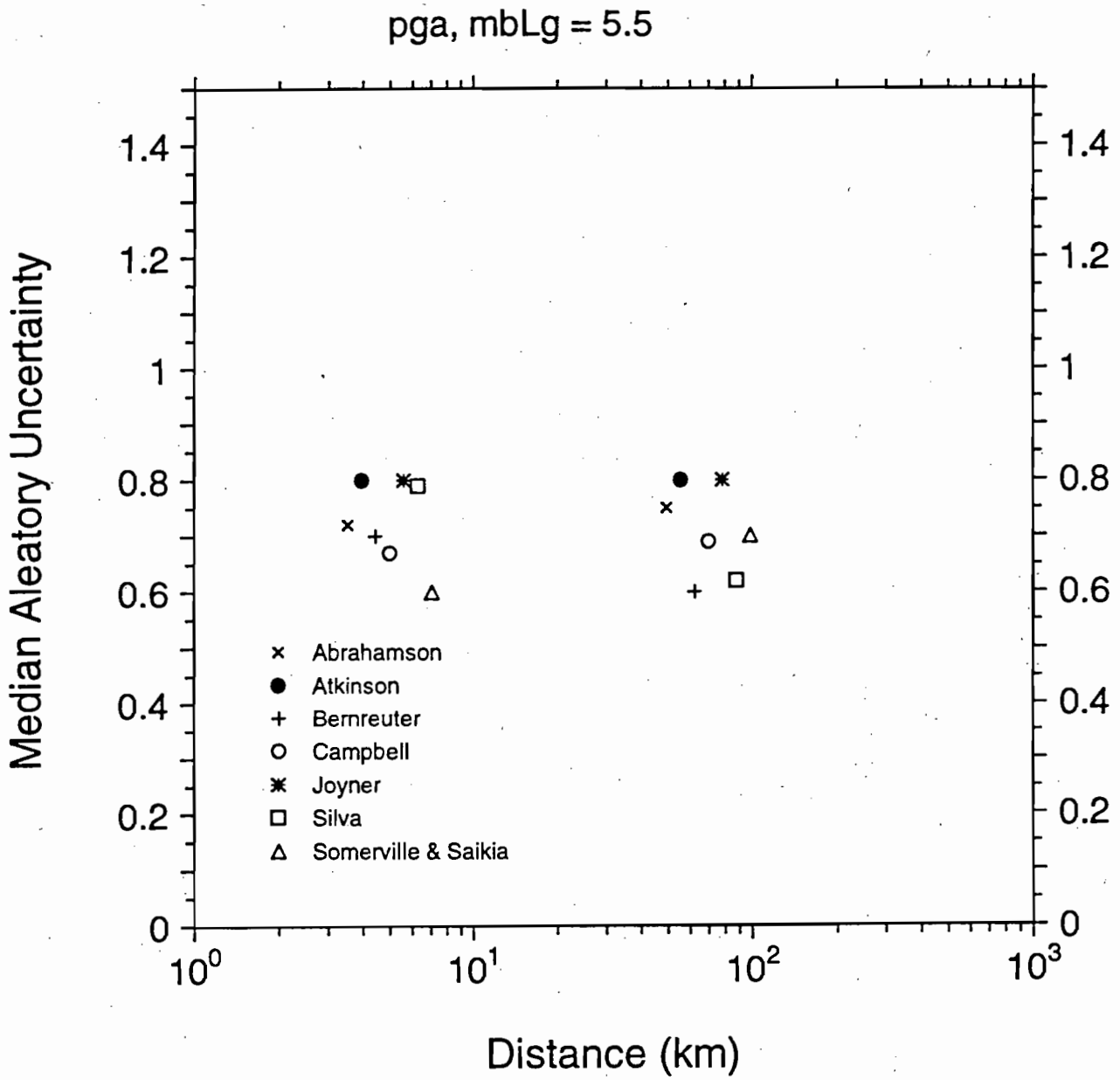

F = 2.5 Hz, mbLg = 7.0
Median Aleatory Uncertainty
Distance (km)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
10^0
10^1
10^2
10^3
Abrahamson
Atkinson
Campbell
Joyner
Silva
Somerville & Saikia

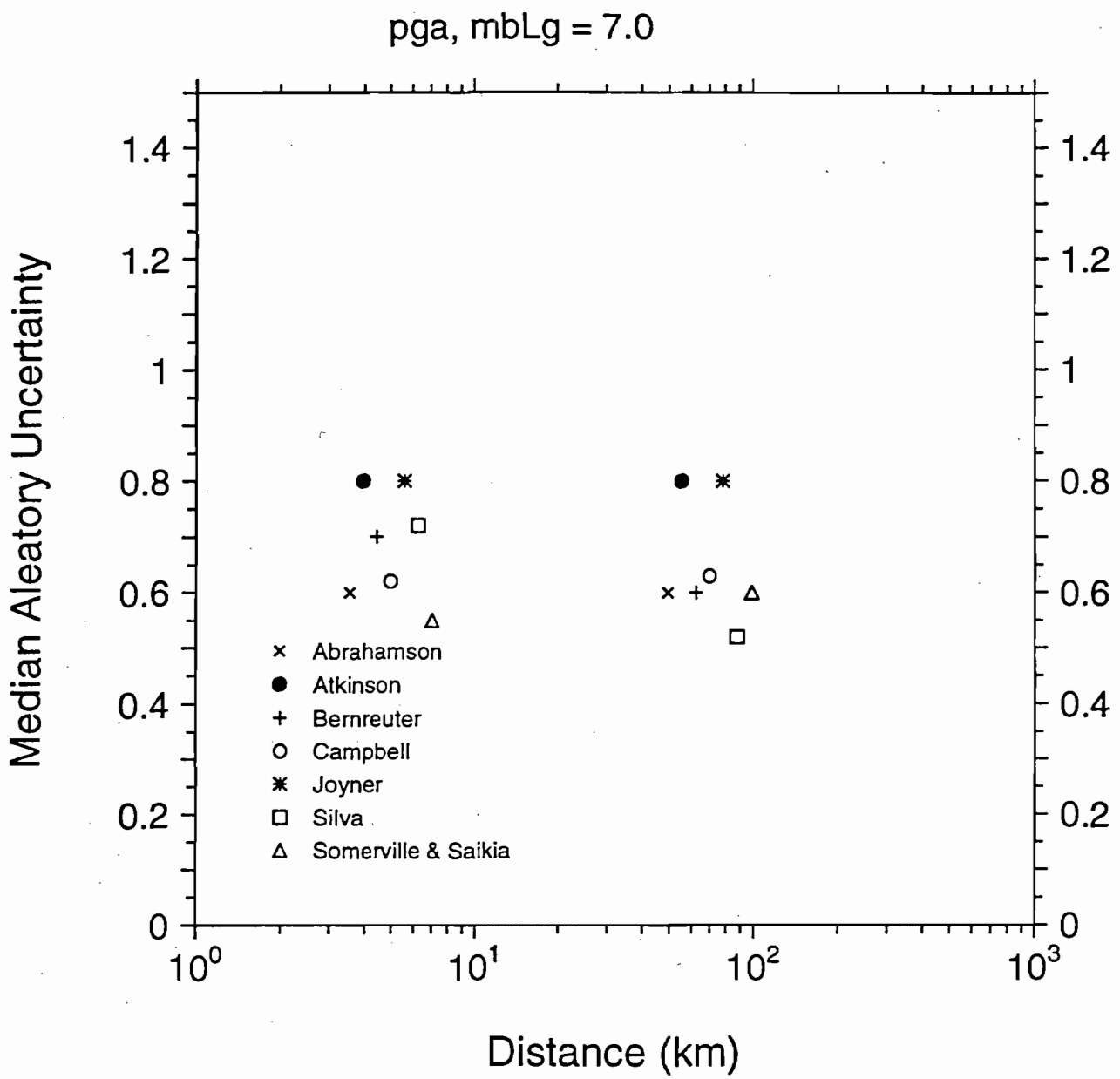

F = 10 Hz, mbLg = 5.5
Median Aleatory Uncertainty
Distance (km)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
10^0
10^1
10^2
10^3
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia

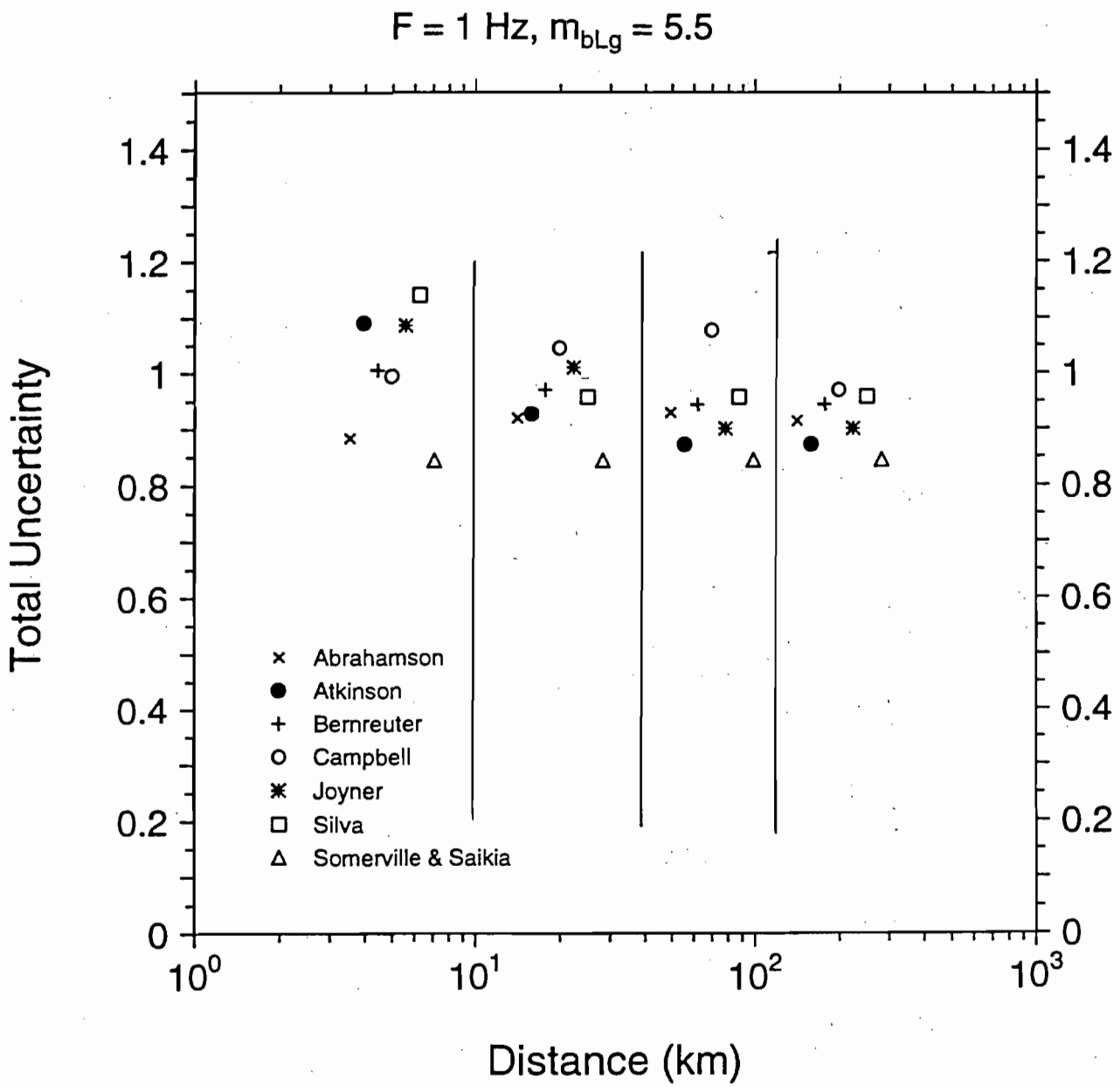

F = 10 Hz, mbLg = 7.0
Median Aleatory Uncertainty
Distance (km)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
10^0
10^1
10^2
10^3
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia

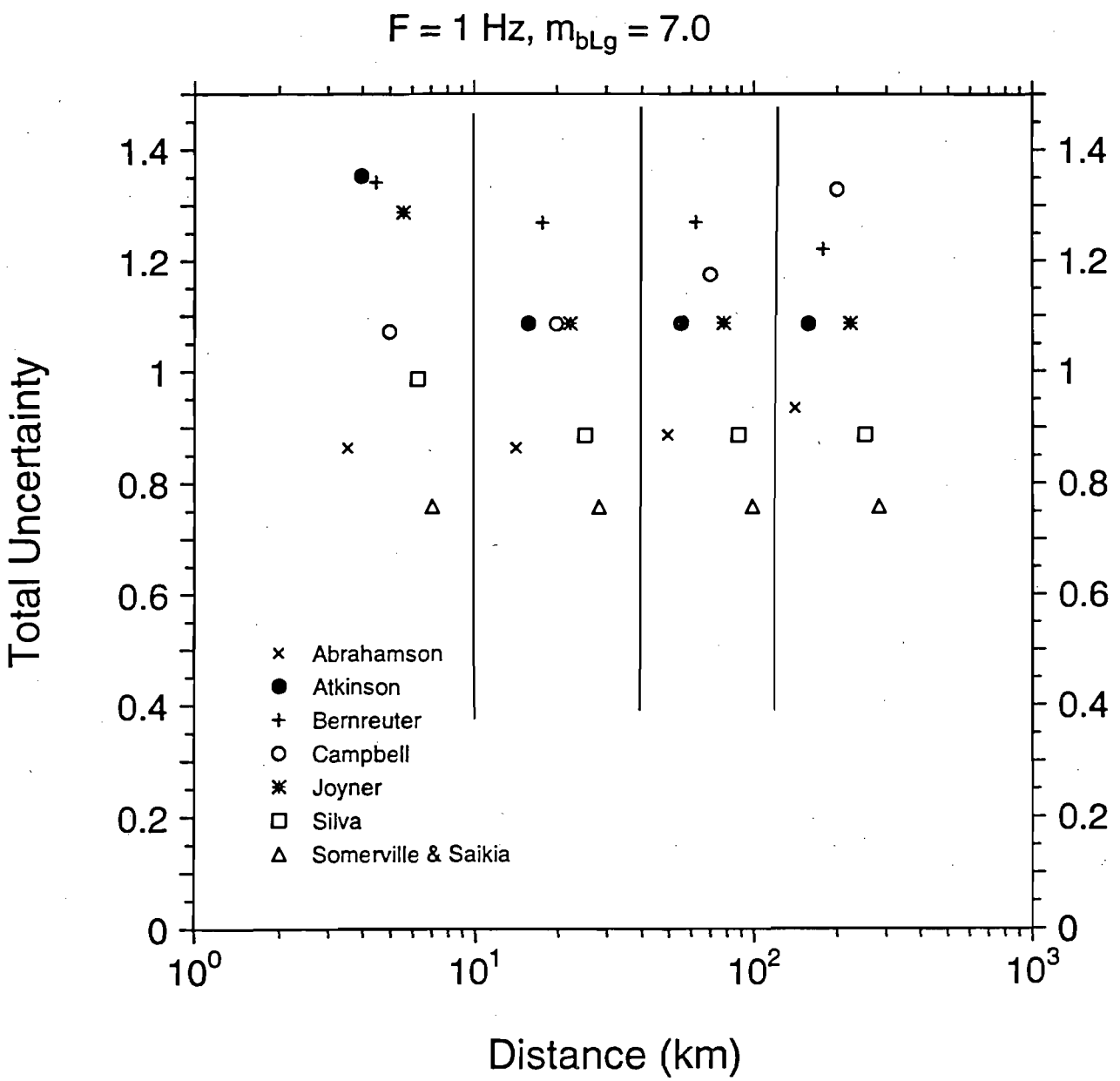

F = 25 Hz, mbLg = 5.5
Median Aleatory Uncertainty
Distance (km)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
10^0
10^1
10^2
10^3
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia

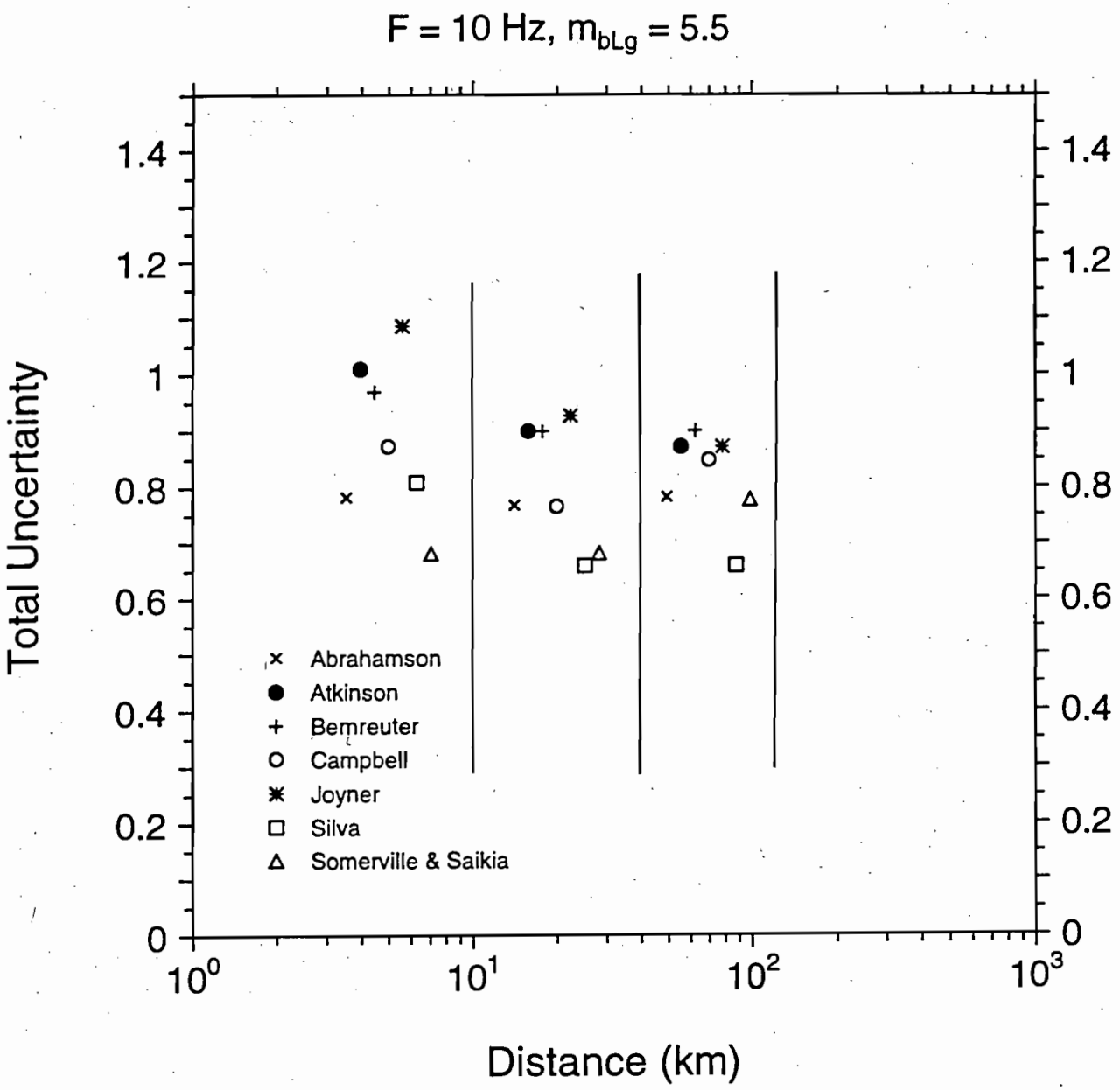

F = 25 Hz, mbLg = 7.0
Median Aleatory Uncertainty
Distance (km)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
10^0
10^1
10^2
10^3
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia

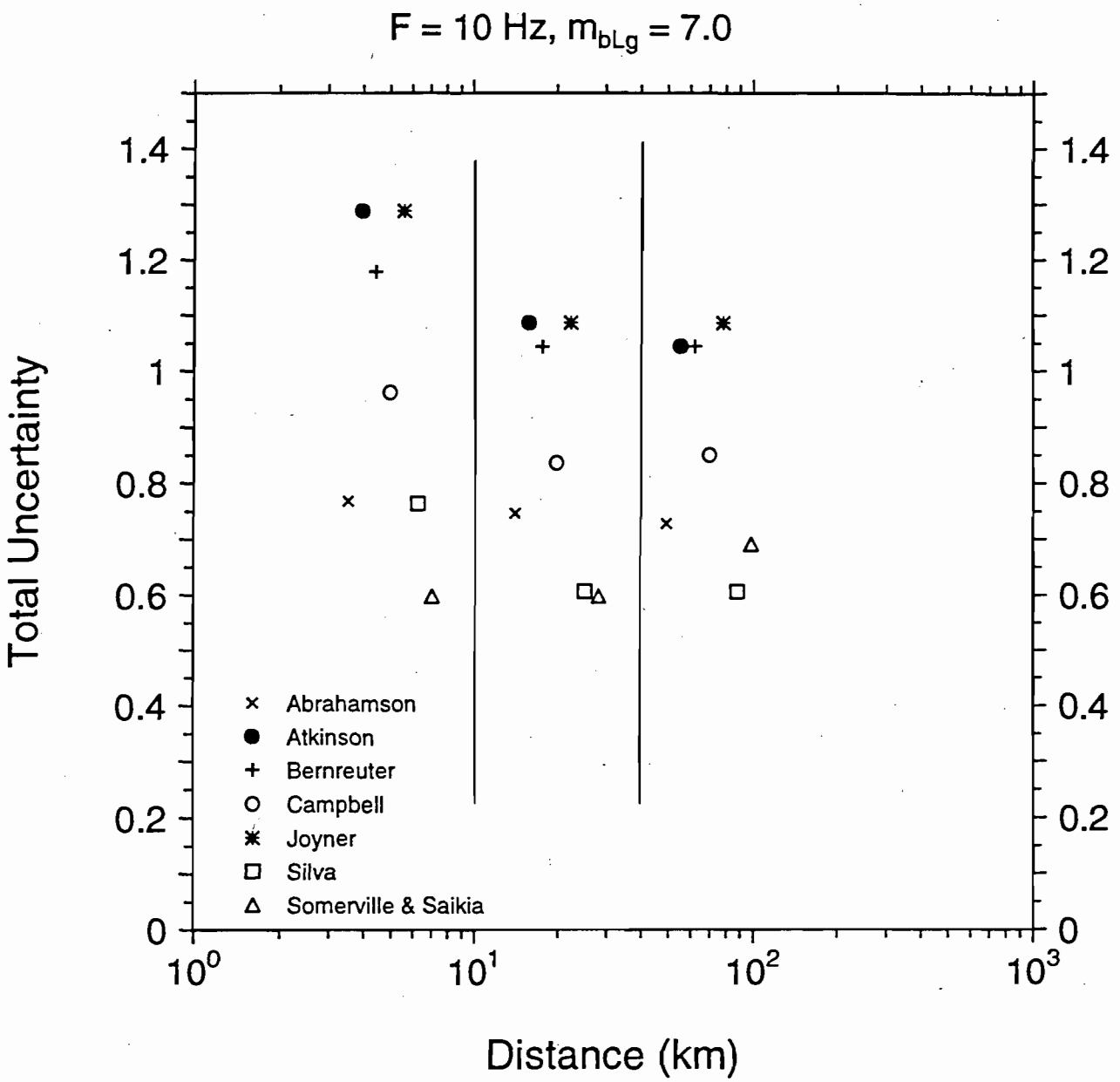

pga, mbLg = 5.5
Median Aleatory Uncertainty
Distance (km)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
10^0
10^1
10^2
10^3
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia

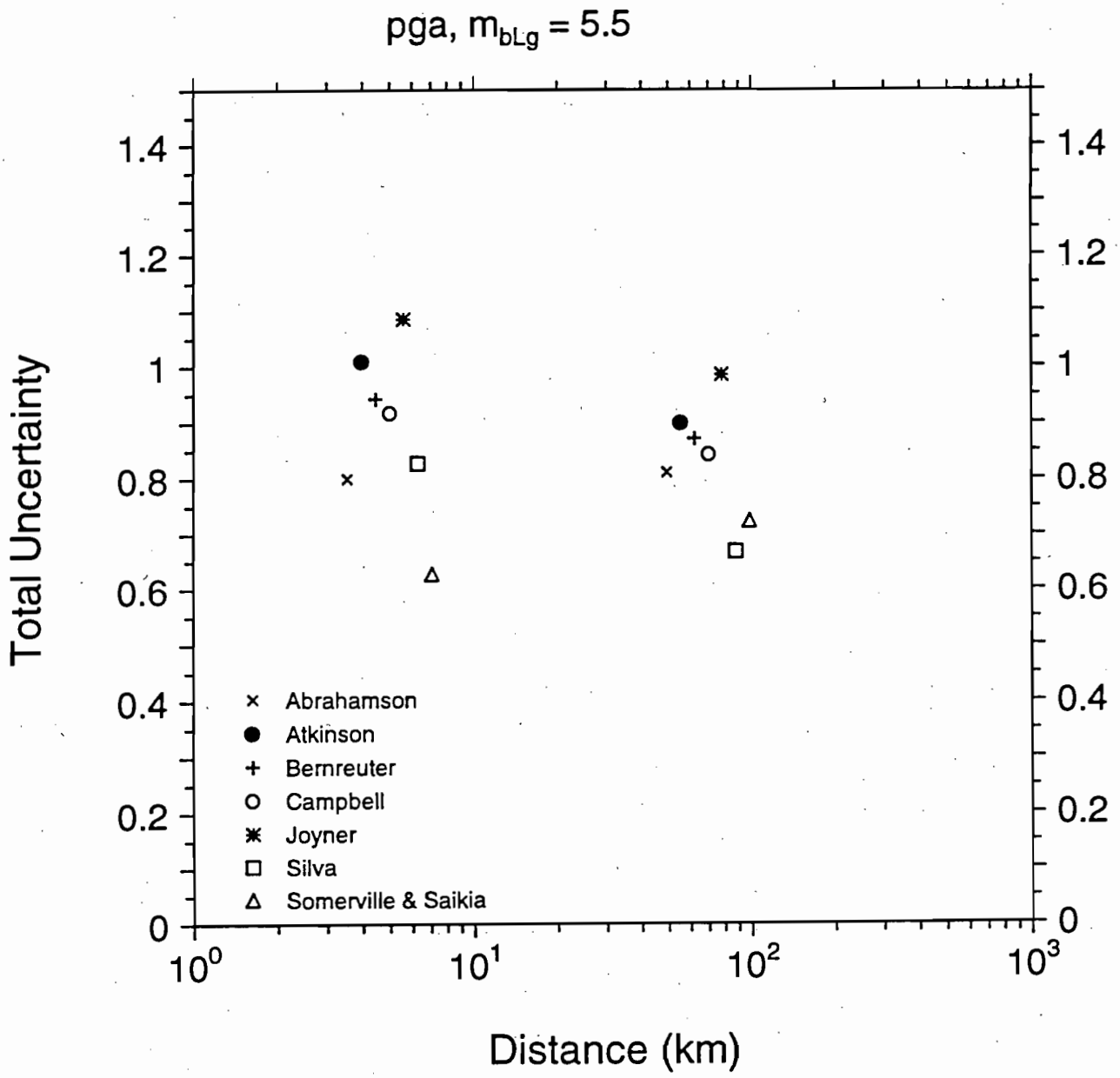

pga, mbLg = 7.0
Median Aleatory Uncertainty
Distance (km)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
10^0
10^1
10^2
10^3
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia

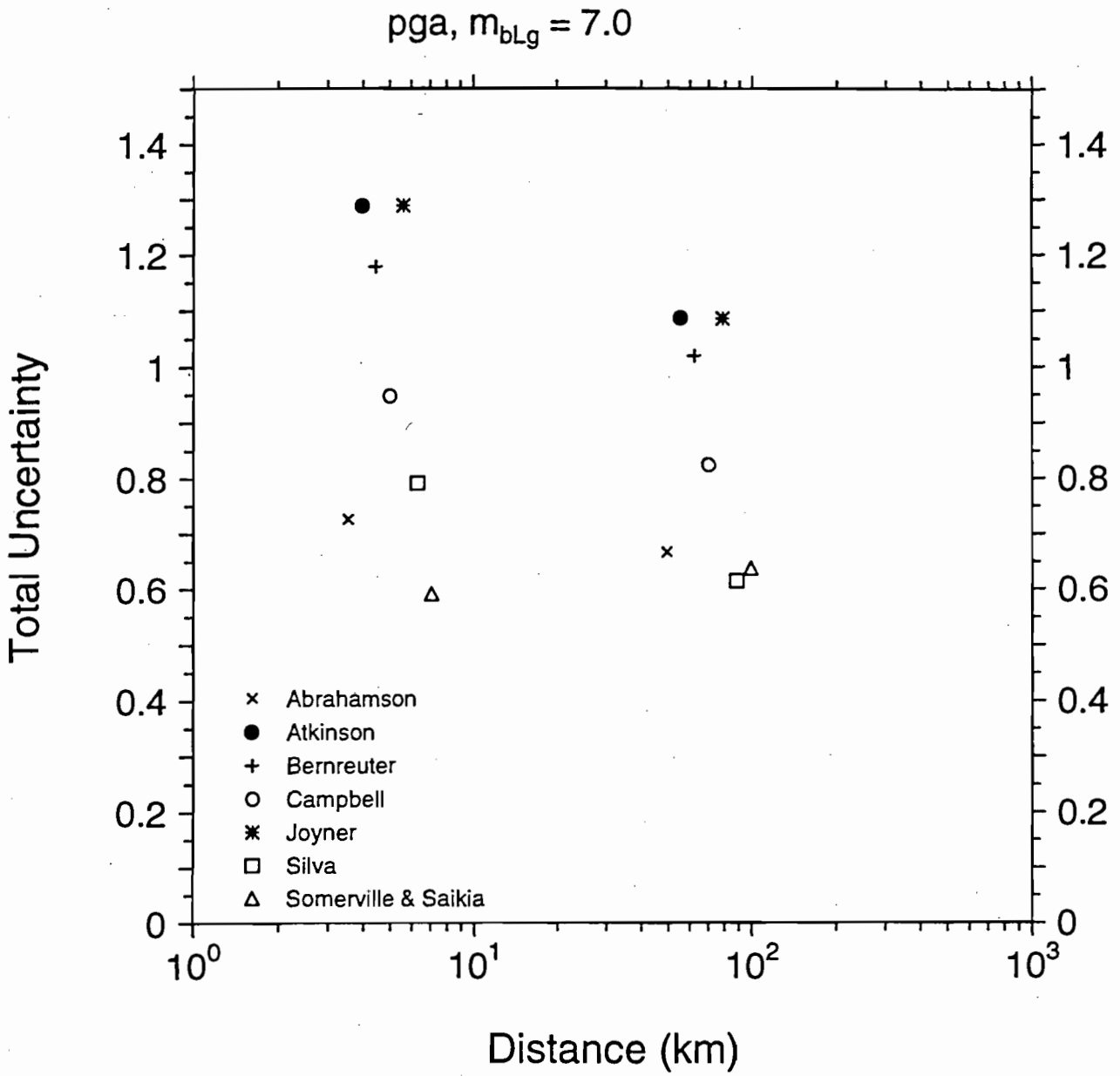

F = 1 Hz, m_{bLg} = 5.5
Total Uncertainty
Distance (km)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
10^0
10^1
10^2
10^3
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia


F = 1 Hz, m_{bLg} = 7.0
Total Uncertainty
Distance (km)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
10^0
10^1
10^2
10^3
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia


F = 10 Hz, m_{bLg} = 5.5
Total Uncertainty
Distance (km)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
10^0
10^1
10^2
10^3
Abrahamson
Atkinson
Bemreuter
Campbell
Joyner
Silva
Somerville & Saikia


F = 10 Hz, m_{bLg} = 7.0
Total Uncertainty
Distance (km)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
10^0
10^1
10^2
10^3
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia


pga, m_{bLg} = 5.5
Total Uncertainty
Distance (km)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
10^0
10^1
10^2
10^3
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia


pga, m_{bLg} = 7.0
Total Uncertainty
Distance (km)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
10^0
10^1
10^2
10^3
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia

ATTACHMENT B-3

PRE-WORKSHOP DISTRIBUTION AND COMPARISON OF EXPERTS' RESULTS

a. Cover memo B-405
b. Plots B-406

Risk Engineering, Inc.
4155 Darley Avenue, Suite A
Boulder, CO 80303 USA
Telephone: (303)499-3000
Fax Number: (303)499-4850

FAX TRANSMITTAL MEMO

To: Gabriel R. Toro (self-copy)	From: Gabriel R. Toro (303)494-1021
Time: 20:16:12	Date: 7/25/94
Pages (including cover): 24	

To: Norm Abrahamson
Gail Atkinson
Don Bernreuter, LLNL
Bill Joyner, USGS
Ken Campbell, EQE
Walt Silva, PEA
Paul Somerville and Chandan Saikia, WCC

From: G. R. Toro

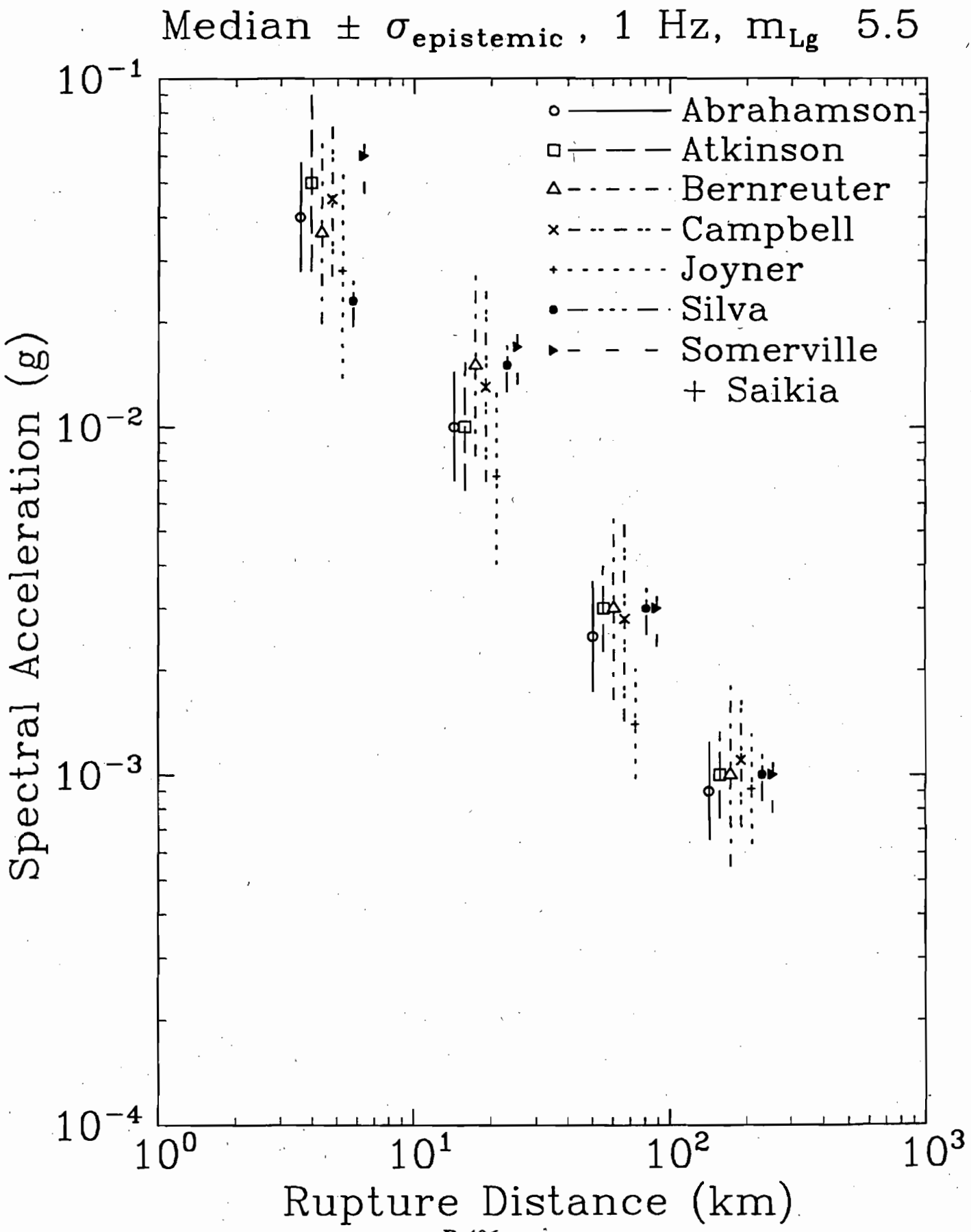
Re: SSHAC Ground Motion Workshop

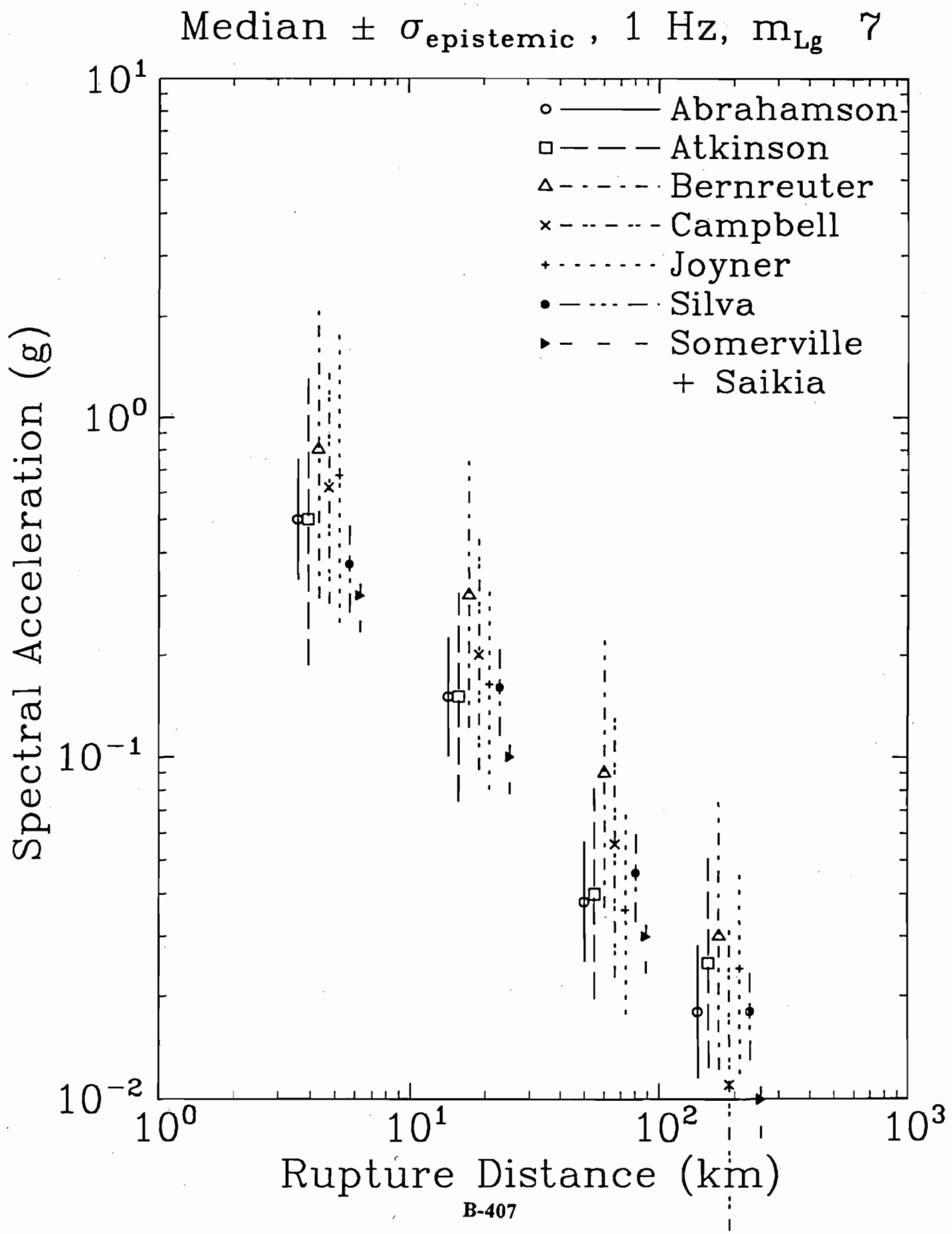
Enclosed are figures comparing the predictions by al ground-motion experts. This set also includes a set of figures showing the median +- total uncertainty (where total uncertainty is sqrt(epistemic**2+sigma**2+sigma(sigma)**2). I will fax Joyner's predictions and documentation later tonight or tomorrow morning.

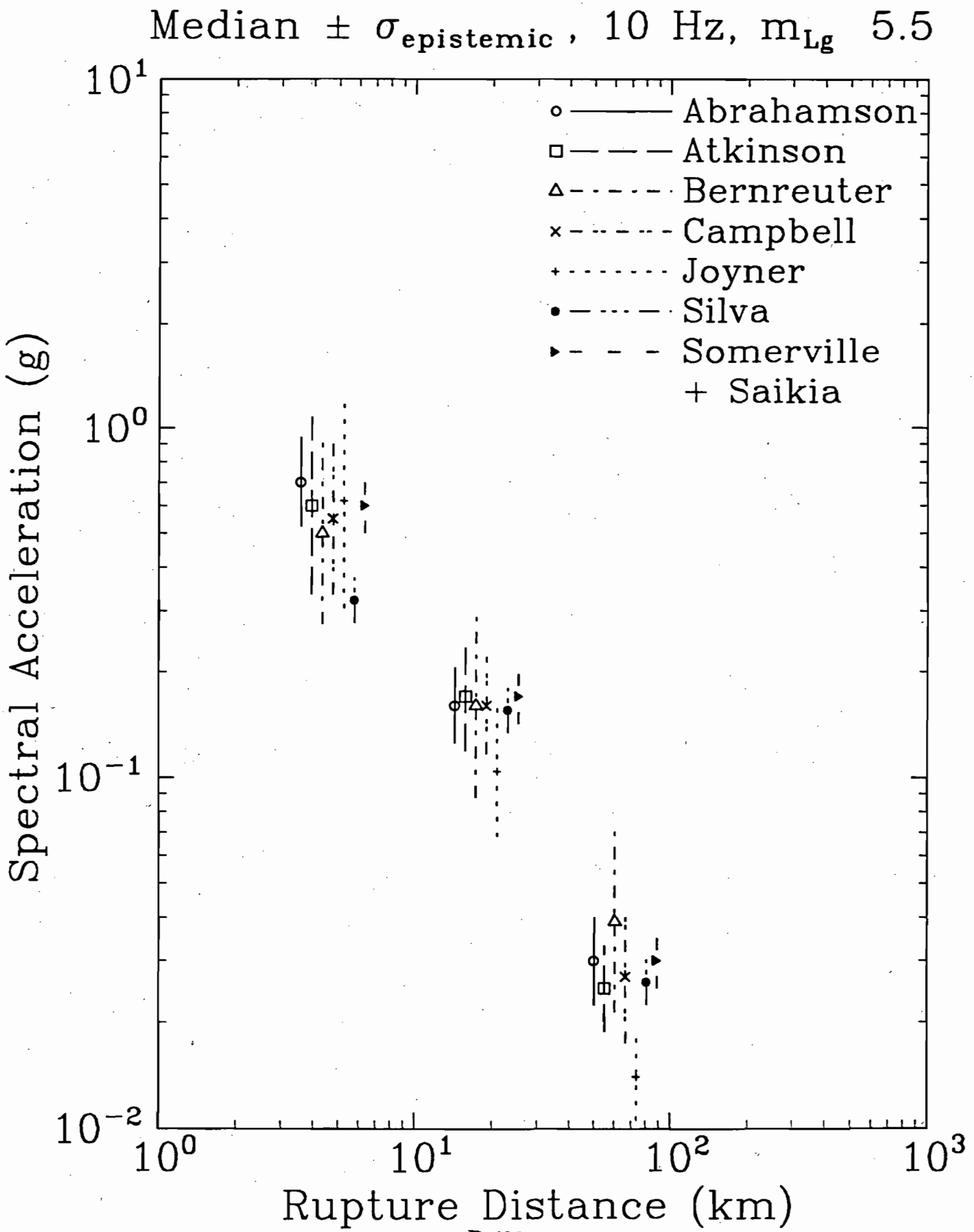
I look forward to very interesting discussions at the workshop.

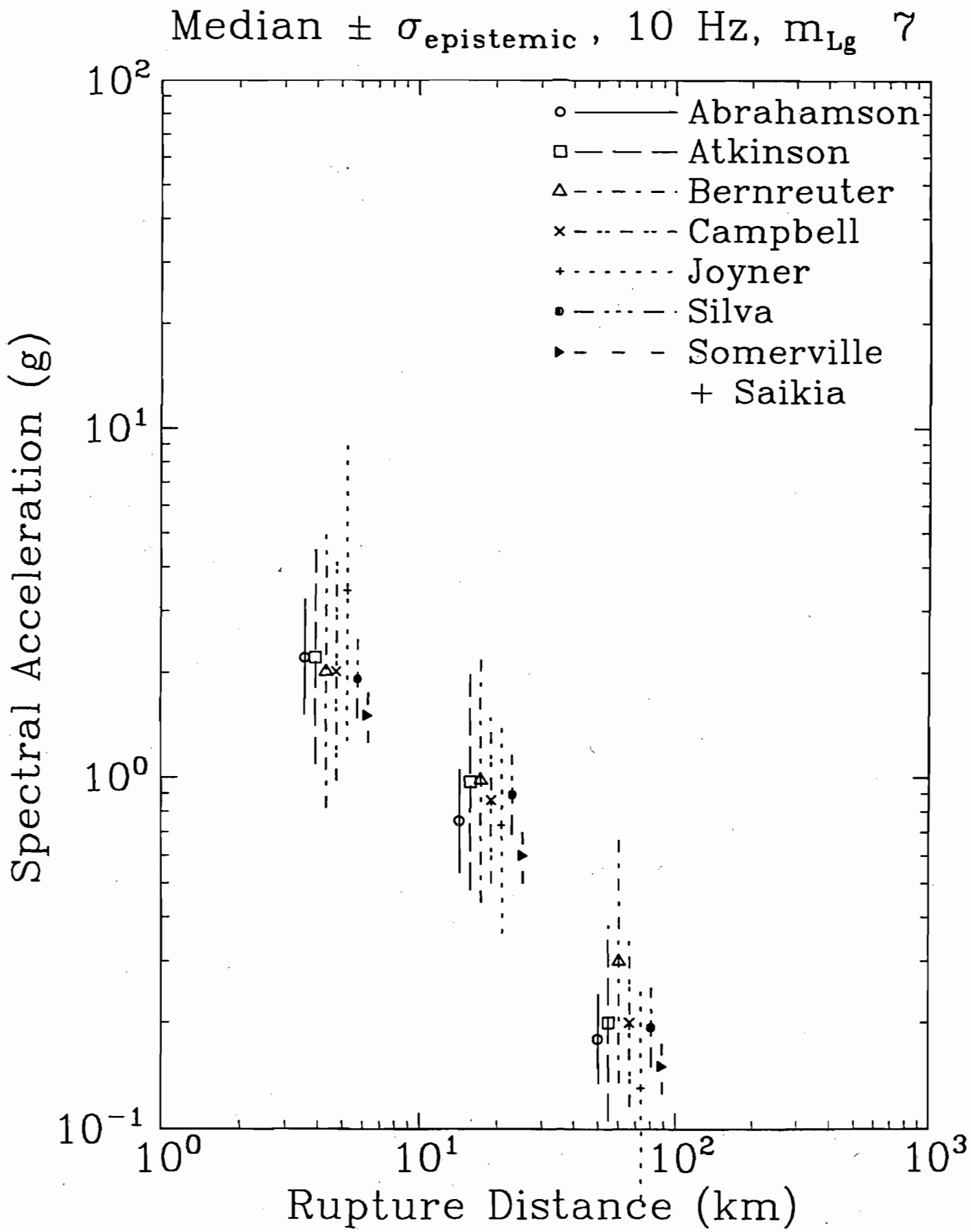
cc. Dave Boore, USGS
C. A. Cornell
Peter Morris, ADA
Richard Mensing, Logicon-RDA

(Four figures revised and three figures removed as per fax of July 26, 1995)

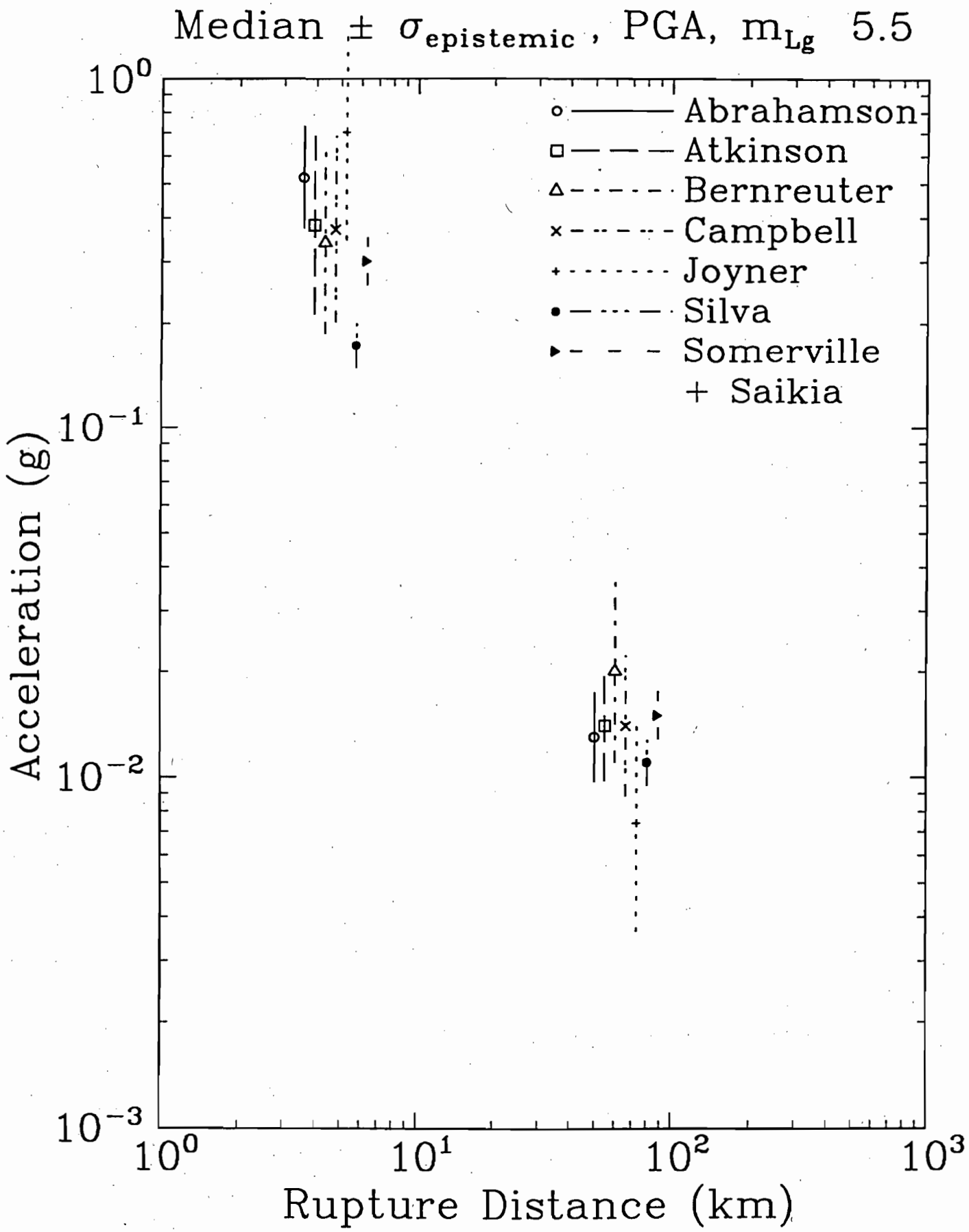

Median ± σepistemic , 1 Hz, mLg 5.5
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville + Saikia
Spectral Acceleration (g)
10−1
10−2
10−3
10−4
100
101
102
103
Rupture Distance (km)


Median ± σepistemic , 1 Hz, mLg 7
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville + Saikia
Spectral Acceleration (g)
Rupture Distance (km)
10^1
10^0
10^-1
10^-2
10^0
10^1
10^2
10^3

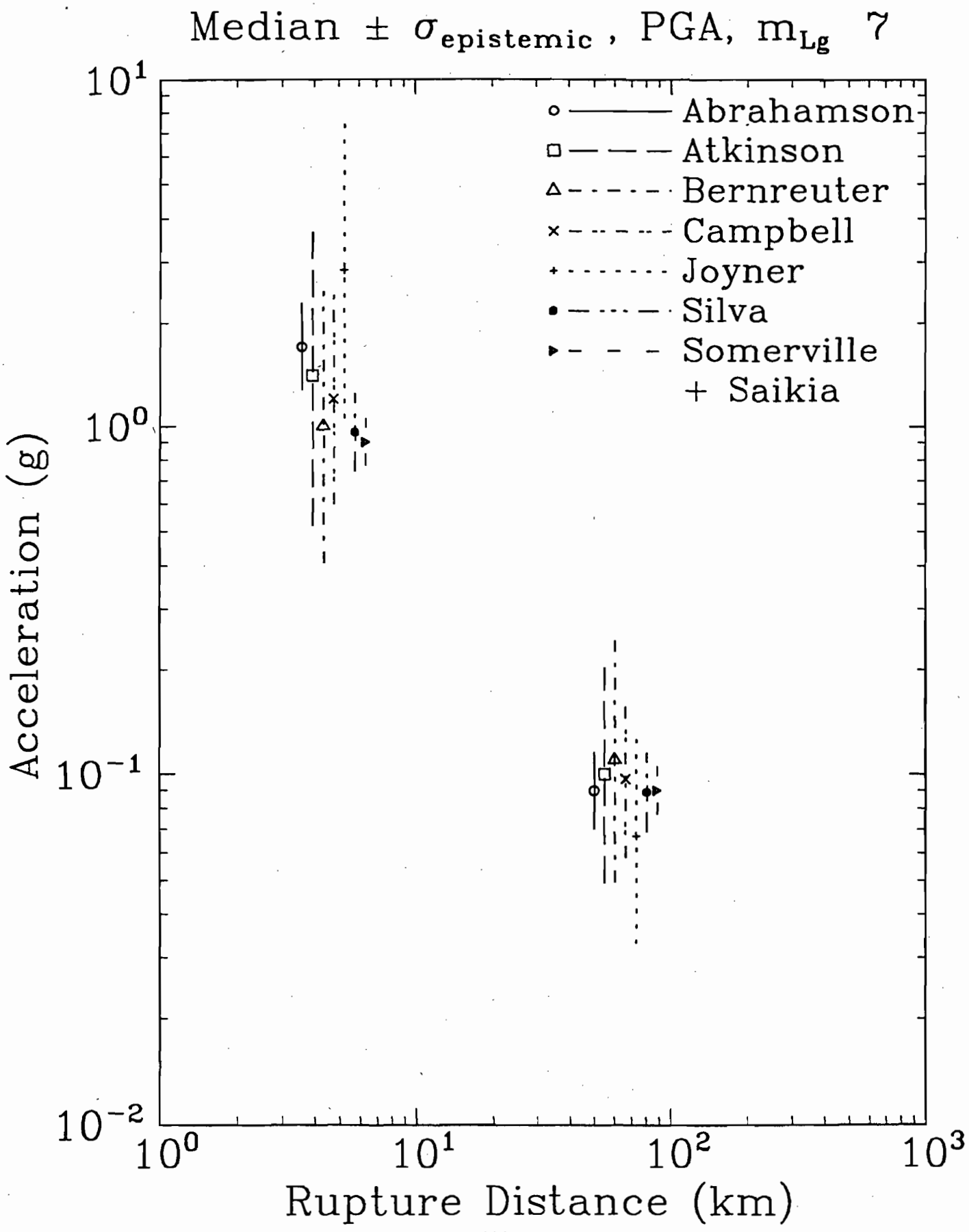

Median ± σepistemic , 10 Hz, mLg 5.5
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville + Saikia
Spectral Acceleration (g)
Rupture Distance (km)
10^1
10^0
10^-1
10^-2
10^0
10^1
10^2
10^3

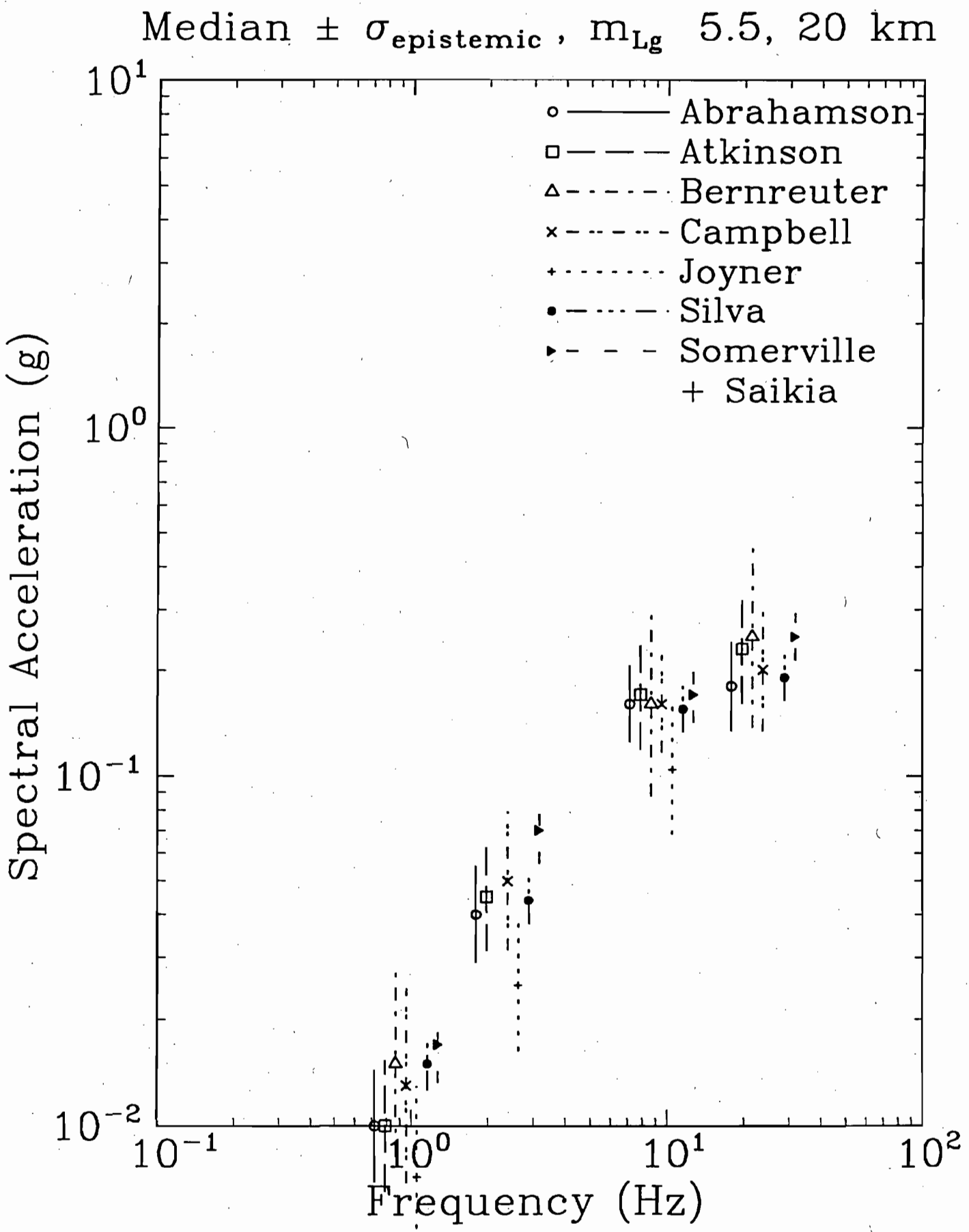

Median ± σepistemic , 10 Hz, mLg 7
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville + Saikia
Spectral Acceleration (g)
Rupture Distance (km)
10^2
10^1
10^0
10^-1
10^0
10^1
10^2
10^3

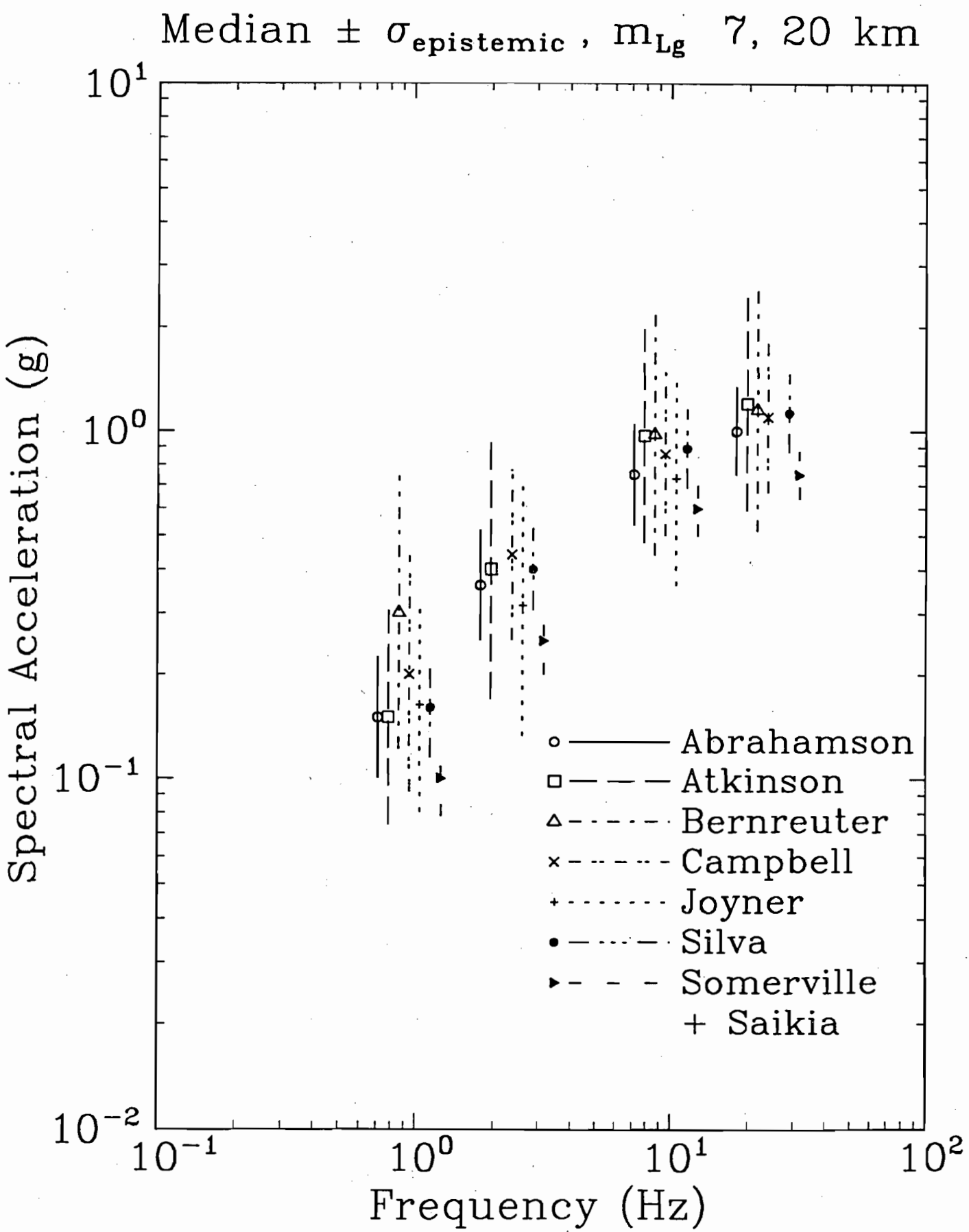
frame 1 $DISK3:[GTOH.9305.WSHOP_2]1_PGA_55.MET;2

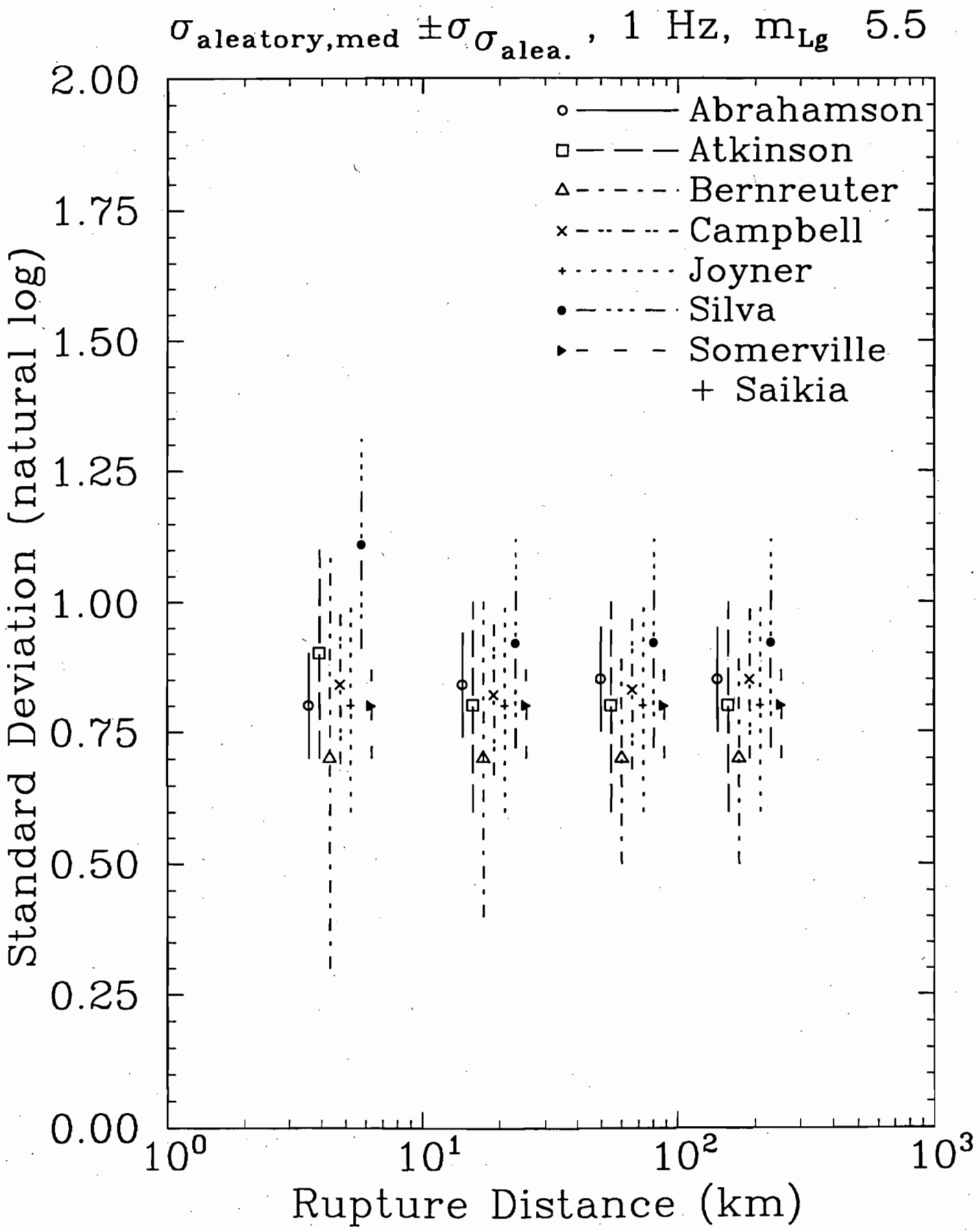


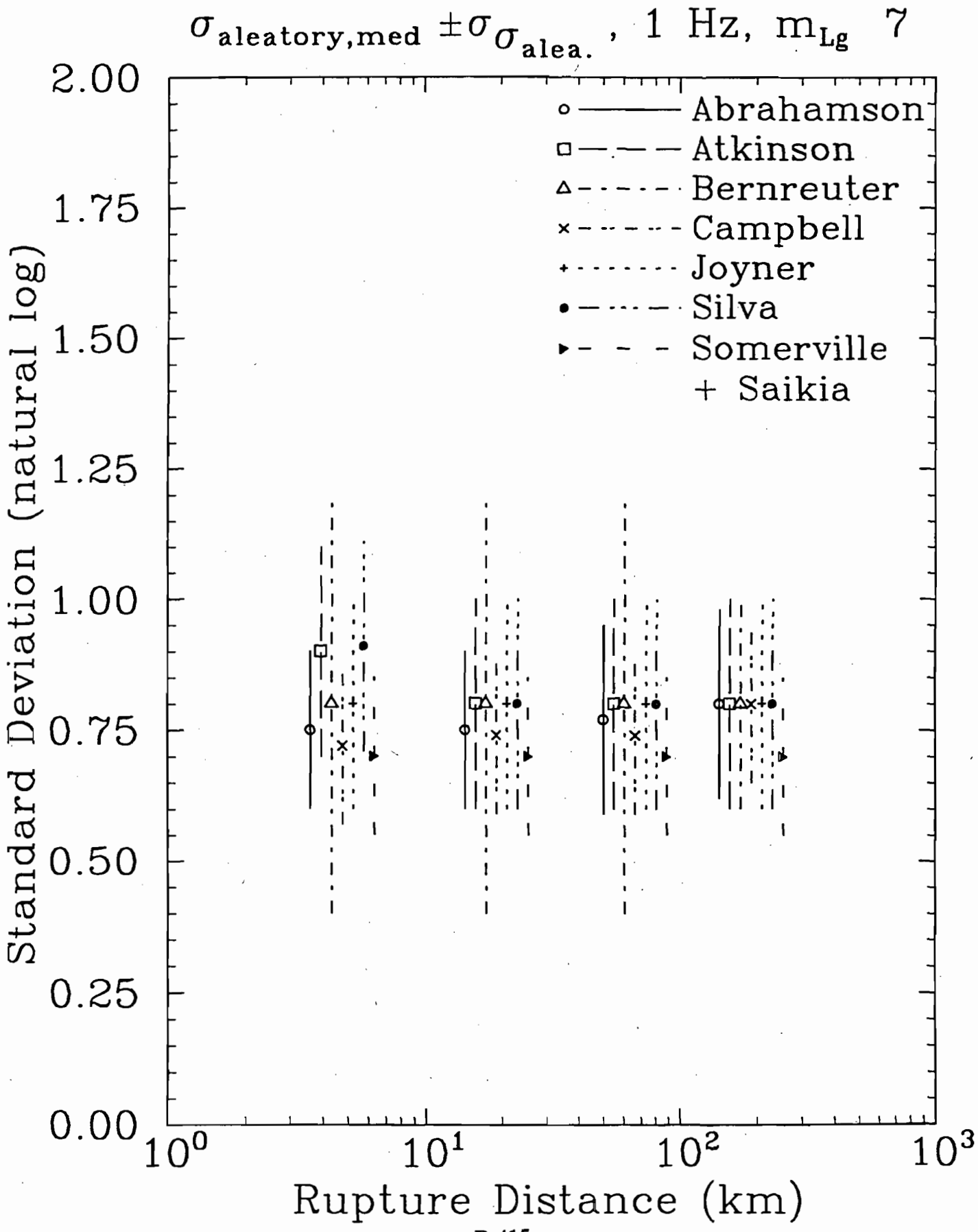
frame 1 $DISK3:[GTOH.9305.WSHOP_2]1_PGA_70.MET;3

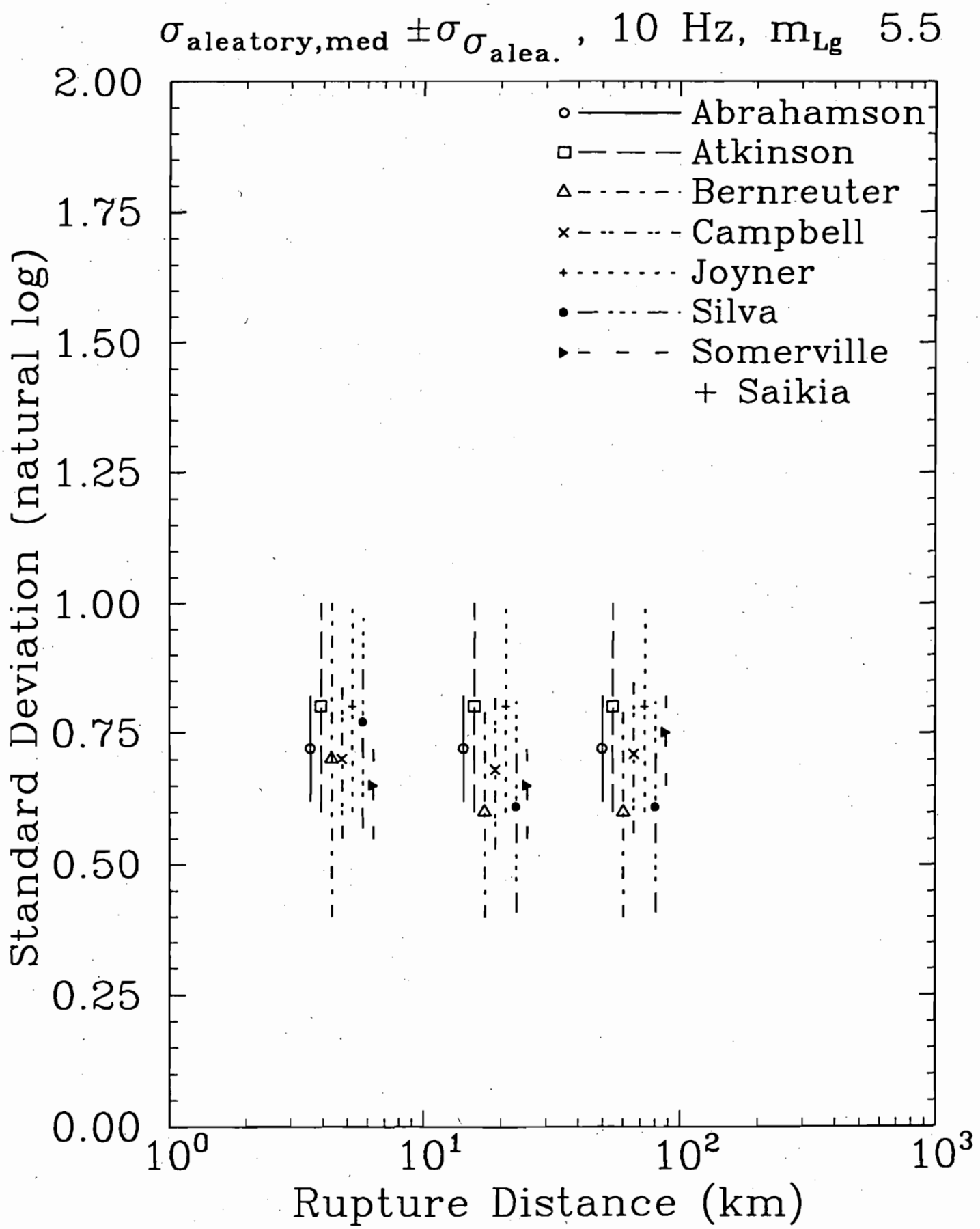


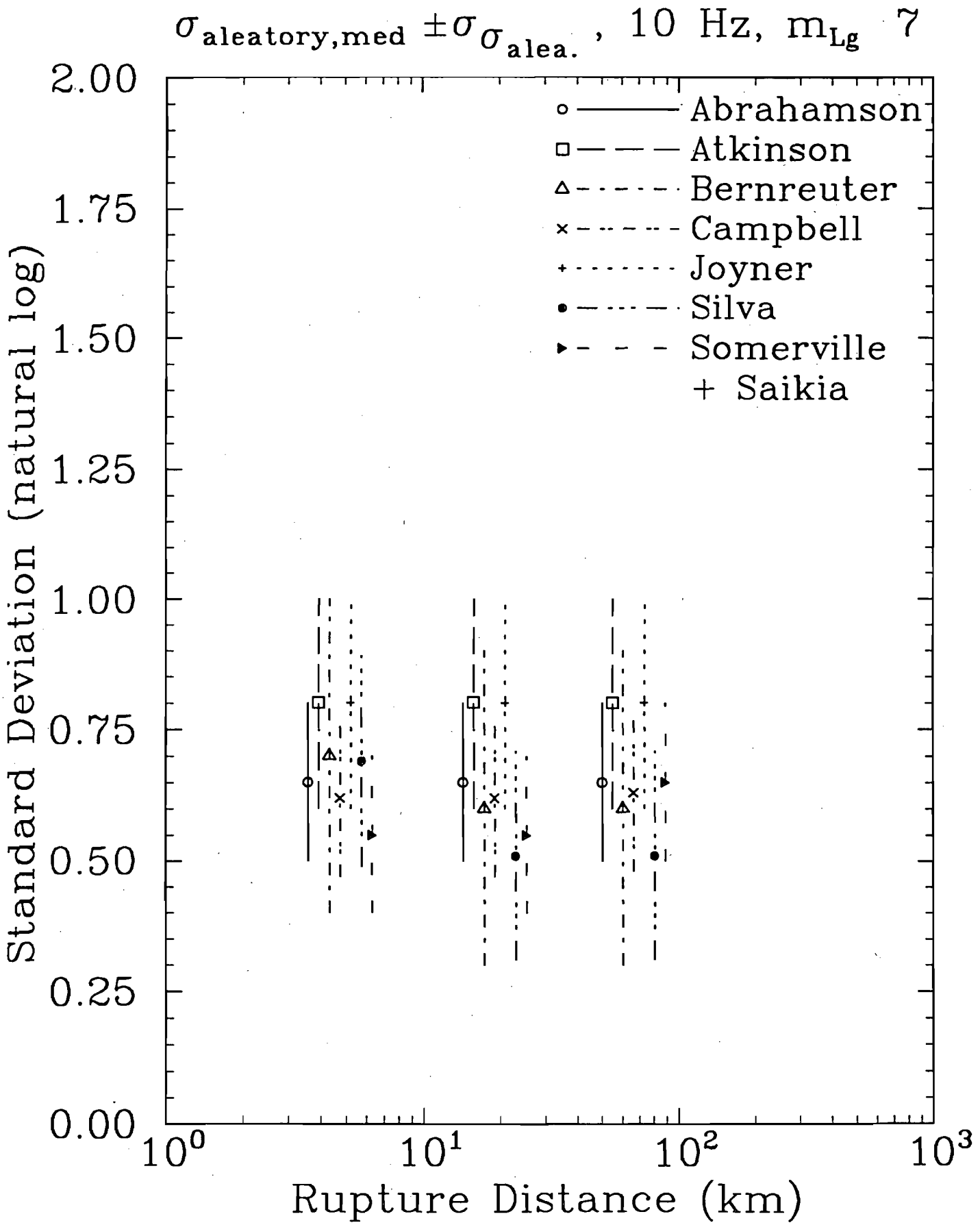

Median ± σepistemic , mLg 5.5, 20 km
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville
+ Saikia
Spectral Acceleration (g)
Frequency (Hz)
10^1
10^0
10^-1
10^-2
10^-1
10^0
10^1
10^2

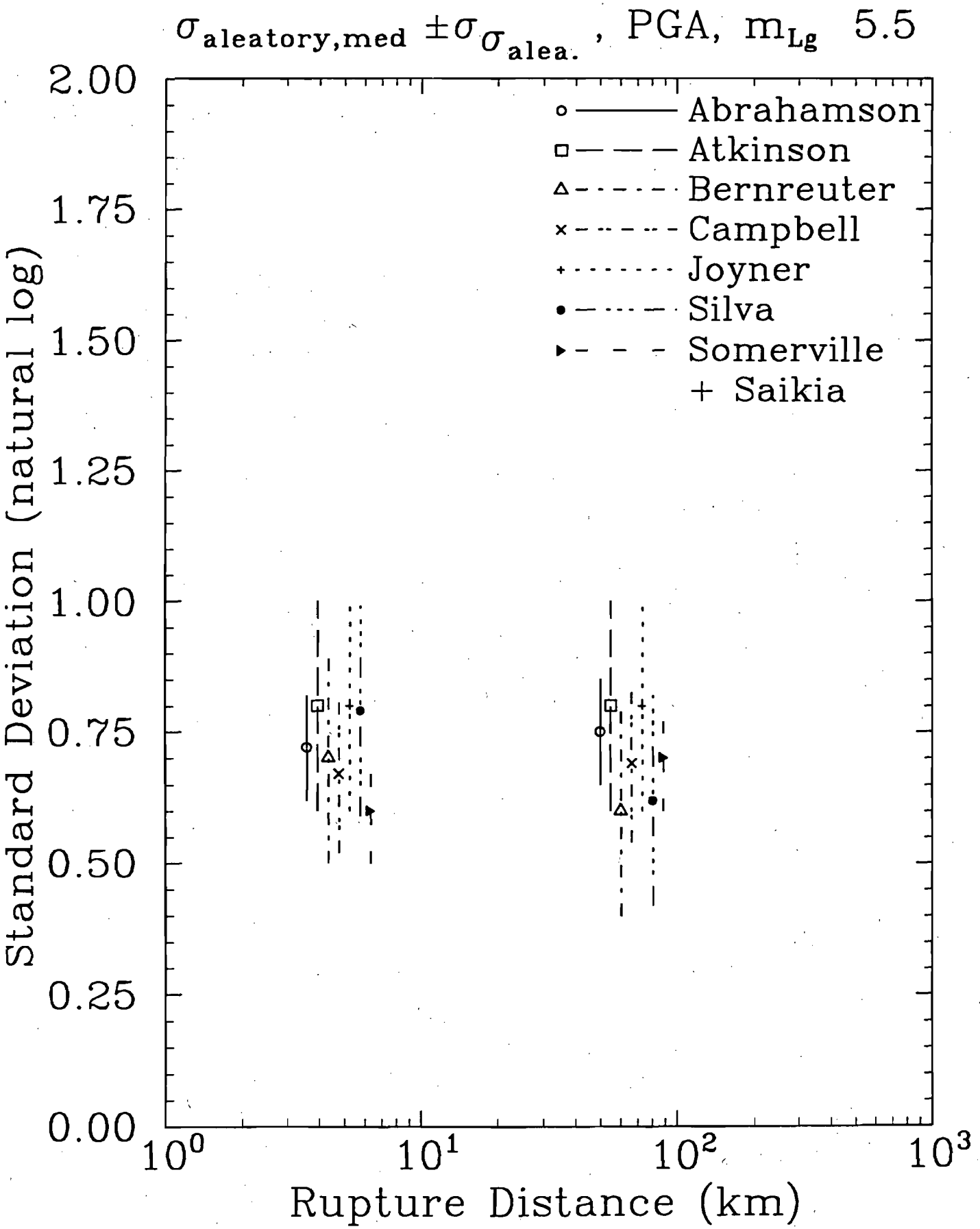

Median ± σepistemic , mLg 7, 20 km
Spectral Acceleration (g)
Frequency (Hz)
10^1
10^0
10^-1
10^-2
10^-1
10^0
10^1
10^2
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville
+ Saikia


$\sigma_{aleatory,med} \pm \sigma_{\sigma_{alea.}}$, 1 Hz, m_{Lg} 5.5
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville + Saikia
Standard Deviation (natural log)
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
10^0
10^1
10^2
10^3
Rupture Distance (km)

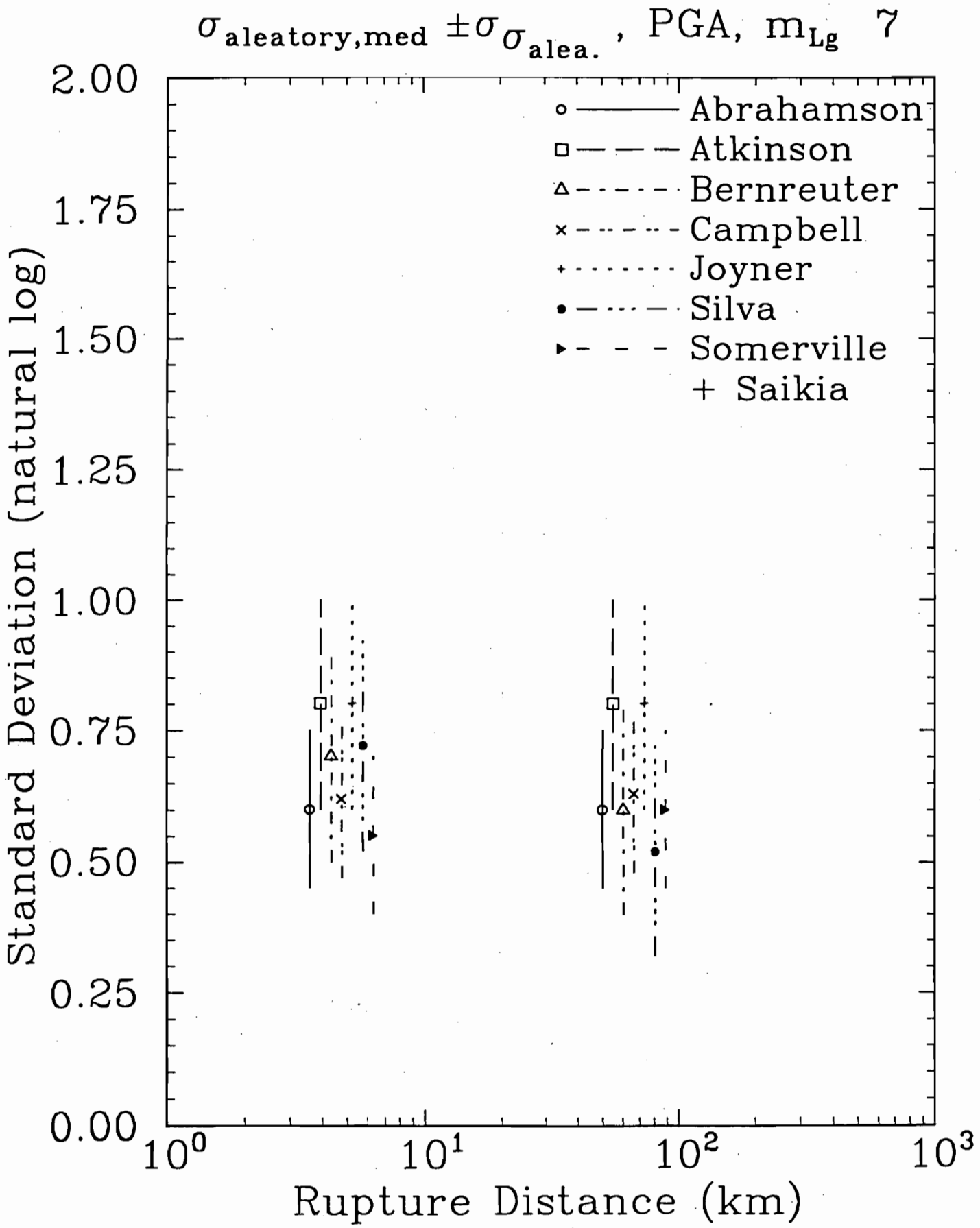

$\sigma_{aleatory,med} \pm \sigma_{\sigma_{alea.}}$, 1 Hz, m_{Lg} 7
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville + Saikia
Standard Deviation (natural log)
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
10^0
10^1
10^2
10^3
Rupture Distance (km)

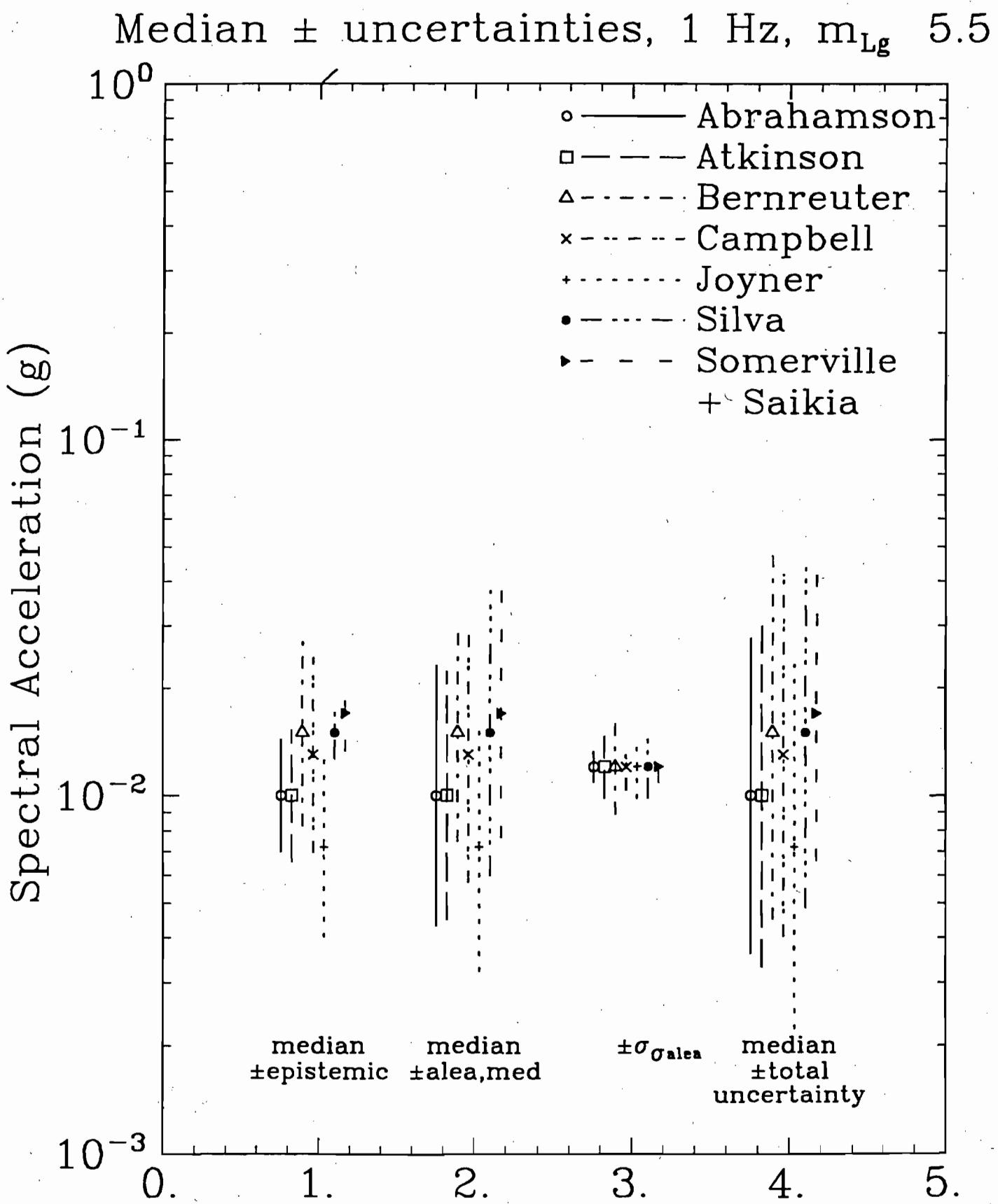

$\sigma_{aleatory,med} \pm \sigma_{\sigma_{alea.}}$, 10 Hz, m_{Lg} 5.5
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville + Saikia
Standard Deviation (natural log)
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
10^0
10^1
10^2
10^3
Rupture Distance (km)

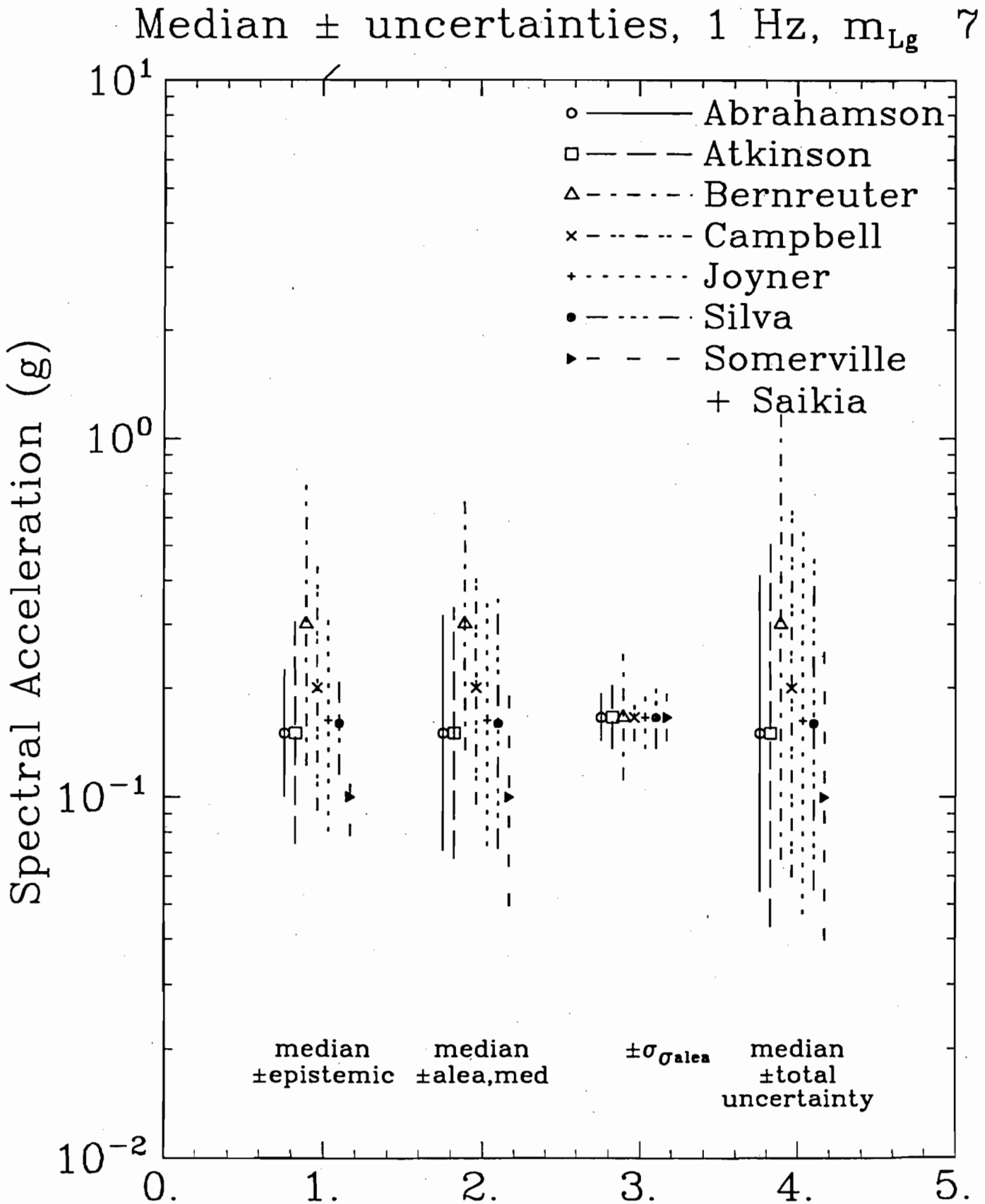

$\sigma_{aleatory,med} \pm \sigma_{\sigma_{alea.}}$, 10 Hz, m_{Lg} 7
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville + Saikia
Standard Deviation (natural log)
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
10^0
10^1
10^2
10^3
Rupture Distance (km)

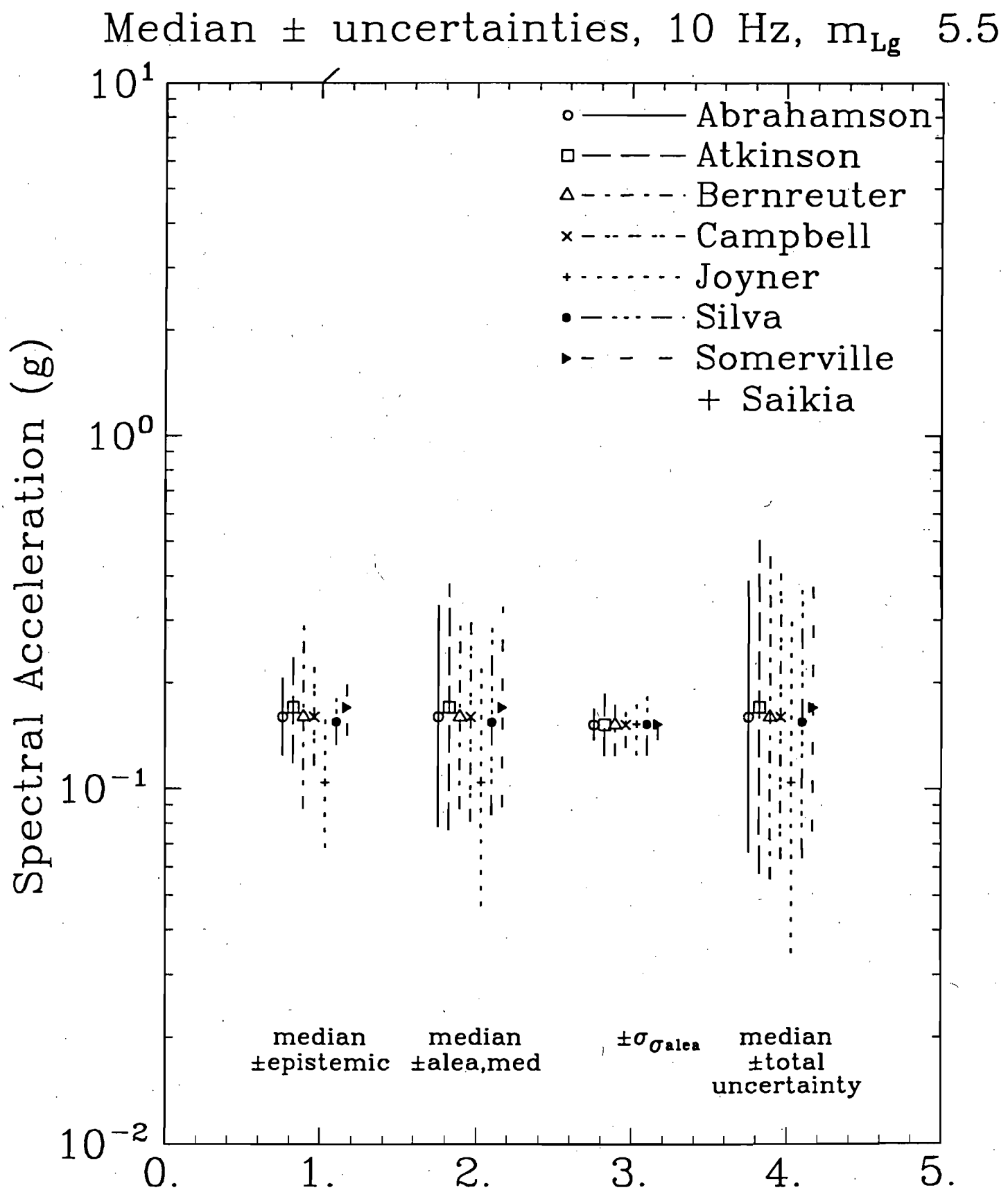

$\sigma_{aleatory,med} \pm \sigma_{\sigma_{alea.}}$, PGA, m_{Lg} 5.5
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville + Saikia
Standard Deviation (natural log)
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
10^0
10^1
10^2
10^3
Rupture Distance (km)

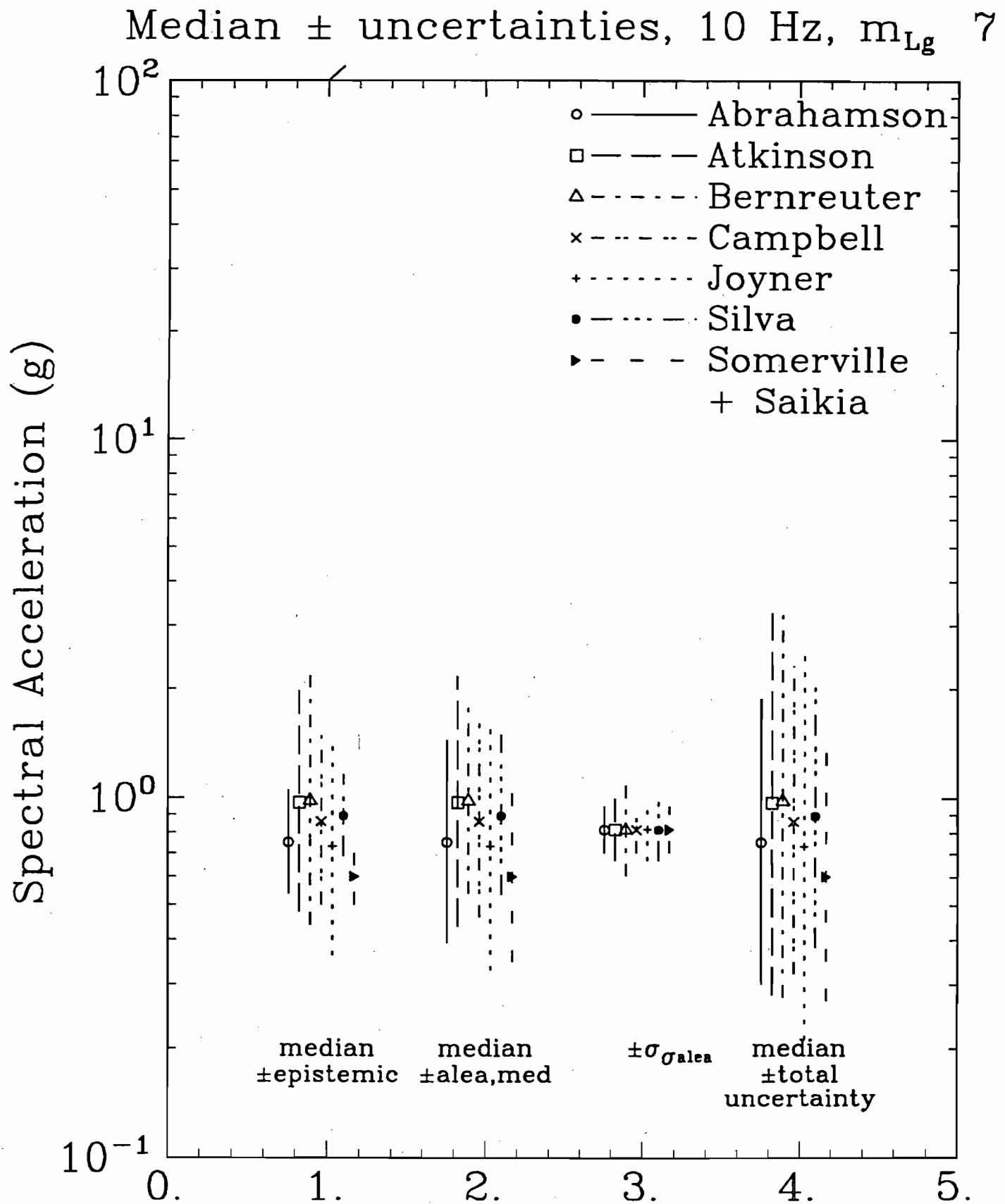
frame 1 $DISK3:[GTOH.9305.WSHOP_2]3_600_70.MET;5

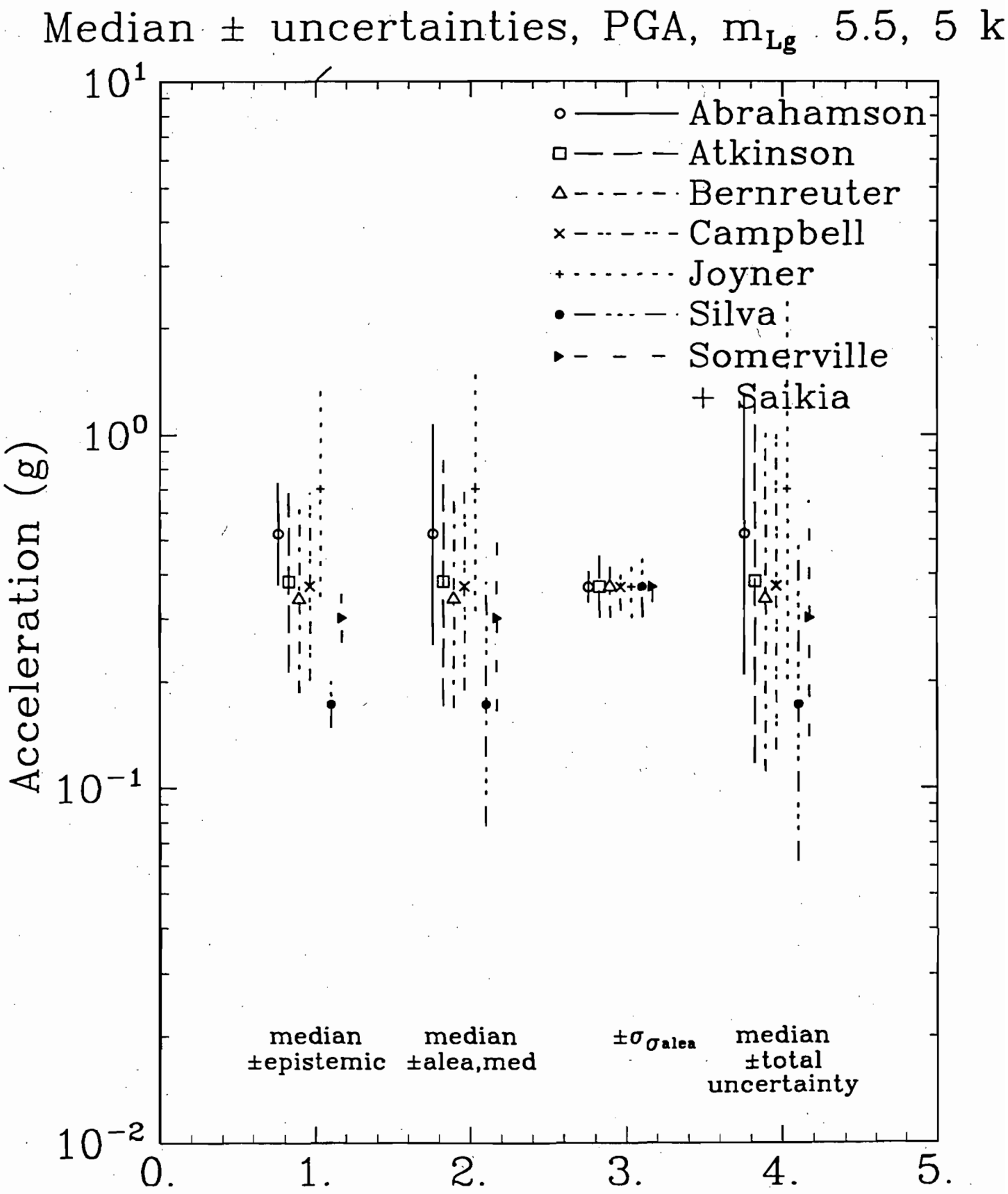


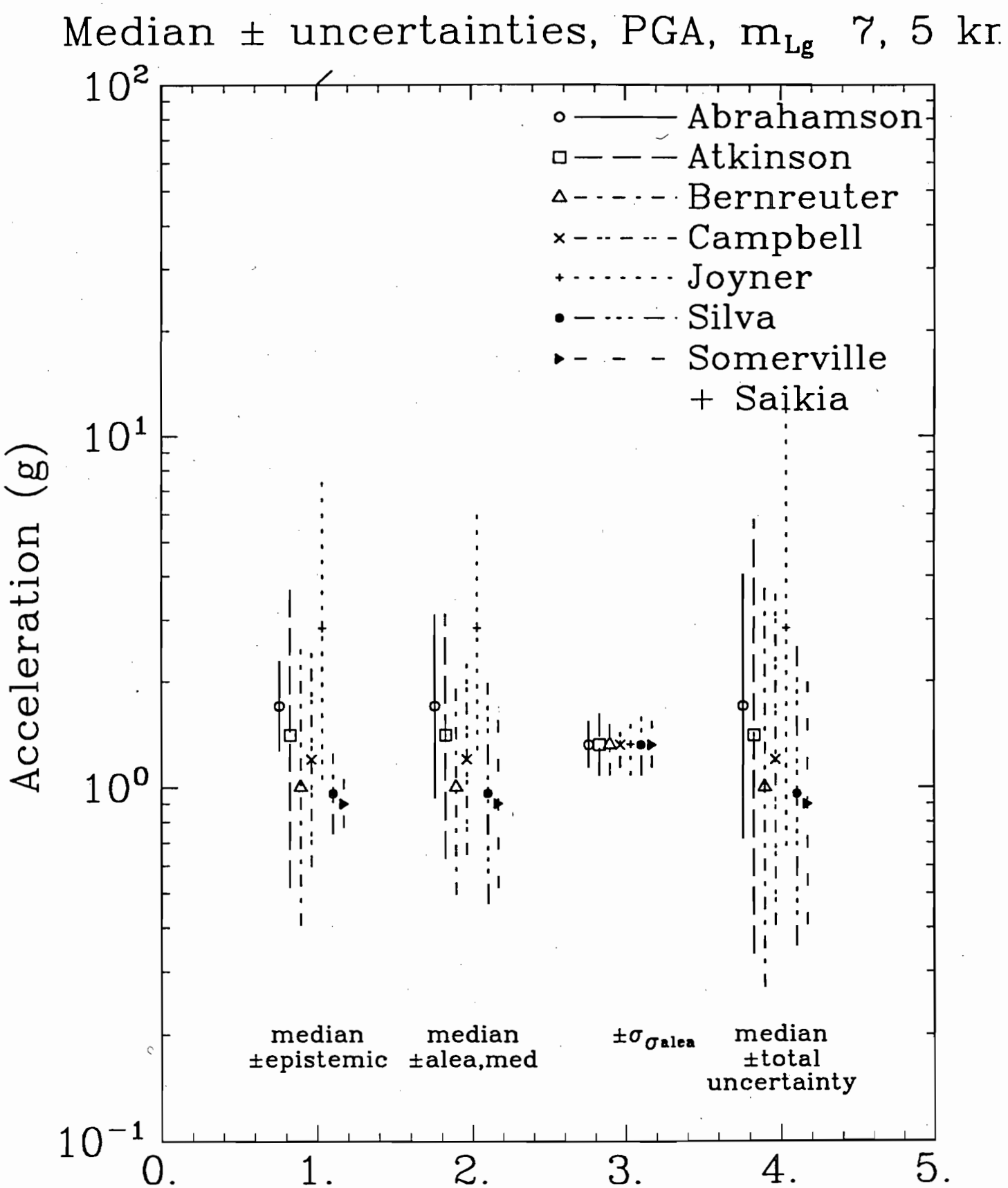

Median ± uncertainties, 1 Hz, m_{Lg} 5.5
Spectral Acceleration (g)
10^0
10^{-1}
10^{-2}
10^{-3}
0.
1.
2.
3.
4.
5.
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville
Saikia
median ±epistemic
median ±alea,med
$\pm\sigma_{\sigma alea}$
median ±total uncertainty


Median ± uncertainties, 1 Hz, m_{Lg} 7
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville
+ Saikia
Spectral Acceleration (g)
10^1
10^0
10^{-1}
10^{-2}
0.
1.
2.
3.
4.
5.
median ±epistemic
median ±alea,med
$\pm\sigma_{\sigma alea}$
median ±total uncertainty


Median ± uncertainties, 10 Hz, m_{Lg} 5.5
Spectral Acceleration (g)
10^1
10^0
10^{-1}
10^{-2}
0.
1.
2.
3.
4.
5.
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville + Saikia
median ±epistemic
median ±alea,med
$\pm\sigma_{\sigma alea}$
median ±total uncertainty


Median ± uncertainties, 10 Hz, m_{Lg} 7
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville + Saikia
Spectral Acceleration (g)
10^2
10^1
10^0
10^{-1}
0.
1.
2.
3.
4.
5.
median ±epistemic
median ±alea,med
$\pm\sigma_{\sigma alea}$
median ±total uncertainty


Median ± uncertainties, PGA, m_{Lg} 5.5, 5 k
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville + Saikia
Acceleration (g)
10^1
10^0
10^{-1}
10^{-2}
0.
1.
2.
3.
4.
5.
median ±epistemic
median ±alea,med
$\pm\sigma_{\sigma alea}$
median ±total uncertainty


Median ± uncertainties, PGA, m_{Lg} 7, 5 kr
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville
+ Saikia
Acceleration (g)
10^2
10^1
10^0
10^{-1}
0.
1.
2.
3.
4.
5.
median ±epistemic
median ±alea,med
$\pm\sigma_{\sigma alea}$
median ±total uncertainty

ATTACHMENT B-4

WORKSHOP-II AGENDA

SSHAC Ground Motion Workshop Number 2

Applied Decision Analysis, Inc.
Menlo Park, California

July 28 -- 29, 1994

First Day

Welcome & Logistics

Introduction

- Agenda
- Goals of workshop

Median Values: Proponent's Results

- Integrator's summary
- Discussion of model issues

Median Values: Expert's Results

- Integrator's summary
- Brief review of procedures by experts
- Discussion of differences

Epistemic Uncertainty in the Median Values: Expert's Results

- Integrator's summary
- Brief review of procedures by experts
- Discussion of differences

Ground Motion Implications of Elicited Information

Homework Assignment

- (including discussion of truncation elicitation)

SSHAC Ground Motion Workshop Number 2

Applied Decision Analysis, Inc.
Menlo Park, California

July 28 -- 29, 1994

Second Day

Discuss Homework

Aleatory Uncertainty: Expert's Results

- Integrator's summary
- Brief review of procedures by experts
- Discussion of differences

Lunch Assignment

- Experts fill out survey
- Integrator's integrate

Review of Integrator's Integration

ATTACHMENT B-5

EXPERTS 2 (CO-WORKSHOP) RESULTS

a. Results B-430
b. Plots of median ± epistemic uncertainty B-451

Expert: Abrahamson

Ground Motion Measure: 1-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			0.30 ↓
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		.0090 ↓	0.15 ×
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude		0.0020 ↓	0.038 ×
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude		.00070 ↓	0.018 ×
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

Line weight on [illegible] & Atkinson for M_{Lg} = 5.5

Expert: Abrahamson

Ground Motion Measure: 2.5-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.040 x	0.36 x
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 3: Page __ of __

Expert: Abrahamson

Ground Motion Measure: 10-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.18 4	0.80 4
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude		0.030 x	.18 x
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:
increase @ 20km

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 4: Page __ of __

Expert: Abrahamson

Ground Motion Measure: 25-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.20	1.0
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

Expert: Abrahamson

Ground Motion Measure: Peak Ground Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude		0.015 ↑	0.10 ↑
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:
increase to account for lower kappa.

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 1: Page 1 of _

Expert: Gail Atkinson July 29 1994

Ground Motion Measure: 1-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
~~5 km~~ d=1	median amplitude		0.02	0.30
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.008	0.12
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude		0.002	0.030
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude		0.0009	0.020
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes: (1) I have not revised epistemic uncertainties but following yesterday's discussion I believe my epistemic uncertainties should be treated as 90% confidence limits rather than ± 1 s.d.

(2) I have moved my median amplitudes back towards my 'proponent' values in light of perceived agreement that data support my results at meeting

Expert: Gail Atkinson July 29

Ground Motion Measure: 2.5-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
~~5 km~~ d=1	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.040	0.34
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

Expert: Gail Atkinson July 29 1994

Ground Motion Measure: 10-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
~~5 km~~ d=1	median amplitude		0.46	2.2
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.17	0.97
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude		0.022	0.17
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 4: Page 4 of __

Expert: Gail Atkinson July 29

Ground Motion Measure: 25-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.23 ~~0.26~~	~~1.3~~ 1.2
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

Expert: Gail Atkinson July 29

Ground Motion Measure: Peak Ground Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
~~5 km~~ d=1	median amplitude		0.30	1.2
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude		0.011	0.09
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 1: Page __ of __

Expert: BERNREUTER

Ground Motion Measure: 1-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.4	0.8
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.4	0.8
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.4	0.8
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes: Might lower median est 1Hz $M_{Lg}=7$ @ 20, 70 and 200 a bit

I lowered my epistemic uncertainties because I think my estimates were more for the 90% or so rather than 85%. I ~~Ess~~ I may still have some aleatory uncertainty mixed in — so they might

Expert: BERNREUTER

Ground Motion Measure: 2.5-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.05	0.43
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.6	0.8
	aleatory uncertainty	median σ	0.7	0.7
		uncertainty in σ	0.3	0.3
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

Expert: _____

Ground Motion Measure: 2.5-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.4	0.6
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

_____

_____

_____

_____

_____

Expert: _____

Ground Motion Measure: 10-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.3	0.6
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.3	0.6
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

Expert: _____

Ground Motion Measure: 25-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.3	0.6
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

Expert: _____

Ground Motion Measure: Peak Ground Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)	0.4	0.6
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 1: Page __ of __

Expert: Somerville / Saikia 7/29/94

Ground Motion Measure: 1-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5 (M_w 5.2)	m_{Lg} 7.0 (M_w 6.7)
5 km	median amplitude		0.05	0.39
	epistemic uncertainty	parametric (ln)	0.3	0.3
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.012	0.13
	epistemic uncertainty	parametric (ln)	0.3	0.3
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude		0.0022	0.039
	epistemic uncertainty	parametric (ln)	0.35	0.35
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude		0.001	0.013
	epistemic uncertainty	parametric (ln)	0.3	0.3
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes: Changes:

1. M_{Lg} 5.5 : Atkinson given .5 weight
2. M_{Lg} 7.0 : now represented by M_w 6.7
3. epistemic parametric uncertainty increased

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 2: Page __ of __

Expert: Somerville / Saikia 7/29/94

Ground Motion Measure: 2.5-Hz Spectral Acceleration (g) M_w 5.2 M_w 6.7

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.05	0.31
	epistemic uncertainty	parametric (ln)	0.2	0.2
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes: Changes:

1. m_{Lg} 5.5 : Atkinson given 0.5 weight
2. m_{Lg} 7.0 : now represented by M_w 6.7
3. parametric epistemic uncertainty increased.

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 3: Page __ of __

Expert: Somerville / Saikia 7/29/94

Ground Motion Measure: 10-Hz Spectral Acceleration (g) M_w 5.2 M_w 6.7

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			1.8
	epistemic uncertainty	parametric (ln)	0.2	0.2
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			0.72
	epistemic uncertainty	parametric (ln)	0.2	0.2
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			0.18
	epistemic uncertainty	parametric (ln)	0.25	0.25
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes: Changes:

1. m_{Lg} 7.0 : now represented by M_w 6.7
2. parametric epistemic uncertainty increased

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 4: Page __ of __

Expert: Somerville / Saikia 7/29/94

Ground Motion Measure: 25-Hz Spectral Acceleration (g) M_w 5.2 M_w 6.7

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			0.9
	epistemic uncertainty	parametric (ln)	0.2	0.2
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes: Changes:

1. M_{Lg} 7.0 now represented by M_w 6.7
2. Parametric epistemic uncertainty increased

SSHAC SECOND
GROUND MOTION WORKSHOP

Form 5: Page __ of __

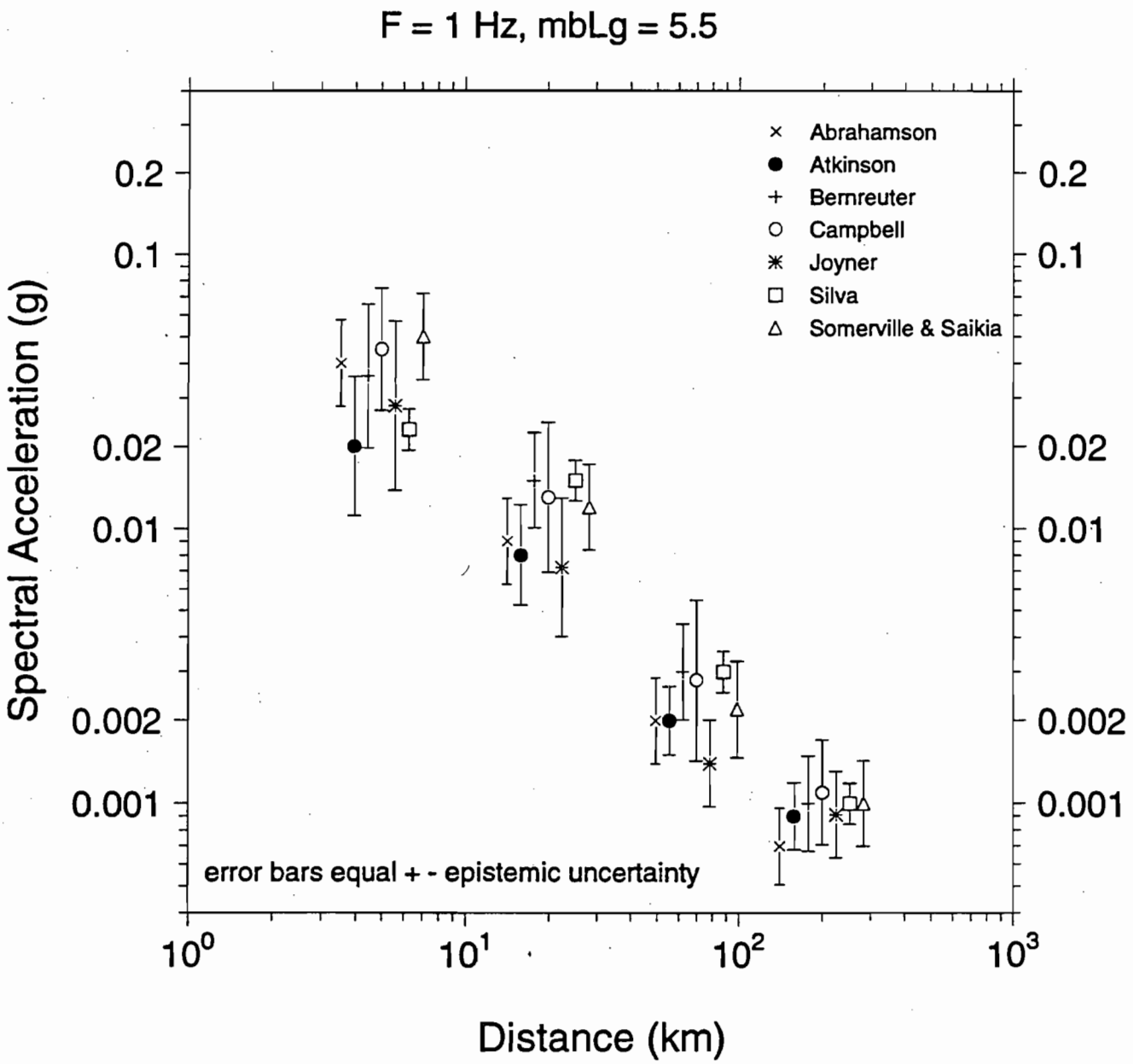
Expert: Somerville / Saikia 7/29/94

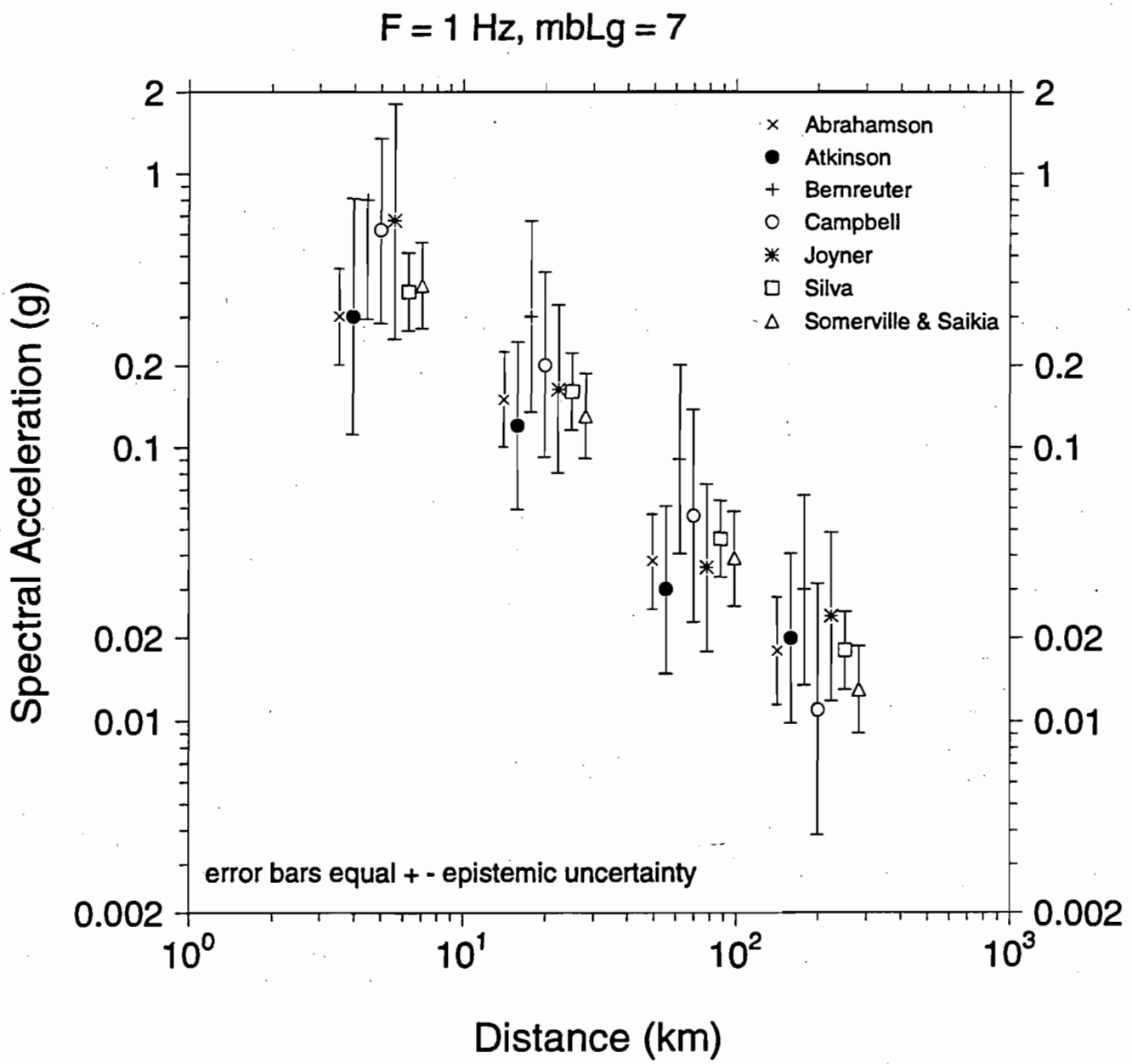
Ground Motion Measure: Peak Ground Acceleration (g)

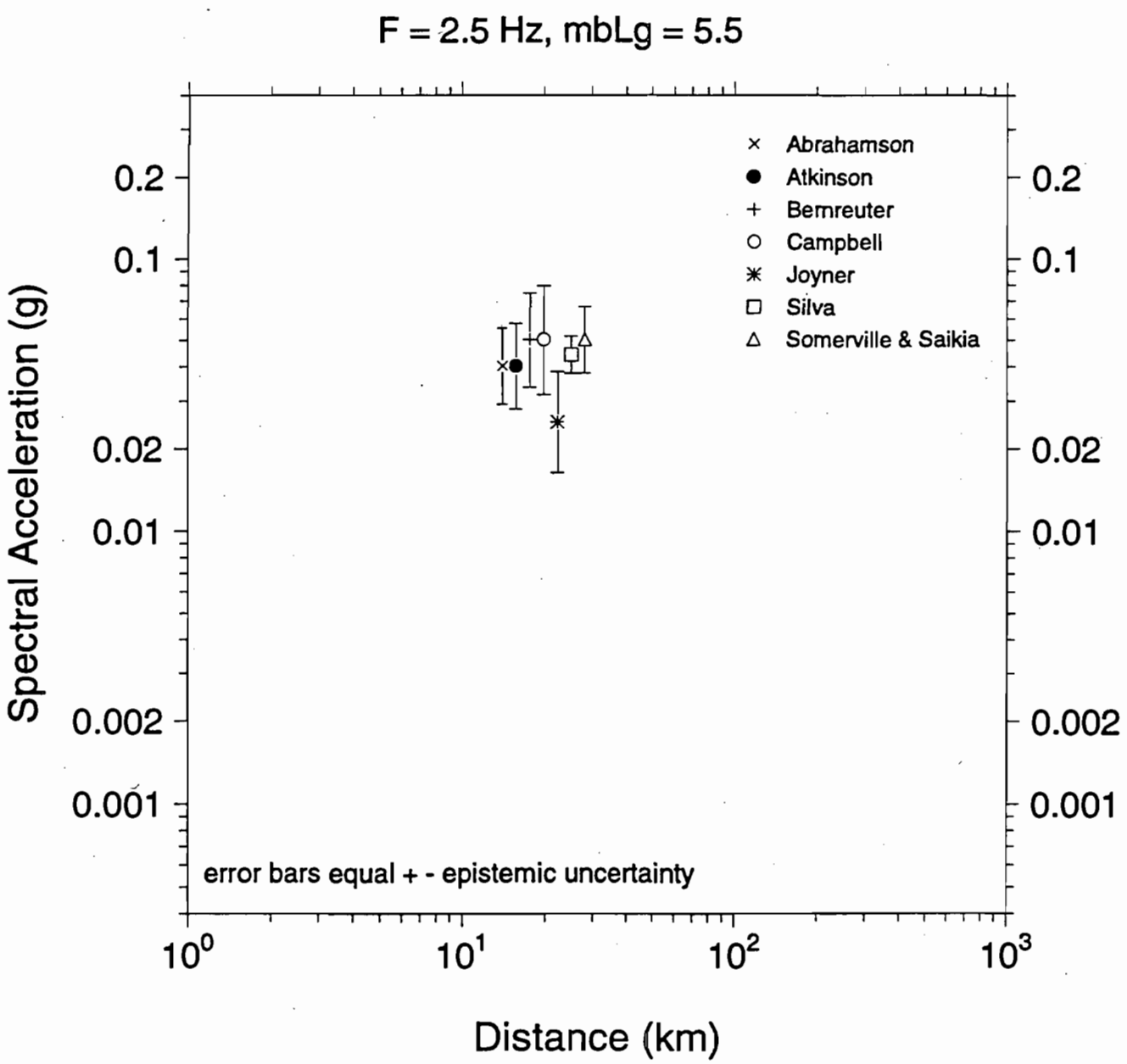
Distance	Quantity		m_{Lg} 5.5 (Mw 5.2)	m_{Lg} 7.0 (Mw 6.7)
5 km	median amplitude			1.1
	epistemic uncertainty	parametric (ln)	0.2	0.2
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			0.11
	epistemic uncertainty	parametric (ln)	0.25	0.25
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

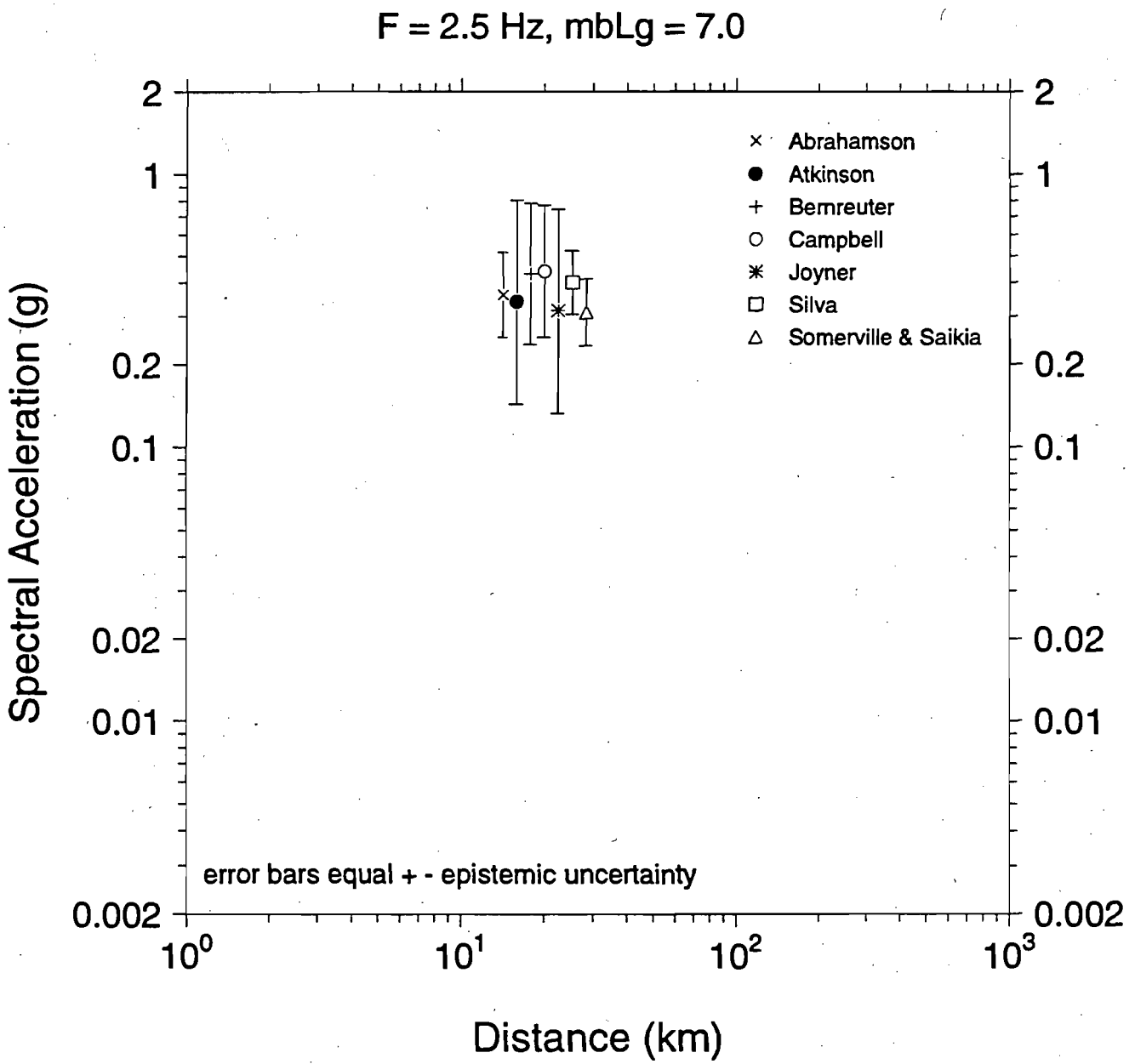
Comments/footnotes: changes

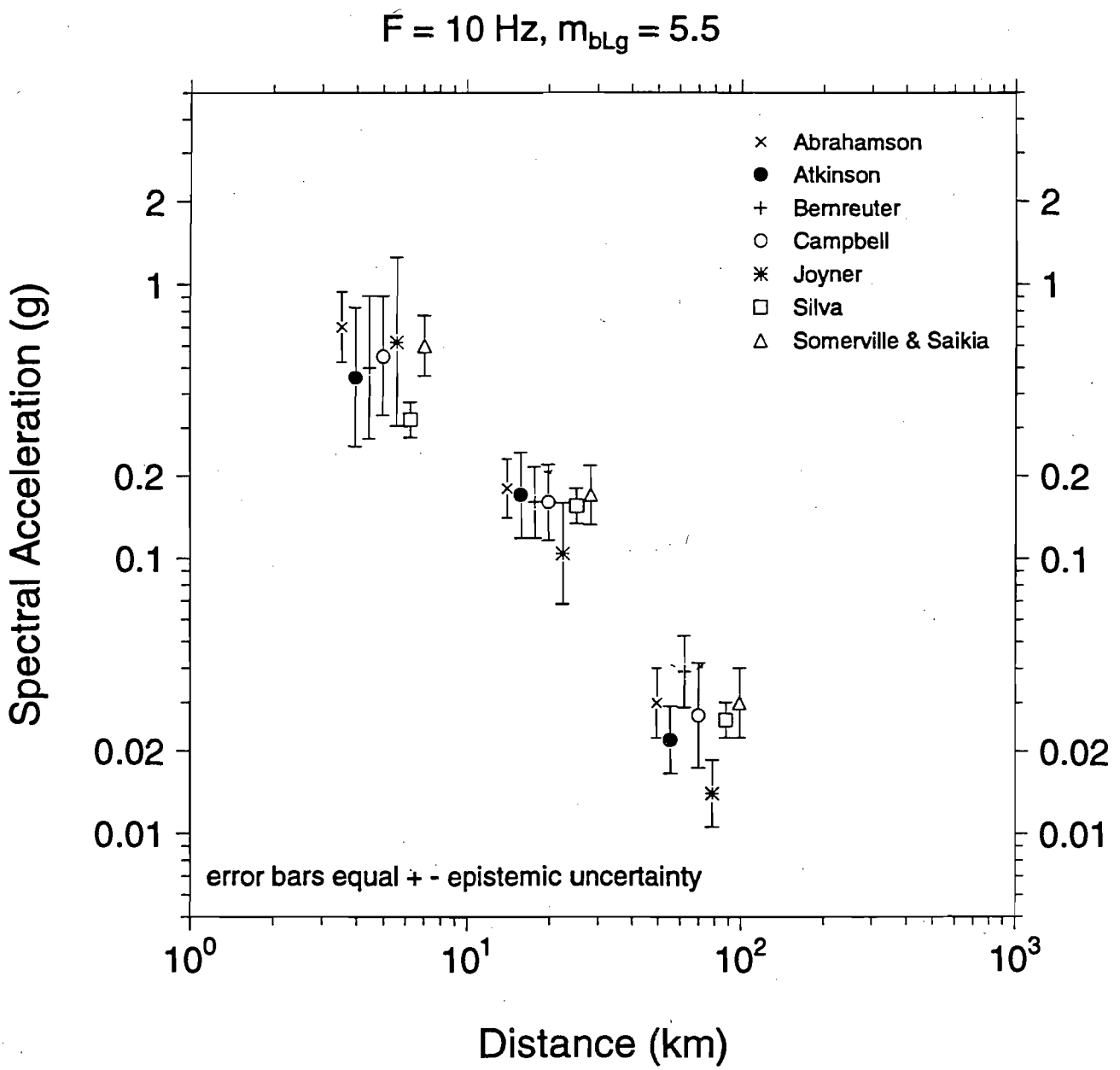
1. m_{Lg} is now represented by Mw 6.7
2. parametric epistemic uncertainty increased.

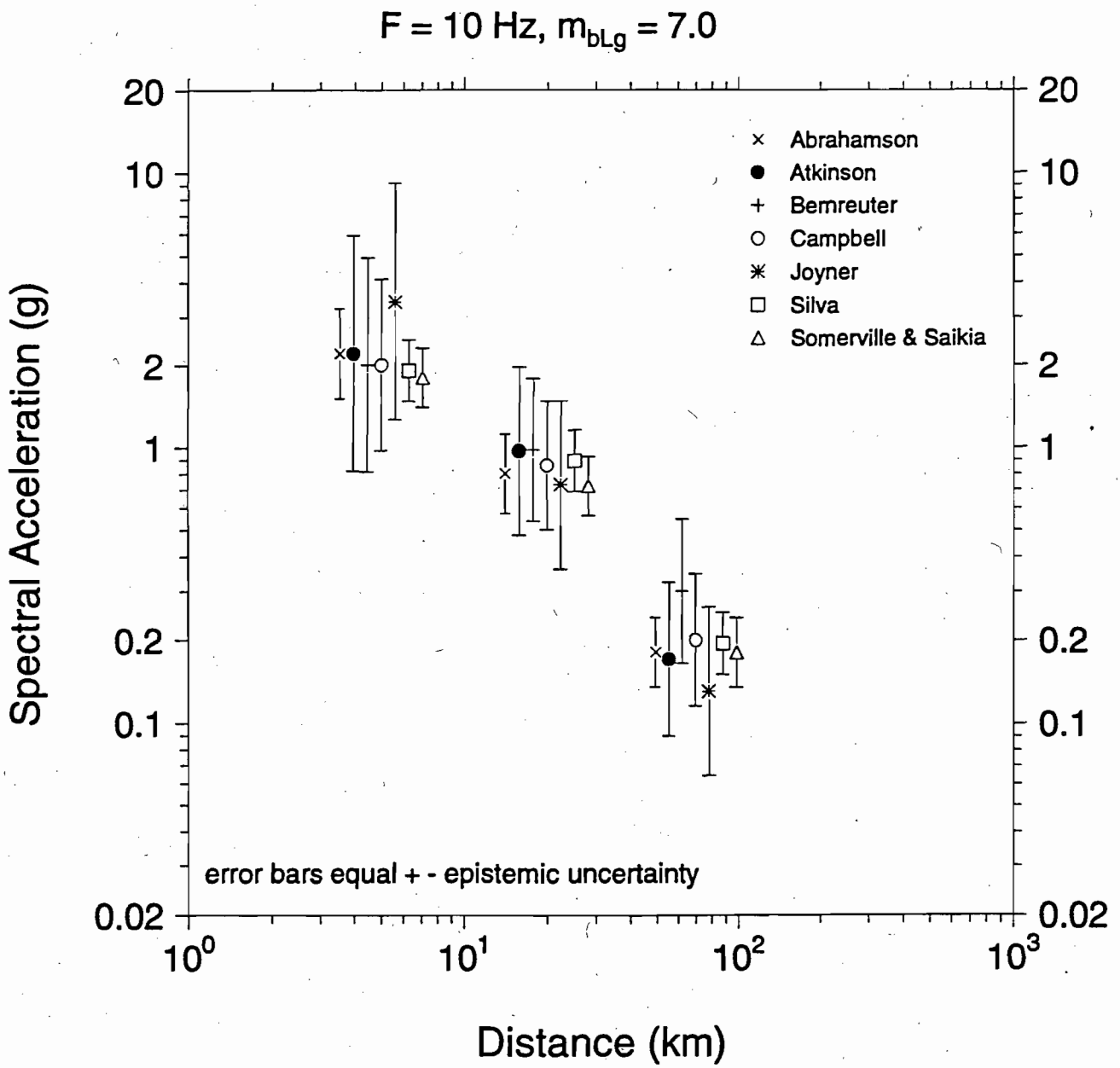

F = 1 Hz, mbLg = 5.5
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
0.2
0.1
0.02
0.01
0.002
0.001
Spectral Acceleration (g)
error bars equal + - epistemic uncertainty
10^0
10^1
10^2
10^3
Distance (km)

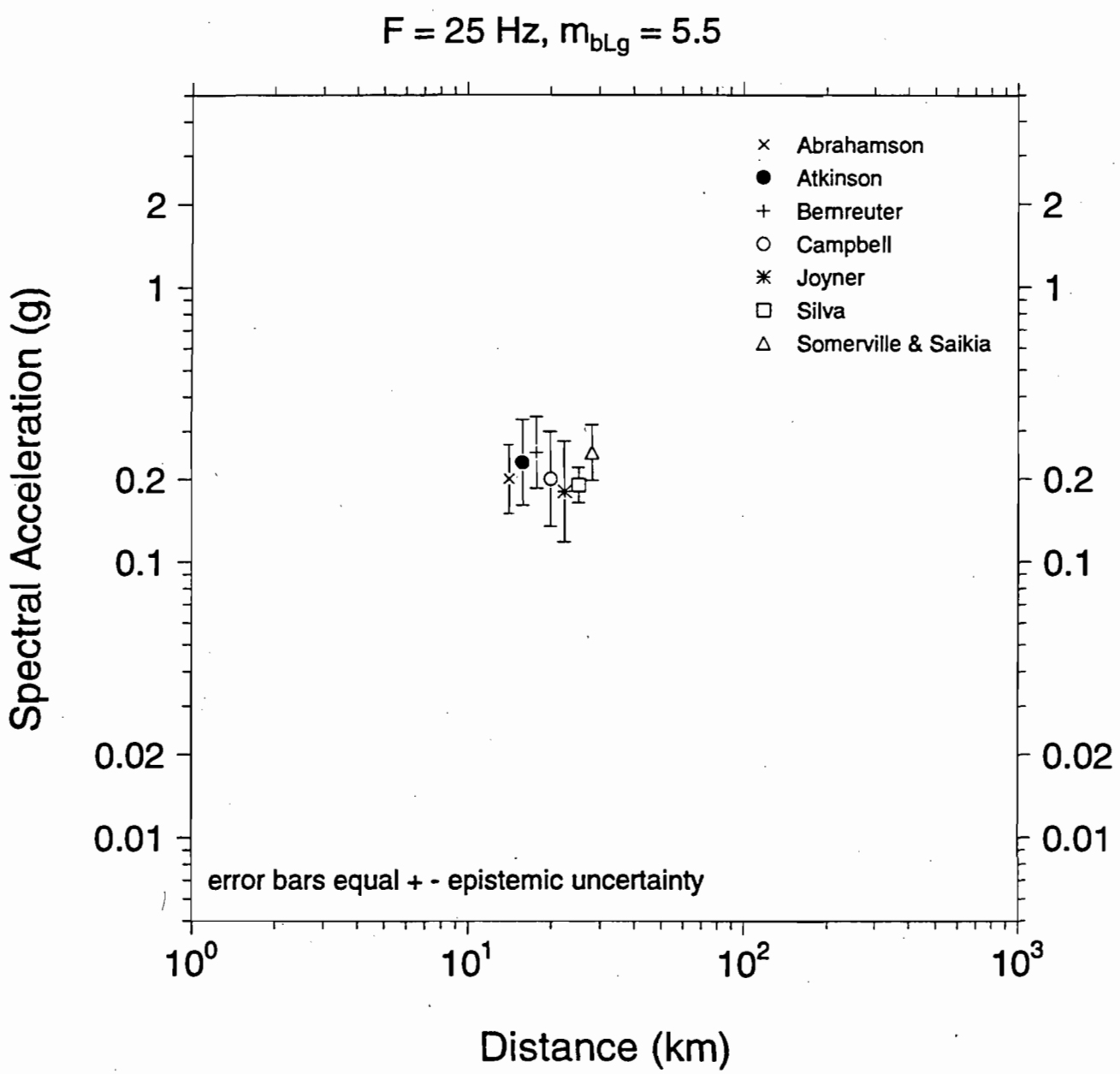

F = 1 Hz, mbLg = 7
Spectral Acceleration (g)
Distance (km)
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty
2
1
0.2
0.1
0.02
0.01
0.002
10^0
10^1
10^2
10^3

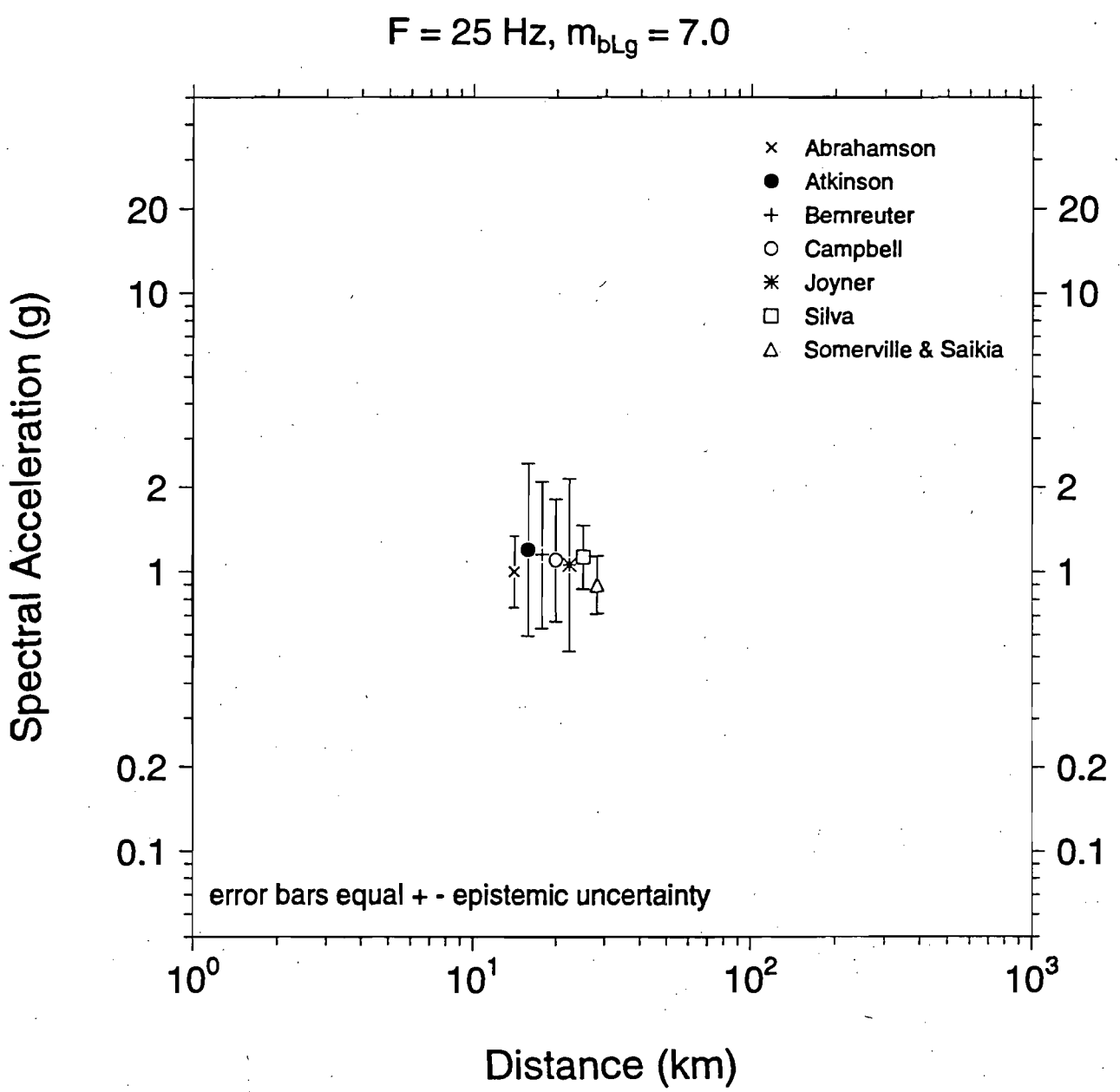

F = 2.5 Hz, mbLg = 5.5
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
Spectral Acceleration (g)
0.2
0.1
0.02
0.01
0.002
0.001
error bars equal + - epistemic uncertainty
10^0
10^1
10^2
10^3
Distance (km)

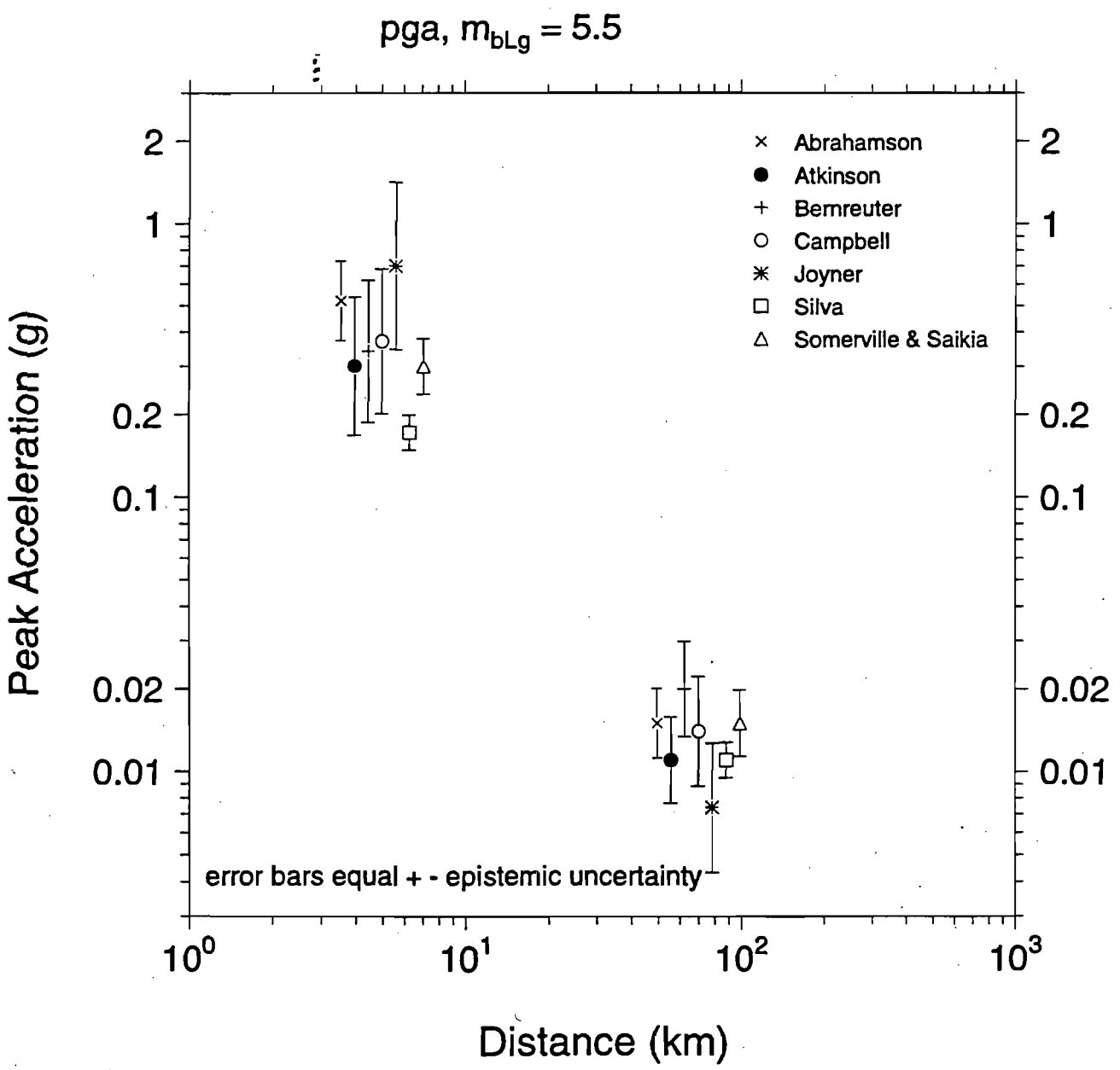

F = 2.5 Hz, mbLg = 7.0
Spectral Acceleration (g)
Distance (km)
2
1
0.2
0.1
0.02
0.01
0.002
10^0
10^1
10^2
10^3
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty

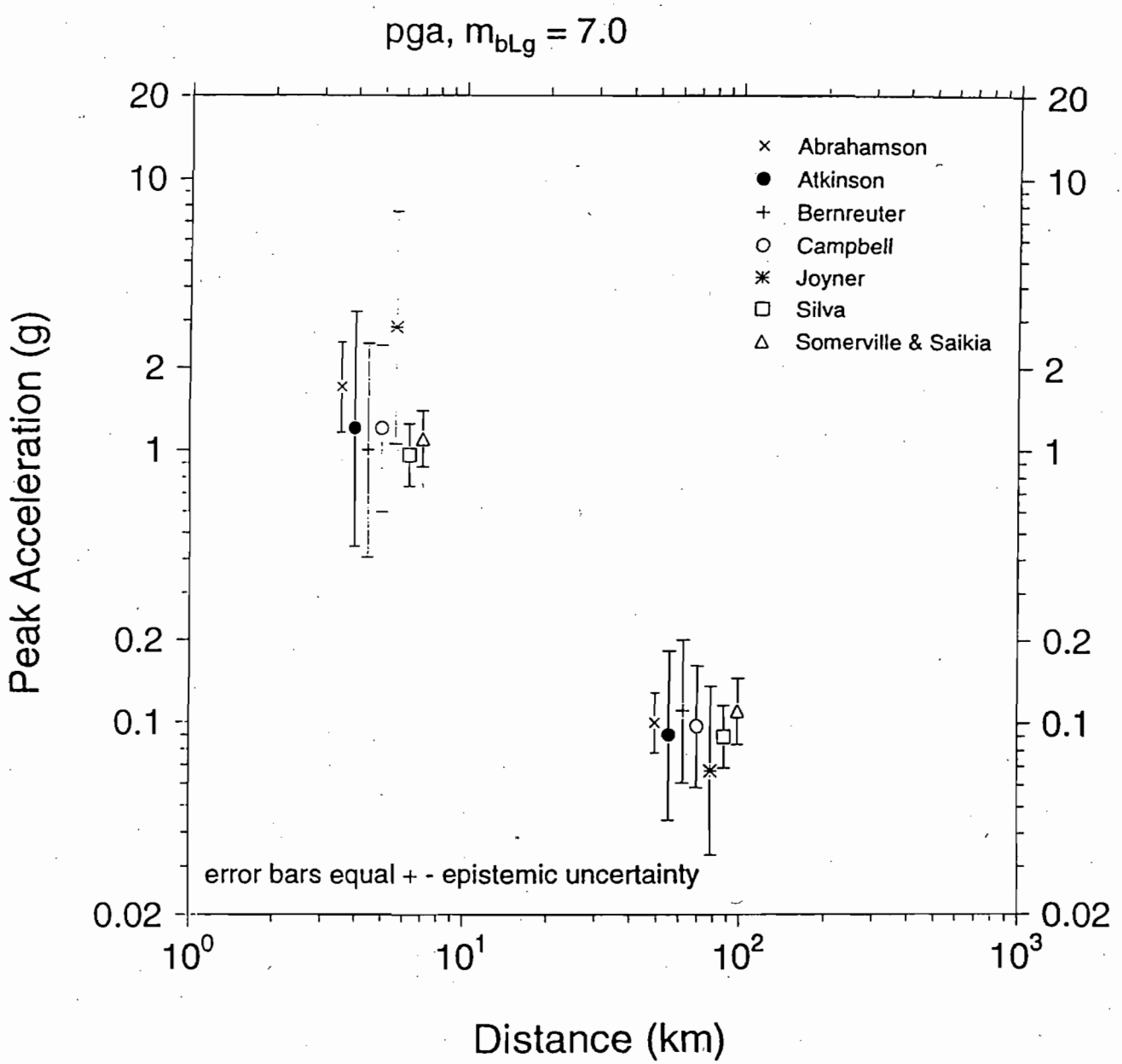

F = 10 Hz, m_{bLg} = 5.5
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty
Spectral Acceleration (g)
2
1
0.2
0.1
0.02
0.01
10^0
10^1
10^2
10^3
Distance (km)


F = 10 Hz, m_{bLg} = 7.0
Spectral Acceleration (g)
Distance (km)
20
10
2
1
0.2
0.1
0.02
10^0
10^1
10^2
10^3
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty


F = 25 Hz, m_{bLg} = 5.5
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
Spectral Acceleration (g)
2
1
0.2
0.1
0.02
0.01
error bars equal + - epistemic uncertainty
10^0
10^1
10^2
10^3
Distance (km)


F = 25 Hz, m_{bLg} = 7.0
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty
Spectral Acceleration (g)
20
10
2
1
0.2
0.1
10^0
10^1
10^2
10^3
Distance (km)


pga, m_{bLg} = 5.5
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty
Peak Acceleration (g)
2
1
0.2
0.1
0.02
0.01
10^0
10^1
10^2
10^3
Distance (km)


pga, m_{bLg} = 7.0
Peak Acceleration (g)
Distance (km)
20
10
2
1
0.2
0.1
0.02
10^0
10^1
10^2
10^3
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty

ATTACHMENT B-6

INTEGRATORS' SURVEY

a. Survey form B-462
b. Experts' written comments B-467
c. Detailed experts' inputs on weighting the forecasts B-472
d. Detailed experts' input on relative forecasting uncertainty B-474

GROUND MOTION WORKSHOP II

INTEGRATORS SURVEY

_____

NAME

'URPOSE OF SURVEY

- GUIDANCE FOR INTEGATORS
- FOR COMPARING APPROACHES, NOT EXPERTS

CONTEXT OF SURVEY

ALL QUESTIONS SHOULD BE ADDRESSED FOR:

- CENTRAL AND EASTERN UNITED STATES ONLY
- HARD ROCK SITE ONLY

RELATIVE ACCURACY OF FORECASTS

ı this exercise, we would like you to judge the ***relative*** ability of each model to produce accurate ground ..ıotion estimates. Relative accuracy will be quantified here as your estimate of the relative forecasting error inherent in each model forecast of median ground motion.

Definition of Forecasting Error: We define forecasting error as the expected standard deviation between the model forecast of median ground motion and the true median ground motion in a large number of applications. Thus, the probability of actual median ground motion falling within the error range should be roughly 68%. The error band should embody ***all reasons*** for forecasting error, including uncertainty in model parameters and model structure.

Relative Forecasting Error: To estimate relative forecasting error, for each application (i.e., each column in the table below) give the model you judge most accurate a rating of 100. Then, estimate the forecasting errors of the other models as percentages of the most accurate (for example, a rating of 150 would indicate an expected error band 50% larger than that of the most accurate model).

RELATIVE EXPECTED FORECASTING ERROR

There should be at least one 100 in each column and each number should be greater than or equal to 100:

Frequency:	1 Hz	1Hz	1Hz	1Hz	2.5Hz	2.5Hz
Magnitude:	m_{Lg} 5.5	m_{Lg} 7.0	m_{Lg} 7.0	m_{Lg} 7.0	m_{Lg} 5.5	m_{Lg} 7.0
Distance:	20 km	5 km	20 km	200 km	20 km	20 km
Stoch. Empirical Atten.	____	____	____	____	____	____
Stoch. Ray Theory Atten.	____	____	____	____	____	____
Hybrid Empirical	____	____	____	____	____	____
Advanced Numerical	____	____	____	____	____	____
Intensity-based	____	____	____	____	____	____

Frequency:	10 Hz	10 Hz	10 Hz	25 Hz	25 Hz
Magnitude:	m_{Lg} 5.5	m_{Lg} 7.0	m_{Lg} 7.0	m_{Lg} 5.5	m_{Lg} 7.0
Distance:	20 km	5 km	20 km	20 km	20 km
Stoch. Empirical Atten.	____	____	____	____	____
Stoch. Ray Theory Atten.	____	____	____	____	____
Hybrid Empirical	____	____	____	____	____
Advanced Numerical	____	____	____	____	____
Intensity-based	____	____	____	____	____

..ıease summarize any key reasons for the judgments (use back of page if necessary):

CORRELATION AMONG MODEL FORECASTS

Rate each pair of models on their similarity using a scale from 0 (least similar) to 100 (most similar) taking into account *both*:

- Similar interpretations, logic and/or variable settings used to develop forecasts
- Overlapping data sets used to develop forecasts

This similarity judgment can be thought of in terms of correlation in forecasting. Suppose some new data or interpretation becomes available that causes Model 1's forecast to change by X units. By how much would you expect Model 2's forecast to change (i.e., by what percentage of X)?

To make the task easier, use the following conventions:

+++	=	extremely similar	(75-100%	forecast correlation)
++	=	highly similar	(50-75%	forecast correlation)
+	=	somewhat similar	(25-50%	forecast correlation)
0	=	not similar	(0-25%	forecast correlation)

	Stochastic Ray Theory Attenuation	Hybrid Empirical Attenuation	Advanced Numerical	Intensity Based
Stochastic Empirical Attenuation	____	____	____	____
Stochastic Ray Theory Attenuation		____	____	____
Hybrid Empirical			____	____
Advanced Numerical				____

Please summarize your reasons for the judgments (use back of page if necessary):

USING THE APPROACHES FOR FORECASTING

Was your final median estimate based on a weighted average of model forecasts?

_____ My final estimate was based on an explicit set of numerical weights
_____ My final estimate was based informally on a set of weights
_____ I did not think about weights in producing my final estimate

Regardless of how you actually formed your final median estimate, please assign a weight (0 to 100) to each approach if you had to weight the results for each specific application. The weights should sum to 100.

Frequency:	1 Hz	1Hz	1Hz	1Hz	2.5Hz	2.5Hz
Magnitude:	m_{Lg} 5.5	m_{Lg} 7.0	m_{Lg} 7.0	m_{Lg} 7.0	m_{Lg} 5.5	m_{Lg} 7.0
Distance:	20 km	5 km	20 km	200 km	20 km	20 km
Stoch. Empirical Atten.	____	____	____	____	____	____
Stoch. Ray Theory Atten.	____	____	____	____	____	____
Hybrid Empirical	____	____	____	____	____	____
Advanced Numerical	____	____	____	____	____	____
Intensity-based	____	____	____	____	____	____
Total	100	100	100	100	100	100

Frequency:	10 Hz	10 Hz	10 Hz	25 Hz	25 Hz
Magnitude:	m_{Lg} 5.5	m_{Lg} 7.0	m_{Lg} 7.0	m_{Lg} 5.5	m_{Lg} 7.0
Distance:	20 km	5 km	20 km	20 km	20 km
Stoch. Empirical Atten.	____	____	____	____	____
Stoch. Ray Theory Atten.	____	____	____	____	____
Hybrid Empirical	____	____	____	____	____
Advanced Numerical	____	____	____	____	____
Intensity-based	____	____	____	____	____
Total	100	100	100	100	100

Please summarize your reasons for the judgments. In particular, please explain if the weights seem inconsistent with your assessments of model accuracies and correlations (use back of page if necessary):

Attachment 2

EXPERTS' WRITTEN COMMENTS

RELATIVE FORECASTING UNCERTAINTY:

Abrahamson:

Key reasons for the judgments:
I don't believe the numerical values of the error bands (epistemic line given by the authors (epistemic line given by authors in parentheses in above [table])
Sigma from Gail scaled by 1.6 to get τ from 90% confidence limits.

Atkinson:

Key reasons for the judgments:
As applied up to today (with modifications)

Bernreuter:

Relative Forecasting Uncertainty — Note: My views have changed somewhat as a result of the meeting, hence my estimates are not totally consistent with my original estimates.

Key reasons for the judgments:
Generically: Very crude relative difference.
As applied: I think the Advanced Numerical Model is the best approach for large earthquakes but I have problems with Paul's M_{eq}-M_w and some other factors of his model. Or at least I'm not sure I understand the sensitivities to elements of his model — e.g., source function rupture velocity, step distribution, etc. For 1 Hz m_{Lg}=7 I liked the hybrid approach because it's data-based. However I see a lot of uncertainty in making the corrections.

I'm not sure yet where I stand relative to Gail's model. Right now I'm giving it equal weight with Walt's application. More generally there is considerable difference between them at both 1 and 10Hz. Thus someday I might give significantly different weights between the two. At 10Hz for 1 Hz m_{Lg}=5.5 I downweight the advanced numerical model a bit due to the complexity of putting a few sources over the small rupture area ... I'm not sure I fully understand all of the elements of Paul's model.

Campbell:

Key reasons for the judgments:
[no comments]

Joyner:

Key reasons for the judgments:
I don't have a basis for a quantitative estimate.

Silva: *Key reasons for the judgments*:
re: pga m_{Lg}5.5 20 km: Not in original request and not enough data (comparisons to answer)
re: pga m_{Lg}7.0 20 km: Bias corrected
Sigma from Gail scaled by 1.6 to get τ from 90% confidence limits.

Somerville/Saikia: *Key reasons for the judgments*:
Note: This will vary for varying distance.

CORRELATION AMONG MODEL FORECASTS:

Abrahamson: *If the numbers would change significantly for different cases, please indicate the cases and how the numbers would change* — less correlation for stochastic empirical and stochastic ray for 1 Hz.

Atkinson: *If the numbers would change significantly for different cases, please indicate the cases and how the numbers would change* — [no comments]

Bernreuter: Generically: Maybe the connections are stronger than I think ... then the correlation is stronger. I would defer to Ken's estimate for correlation.

[Stochastic Empirical Attenuation/Stochastic Ray Theory Attenuation] depends upon source model. E.g., if we assume the Stochastic Empirical always includes Gail's model then only ++ but if they are both Burne Models then +++.

Campbell: *If the numbers would change significantly for different cases, please indicate the cases and how the numbers would change* — [no comments]

Joyner: *If the numbers would change significantly for different cases, please indicate the cases and how the numbers would change* — I would expect all of the models to give highly (?) similar results. My choice of 100% as a weighting factor for Stochastic Empirical does not imply that I think the other models are worthless.

Silva: *If the numbers would change significantly for different cases, please indicate the cases and how the numbers would change* — [no comments]

Somerville/Saikia: *If the numbers would change significantly for different cases, please indicate the cases and how the numbers would change* — [no comments]

USING THE APPROACHES FOR FORECASTING:

Abrahamson: *Please summarize any key reasons for the judgments*:
Re pga weights, I would have to see the predictions before assigning weights.

Atkinson: *Please summarize any key reasons for the judgments*:
I gave the stochastic with empirical inputs half the weight since I think the inputs and results have the best empirical validation, and agree fairly well with independent estimates. I lined up the other 50% based on relative merits and overlaps between them.

Bernreuter: *Please summarize any key reasons for the judgments*:
Generically: Depended upon the case — I also used other models e.g., the LLNL composite model. ..... Because of magnitude translation problem I did not tend to give Advanced Numerical Model much weight at m_{Lg}=7.
As applied: Didn't use formal weights. Composite Gail's gave same result. Balanced Silva off Campbell.

Campbell: *Please summarize any key reasons for the judgments*:
Note: Experts were not asked to give results based on 20 km for PGA. These values are what I would have given, had I been asked.

See my discussion in my write-up for reasons for assigning weights. I have increased the weight of the Advanced Numerical based on Paul's increase of his M_W for m_{Lg} = 7 to 6.7.

Joyner: *Please summarize any key reasons for the judgments*:
My weighting represents my judgment that the first model is clearly superior not that the others are grossly defective. If I were genuinely uncertain as to which was superior and if they gave different results I might depart from 100% weighting.

Silva: *Key reasons for the judgments*:
re: pga m_{Lg}5.5 20 km and pga m_{Lg}7.0 20 km: Not in original request; assumed weights apply

Somerville/Saikia: *Key reasons for the judgments*:
Note: These weights apply after making the following magnitude adjustments:
m_{Lg}5.5: treat as m_W 5.2
M_{Lg}7.0: treat as M_W 6.7

Stochastic with empirical attenuation: high weight for m_{Lg}5.5 due to source model based on data from region and use of an empirical attenuation function.

Both Stochastic models: low weight for m_{Lg}7.0 due to point source (or adjusted point source) model.

Hybrid empirical — relatively large weight for m_{Lg}7.0 due to constraints from WNA data.

Attachment 3

DETAILED EXPERT INPUTS ON WEIGHTING THE FORECASTS

GROUND MOTION WORKSHOP II

INTEGRATOR SURVEY: EXPERT INPUTS

WEIGHTING THE FORECASTS

Freq.	1
Mag.	5.5
Dist.	20

Exp	SE	SR	HE	AN	TOT
NA	33	25	17	25	100
GA	50	20	10	20	100
DB	34	0	33	33	100
KC	25	25	25	25	100
WJ	100	0	0	0	100
WS	30	50	0	20	100
PS	50	10	10	30	100
Avg	**46**	**19**	**14**	**22**	**100**

Freq.	1
Mag.	7.0
Dist.	20

Exp	SE	SR	HE	AN	TOT
NA	35	18	12	35	100
GA	50	10	10	30	100
DB	x	x	x	x	x
KC	28	28	28	16	100
WJ	100	0	0	0	100
WS	30	50	0	20	100
PS	10	10	30	50	100
Avg	**42**	**19**	**13**	**25**	**100**

Freq.	10
Mag.	5.5
Dist.	20

Exp	SE	SR	HE	AN	TOT
NA	31	23	15	31	100
GA	50	20	10	20	100
DB	25	25	25	25	100
KC	25	25	25	25	100
WJ	100	0	0	0	100
WS	30	50	0	20	100
PS	30	20	20	30	100
Avg	**42**	**23**	**14**	**22**	**100**

Freq.	10
Mag.	7.0
Dist.	20

Exp	SE	SR	HE	AN	TOT
NA	25	25	25	25	100
GA	50	20	10	20	100
DB	x	x	x	x	x
KC	28	28	28	16	100
WJ	100	0	0	0	100
WS	30	50	0	20	100
PS	10	10	30	50	100
Avg	**41**	**22**	**16**	**22**	**100**

Freq.	10
Mag.	5.5
Dist.	20

Exp	SE	SR	HE	AN	TOT
NA	31	23	15	31	100
GA	50	20	10	20	100
DB	25	25	25	25	100
KC	25	25	25	25	100
WJ	100	0	0	0	100
WS	30	50	0	20	100
PS	30	20	20	30	100
Avg	**42**	**23**	**14**	**22**	**100**

Freq.	10
Mag.	7.0
Dist.	20

Exp	SE	SR	HE	AN	TOT
NA	25	25	25	25	100
GA	50	20	10	20	100
DB	x	x	x	x	x
KC	28	28	28	16	100
WJ	100	0	0	0	100
WS	30	50	0	20	100
PS	10	10	30	50	100
Avg	**41**	**22**	**16**	**22**	**100**

*Note: Some experts gave weights to other models. For this table, the weights for the four proponent models were renormalized.

Attachment 4

DETAILED EXPERT INPUTS ON RELATIVE FORECASTING UNCERTAINTY

GROUND MOTION WORKSHOP II

INTEGRATOR SURVEY: EXPERT INPUTS

RELATIVE FORECASTING UNCERTAINTY

Freq.		1			
Mag.		5.5			
Dist.		20			
Exp	SE	SR	HE	AN	AVG
NA	100	100	200	100	125
GA	100	130	150	120	125
DB	100	100	200	125	131
KC	100	120	120	130	118
WJ	x	x	x	x	x
WS	100	125	125	150	125
PS	100	125	125	150	125
Avg	100	117	153	129	125

Freq.		1			
Mag.		7.0			
Dist.		20			
Exp	SE	SR	HE	AN	AVG
NA	100	100	100	100	100
GA	110	120	120	100	113
DB	150	150	100	200	150
KC	100	100	100	140	110
WJ	x	x	x	x	x
WS	125	100	125	150	125
PS	125	100	125	150	125
Avg	118	112	112	140	120

Freq.		10			
Mag.		5.5			
Dist.		20			
Exp	SE	SR	HE	AN	AVG
NA	100	100	200	100	125
GA	100	100	180	100	120
DB	100	100	200	110	128
KC	100	110	110	120	110
WJ	x	x	x	x	x
WS	100	125	125	150	125
PS	100	125	125	150	125
Avg	100	110	157	122	122

Freq.		1			
Mag.		5.5			
Dist.		5			
Exp	SE	SR	HE	AN	AVG
NA	100	100	100	100	100
GA	100	100	120	100	105
DB	100	100	200	200	150
KC	100	100	100	120	105
WJ	x	x	x	x	x
WS	125	100	125	150	125
PS	150	150	120	100	130
Avg	113	108	128	128	119

Freq.		1			
Mag.		5.5			
Dist.		70			
Exp	SE	SR	HE	AN	AVG
NA	x	x	x	x	x
GA	100	110	180	130	130
DB	100	100	200	110	128
KC	100	110	110	120	110
WJ	x	x	x	x	x
WS	x	x	x	x	x
PS	120	140	140	100	125
Avg	105	115	158	115	123

Freq.		1			
Mag.		5.5			
Dist.		200			
Exp	SE	SR	HE	AN	AVG
NA	x	x	x	x	x
GA	100	110	120	110	110
DB	100	100	200	200	150
KC	100	100	100	120	105
WJ	x	x	x	x	x
WS	x	x	x	x	x
PS	150	150	120	100	130
Avg	113	115	135	133	124

ATTACHMENT B-7

EXPERTS 3 (POST-WORKSHOP) RESULTS

a. Instructions B-477
b Results B-481
c. Plots of median ± epistemic uncertainty B-497

FOLLOW UP TO SECOND SSHAC GROUND MOTION WORKSHOP

by

Gabriel R. Toro
Risk Engineering, Inc.

As part of the follow-up and documentation effort following the second ground-motion workshop, we are giving you the opportunity to make first-order revisions to your expert's estimates of ground motion amplitude, epistemic uncertainty, and aleatory uncertainty. We are also seeking additional funding from the project sponsors in order to have you address these issues in more detail and provide predictions over a more dense magnitude-distance grid.

We ask you to consider the following issues, which came up at the Workshop of July 28 and 29.

- Distance. You may ignore the estimates for 5 km. Alternatively, you may provide estimates for 5 km horizontal distance, with due consideration for the effect of focal depth on aleatory uncertainty.

- Aleatory Uncertainty. Recall that your estimates of the aleatory uncertainty are to be applicable to hard-rock conditions. It was mentioned at the Workshop that some estimates of aleatory uncertainty (in particular, EPRI, 1993) contain aleatory uncertainty associated with recordings obtained at sites other than rock sites. If this is the case for your estimates, please make first-order, judgmental corrections to your estimates of aleatory uncertainty so that they represent hard-rock conditions.

- Epistemic Uncertainty. The quantity that we wanted to obtain from the experts is the logarithmic standard deviation that quantifies epistemic uncertainty. One way to think of this quantity, under the assumption of a lognormal distribution, is that the probability of the true median falling outside the [estimated median]×exp[$\pm\sigma_{epistemic}$] range is approximately 30%. Some experts stated that their estimates of epistemic uncertainty in the median represent two logarithmic standard deviations (i.e., the expert estimates that the probability of the true median falling outside the [estimated median]×exp[±uncertainty] range is approximately 5%). Please revise your estimates of epistemic uncertainty, if necessary, so that your estimate represents one logarithmic standard deviation.

  If you think another type of distribution (i.e., triangular) is more appropriate or more intuitive for the representation of epistemic uncertainty, you may use that distribution. If so, please provide adequate information to completely specify the distribution (e.g., provide the 5th and 95th fractiles, as well as the most likely value).

  We also noticed that the epistemic-uncertainty provided by an expert did not include the median estimate of some of the other experts (see the graphs enclosed with these instructions). Please consider this when reviewing your epistemic-uncertainty values. In

particular, if one expert's estimate of median amplitude does not fall within your uncertainty range, and you attach some significant credibility to that expert's methods and arguments, you may (or may not) wish to increase your estimates of epistemic uncertainty. If your uncertainty range does not include other experts' median estimates, or is much wider than the scatter among the experts' median estimates, please explain.

The same issues may also apply to your estimates of the uncertainty in the value of the aleatory sigma.

- Data. The issue of what is ENA data was raised during the workshop. Please comment on which ENA data should be used for comparison to your predictions and those of other experts. In particular address issues of: (1) magnitude and distance range to consider, (2) inclusion of vertical data (if so, how to convert to horizontal?), and inclusion of data from soil or soft rock sites (if so, how to convert to hard rock?).

- Documentation: Please describe briefly the rationale for any revisions you make.

Documentation from N. Abrahamson (9/12/94)

Epistemic Uncertainty

I have based my epistemic uncertainties on the range of the medians from the proponent models (excluding Joyner) as well as the empirical data presented in EPRI (1993). One standard deviation is approximated by the range of the proponent medians and empirical data, excluding the largest outlier of the proponent medians. I have excluded the largest outlier because the epistemic uncertainty is a standard deviation and not a bound.

In addition, a minimum value of the epistemic uncertainty is used if the proponent medians all happen to be very similar (lower bound = 0.25). This lower bound is based on the EPRI (1993) epistemic uncertainties rather than the proponent epistemic uncertainties because it is an approximation of the standard error and not a subjective judgment of uncertainty.

With the approach that I have used, there are some cases in which my estimate of the epistemic uncertainty will not cover all of the medians from the different proponents.

Ideally, the epistemic uncertainty should be computed formally using the median and epistemic uncertainty for each proponent model. The expert estimate of the epistemic uncertainty should be the uncertainty of medians of the models, not the uncertainty of a single sample from any of the models. However, we need to account for the correlations between the proponent models.

Data

My comparisons to "data" are based on the EPRI (1993) data set plots. I only considered the horizontal component rock data. I think that the EUS data set is useful for m_{LG} magnitudes 4 to 5.5 and for the distances of 5 to 400 km. The ground motions are not all well constrained over this entire magnitude and distance range, but they do give useful checks against the models.

Since the data set is limited, I think that it is important to check the models using the specific source parameter values (e.g. stress-drop) for the events in the data. The models should not just be checked against the data using comparing the data to the median model predictions for future earthquakes.

I am not in favor of using vertical component data, but since vertical data makes up a large part of the data set, it may be necessary to include it. If verticals are used, the uncertainty of estimating horizontal motion from vertical motion should be included as error bars on the converted data.

The use of data from soil sites can be useful as a guide for some cases, taking into account the expected site effects. For example, at low frequencies, we expect the ground motion on soil to be larger than on rock. If the models significantly overpredict the soil data, then the model will probably overpredict rock data by a larger amount.

Notes:

I assumed an increase in Paul's proponent values for m_{LG}=7.0 to account for his increase of the moment magnitude from 6.4 to 6.7 as discussed at the workshop.

I reduced the aleatory uncertainty to correct for variable site condition. The variable site condition manifests itself in the modeling uncertainty. It may also impact the variability of the stress parameter but I didn't correct for this. I assumed that half of the modeling uncertainty was due to site variability. I then reduced the aleatory standard error appropriately. Since the modeling uncertainty is largest for low frequencies, the largest correction was at 1 Hz.

FOLLOW-UP TO SSHAC SECOND GROUND MOTION WORKSHOP

Form 2: Page __ of __

Expert: N. Abrahamson

Ground Motion Measure: 1-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.009 ✓	0.15 ✓
	epistemic uncertainty	parametric (ln)	0.30 ✓	0.35 ✓
		median bias	0	0
		uncert. in bias (ln)	0.26	0.30 ✓
	aleatory uncertainty	median σ	0.75 ✓	0.65 ✓
		uncertainty in σ	0.10 ✓	0.15 ✓
70 km	median amplitude		0.0020	0.038
	epistemic uncertainty	parametric (ln)	0.30 ✓	0.35
		median bias	0	0
		uncert. in bias (ln)	0.44 ✓	0.54
	aleatory uncertainty	median σ	0.75 ✓	0.65
		uncertainty in σ	0.10 ✓	0.15
200 km	median amplitude		0.00070	0.018 ✓
	epistemic uncertainty	parametric (ln)	0.25 ✓	0.40 ✓
		median bias	0	0 ✓
		uncert. in bias (ln)	0.25 ✓	0.40 ✓
	aleatory uncertainty	median σ	0.75 ✓	0.70 ✓
		uncertainty in σ	0.10 ✓	0.18 ✓

Comments/footnotes:

FOLLOW-UP TO SSHAC SECOND GROUND MOTION WORKSHOP

Form 2: Page __ of __

Expert: N. Abrahamson

Ground Motion Measure: 2.5-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.040 ✓	0.36 ✓
	epistemic uncertainty	parametric (ln)	0.25 ✓	0.30 ✓
		median bias	0 ✓	0 ✓
		uncert. in bias (ln)	0.20 ✓	0.25 ✓
	aleatory uncertainty	median σ	0.70 ✓	0.60 ✓
		uncertainty in σ	0.10 ✓	0.15 ✓
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

FOLLOW-UP TO SSHAC SECOND GROUND MOTION WORKSHOP

Form 3: Page __ of __

Expert: N. Abrahamson

Ground Motion Measure: 10-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.18 ✓	0.80 ✓
	epistemic uncertainty	parametric (ln)	.20 ✓	0.25 ✓
		median bias	0 ✓	0 ✓
		uncert. in bias (ln)	.15 ✓	.16 ✓
	aleatory uncertainty	median σ	0.70 ✓	0.62 ✓
		uncertainty in σ	0.10 ✓	0.15 ✓
70 km	median amplitude		0.030 ✓	0.18 ✓
	epistemic uncertainty	parametric (ln)	0.25 ✓	0.25 ✓
		median bias	0 ✓	0 ✓
		uncert. in bias (ln)	0.16 ✓	0.20 ✓
	aleatory uncertainty	median σ	0.70 ✓	0.62 ✓
		uncertainty in σ	0.10 ✓	0.15
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

FOLLOW-UP TO SSHAC SECOND GROUND MOTION WORKSHOP

Form 4: Page __ of __

Expert: N. Abrahamson

Ground Motion Measure: 25-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude		0.20 ✓	1.0 ✓
	epistemic uncertainty	parametric (ln)	0.25 ✓	0.25 ✓
		median bias	0 ✓	0 ✓
		uncert. in bias (ln)	0.15 ✓	0.15 ✓
	aleatory uncertainty	median σ	0.70 ✓	0.57 ✓
		uncertainty in σ	0.10 ✓	0.15 ✓
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

Follow-up to SSHAC SECOND GROUND MOTION WORKSHOP

Form 5: Page __ of __

Expert: N. Abrahamson

Ground Motion Measure: Peak Ground Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude		0.015 ✓	0.10 ✓
	epistemic uncertainty	parametric (ln)	0.25 ✓	0.20 ✓
		median bias	0 ✓	0 ✓
		uncert. in bias (ln)	0.24 ✓	0.15 ✓
	aleatory uncertainty	median σ	0.75 ✓	0.60 ✓
		uncertainty in σ	0.10 ✓	0.15 ✓
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

FOLLOW-UP TO SSHAC SECOND GROUND MOTION WORKSHOP

Expert: Gail Atkinson Aug 20 1994

Ground Motion Measure: 2.5-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		0.4 ✓
		median bias		
		uncert. in bias (ln)		0.5 ✓
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes: These pages show revisions to uncertainty (no entry = no revision).

DATA: Data for comparisons should include all ENA mainshock records on hard-rock, M≥4. Soil included only if soil response can be reliably estimated. Vert. should be included due to abundance of these data. See Atkinson 1995 for H/V conversion for ECAS.

All distances R≲1000 km can be included since atten. is well-determined both empirically + theoretically.

FOLLOW-UP TO SSHAC SECOND GROUND MOTION WORKSHOP

Expert: Gail Atkinson

Ground Motion Measure: 10-Hz Spectral Acceleration (g)

Distance	Quantity		m_{L_g} 5.5	m_{L_g} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		0.5 ✓
		median bias		
		uncert. in bias (ln)		0.5 ✓
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		0.4 ✓
		median bias		
		uncert. in bias (ln)		0.4 ✓
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		0.4 ✓
		median bias		
		uncert. in bias (ln)		0.4 ✓
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

FOLLOW-UP TO SSHAC SECOND GROUND MOTION WORKSHOP

Expert: Gail Atkinson

***Ground Motion Measure:* 25-Hz Spectral Acceleration (g)**

Distance	Quantity		m_{L_g} 5.5	m_{L_g} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		0.4
		median bias		
		uncert. in bias (ln)		0.4
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

Follow-up to SSHAC SECOND GROUND MOTION WORKSHOP

Expert: Gail Atkinson

Ground Motion Measure: Peak Ground Acceleration (g)

Distance	Quantity		m_{L_g} 5.5	m_{L_g} 7.0
5 km	median amplitude			
	epistemic uncertainty	parametric (ln)		0.5 ✓
		median bias		
		uncert. in bias (ln)		0.5 ✓
	aleatory uncertainty	median σ		
		uncertainty in σ		
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		0.4 ✓
		median bias		
		uncert. in bias (ln)		0.4 ✓
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

EQE
ENGINEERING AND DESIGN

A Division of EQE International

MEMORANDUM

To: Gab Toro
Risk Engineering, Inc.

From: Ken Campbell Ken
EQE International, Inc.

Date: August 27, 1994

Subject: ***Follow-up to Second SSHAC Ground Motion Workshop***

Ideally, I would like to make some changes to both my proponent and expert ground-motion estimates. However, due to my current work load, I am unable to make these changes by your August 31 deadline. I would not, however, expect these anticipated revisions to give significantly different results than those I have already given to you.

The additional effort would account for a revision in my proponent model, a revision in the other proponent models, and a corresponding change in the weights and estimates provided in my expert model. These modifications will have to wait for the additional SSHAC funds, should they be approved.

6555 Olympus Drive ▪ Evergreen, CO 80439 ▪ Telephone/FAX (303) 674-2990

REVISIONS TO GROUND-MOTION ESTIMATES FOR THE NORTHEASTERN U.S. OR SOUTHEASTERN CANADA

W. B. Joyner
August 17, 1994

The ground-motion estimates for 5 km were revised to correspond to 5 km horizontal distance. In my view point-source stochastic models can provide good ground-motion estimates for small horizontal distances if the proper pseudo-depth is used. The pseudo-depth is region-dependent and should scale as the depth distribution of slip in an earthquake. The parameter h of Joyner and Boore (1982) is such a pseudo-depth, and it is largely controlled by data from the 1979 Imperial Valley, California earthquake. For periods of 1 s and longer h has a value about half the depth of the maximum strike-slip offsets in Archuleta's (1984) model of the 1979 earthquake. The small value of pseudo-depth can be explained (Boore and Joyner, 1989) as a consequence of the preferentially greater effect of directivity at sites near the source. For peak acceleration and for response spectra at periods shorter than 0.4 s the values of h are greater, suggesting reduced effects of directivity at shorter periods. The work of Boatwright and Boore (1982), however, has shown that, for some earthquakes at least, there is a large directivity effect at short periods. So, I assume for Eastern North America that the proper pseudo-depth is half the depth of maximum slip. The depth of maximum slip is assumed to be the median hypocentral depth. From the hypocentral data given by EPRI (1993) the pseudo-depth is found to be 7 km with 16 and 84th percentile values of 4 and 13 km. The ground-motion estimates for 5 km horizontal distance were revised using the 7 km pseudo-depth, and the aleatory uncertainty was recomputed to reflect the uncertainty in that parameter. With the 7 km value for pseudo-depth, the estimates previously made for 20, 70, and 200 km correspond to horizontal distances of 18.7, 69.6, and 199.9 km.

I reviewed Gail Atkinson's estimates (as proponent) for aleatory sigma and the uncertainty of aleatory sigma, which I had adopted previously for lack of time to make my own estimates, and agreed with them. I do not have time to make an estimate of epistemic uncertainty.

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EPRI (1993).Guidelines for determining design basis ground motions, Volume 1: Method and guidelines for estimating earthquake ground motion in eastern North America, EPRI TR-102293, Electric Power Research Institute.

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FOLLOW-UP TO SSHAC SECOND GROUND MOTION WORKSHOP

Expert: W. B. Joyner 8-17-94

Ground Motion Measure: 1-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km Horiz.	median amplitude		0.0175	0.202
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ	0.9	0.9
		uncertainty in σ	0.2	0.2
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ	0.8	0.8
		uncertainty in σ	0.2	0.2
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes: m_{Lg} 5.5 ≃ M 5.0
m_{Lg} 7.0 ≃ M 7.0
Aleatory uncertainty based on use of m_{Lg}. If M had been used the Aleatory Uncertainty would have been 0.55 for all frequencies (at distances of 20 km or greater) with a σ of 0.1.

FOLLOW-UP TO SSHAC SECOND GROUND MOTION WORKSHOP

Expert: W. B. Joyner 8-17-94

Ground Motion Measure: 10-Hz Spectral Acceleration (g)

Distance	Quantity		m_{Lg} 5.5	m_{Lg} 7.0
5 km	median amplitude		0.392 ✓	-1.62 ✓
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ	0.9 ✓	0.9 ✓
		uncertainty in σ	0.2 ✓	0.2 ✓
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

FOLLOW-UP TO SSHAC SECOND GROUND MOTION WORKSHOP

Form 5: Page __ of __

Expert: W. B. Joyner 8-17-94

Ground Motion Measure: Peak Ground Acceleration (g)

Distance	Quantity		m_{LR} 5.5	m_{LR} 7.0
5 km	median amplitude		0.429 ✓	1.32 ✓
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ	0.9 ✓	0.9
		uncertainty in σ	0.2 ✓	0.2
20 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
70 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		
200 km	median amplitude			
	epistemic uncertainty	parametric (ln)		
		median bias		
		uncert. in bias (ln)		
	aleatory uncertainty	median σ		
		uncertainty in σ		

Comments/footnotes:

Woodward-Clyde

Engineering & sciences applied to the earth & its environment

August 31, 1994

Dr Gabriel Toro
Risk Engineering, Inc.
4155 Darley Ave, Suite 1
Boulder, Co 80303

Dear Gabriel,

The following is our response to your request for follow up to the second SSHAC ground motion workshop.

We have decided to make no changes in the numerical values that we provided at the second day of the second SSHAC workshop. Our responses to the issues that you raised are as follows.

1. Distance. We do not provide estimates for 5 km horizontal distance. Our estimates for 5 km should be ignored.

2. Aleatory Uncertainty. We think that it is important to reevaluate our estimates of aleatory uncertainty to make them applicable to hard rock conditions. Lack of time makes this impractical for now, but we would like to do this as part of further work.

3. Epistemic Uncertainty. Our epistemic uncertainty estimates are for one logarithmic standard deviation. In most cases, our epistemic uncertainty estimates span the median estimates of the three other proponents. In some cases, our epistemic uncertainty estimates do not span the median estimates of other experts. We have not had the opportunity to evaluate the approaches of the other experts in detail, and so for now we have made no adjustments to our epistemic uncertainty estimates, but we are prepared to consider doing so in future work.

4. Data.

Magnitude range: mblg 5.0 and above.

Distance range: 0 to 500 km, with the main focus on 0 to 200 km.

Inclusion of vertical data: The spectral characteristics of vertical data are usually very different from those of horizontal data, and the ratio of vertical to horizontal ground motion amplitudes is also highly variable. We have not used vertical data in deriving our proponents' estimates, and would place low weight on estimates obtained by other proponents and experts using vertical data.

Inclusion of data from soil or soft rock sites: we think that it is possible to adjust these data to hard rock conditions, but have not done so and propose no method here.

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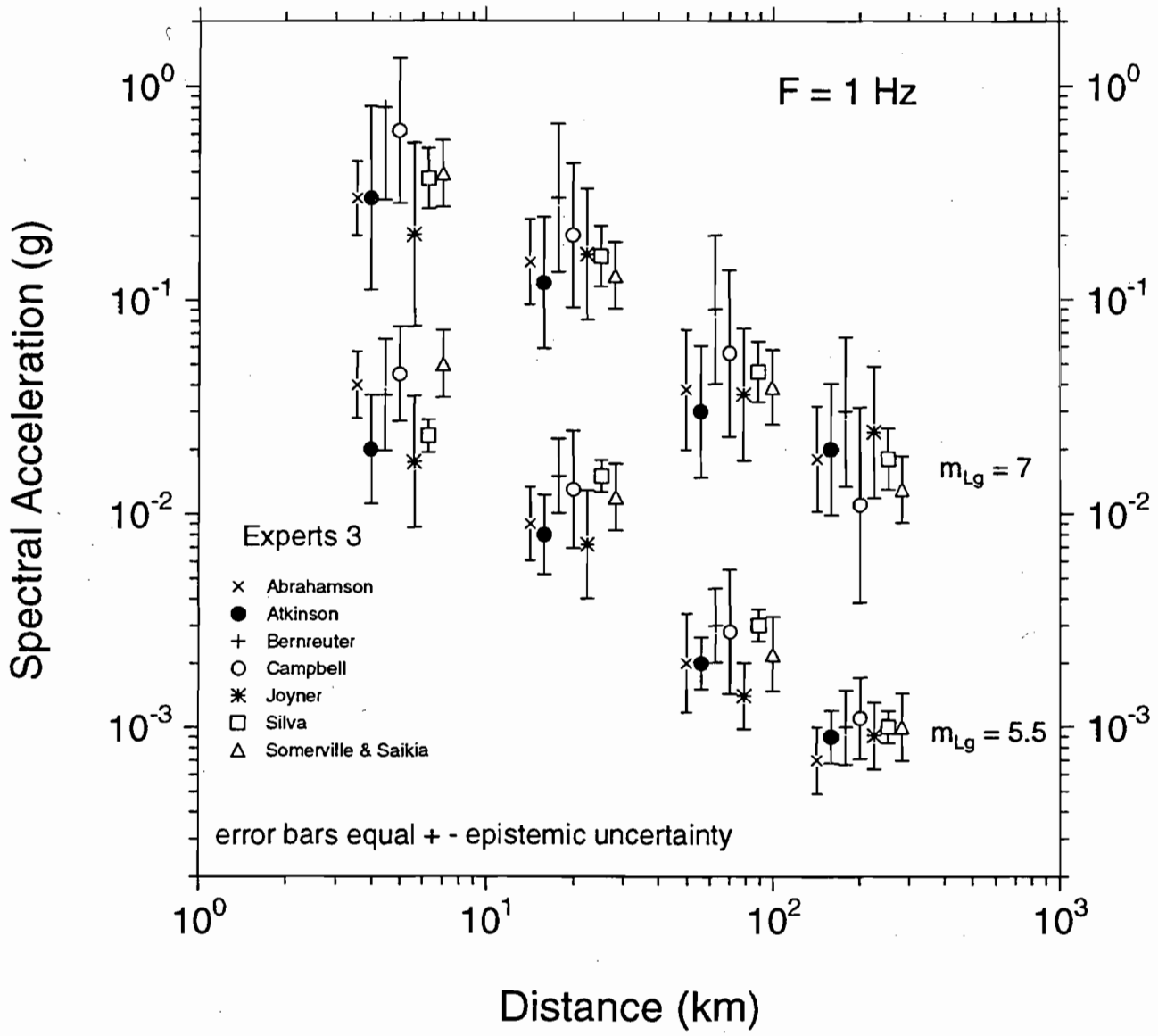
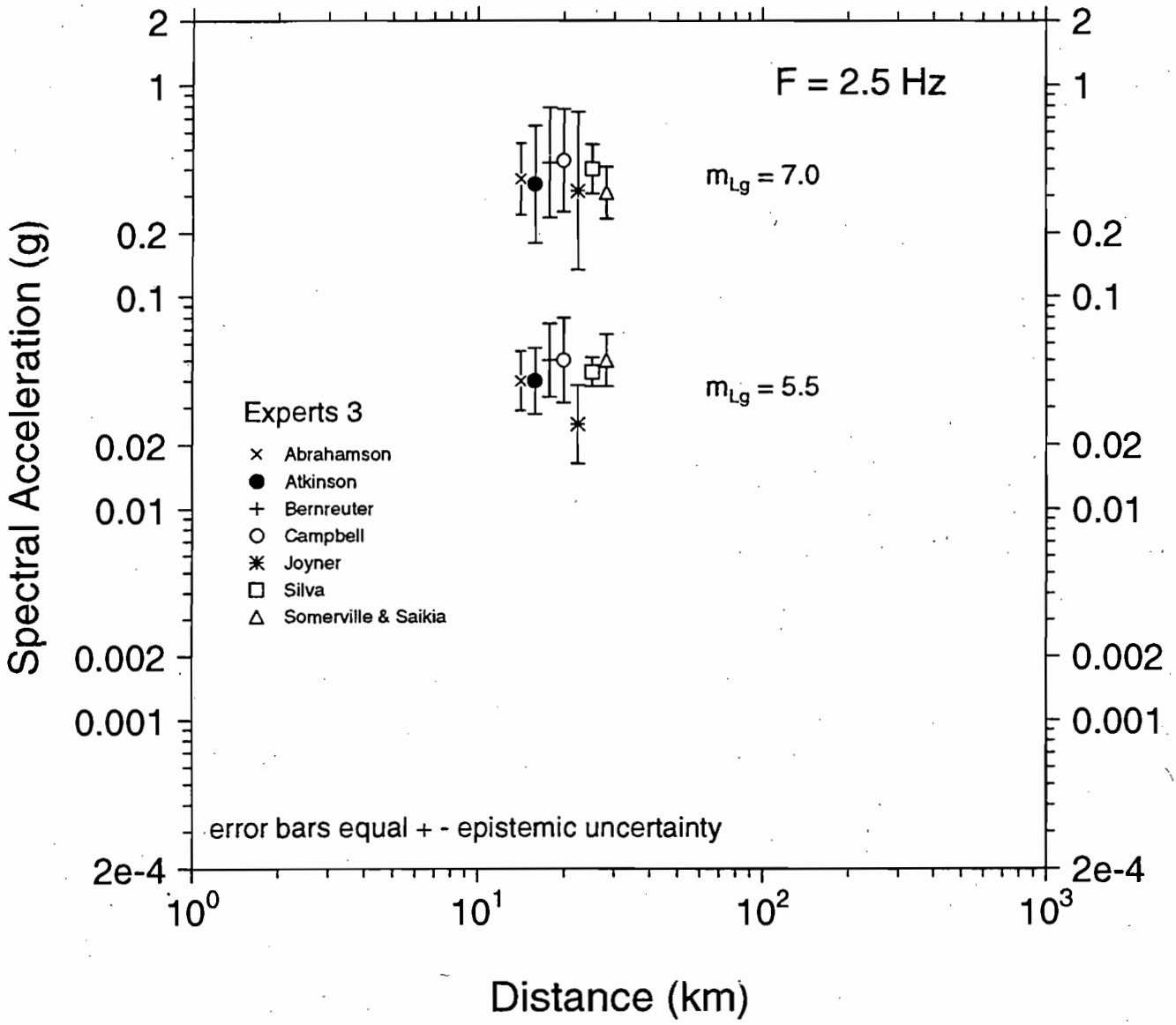
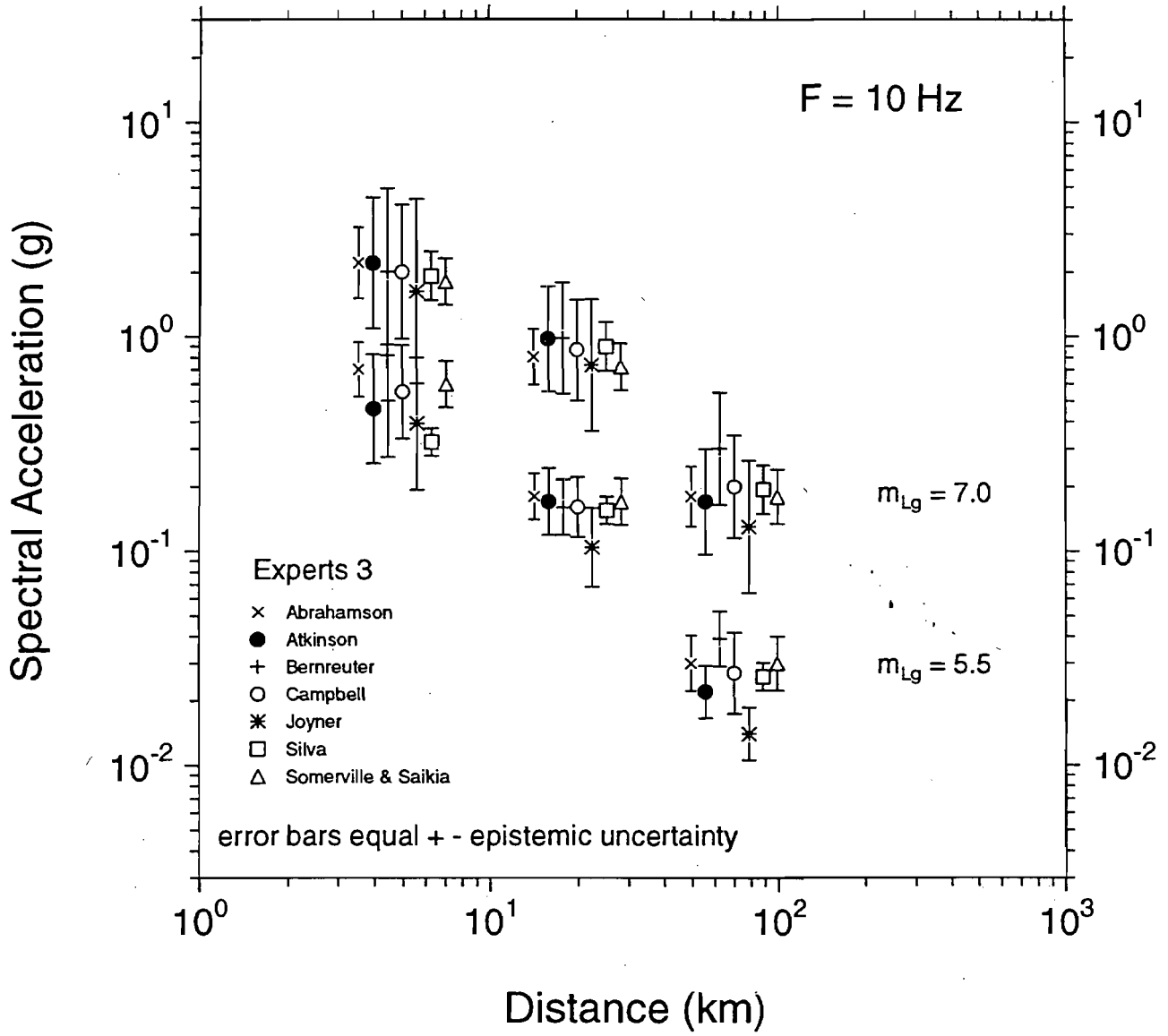
Sincerely,

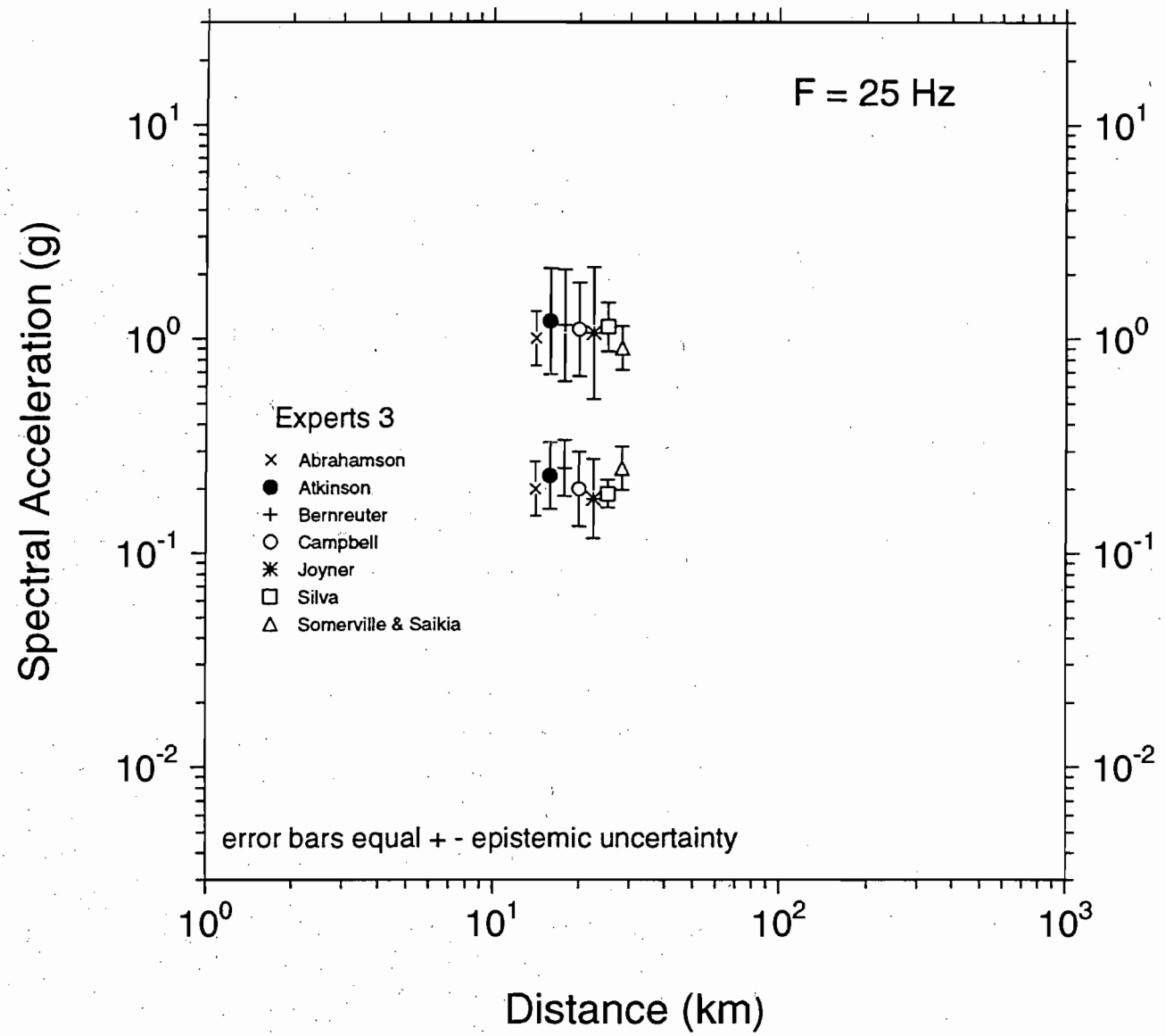
Paul Somerville

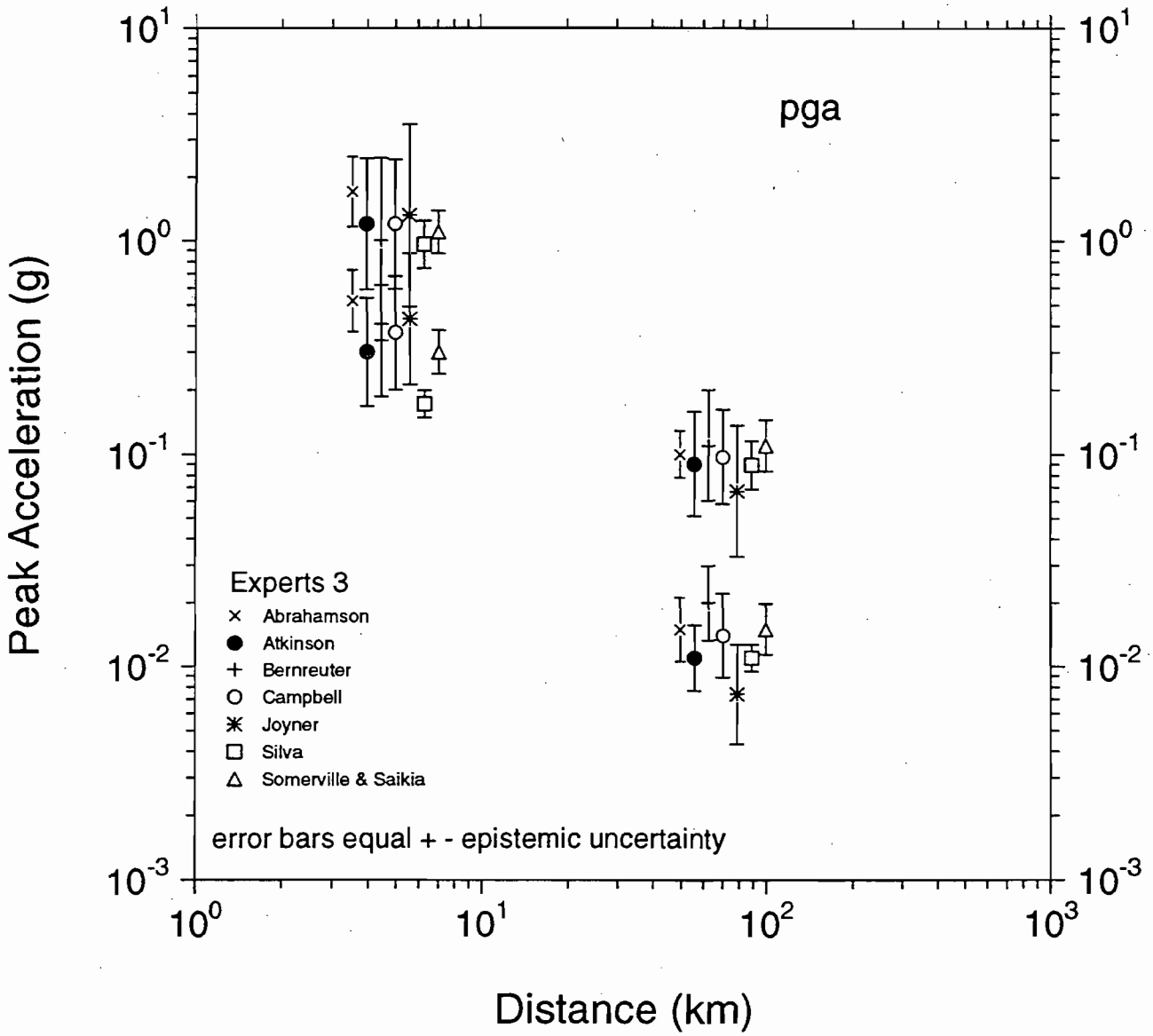
Chandan Saikia


F = 1 Hz
Experts 3
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty
m_{Lg} = 7
m_{Lg} = 5.5
Spectral Acceleration (g)
Distance (km)
10^0
10^{-1}
10^{-2}
10^{-3}
10^1
10^2
10^3


F = 2.5 Hz
m_{Lg} = 7.0
m_{Lg} = 5.5
Experts 3
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty
Spectral Acceleration (g)
Distance (km)
2
1
0.2
0.1
0.02
0.01
0.002
0.001
2e-4
10^0
10^1
10^2
10^3


F = 10 Hz
Spectral Acceleration (g)
Distance (km)
10^1
10^0
10^{-1}
10^{-2}
10^0
10^1
10^2
10^3
$m_{Lg} = 7.0$
$m_{Lg} = 5.5$
Experts 3
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty


F = 25 Hz
Experts 3
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty
Spectral Acceleration (g)
Distance (km)
10^1
10^0
10^{-1}
10^{-2}
10^0
10^1
10^2
10^3


pga
Experts 3
Abrahamson
Atkinson
Bernreuter
Campbell
Joyner
Silva
Somerville & Saikia
error bars equal + - epistemic uncertainty
Peak Acceleration (g)
Distance (km)
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^0
10^1
10^2
10^3

ATTACHMENT B-8

PREPARATION OF DATA

Attachment 8 - Preparation of Data Set for Comparison with Expert Estimates (by D. Boore)

The source of the data was the EPRI catalog, as described in volume 2 of "Guidelines for Determining Design Basis Ground Motions" (EPRI TR-102293). A subset of data was extracted from the catalog according to the following criteria:

- No aftershocks, whose stress parameters may not be representative of those from mainshocks (e.g., Boore and Atkinson, 1989).
- No recordings from large structures
- Rock recordings (as indicated by "A" in the Cl 3 classification code).
- One subset with m_{bLg} between 4.5 and 6.5, and another with **M** between 4.02 and 6.28 (the reasons for these limits will be discussed shortly).
- Data from vertical and horizontal components of motion extracted separately.

In the course of the work, an error was discovered in the EPRI database response spectral values for the 1990 Mount Laurier, Quebec earthquakes. Upon inquiry, Robert Youngs of Geomatrix Consultants discovered the source of the erroneous values and provided a diskette with the corrected values.

The extracted data are given in Tables 8-1 and 8-2 for the vertical and horizontal components of motion, respectively. After extracting a subset of data, the data were scaled to a fixed magnitude of m_{bLg} 5.5. This was done by using the lookup tables of Atkinson and Boore (1995) to provide the appropriate magnitude scaling (the limits on magnitudes given above were imposed to restrict the magnitude range over which the scaling would be done to plus and minus one unit of m_{bLg} around 5.5). The scaling was done using both magnitude measures if available, and if not available, by using the published magnitude measure. The vertical component data were converted to horizontal component data by multiplying by the frequency-dependent relation given in equation (7) of Atkinson (1993). The scaled data are given in Tables 8-3 and 8-4. For the horizontal component the geometric average of the two horizontal components of motion was used.

Plots of the data using the moment magnitude as the measure of the earthquake size are given in Figures 19 through 29 of Appendix B. The corrected-vertical and horizontal component motions are indicated by different symbols in those figures. There seems to be no systematic difference in the two components of data, giving support to the use of the more numerous vertical-component data. Separation according to the measure of earthquake size, not included here, showed little overall difference.

It should be noted that a disproportionate number of the data come from two well-recorded earthquakes with unusually high stress parameters-- 1988 Saguenay and 1990 Mt. Laurier earthquakes, both having a stress parameter of 517 bars (Atkinson and Boore, 1995). In other

words, the dataset may not be representative of the median ground motions expected for the whole population of earthquakes. This must be considered when comparing the ground-motion estimates to the data.

References:

Atkinson, G.M. (1993). Notes on ground motion parameters for eastern North America: duration and H/V ratio, *Bull. Seism. Soc. Am.* **83**, 587--596.

Atkinson, G.M. and D.M. Boore (1995). Ground-motion relations for eastern North America, *Bull. Seism. Soc. Am.* **85**, 17--30.

Boore, D.M. and G.M. Atkinson (1989). Spectral scaling of the 1985 to 1988 Nahanni, Northwest Territories, earthquakes, *Bull. Seism. Soc. Am.* **79**, 1736--1761.

Table 8-1: Vertical component data

Eqid	Eqname	St_no	Desp	Mblg	Mw	Hyp	Epd	Lp	Comp	Amax	F1	F2_5	F10	F25
CG900900	CAPE GIRARDEAU	OLAP	OLD APPLETON, MISSOU	5.00	0.00	47.7	46.2	0.0	VRT	.03414	.00035	.00152	.03130	.16245
FK820100	FRANKLIN FALLS, NH	GNT	ECTN :GNT	4.80	4.35	322.2	322.2	12.0	Z	.00007	.00002	.00009	.00016	.00007
FK820100	FRANKLIN FALLS, NH	LPQ	ECTN :LPQ	4.80	4.35	443.8	443.8	12.0	Z	.00015	.00001	.00008	.00019	.00028
FK820100	FRANKLIN FALLS, NH	MNT	ECTN :MNT	4.80	4.35	272.2	272.1	12.0	Z	.00024	.00001	.00011	.00079	.00029
FK820100	FRANKLIN FALLS, NH	OTT	ECTN :OTT	4.80	4.35	386.6	386.6	12.0	Z	.00015	.00001	.00013	.00042	.00016
FK820100	FRANKLIN FALLS, NH	SBQ	ECTN :SBQ	4.80	4.35	209.4	209.3	12.0	Z	.00033	.00002	.00030	.00075	.00039
FK820100	FRANKLIN FALLS, NH	WBO	ECTN :WBO	4.80	4.35	335.2	335.1	12.0	Z	.00011	.00002	.00011	.00040	.00017
FK820100	FRANKLIN FALLS, NH	2629A	NORTH HARTLAND DAM,	4.80	4.35	62.7	62.6	50.0	VRT	.00382	.00139	.00230	.00745	.01239
FK820100	FRANKLIN FALLS, NH	2630B	NORTH SPRINGFIELD DA	4.80	4.35	76.1	76.0	50.0	VRT	.01392	.00111	.00179	.03526	.03181
GN831000	GOODNOW, NY	CKO	ECTN :CKO	5.60	5.00	339.4	339.4	12.0	Z	.00052	.00015	.00165	.00148	.00056
GN831000	GOODNOW, NY	GNT	ECTN :GNT	5.60	5.00	306.7	306.7	12.0	Z	.00046	.00037	.00105	.00082	.00049
GN831000	GOODNOW, NY	GRQ	ECTN :GRQ	5.60	5.00	322.3	322.3	12.0	Z	.00054	.00014	.00065	.00139	.00062
GN831000	GOODNOW, NY	LPQ	ECTN :LPQ	5.60	5.00	501.3	501.3	12.0	Z	.00024	.00014	.00061	.00047	.00025
GN831000	GOODNOW, NY	MNT	ECTN :MNT	5.60	5.00	180.4	180.4	12.0	Z	.00151	.00040	.00142	.00607	.00212
GN831000	GOODNOW, NY	OTT	ECTN :OTT	5.60	5.00	198.7	198.7	12.0	Z	.00130	.00024	.00166	.00545	.00182
GN831000	GOODNOW, NY	SBQ	ECTN :SBQ	5.60	5.00	243.4	243.4	12.0	Z	.00120	.00045	.00175	.00267	.00132
GN831000	GOODNOW, NY	TRQ	ECTN :TRQ	5.60	5.00	254.6	254.5	12.0	Z	.00135	.00023	.00214	.00393	.00162
GN831000	GOODNOW, NY	WBO	ECTN :WBO	5.60	5.00	143.4	143.4	12.0	Z	.00236	.00017	.00152	.00462	.00352
ML901000	MOUNT-LAURIER QUEBEC	A11	ECTN :A11	5.10	4.70	418.6	418.4	12.0	Z	.00026	.00012	.00064	.00045	.00027
ML901000	MOUNT-LAURIER QUEBEC	A16	ECTN :A16	5.10	4.70	437.4	437.2	12.0	Z	.00028	.00011	.00035	.00061	.00031
ML901000	MOUNT-LAURIER QUEBEC	A21	ECTN :A21	5.10	4.70	466.7	466.5	12.0	Z	.00024	.00008	.00052	.00052	.00026
ML901000	MOUNT-LAURIER QUEBEC	A54	ECTN :A54	5.10	4.70	407.9	407.7	12.0	Z	.00040	.00010	.00081	.00101	.00043
ML901000	MOUNT-LAURIER QUEBEC	A61	ECTN :A61	5.10	4.70	437.5	437.3	12.0	Z	.00015	.00005	.00036	.00036	.00016
ML901000	MOUNT-LAURIER QUEBEC	A64	ECTN :A64	5.10	4.70	456.2	456.0	12.0	Z	.00016	.00007	.00032	.00034	.00017
ML901000	MOUNT-LAURIER QUEBEC	CKO	ECTN :CKO	5.10	4.70	153.6	153.1	12.0	Z	.01101	.00309	.00591	.02254	.01179
ML901000	MOUNT-LAURIER QUEBEC	DPQ	ECTN :DPQ	5.10	4.70	216.7	216.3	12.0	Z	.00206	.00020	.00147	.00541	.00222
ML901000	MOUNT-LAURIER QUEBEC	EEO	ECTN :EEO	5.10	4.70	265.9	265.5	12.0	Z	.00042	.00013	.00034	.00136	.00047
ML901000	MOUNT-LAURIER QUEBEC	GRQ	ECTN :GRQ	5.10	4.70	26.7	23.3	12.0	Z	.09164	.00741	.04047	.23522	.10869
ML901000	MOUNT-LAURIER QUEBEC	MNT	ECTN :MNT	5.10	4.70	189.4	189.0	12.0	Z	.00105	.00009	.00062	.00439	.00113
ML901000	MOUNT-LAURIER QUEBEC	OTT	ECTN :OTT	5.10	4.70	124.4	123.7	12.0	Z	.00140	.00026	.00230	.00493	.00149
ML901000	MOUNT-LAURIER QUEBEC	SBQ	ECTN :SBQ	5.10	4.70	310.0	309.7	12.0	Z	.00044	.00015	.00069	.00113	.00045
ML901000	MOUNT-LAURIER QUEBEC	SUO	ECTN :SUO	5.10	4.70	414.6	414.4	12.0	Z	.00011	.00006	.00011	.00031	.00012
ML901000	MOUNT-LAURIER QUEBEC	SWO	ECTN :SWO	5.10	4.70	413.2	413.0	12.0	Z	.00015	.00008	.00014	.00037	.00016
ML901000	MOUNT-LAURIER QUEBEC	SZO	ECTN :SZO	5.10	4.70	451.8	451.6	12.0	Z	.00011	.00007	.00016	.00041	.00012
ML901000	MOUNT-LAURIER QUEBEC	TRQ	ECTN :TRQ	5.10	4.70	86.6	85.6	12.0	Z	.02936	.00184	.02007	.07323	.03285
ML901000	MOUNT-LAURIER QUEBEC	WBO	ECTN :WBO	5.10	4.70	169.0	168.5	12.0	Z	.01004	.00151	.01182	.02155	.01059
NH851200	NAHANNI, CAN	6097	NW TERR, CANADA: MAC	6.10	6.80	9.7	7.6	50.0	VRT	2.36736	.40354	.63091	5.41788	4.06184
NH851200	NAHANNI, CAN	6099	NW TERR, CANADA: MAC	6.10	6.80	23.4	22.6	50.0	VRT	.18149	.03872	.06846	.26202	.57841
NM760300	NEW MADRID, MO	2415B	WAPPAPELLO DAM, MO,	0.00	4.60	150.5	150.0	25.0	VRT	.00547	.00091	.00172	.01548	.01382
NM910501	NEW MADRID, MO	OLAP	OLD APPLETON, MISSOU	4.60	4.25	114.2	114.0	0.0	VRT	.00880	.00025	.00086	.00843	.02368
NM890400	NEW MADRID, MO	OLAP	OLD APPLETON, MISSOU	4.70	4.70	174.2	173.9	0.0	VRT	.00347	.00023	.00039	.00543	.00909
SG881101	SAGUENAY, CAN	DCKY	DICKEY, MAINE	6.50	5.80	197.0	194.8	50.0	VRT	.03297	.01623	.08274	.06292	.03412
SG881101	SAGUENAY, CAN	EMME	EAST MACHIAS, MAINE	6.50	5.80	472.3	471.4	50.0	VRT	.00178	.00207	.00325	.00280	.00191
SG881101	SAGUENAY, CAN	GGN	ECTN :GGN	6.50	5.80	471.9	471.0	12.0	Z	.00197	.00301	.00389	.00255	.00200
SG881101	SAGUENAY, CAN	GRQ	ECTN :GRQ	6.50	5.80	391.2	390.2	12.0	Z	.00299	.00147	.00534	.00594	.00328
SG881101	SAGUENAY, CAN	GSQ	ECTN :GSQ	6.50	5.80	313.5	312.2	12.0	Z	.00326	.00267	.01492	.00570	.00349
SG881101	SAGUENAY, CAN	KLN	ECTN :KLN	6.50	5.80	389.3	388.2	12.0	Z	.00161	.00162	.00391	.00354	.00164
SG881101	SAGUENAY, CAN	SBQ	ECTN :SBQ	6.50	5.80	311.1	309.8	12.0	Z	.00546	.00472	.00826	.01179	.00615
SG881101	SAGUENAY, CAN	TRQ	ECTN :TRQ	6.50	5.80	332.6	331.3	12.0	Z	.00438	.00266	.00654	.00957	.00498
SG881101	SAGUENAY, CAN	WBO	ECTN :WBO	6.50	5.80	468.2	467.3	12.0	Z	.00283	.00118	.01184	.00562	.00291
SG881101	SAGUENAY, CAN	GSC10	GSC SITE 10 - RIVIER	6.50	5.80	118.1	114.5	50.0	VRT	.02329	.00930	.04130	.05314	.04261
SG881101	SAGUENAY, CAN	GSC14	GSC SITE 14 - Ste-LU	6.50	5.80	101.3	97.1	50.0	VRT	.02101	.01081	.03047	.03555	.03104
SG881101	SAGUENAY, CAN	GSC17	GSC SITE 17 - St-AND	6.50	5.80	70.4	64.1	50.0	VRT	.04522	.00278	.01632	.13527	.11008
SG881101	SAGUENAY, CAN	GSC20	GSC SITE 20 - LES EB	6.50	5.80	95.0	90.4	50.0	VRT	.23434	.01378	.15177	.25816	1.00455
SG881101	SAGUENAY, CAN	GSC5	GSC SITE 5 - TADOUSS	6.50	5.80	113.1	109.3	50.0	VRT	.05328	.01149	.03384	.09346	.11867
SG881101	SAGUENAY, CAN	GSC8	GSC SITE 8 - LA MALB	6.50	5.80	97.5	93.1	50.0	VRT	.06780	.00832	.04335	.15015	.08215
SG881101	SAGUENAY, CAN	GSC9	GSC SITE 9 - St-PASC	6.50	5.80	132.5	129.3	50.0	VRT	.03661	.00965	.07354	.05084	.03750
SG881101	SAGUENAY, CAN	ISFL	ISLAND FALLS, MAINE	6.50	5.80	325.8	324.5	50.0	VRT	.00401	.00253	.00710	.00576	.00490
SG881101	SAGUENAY, CAN	MIME	MILO, MAINE	6.50	5.80	360.8	359.6	50.0	VRT	.00121	.00036	.00092	.00145	.00123
SG881100	SAGUENAY, CAN (F1)	DCKY	DICKEY, MAINE	4.80	4.50	198.6	196.6	50.0	VRT	.00071	.00021	.00081	.00193	.00162
SG881100	SAGUENAY, CAN (F1)	A11	ECTN :A11	4.80	4.50	127.3	124.0	12.0	Z	.00057	.00008	.00035	.00147	.00068

SG881100	SAGUENAY, CAN (F1)	A16	ECTN	:A16	4.80	4.50	118.8	115.2	12.0	Z	.00054	.00006	.00013	.00195	.00076
SG881100	SAGUENAY, CAN (F1)	A21	ECTN	:A21	4.80	4.50	125.6	122.2	12.0	Z	.00066	.00009	.00018	.00223	.00086
SG881100	SAGUENAY, CAN (F1)	A61	ECTN	:A61	4.80	4.50	100.3	96.1	12.0	Z	.00088	.00011	.00030	.00271	.00108
SG881100	SAGUENAY, CAN (F1)	A64	ECTN	:A64	4.80	4.50	107.0	103.0	12.0	Z	.00052	.00005	.00028	.00231	.00065
SG881100	SAGUENAY, CAN (F1)	DPQ	ECTN	:DPQ	4.80	4.50	202.3	200.2	12.0	Z	.00109	.00006	.00055	.00253	.00123
SG881100	SAGUENAY, CAN (F1)	EBN	ECTN	:EBN	4.80	4.50	232.1	230.3	12.0	Z	.00013	.00005	.00011	.00039	.00014
SG881100	SAGUENAY, CAN (F1)	GGN	ECTN	:GGN	4.80	4.50	473.8	472.9	12.0	Z	.00003	.00003	.00004	.00006	.00003
SG881100	SAGUENAY, CAN (F1)	GRQ	ECTN	:GRQ	4.80	4.50	390.3	389.2	12.0	Z	.00031	.00004	.00036	.00049	.00032
SG881100	SAGUENAY, CAN (F1)	GSQ	ECTN	:GSQ	4.80	4.50	314.6	313.2	12.0	Z	.00006	.00005	.00012	.00014	.00007
SG881100	SAGUENAY, CAN (F1)	HTQ	ECTN	:HTQ	4.80	4.50	239.3	237.5	12.0	Z	.00020	.00002	.00008	.00052	.00022
SG881100	SAGUENAY, CAN (F1)	KLN	ECTN	:KLN	4.80	4.50	391.1	390.0	12.0	Z	.00003	.00002	.00004	.00012	.00004
SG881100	SAGUENAY, CAN (F1)	LPQ	ECTN	:LPQ	4.80	4.50	128.3	125.0	12.0	Z	.00066	.00011	.00032	.00238	.00076
SG881100	SAGUENAY, CAN (F1)	MNT	ECTN	:MNT	4.80	4.50	346.6	345.4	12.0	Z	.00019	.00003	.00015	.00049	.00020
SG881100	SAGUENAY, CAN (F1)	OTT	ECTN	:OTT	4.80	4.50	460.4	459.5	12.0	Z	.00012	.00004	.00026	.00027	.00013
SG881100	SAGUENAY, CAN (F1)	SBQ	ECTN	:SBQ	4.80	4.50	311.9	310.6	12.0	Z	.00017	.00011	.00024	.00063	.00019
SG881100	SAGUENAY, CAN (F1)	TRQ	ECTN	:TRQ	4.80	4.50	332.1	330.8	12.0	Z	.00032	.00004	.00043	.00074	.00034
SG881100	SAGUENAY, CAN (F1)	WBO	ECTN	:WBO	4.80	4.50	468.0	467.1	12.0	Z	.00009	.00003	.00016	.00021	.00009

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Table 8-2: Horizontal component data

Eqid	Eqname	St_no	Desp	Mblg	Mw	Hyp	Epd	Lp	Comp	Amax	F1	F2_5	F10	F25
CG900900	CAPE GIRARDEAU	OLAP	OLD APPLETON, MISSOU	5.00	0.00	47.7	46.2	0.0	070	.01899	.00031	.00110	.03366	.05143
CG900900	CAPE GIRARDEAU	OLAP	OLD APPLETON, MISSOU	5.00	0.00	47.7	46.2	0.0	340	.02071	.00038	.00286	.02959	.05788
FK820100	FRANKLIN FALLS, NH	2629A	NORTH HARTLAND DAM,	4.80	4.35	62.7	62.6	50.0	015	.00721	.00117	.00160	.01004	.02240
FK820100	FRANKLIN FALLS, NH	2629A	NORTH HARTLAND DAM,	4.80	4.35	62.7	62.6	50.0	285	.00697	.00087	.00262	.01151	.02284
FK820100	FRANKLIN FALLS, NH	2630B	NORTH SPRINGFIELD DA	4.80	4.35	76.1	76.0	50.0	185	.02303	.00129	.00211	.03414	.10585
FK820100	FRANKLIN FALLS, NH	2630B	NORTH SPRINGFIELD DA	4.80	4.35	76.1	76.0	50.0	275	.02425	.00147	.00262	.05524	.08131
ML901000	MOUNT-LAURIER QUEBEC	A11	ECTN :A11	5.10	4.70	418.6	418.4	12.0	E	.00025	.00012	.00057	.00063	.00026
ML901000	MOUNT-LAURIER QUEBEC	A11	ECTN :A11	5.10	4.70	418.6	418.4	12.0	N	.00018	.00016	.00053	.00037	.00018
ML901000	MOUNT-LAURIER QUEBEC	A16	ECTN :A16	5.10	4.70	437.4	437.2	12.0	E	.00024	.00009	.00042	.00052	.00026
ML901000	MOUNT-LAURIER QUEBEC	A16	ECTN :A16	5.10	4.70	437.4	437.2	12.0	N	.00022	.00010	.00041	.00045	.00023
ML901000	MOUNT-LAURIER QUEBEC	A21	ECTN :A21	5.10	4.70	466.7	466.5	12.0	E	.00040	.00010	.00076	.00079	.00044
ML901000	MOUNT-LAURIER QUEBEC	A21	ECTN :A21	5.10	4.70	466.7	466.5	12.0	N	.00522	.00087	.00382	.00926	.00631
ML901000	MOUNT-LAURIER QUEBEC	A54	ECTN :A54	5.10	4.70	407.9	407.7	12.0	E	.00029	.00006	.00065	.00091	.00033
ML901000	MOUNT-LAURIER QUEBEC	A54	ECTN :A54	5.10	4.70	407.9	407.7	12.0	N	.00065	.00011	.00099	.00102	.00072
ML901000	MOUNT-LAURIER QUEBEC	A61	ECTN :A61	5.10	4.70	437.5	437.3	12.0	E	.00029	.00006	.00047	.00072	.00032
ML901000	MOUNT-LAURIER QUEBEC	A61	ECTN :A61	5.10	4.70	437.5	437.3	12.0	N	.00033	.00014	.00050	.00070	.00035
ML901000	MOUNT-LAURIER QUEBEC	A64	ECTN :A64	5.10	4.70	456.2	456.0	12.0	E	.00023	.00005	.00034	.00056	.00025
ML901000	MOUNT-LAURIER QUEBEC	A64	ECTN :A64	5.10	4.70	456.2	456.0	12.0	N	.00024	.00008	.00054	.00051	.00026
NH851200	NAHANNI, CAN	6097	NW TERR, CANADA: MAC	6.10	6.80	9.7	7.6	50.0	010	1.10133	.43843	.85652	2.49706	2.08663
NH85120D	NAHANNI, CAN	6097	NW TERR, CANADA: MAC	6.10	6.80	9.7	7.6	50.0	280	1.34463	.48920	.91542	2.79211	1.39409
NH851200	NAHANNI, CAN	6098	NW TERR, CANADA: MAC	6.10	6.80	9.5	7.4	50.0	240	.54479	.13446	.46777	.65824	1.16859
NH851200	NAHANNI, CAN	6098	NW TERR, CANADA: MAC	6.10	6.80	9.5	7.4	50.0	330	.38978	.28621	.44325	.56768	.68850
NH851200	NAHANNI, CAN	6099	NW TERR, CANADA: MAC	6.10	6.80	23.4	22.6	50.0	270	.18594	.03533	.08840	.29055	.47826
NH851200	NAHANNI, CAN	6099	NW TERR, CANADA: MAC	6.10	6.80	23.4	22.6	50.0	360	.19388	.02325	.05916	.32180	.58918
NH851100	NAHANNI, CAN (F1)	6098	NW TERR, CANADA: MAC	0.00	4.60	18.8	5.5	50.0	240	.45969	.01437	.07207	.48599	.50537
NH851100	NAHANNI, CAN (F1)	6098	NW TERR, CANADA: MAC	0.00	4.60	18.8	5.5	50.0	330	.38152	.01200	.06345	.43404	.47502
NM760300	NEW MADRID, MO	2415B	WAPPAPELLO DAM, MO,	0.00	4.60	150.5	150.0	25.0	128	.01193	.00075	.00241	.01510	.02681
NM760300	NEW MADRID, MO	2415B	WAPPAPELLO DAM, MO,	0.00	4.60	150.5	150.0	25.0	218	.01016	.00042	.00223	.02227	.02000
NM910501	NEW MADRID, MO	OLAP	OLD APPLETON, MISSOU	4.60	4.25	114.2	114.0	0.0	070	.00698	.00029	.00088	.01550	.01596
NM910501	NEW MADRID, MO	OLAP	OLD APPLETON, MISSOU	4.60	4.25	114.2	114.0	0.0	340	.00796	.00043	.00217	.01569	.01693
NM890400	NEW MADRID, MO	OLAP	OLD APPLETON, MISSOU	4.70	4.70	174.2	173.9	0.0	N34	.00278	.00025	.00048	.00594	.00591
NM890400	NEW MADRID, MO	OLAP	OLD APPLETON, MISSOU	4.70	4.70	174.2	173.9	0.0	N70	.00370	.00024	.00044	.00749	.00676
SG881101	SAGUENAY, CAN	DCKY	DICKEY, MAINE	6.50	5.80	197.0	194.8	50.0	N00	.06311	.01633	.08517	.10481	.06511
SG881101	SAGUENAY, CAN	DCKY	DICKEY, MAINE	6.50	5.80	197.0	194.8	50.0	N90	.09152	.02281	.05264	.15159	.09611
SG881101	SAGUENAY, CAN	EMME	EAST MACHIAS, MAINE	6.50	5.80	472.3	471.4	50.0	N33	.00130	.00142	.00252	.00326	.00247
SG881101	SAGUENAY, CAN	EMME	EAST MACHIAS, MAINE	6.50	5.80	472.3	471.4	50.0	N65	.00215	.00275	.00527	.00387	.00282
SG881101	SAGUENAY, CAN	GSC10	GSC SITE 10 - RIVIER	6.50	5.80	118.1	114.5	50.0	000	.04036	.02536	.05401	.10973	.04894
SG881101	SAGUENAY, CAN	GSC10	GSC SITE 10 - RIVIER	6.50	5.80	118.1	114.5	50.0	270	.05700	.02685	.11554	.16052	.06334
SG881101	SAGUENAY, CAN	GSC14	GSC SITE 14 - Ste-LU	6.50	5.80	101.3	97.1	50.0	000	.01384	.00341	.02041	.03198	.02125
SG881101	SAGUENAY, CAN	GSC14	GSC SITE 14 - Ste-LU	6.50	5.80	101.3	97.1	50.0	270	.02328	.00892	.02865	.02867	.02895
SG881101	SAGUENAY, CAN	GSC17	GSC SITE 17 - St-AND	6.50	5.80	70.4	64.1	50.0	000	.15588	.00438	.05348	.15482	.40242
SG881101	SAGUENAY, CAN	GSC17	GSC SITE 17 - St-AND	6.50	5.80	70.4	64.1	50.0	270	.09109	.00411	.02035	.19066	.28120
SG881101	SAGUENAY, CAN	GSC20	GSC SITE 20 - LES EB	6.50	5.80	95.0	90.4	50.0	000	.12545	.01934	.13470	.24654	.20106
SG881101	SAGUENAY, CAN	GSC20	GSC SITE 20 - LES EB	6.50	5.80	95.0	90.4	50.0	270	.10221	.01713	.08726	.19654	.28079
SG881101	SAGUENAY, CAN	GSC5	GSC SITE 5 - TADOUSS	6.50	5.80	113.1	109.3	50.0	007	.00218	.00119	.00145	.00189	.00234
SG881101	SAGUENAY, CAN	GSC5	GSC SITE 5 - TADOUSS	6.50	5.80	113.1	109.3	50.0	097	.02688	.00363	.02400	.06254	.06587
SG881101	SAGUENAY, CAN	GSC8	GSC SITE 8 - LA MALB	6.50	5.80	97.5	93.1	50.0	063	.12418	.03373	.13460	.24726	.15213
SG881101	SAGUENAY, CAN	GSC8	GSC SITE 8 - LA MALB	6.50	5.80	97.5	93.1	50.0	333	.05987	.01207	.04451	.10266	.10569
SG881101	SAGUENAY, CAN	GSC9	GSC SITE 9 - St-PASC	6.50	5.80	132.5	129.3	50.0	000	.04634	.02724	.05870	.08269	.06788
SG881101	SAGUENAY, CAN	GSC9	GSC SITE 9 - St-PASC	6.50	5.80	132.5	129.3	50.0	270	.05576	.01719	.07223	.14121	.07114
SG881101	SAGUENAY, CAN	ISFL	ISLAND FALLS, MAINE	6.50	5.80	325.8	324.5	50.0	N17	.00538	.00552	.01202	.00731	.00678
SG881101	SAGUENAY, CAN	ISFL	ISLAND FALLS, MAINE	6.50	5.80	325.8	324.5	50.0	N26	.00551	.00375	.01128	.00855	.01071
SG881101	SAGUENAY, CAN	MIME	MILO, MAINE	6.50	5.80	360.8	359.6	50.0	N32	.00117	.00039	.00107	.00154	.00155
SG881101	SAGUENAY, CAN	MIME	MILO, MAINE	6.50	5.80	360.8	359.6	50.0	N56	.00118	.00047	.00096	.00169	.00174
SG881100	SAGUENAY, CAN (F1)	DCKY	DICKEY, MAINE	4.80	4.50	198.6	196.6	50.0	000	.00109	.00018	.00073	.00256	.00170
SG881100	SAGUENAY, CAN (F1)	DCKY	DICKEY, MAINE	4.80	4.50	198.6	196.6	50.0	090	.00116	.00019	.00091	.00391	.00195
SG881100	SAGUENAY, CAN (F1)	A11	ECTN :A11	4.80	4.50	127.3	124.0	12.0	E	.00058	.00005	.00062	.00153	.00069
SG881100	SAGUENAY, CAN (F1)	A11	ECTN :A11	4.80	4.50	127.3	124.0	12.0	N	.00060	.00018	.00076	.00219	.00068
SG881100	SAGUENAY, CAN (F1)	A16	ECTN :A16	4.80	4.50	118.8	115.2	12.0	E	.00086	.00005	.00027	.00296	.00106
SG881100	SAGUENAY, CAN (F1)	A16	ECTN :A16	4.80	4.50	118.8	115.2	12.0	N	.00070	.00007	.00037	.00222	.00084
SG881100	SAGUENAY, CAN (F1)	A21	ECTN :A21	4.80	4.50	125.6	122.2	12.0	E	.00113	.00010	.00043	.00428	.00134

SG881100	SAGUENAY, CAN (F1)	A21	ECTN :A21	4.80	4.50	125.6	122.2	12.0	N	.00162	.00006	.00044	.00499	.00181
SG881100	SAGUENAY, CAN (F1)	A61	ECTN :A61	4.80	4.50	100.3	96.1	12.0	E	.00172	.00010	.00045	.00441	.00221
SG881100	SAGUENAY, CAN (F1)	A61	ECTN :A61	4.80	4.50	100.3	96.1	12.0	N	.00159	.00010	.00031	.00401	.00203
SG881100	SAGUENAY, CAN (F1)	A64	ECTN :A64	4.80	4.50	107.0	103.0	12.0	E	.00069	.00009	.00018	.00282	.00090
SG881100	SAGUENAY, CAN (F1)	A64	ECTN :A64	4.80	4.50	107.0	103.0	12.0	N	.00121	.00006	.00021	.00353	.00149

Table 8-3: Scaled vertical component data

eqid	staid	Lp	hypd	epd	mbLg	pgambLg	f1mbLg	f2p5mLg	f10mbLg	f25mbLg	mw	pgamw	f1mw	f2p5mw	f10mw	f25mw
CG900900	OLAP	0.0	47.7	46.2	5.00	0.06142	0.00107	0.00436	0.08228	0.47927	0.00	0.00000	0.00000	0.00000	0.00000	0.00000
FK820100	GNT	12.0	322.2	322.2	4.80	0.00018	0.00011	0.00037	0.00060	0.00000	4.35	0.00017	0.00010	0.00035	0.00057	0.00000
FK820100	LPQ	12.0	443.8	443.8	4.80	0.00042	0.00006	0.00034	0.00070	0.00000	4.35	0.00039	0.00005	0.00032	0.00067	0.00000
FK820100	MNT	12.0	272.2	272.1	4.80	0.00062	0.00005	0.00046	0.00288	0.00000	4.35	0.00059	0.00005	0.00043	0.00273	0.00000
FK820100	OTT	12.0	386.6	386.6	4.80	0.00041	0.00006	0.00055	0.00156	0.00000	4.35	0.00039	0.00005	0.00051	0.00149	0.00000
FK820100	SBQ	12.0	209.4	209.3	4.80	0.00083	0.00011	0.00128	0.00271	0.00000	4.35	0.00079	0.00010	0.00119	0.00258	0.00000
FK820100	WBO	12.0	335.2	335.1	4.80	0.00029	0.00011	0.00046	0.00149	0.00000	4.35	0.00027	0.00010	0.00043	0.00141	0.00000
FK820100	2629A	50.0	62.7	62.6	4.80	0.00869	0.00667	0.00931	0.02601	0.04572	4.35	0.00833	0.00612	0.00877	0.02483	0.04351
FK820100	2630B	50.0	76.1	76.0	4.80	0.03209	0.00555	0.00746	0.12630	0.11361	4.35	0.03066	0.00507	0.00699	0.11976	0.10839
GN831000	CKO	12.0	339.4	339.4	5.60	0.00043	0.00013	0.00162	0.00182	0.00000	5.00	0.00052	0.00017	0.00207	0.00218	0.00000
GN831000	GNT	12.0	306.7	306.7	5.60	0.00038	0.00032	0.00103	0.00101	0.00000	5.00	0.00046	0.00042	0.00132	0.00121	0.00000
GN831000	GRQ	12.0	322.3	322.3	5.60	0.00045	0.00012	0.00064	0.00171	0.00000	5.00	0.00054	0.00016	0.00082	0.00205	0.00000
GN831000	LPQ	12.0	501.3	501.3	5.60	0.00019	0.00012	0.00061	0.00057	0.00000	5.00	0.00024	0.00016	0.00077	0.00069	0.00000
GN831000	MNT	12.0	180.4	180.4	5.60	0.00128	0.00034	0.00143	0.00754	0.00000	5.00	0.00151	0.00045	0.00178	0.00896	0.00000
GN831000	OTT	12.0	198.7	198.7	5.60	0.00111	0.00021	0.00168	0.00679	0.00000	5.00	0.00130	0.00027	0.00208	0.00804	0.00000
GN831000	SBQ	12.0	243.4	243.4	5.60	0.00099	0.00039	0.00176	0.00331	0.00000	5.00	0.00120	0.00051	0.00220	0.00394	0.00000
GN831000	TRQ	12.0	254.6	254.5	5.60	0.00110	0.00020	0.00214	0.00486	0.00000	5.00	0.00135	0.00026	0.00268	0.00580	0.00000
GN831000	WBO	12.0	143.4	143.4	5.60	0.00198	0.00015	0.00153	0.00572	0.00000	5.00	0.00236	0.00019	0.00191	0.00682	0.00000
ML901000	A11	12.0	418.6	418.4	5.10	0.00046	0.00032	0.00156	0.00111	0.00000	4.70	0.00040	0.00026	0.00133	0.00098	0.00000
ML901000	A16	12.0	437.4	437.2	5.10	0.00050	0.00029	0.00086	0.00150	0.00000	4.70	0.00043	0.00024	0.00073	0.00133	0.00000
ML901000	A21	12.0	466.7	466.5	5.10	0.00043	0.00021	0.00128	0.00128	0.00000	4.70	0.00037	0.00017	0.00110	0.00114	0.00000
ML901000	A54	12.0	407.9	407.7	5.10	0.00070	0.00027	0.00197	0.00249	0.00000	4.70	0.00062	0.00022	0.00167	0.00219	0.00000
ML901000	A61	12.0	437.5	437.3	5.10	0.00027	0.00013	0.00088	0.00089	0.00000	4.70	0.00023	0.00011	0.00075	0.00078	0.00000
ML901000	A64	12.0	456.2	456.0	5.10	0.00028	0.00019	0.00079	0.00084	0.00000	4.70	0.00025	0.00015	0.00067	0.00074	0.00000
ML901000	CKO	12.0	153.6	153.1	5.10	0.01814	0.00787	0.01458	0.05593	0.00000	4.70	0.01611	0.00642	0.01245	0.05022	0.00000
ML901000	DPQ	12.0	216.7	216.3	5.10	0.00346	0.00052	0.00356	0.01321	0.00000	4.70	0.00305	0.00042	0.00304	0.01183	0.00000
ML901000	EEO	12.0	265.9	265.5	5.10	0.00071	0.00033	0.00080	0.00333	0.00000	4.70	0.00062	0.00028	0.00067	0.00298	0.00000
ML901000	GRQ	12.0	26.7	23.3	5.10	0.14220	0.01818	0.09500	0.54413	0.00000	4.70	0.12845	0.01491	0.08041	0.47931	0.00000
ML901000	MNT	12.0	189.4	189.0	5.10	0.00176	0.00023	0.00153	0.01076	0.00000	4.70	0.00155	0.00019	0.00131	0.00965	0.00000
ML901000	OTT	12.0	124.4	123.7	5.10	0.00222	0.00069	0.00572	0.01217	0.00000	4.70	0.00197	0.00056	0.00498	0.01082	0.00000
ML901000	SBQ	12.0	310.0	309.7	5.10	0.00074	0.00039	0.00164	0.00278	0.00000	4.70	0.00065	0.00032	0.00138	0.00248	0.00000
ML901000	SUO	12.0	414.6	414.4	5.10	0.00019	0.00016	0.00027	0.00076	0.00000	4.70	0.00017	0.00013	0.00023	0.00067	0.00000
ML901000	SWO	12.0	413.2	413.0	5.10	0.00026	0.00021	0.00034	0.00091	0.00000	4.70	0.00023	0.00018	0.00029	0.00080	0.00000
ML901000	SZO	12.0	451.8	451.6	5.10	0.00019	0.00019	0.00039	0.00101	0.00000	4.70	0.00017	0.00015	0.00034	0.00089	0.00000
ML901000	TRQ	12.0	86.6	85.6	5.10	0.04688	0.00475	0.05057	0.17596	0.00000	4.70	0.04164	0.00386	0.04307	0.15912	0.00000
ML901000	WBO	12.0	169.0	168.5	5.10	0.01670	0.00385	0.02918	0.05325	0.00000	4.70	0.01480	0.00314	0.02486	0.04785	0.00000
NH851200	6097	50.0	9.7	7.6	6.10	1.45879	0.15210	0.30660	4.09583	3.74862	6.80	0.74176	0.03906	0.09745	1.91306	1.89750
NH851200	6099	50.0	23.4	22.6	6.10	0.08866	0.01376	0.03125	0.17827	0.46160	6.80	0.03893	0.00350	0.00932	0.07387	0.20088
NM760300	2415B	25.0	150.5	150.0	0.00	0.00000	0.00000	0.00000	0.00000	0.00000	4.60	0.00907	0.00237	0.00430	0.03877	0.03528
NM910501	OLAP	0.0	114.2	114.0	4.60	0.02702	0.00216	0.00549	0.04012	0.11601	4.25	0.02240	0.00152	0.00407	0.03331	0.09803
NM890400	OLAP	0.0	174.2	173.9	4.70	0.00978	0.00157	0.00205	0.02306	0.03839	4.70	0.00512	0.00048	0.00082	0.01202	0.02101
SG881101	DCKY	50.0	197.0	194.8	6.50	0.00771	0.00247	0.01724	0.02291	0.01430	5.80	0.01332	0.00494	0.03324	0.03714	0.02262
SG881101	EMME	50.0	472.3	471.4	6.50	0.00034	0.00029	0.00065	0.00089	0.00063	5.80	0.00061	0.00059	0.00124	0.00153	0.00113
SG881101	GGN	12.0	471.9	471.0	6.50	0.00037	0.00042	0.00078	0.00081	0.00000	5.80	0.00067	0.00086	0.00148	0.00139	0.00000
SG881101	GRQ	12.0	391.2	390.2	6.50	0.00059	0.00022	0.00108	0.00200	0.00000	5.80	0.00106	0.00045	0.00202	0.00334	0.00000
SG881101	GSQ	12.0	313.5	312.2	6.50	0.00067	0.00039	0.00301	0.00199	0.00000	5.80	0.00117	0.00079	0.00566	0.00322	0.00000
SG881101	KLN	12.0	389.3	388.2	6.50	0.00032	0.00024	0.00079	0.00119	0.00000	5.80	0.00057	0.00049	0.00148	0.00199	0.00000
SG881101	SBQ	12.0	311.1	309.8	6.50	0.00113	0.00069	0.00167	0.00413	0.00000	5.80	0.00196	0.00140	0.00314	0.00666	0.00000
SG881101	TRQ	12.0	332.6	331.3	6.50	0.00090	0.00039	0.00132	0.00332	0.00000	5.80	0.00157	0.00080	0.00248	0.00540	0.00000
SG881101	WBO	12.0	468.2	467.3	6.50	0.00054	0.00017	0.00237	0.00179	0.00000	5.80	0.00097	0.00034	0.00451	0.00307	0.00000
SG881101	GSC10	50.0	118.1	114.5	6.50	0.00573	0.00148	0.00908	0.01921	0.01874	5.80	0.00944	0.00299	0.01612	0.03213	0.02992
SG881101	GSC14	50.0	101.3	97.1	6.50	0.00525	0.00172	0.00671	0.01255	0.01309	5.80	0.00852	0.00332	0.01231	0.02097	0.02120
SG881101	GSC17	50.0	70.4	64.1	6.50	0.01164	0.00042	0.00351	0.04955	0.04628	5.80	0.01830	0.00086	0.00658	0.08119	0.07438
SG881101	GSC20	50.0	95.0	90.4	6.50	0.05881	0.00216	0.03348	0.09154	0.42038	5.80	0.09493	0.00428	0.06174	0.15284	0.68109
SG881101	GSC5	50.0	113.1	109.3	6.50	0.01316	0.00183	0.00745	0.03356	0.05158	5.80	0.02161	0.00365	0.01334	0.05612	0.08268
SG881101	GSC8	50.0	97.5	93.1	6.50	0.01698	0.00131	0.00956	0.05306	0.03445	5.80	0.02748	0.00257	0.01760	0.08864	0.05584
SG881101	GSC9	50.0	132.5	129.3	6.50	0.00894	0.00153	0.01605	0.01865	0.01638	5.80	0.01489	0.00310	0.02851	0.03112	0.02626
SG881101	ISFL	50.0	325.8	324.5	6.50	0.00082	0.00037	0.00143	0.00200	0.00182	5.80	0.00143	0.00076	0.00269	0.00325	0.00321
SG881101	MIME	50.0	360.8	359.6	6.50	0.00024	0.00005	0.00019	0.00049	0.00045	5.80	0.00043	0.00011	0.00035	0.00082	0.00079
SG881100	DCKY	50.0	198.6	196.6	4.80	0.00179	0.00112	0.00346	0.00700	0.00608	4.50	0.00138	0.00069	0.00241	0.00536	0.00495
SG881100	A11	12.0	127.3	124.0	4.80	0.00134	0.00041	0.00145	0.00537	0.00000	4.50	0.00104	0.00027	0.00102	0.00418	0.00000
SG881100	A16	12.0	118.8	115.2	4.80	0.00127	0.00031	0.00054	0.00707	0.00000	4.50	0.00099	0.00020	0.00039	0.00547	0.00000

SG881100	A21	12.0	125.6	122.2	4.80	0.00155	0.00046	0.00075	0.00813	0.00000	4.50	0.00120	0.00030	0.00052	0.00634	0.00000
SG881100	A61	12.0	100.3	96.1	4.80	0.00205	0.00060	0.00130	0.00966	0.00000	4.50	0.00164	0.00038	0.00094	0.00728	0.00000
SG881100	A64	12.0	107.0	103.0	4.80	0.00121	0.00027	0.00120	0.00828	0.00000	4.50	0.00096	0.00017	0.00086	0.00631	0.00000
SG881100	DPQ	12.0	202.3	200.2	4.80	0.00275	0.00032	0.00235	0.00916	0.00000	4.50	0.00213	0.00020	0.00163	0.00703	0.00000
SG881100	EBN	12.0	232.1	230.3	4.80	0.00033	0.00026	0.00047	0.00141	0.00000	4.50	0.00025	0.00016	0.00032	0.00108	0.00000
SG881100	GGN	12.0	473.8	472.9	4.80	0.00008	0.00017	0.00017	0.00022	0.00000	4.50	0.00006	0.00010	0.00012	0.00017	0.00000
SG881100	GRQ	12.0	390.3	389.2	4.80	0.00084	0.00023	0.00153	0.00182	0.00000	4.50	0.00063	0.00014	0.00106	0.00141	0.00000
SG881100	GSQ	12.0	314.6	313.2	4.80	0.00016	0.00027	0.00049	0.00052	0.00000	4.50	0.00012	0.00016	0.00035	0.00039	0.00000
SG881100	HTQ	12.0	239.3	237.5	4.80	0.00051	0.00010	0.00034	0.00187	0.00000	4.50	0.00039	0.00006	0.00023	0.00145	0.00000
SG881100	KLN	12.0	391.1	390.0	4.80	0.00008	0.00011	0.00017	0.00045	0.00000	4.50	0.00006	0.00007	0.00012	0.00034	0.00000
SG881100	LPQ	12.0	128.3	125.0	4.80	0.00156	0.00056	0.00133	0.00869	0.00000	4.50	0.00121	0.00037	0.00093	0.00676	0.00000
SG881100	MNT	12.0	346.6	345.4	4.80	0.00050	0.00016	0.00063	0.00183	0.00000	4.50	0.00038	0.00010	0.00044	0.00139	0.00000
SG881100	OTT	12.0	460.4	459.5	4.80	0.00034	0.00022	0.00111	0.00100	0.00000	4.50	0.00025	0.00014	0.00077	0.00077	0.00000
SG881100	SBQ	12.0	311.9	310.6	4.80	0.00044	0.00058	0.00099	0.00234	0.00000	4.50	0.00033	0.00036	0.00070	0.00177	0.00000
SG881100	TRQ	12.0	332.1	330.8	4.80	0.00084	0.00022	0.00178	0.00276	0.00000	4.50	0.00063	0.00013	0.00127	0.00209	0.00000
SG881100	WBO	12.0	468.0	467.1	4.80	0.00025	0.00017	0.00069	0.00078	0.00000	4.50	0.00019	0.00010	0.00047	0.00059	0.00000

IC/4PRINT

Tabel 8-4: Scaled horizontal component data

eqid	staid	Lp	hypd	epd	mbLg	pgambLg	f1mbLg	f2p5mLg	f10mbLg	f25mbLg	mw	pgamw	f1mw	f2p5mw	f10mw	f25mw
CG900900	OLAP	0.0	47.7	46.2	5.00	0.03568	0.00093	0.00405	0.05623	0.09801	0.00	0.00000	0.00000	0.00000	0.00000	0.00000
FK820100	2629A	50.0	62.7	62.6	4.80	0.01613	0.00430	0.00661	0.02544	0.05082	4.35	0.01545	0.00394	0.00622	0.02428	0.04836
FK820100	2630B	50.0	76.1	76.0	4.80	0.05449	0.00610	0.00781	0.10544	0.20175	4.35	0.05205	0.00559	0.00732	0.09998	0.19248
ML901000	A11	12.0	418.6	418.4	5.10	0.00037	0.00033	0.00107	0.00081	0.00000	4.70	0.00033	0.00027	0.00091	0.00071	0.00000
ML901000	A16	12.0	437.4	437.2	5.10	0.00041	0.00022	0.00081	0.00081	0.00000	4.70	0.00036	0.00018	0.00069	0.00071	0.00000
ML901000	A21	12.0	466.7	466.5	5.10	0.00256	0.00069	0.00335	0.00451	0.00000	4.70	0.00225	0.00056	0.00287	0.00400	0.00000
ML901000	A54	12.0	407.9	407.7	5.10	0.00076	0.00019	0.00155	0.00161	0.00000	4.70	0.00067	0.00016	0.00132	0.00141	0.00000
ML901000	A61	12.0	437.5	437.3	5.10	0.00055	0.00022	0.00095	0.00118	0.00000	4.70	0.00048	0.00018	0.00081	0.00105	0.00000
ML901000	A64	12.0	456.2	456.0	5.10	0.00042	0.00015	0.00084	0.00089	0.00000	4.70	0.00036	0.00012	0.00072	0.00079	0.00000
NH851200	6097	50.0	9.7	7.6	6.10	0.74987	0.15489	0.34302	1.35298	0.95842	6.80	0.38129	0.03978	0.10903	0.63195	0.48514
NH851200	6098	50.0	9.5	7.4	6.10	0.28396	0.06561	0.17639	0.31322	0.50405	6.80	0.14439	0.01685	0.05607	0.14630	0.25514
NH851200	6099	50.0	23.4	22.6	6.10	0.09275	0.00903	0.02631	0.14101	0.25795	6.80	0.04072	0.00230	0.00785	0.05843	0.11225
NH851100	6098	50.0	18.8	5.5	0.00	0.00000	0.00000	0.00000	0.00000	0.00000	4.60	0.63856	0.02631	0.12093	0.70304	0.73327
NM760300	2415B	25.0	150.5	150.0	0.00	0.00000	0.00000	0.00000	0.00000	0.00000	4.60	0.01825	0.00130	0.00462	0.03113	0.03600
NM910501	OLAP	0.0	114.2	114.0	4.60	0.02289	0.00271	0.00703	0.05030	0.04903	4.25	0.01897	0.00191	0.00522	0.04177	0.04144
NM890400	OLAP	0.0	174.2	173.9	4.70	0.00904	0.00149	0.00193	0.01920	0.01625	4.70	0.00473	0.00045	0.00077	0.01001	0.00889
SG881101	DCKY	50.0	197.0	194.8	6.50	0.01777	0.00261	0.01112	0.03111	0.02018	5.80	0.03071	0.00521	0.02145	0.05042	0.03194
SG881101	EMME	50.0	472.3	471.4	6.50	0.00032	0.00025	0.00058	0.00077	0.00053	5.80	0.00057	0.00050	0.00111	0.00131	0.00095
SG881101	GSC10	50.0	118.1	114.5	6.50	0.01179	0.00369	0.01385	0.03252	0.01491	5.80	0.01945	0.00745	0.02458	0.05439	0.02381
SG881101	GSC14	50.0	101.3	97.1	6.50	0.00448	0.00078	0.00425	0.00724	0.00637	5.80	0.00728	0.00150	0.00779	0.01211	0.01032
SG881101	GSC17	50.0	70.4	64.1	6.50	0.03068	0.00056	0.00566	0.04266	0.08612	5.80	0.04821	0.00117	0.01060	0.06989	0.13840
SG881101	GSC20	50.0	95.0	90.4	6.50	0.02842	0.00253	0.01907	0.05291	0.06054	5.80	0.04587	0.00502	0.03516	0.08833	0.09809
SG881101	GSC5	50.0	113.1	109.3	6.50	0.00189	0.00029	0.00103	0.00265	0.00329	5.80	0.00310	0.00059	0.00185	0.00442	0.00527
SG881101	GSC8	50.0	97.5	93.1	6.50	0.02160	0.00282	0.01360	0.03816	0.03237	5.80	0.03495	0.00552	0.02505	0.06375	0.05248
SG881101	GSC9	50.0	132.5	129.3	6.50	0.01241	0.00305	0.01133	0.02687	0.01849	5.80	0.02068	0.00618	0.02013	0.04483	0.02963
SG881101	ISFL	50.0	325.8	324.5	6.50	0.00112	0.00059	0.00187	0.00186	0.00193	5.80	0.00195	0.00121	0.00352	0.00302	0.00340
SG881101	MIME	50.0	360.8	359.6	6.50	0.00024	0.00006	0.00016	0.00037	0.00037	5.80	0.00042	0.00011	0.00031	0.00062	0.00064
SG881100	DCKY	50.0	198.6	196.6	4.80	0.00283	0.00088	0.00277	0.00778	0.00416	4.50	0.00219	0.00054	0.00194	0.00596	0.00339
SG881100	A11	12.0	127.3	124.0	4.80	0.00139	0.00043	0.00227	0.00453	0.00000	4.50	0.00108	0.00028	0.00159	0.00353	0.00000
SG881100	A16	12.0	118.8	115.2	4.80	0.00182	0.00027	0.00105	0.00630	0.00000	4.50	0.00142	0.00018	0.00075	0.00487	0.00000
SG881100	A21	12.0	125.6	122.2	4.80	0.00318	0.00035	0.00144	0.01142	0.00000	4.50	0.00246	0.00023	0.00101	0.00890	0.00000
SG881100	A61	12.0	100.3	96.1	4.80	0.00385	0.00048	0.00129	0.01016	0.00000	4.50	0.00308	0.00031	0.00094	0.00766	0.00000
SG881100	A64	12.0	107.0	103.0	4.80	0.00213	0.00035	0.00066	0.00767	0.00000	4.50	0.00169	0.00022	0.00048	0.00584	0.00000

APPENDIX C

MAGNITUDE WORKSHOP

JUNE 14, 1994

BOULDER, COLORADO

C.1 PURPOSE OF WORKSHOP

The magnitude measures used in PSHA are different in the tectonically active western United States and in the more stable parts of the country. In the west, the moment magnitude is the most commonly used magnitude, whereas in the rest of the country the shorter-period magnitude m_{bLg} is used. To some extent this difference in usage stems from historical reasons. The chairmen of the SSHAC subcommittees on Seismicity and Source Characterization (Kevin J. Coppersmith) and Ground Motion (David M. Boore) organized a workshop to discuss whether the existing usage of magnitudes should continue, or whether the SSHAC recommendation should be that one magnitude measure be used for PSHA throughout the country and if so, which one.

C.2 BACKGROUND DISCUSSION

Decisions regarding which magnitude to use should be guided by this fundamental question: what magnitude will lead to the smallest uncertainty in the PSHA results? The answer to this question depends on many factors, and may depend on the period of ground motion for which PSHA results are being computed. The interplay between SSC and ground motion needs is crucial and can be complex. An ideal magnitude from the point of view of those predicting ground motion is useless if that magnitude cannot be predicted for future events in the region for which a PSHA is being computed. A few background comments are given here for those readers not familiar with the various magnitudes, how they influence ground motion predictions, and how they are typically determined for use in a PSHA.

Moment magnitude (**M**) is simply related to the seismic moment of an earthquake through the equation $\mathbf{M} = (2/3) \log M_0 - 10.7$ (Hanks and Kanamori, 1979, equation 7). The seismic moment is determined from the area and amount of slip across the rupture surface or from waves at periods great enough that the wavelengths exceed the dimensions of the rupture surface. m_{bLg}, on the

other hand, is measured from the peak amplitudes of seismographs with natural periods between about 0.2 and 10 seconds.

A critical question is how the magnitudes are determined for previous events. In the tectonically active parts of the United States earthquakes occur frequently enough that the seismicity catalogs required for PSHA can rely almost entirely on instrumentally-recorded earthquakes. This is in distinct contrast to the other parts of the country, where historical descriptions of damage (intensity) must be used. In the latter case, correlations between intensity measures and the magnitudes, developed from instrumental data from the region under consideration or by combining data from similar regions throughout the world, are used to assign magnitudes.

In the tectonically-active regions, seismic moment is, without question, the preferred magnitude. There is not only a large body of instrumental data, but also paleoseismological studies of slip rates and recurrence on faults can be used in PSHA. Because of this, the main focus in the rest of this Appendix will be on what magnitudes to use for PSHA in other parts of the country. In other parts of the country m_{bLg} is the commonly-used magnitude. This is to some extent due to its invention by Otto Nuttli, who had a great interest in earthquakes in central and eastern United States; Prof. Nuttli not only invented the magnitude, but he also derived ways to relate it to intensity. It is also true that recurrence statistics must often by computed from the statistics of events with magnitudes less than about 3.5, and the catalog of instrumentally recorded events for such small earthquakes is almost exclusively in terms of m_{bLg}. In the last few years, however, a major project has been completed that has made significant progress on using seismic intensities to determine moment magnitudes for historical earthquakes (Johnston et al, 1993, Johnston, 1995a, 1995b, 1995c).

How are magnitudes used in predicting ground motions? A basic understanding of this can be obtained by considering a simple, and commonly used, spectral scaling model. Figure C1 shows the source acceleration spectra for M = 6.5 and 7.5 earthquakes, for two values of the stress parameter. Note that by definition, the curves differ by a factor of $10^{1.5}$ at low frequencies (the levels of this part of the spectra are directly proportional to seismic moment). The stress parameter is introduced to allow for variable amounts of high-frequency radiation for a fixed seismic moment. This parameterization has been used to analyze many earthquakes in the United States, and therefore some statistics are available on the stress parameters. Returning to Fig. C1, note that predictions of ground shaking will be most sensitive to stress parameter variations at the higher frequencies of most interest to earthquake hazard reduction (the stress dependence of the ground motion for different oscillator frequencies is shown in Fig. C2 for a fixed moment magnitude). On the other hand, if the spectra had been plotted for two magnitudes defined at 1 Hz, for example,

then by definition the spectra at high frequency would be independent of the stress parameter (the high frequency spectral level goes as $M_0^{1/3}\Delta\sigma^{2/3}$, and earthquakes with different stress parameters can lead to the same high frequency levels if their seismic moments differ so that the level stays the same); in this case, the variation in the spectral levels shifts from high frequency to low frequency. Ground motions are often computed using spectral scaling models such as these, particularly in the central and eastern United States. It is clear that predictions of ground motions at the higher frequencies in terms of **M** will be subject to aleatory uncertainty due to variable stress parameters. It would seem to make sense, then, to use a higher-frequency measure of magnitude, such as m_{bLg}. As we will shortly discuss, there are practical difficulties in determining m_{bLg} that can introduce considerable epistemic uncertainty in that measure. Recently, Atkinson and Hanks (1995) have proposed a magnitude (**m**) that is proportional to the high-frequency level of the acceleration source spectra. This would be the ideal measure if seismic recurrence can be derived in terms of **m**. Atkinson and Hanks demonstrate that **m** can be determined from intensity observations with equal or less uncertainty than **M**. Discussion at the workshop involved all three magnitudes.

It is not necessarily a straightforward matter to shift between magnitude measures. Most methods for predicting ground motions in the central and eastern United States use the moment magnitude as a fundamental parameter, and the seismicity and earthquake recurrence is usually given in terms of m_{bLg}. According to the previous discussion, the ground-motion predictions should be done for a range of stress parameters and seismic moments that all give the specified short-period magnitude. This is seldom done, and requires additional assumptions about instrument type, attenuation of waves with distance, and so on. Empirical relations have been used, but these are not well-determined from data. This is shown in Fig. C3. The data in Figure C3 can be fit with a straight line, but all theoretical calculations find that the relation should be curved. Unfortunately, the curvature is most pronounced for the magnitudes for which there is little data. As shown in the figure, uncertainty in correlation of magnitudes can lead to ground-motion uncertainties of a factor of 2 at large magnitudes.

C.3 ORGANIZATION OF THE WORKSHOP

The workshop was held on the afternoon of June 14, 1994, at the Boulderado Hotel in Boulder, Colorado, immediately following the SSC workshop described in Appendix H. Many of the attendees at the SSC workshop were encouraged to stay for the Magnitude Workshop. The list of attendees is given in Table C1. The agenda for the workshop was very simple. After a welcome and introduction by the organizers, Dr. Gail Atkinson presented a review of the new magnitude **m**

and her views and studies related to the fundamental question of the workshop (her presentation has been published as Atkinson, 1995). The rest of the workshop consisted of a group discussion first of Dr. Atkinson's presentation and then directed toward the questions of whether **M** or **m** should be used for all PSHA.

C.4 SUMMARY OF PRESENTATION

Dr. Atkinson studied the residuals between observed ground motions and predictions made in terms of the three magnitudes **M**, **m**, and m_{bLg} (which she calls m_N). Her conclusions from the residuals are best summarized in the following quote from her paper (Atkinson, 1995):

> "The optimal choice of magnitude scale for seismic hazard evaluation is that which reduces random uncertainty in ground motion predictions to the lowest possible levels. For moderate earthquakes, **M** is optimal for frequencies of 2Hz or less, while **m** is optimal for greater frequencies. m_N is not an optimal choice in any frequency band. If a single magnitude scale is to be used, then **m** will be the best choice in most cases, for two reasons: (i) for large (**M**>6) events, it will yield the lowest uncertainty in predicted ground motions over the primary frequency and of engineering interest (1 to 10 Hz); and (ii) it is the only magnitude that can be reliably determined for both modern and pre-instrumental earthquakes."

As discussed in the previous section, the high-frequency spectral level of ground motion is controlled by seismic moment and the stress parameter (which is also commonly referred to as the "stress drop"). Dr. Atkinson considered using the stress parameter as an additional parameter in ground motion predictions, with these conclusions (also taken from Atkinson, 1995):

> "An alternative to using a high-frequency magnitude scale in hazard analysis would be to include stress drop as a predictive variable in ground motion relations (M. Chapman, personal communication, 1994). We could estimate ground motion amplitudes at all frequencies, with minimal scatter, from **M**, stress drop, and distance, and then integrate over these variables in the hazard analysis. However this would require explicit specification of the stress drop distribution for each source zone (since high-frequency amplitudes depend on both **M** and stress drop). The advantage of using **m** is that it obviates this need, because it implicitly carries the required high-frequency information that is provided by moment and stress drop."

C.5 DISCUSSIONS AND CONCLUSIONS

After Dr. Atkinson's presentation of these results and conclusions, there was considerable discussion among the attendees. The discussion was initially focused on the idea of using **m** as the sole magnitude. In view of the work of Johnston and colleagues (Johnston et al, 1993; Johnston, 1995a, 1995b, 1995c), it was not generally agreed that "it is the only magnitude that can be reliably determined for both modern and pre-instrumental earthquakes". On the other hand, there was considerable interest in **m**. Noting, however, that it has not been sufficiently tested (for example, in western North America), the general consensus was that **m** should not be used for PSHA during the short-term. There was strong agreement, however, that **m** shows much promise and that a vigorous evaluation of **m** should be made for possible future use as the magnitude of choice in PSHA.

The discussion then turned to a consideration of moment magnitude, **M**; should it replace m_{bLg}? It was noted that any magnitude measure has pros and cons: for m_{bLg}, the pros are that it is the magnitude used for seismicity catalogs, and that ground motions for a specified m_{bLg} should be less variable at periods of interest than for those for a given **M**; the cons are that the catalog values are not particularly well determined, both instrumentally (because of differences in response of the seismographs and in analysis procedures) and from pre-instrumental earthquakes (which are usually based on an epicentral intensity, I_0), and is not a natural parameter in the usual methods for predicting ground motions. For **M** the pros are that it is a natural variable for ground-motion models and that it is can be determined from paleoseismological information; its cons are that it is a measure of motion at long periods and therefore ground motions computed using it are subject to variability due to variability in the stress parameter.

One of the apparent advantages of m_{bLg} is that the seismicity catalog uses it as the magnitude measure. There was considerable discussion about whether **M** could be determined for the earthquakes in the catalog. It is clear that this can be done for larger events, for which the area enclosed within intensities of various levels are available. The main problem would be with the smaller events, for which the only data are either I_0 or difficult-to-digitize instrumental recordings from seismographs of limited bandwidth. There was general optimism, however, that the seismicity catalog could be restructured in terms of **M**.

The following conclusions were reached by the participants:

1. Keep the status quo for the time being (**M** for PSHA in the west, m_{bLg} for PSHA in the rest of the country).

2. Initiate a project to redo the seismicity catalog in terms of **M**. It was felt that this project could be completed within a few years, and the consensus was that **M** would then become the standard analysis for PSHA (for a length of time depending on the outcome of the next recommendation). It is essential that SSC experts be involved in the effort to do the magnitude conversions.

3. Encourage in-depth evaluation of the newly proposed magnitude **m**.

TABLE C1
PARTICIPANTS IN MAGNITUDE WORKSHOP
JUNE 14, 1994

Gail Atkinson
Don L. Bernreuter
David M. Boore
Kevin Coppersmith
Arch C. Johnston
Jeffrey K. Kimball
Carl Kisslinger
Joe J. Litehiser, Jr.
Jean B. Savy
John F. Schneider
J. Carl Stepp
Gabriel R. Toro

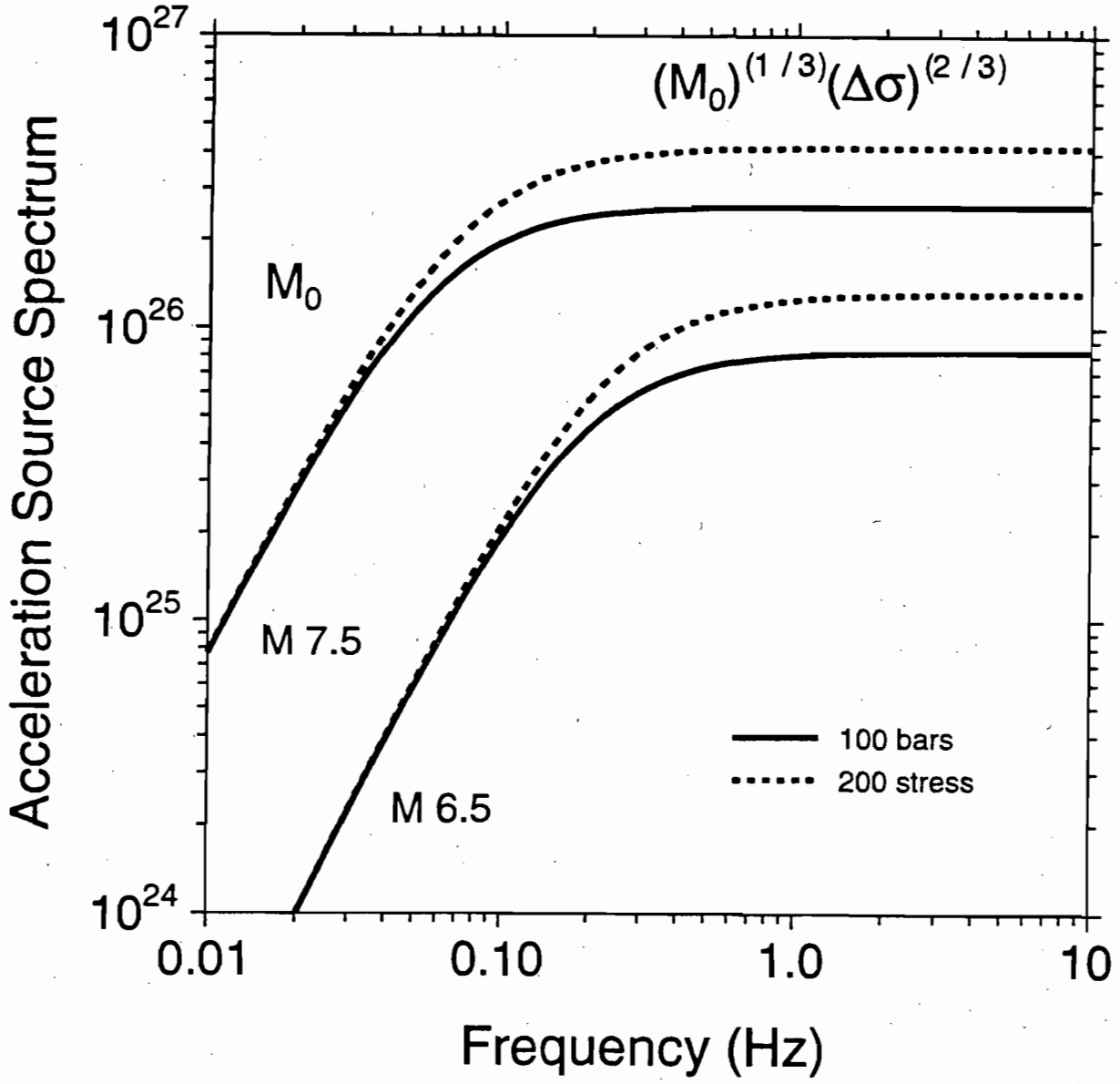


Figure C-1 Source acceleration spectra for moment magnitudes 6.5 and 7.5 and stress parameters of 100 and 200 bars. The low-frequency and high-frequency spectral levels scales as seismic moment (M_0) and seismic moment to the 1/3 power times stress parameter ($\Delta\sigma$) to the 2/3 power, respectively.

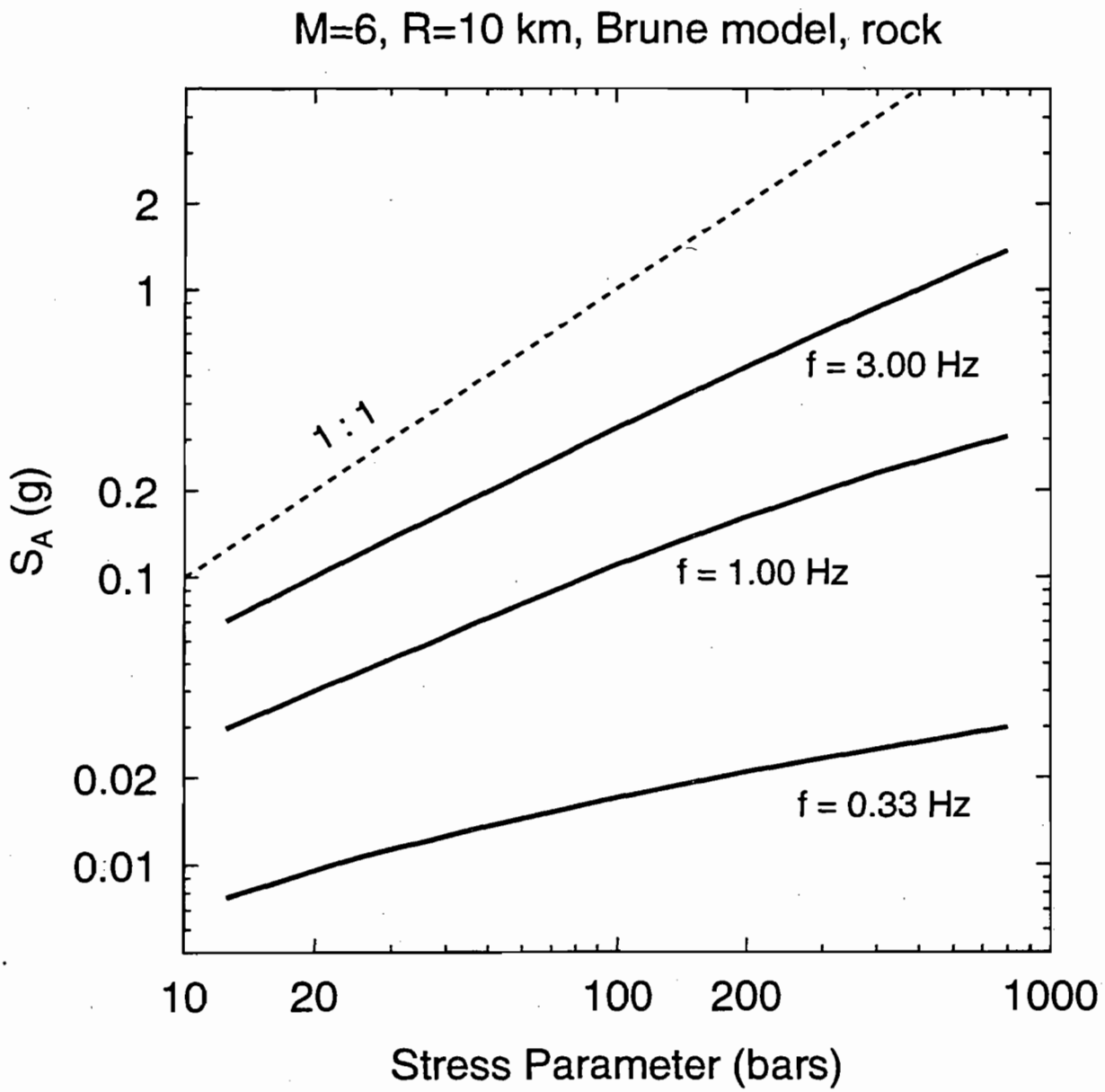
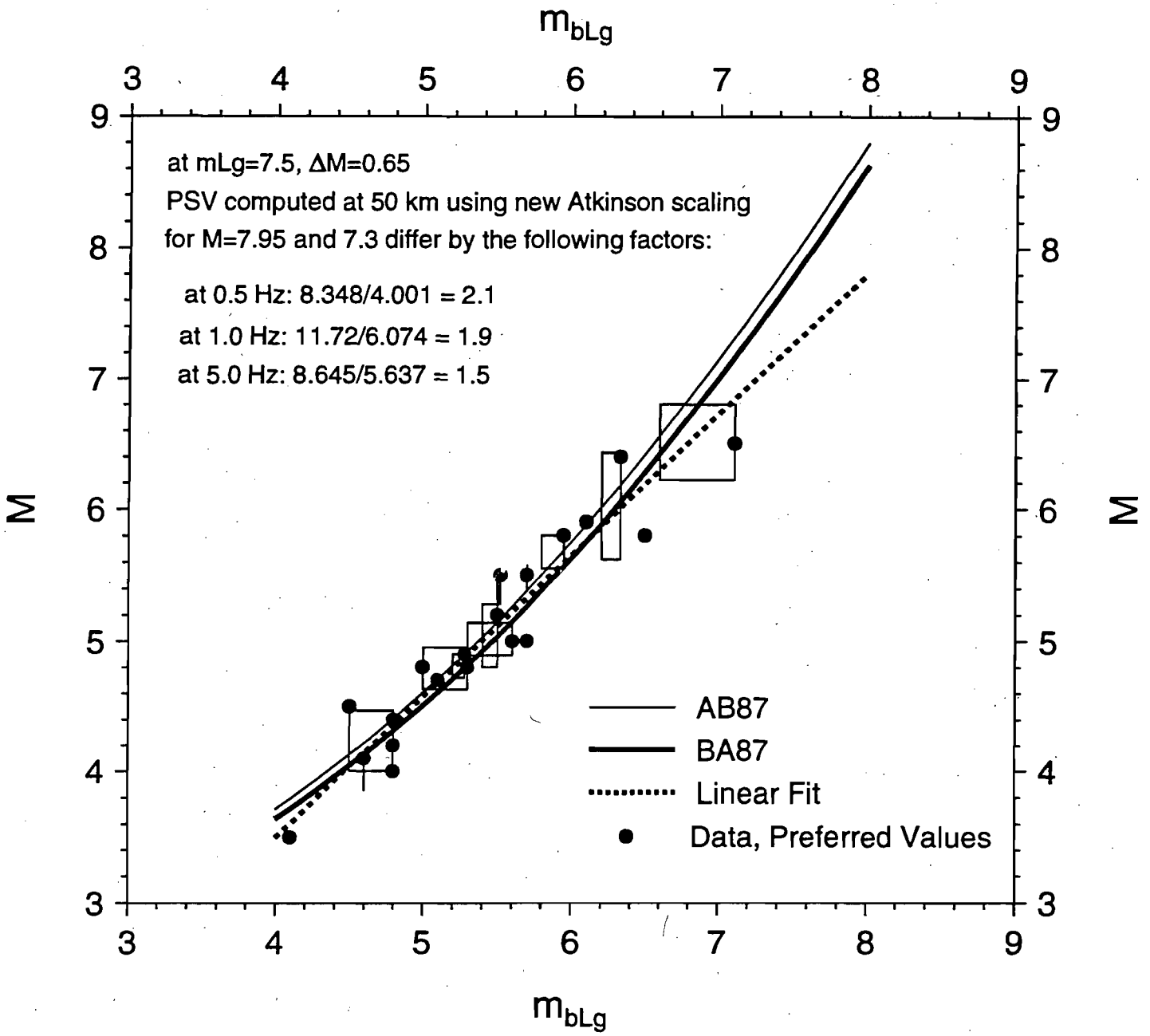


Figure C-2 **The dependence of acceleration response spectra on stress parameter, for a fixed distance of 10 km and a seismic moment of 6.0. The dependence is shown for oscillator frequencies of 0.33, 1.0, and 3.0 Hz. The dashed line shows a 1:1 ratio, for reference. Note that the dependence on stress parameter is greater for higher frequencies.**



mmnsshac.grg mmndata1.gra Dec 5, 1994 2:37:07 pm mmndata2.gra Dec 5, 1994 2:37:07 pm

m4sshac.gra Dec 5, 1994 2:37:07 pm D. M. Boore

Figure C-3 M versus M_{blg}, adapted from Boore and Atkinson (1987). The curves labeled "AB87" and BA87" are from Atkinson and Boore (1987) and Boore and Atkinson (1987), respectively. The boxes indicate the range of values, with the preferred values given by the solid dots. The difference in ground-motion predictions for two possible moment magnitudes estimated for a short period magnitude of 7.5 is summarized in the notes in the upper left-hand corner of the figure.

APPENDIX D

LESSONS LEARNED FROM LLNL ELICITATION OF GROUND MOTION

by

Richard W. Mensing

The basic seismic hazard calculation involves evaluating the sum:

$$\sum_k \lambda_{ok} \int_r \int_m P\left(GM > a_o \mid m,r\right) dH_k\,(m)\, dG_k(r) \qquad (1)$$

where λ_{ok} is the expected number of earthquakes, per time period and unit area, in the kth area of homogeneous seismicity; H_k (m and G_k (r) are the magnitude and distance (from the site) distributions applicable to the kth area and P (·) is the conditional complementary distribution function of the ground motion measure, e.g., peak ground acceleration.

The important point to be recognized, from the perspective of eliciting ground motion, is that the ground motion information needed for a seismic hazard (SH) assessment is the conditional frequency distribution of ground motion at a site, conditional on earthquakes of magnitude m occurring at distance r from the site, for all m, r. Recognition and acceptance of this fact influences the elicitation of ground motion information. A second important point is the need to have a clear understanding of what the distribution represents. In principle, given a site, the distribution represents the potential variation in the ground motion measure at the site among all earthquakes of magnitude m occurring at locations which are r distance units from the site. There are many causes for this variation. One cause is the variation in the source characteristics at the different locations which are the same distance from the site. Similarly, differences in the earth's structure between the site and these different locations will cause the characteristics of the seismic waves travel paths to be variable and contribute to the variation in the ground motion measure at the site. Identification and representation of the variation in the ground motion attributable to them is an important issue relevant to elicitation of ground motion. This issue will be discussed further in the succeeding sections.

The purpose of this paper is to identify some of the lessons learned by EPRI and LLNL during their past experiences developing ground motion information. Hopefully, describing these experiences will be helpful in developing a sound credible methodology for eliciting ground motion information needed for SH assessments. Section 2 outlines LLNL's experiences eliciting ground motion information using panels of experts. Several lessons learned are highlighted. The EPRI experiences, lessons learned and a discussion of their current approach and position regarding ground motion models are the topics of Section 3.

LLNL's Experiences Eliciting Ground Motion Information (R. Mensing, LLNL)

LLNL's efforts at deriving ground motion information has been based on eliciting the judgments of experts. The initial efforts were based primarily on having experts make judgments about ground motion models and the level of random variation as quantified by the standard deviation of the natural logarithm of the ground motion measure. The primary lessons learned from the initial elicitations were:

Lesson 1: Asking experts to weigh ground motion models is <u>NOT</u> a good way to elicit the needed ground motion information

Lesson 2: Experts have difficulty quantifying the standard deviation of the natural logarithm of a ground motion measure

Having experts weigh ground motion models is based on the assumption that the variation in ground motion, conditional on m, r, is best described by a lognormal distribution. In this case, ground motion models are descriptions of the expected value (mean) of the natural logarithm of a ground motion measure as a function of m, r, and, perhaps, other variables. Having experts weigh ground motion models was an attempt to quantify their uncertainty in specifying the expected value as a function of m, r. This was not successful because:

- It is asking the <u>wrong</u> question; to ask experts to weight models directs their attention to the models instead of the parameter of interest—the expected value or mean of the logarithm of the ground motion measure.

- Weighing models is a very restrictive way of asking experts to quantify the level of evidence of their state of knowledge regarding the parameter of interest—the expected value

Quantifying the standard deviation is difficult because:

- It is a mathematical concept and does not have any physical meaning; this forces the experts to rely on statistical calculations to provide values; these calculations are data and model dependent; thus, the experts provide a WIDE range of estimates

- There is a lot of uncertainty, lack of understanding, and lack of knowledge regarding what sources of variation should be included in the standard deviation and what, if any, variation is accounted for in the variation between different ground motion models

Overall, the lessons learned were that asking experts to weigh models and estimate the standard deviation were <u>not</u> the appropriate way to elicit ground motion information.

Prior to LLNL's most recent attempt to elicit ground motion information, a workshop on eliciting ground motion information was held (Ref. 1*). The workshop involved discussion and interaction with a panel of experts on eliciting and aggregating expert opinions. Based on the panels deliberations, it was clear that any approach to eliciting ground motion information must concentrate on the ground motion distribution. Based on the recommendations of the panel, LLNL's most recent elicitation was based on eliciting

1) The distributional model for the conditional ground motion distribution

2) The experts' probability distributions for the parameters of the conditional ground motion distribution as a function of m, r

With regard to the distributional model, the lesson learned was:

Lesson 3: The lognormal model is the accepted distribution model for the conditional ground motion frequency distribution, given m, r.

Based on the experts' 100 percent selection of the lognormal model, elicitation of the parameters was based on eliciting the experts' probability (uncertainty) distribution of the expected value and standard deviation of the logarithm of the ground motion measure at several pairs of values of m, r spanning the ranges of m and r. LLNL's experience in this elicitation was much more positive, at least with regard to the expected value. the lesson learned was:

Lesson 4: Experts are able to quantify their judgments about the expected value of the lognormal conditional ground motion frequency distributions as a function of m, r, the experts concentrated on specifying their judgments about the value of the expected value and their uncertainty/level of evidence about that value, rather than on the "quality" of ground motion models, i.e. they focused on the parameter of interest.

The experts' probability distributions were elicited in terms of bounds and a most likely value. Although one or two gave values as a function of m, r directly, most expressed their state of knowledge by providing a recipe for assessing the bounds and most likely value as a function on m, r in terms of:

- Weighted combinations of ground motion models for the bounds and most likely value as a function of m, r

- A weighted combination of ground motion models for the most likely value and multiplying factors, as a function of m, r, for the bounds

Overall, the quality of information about the expected value accumulated in the latest elicitation was considered quite satisfactory and certainly much better than the earlier elicitations. On the other hand, even wit considerable concentrated efforts at improving the information about the standard deviations, the results are not encouraging. The latest LLNL approach included trying to have experts assess fractiles of the ground motion frequency distributions as a function of m, r. This was not successful; most experts are strongly committed to assessing the standard deviation. Thus, the lesson learned was:

Lesson 5: There is a need to derive information about the random variation in ground motion, given m, r, in some other way than direct elicitation from experts.

One hypotheses for the possible difficulties in eliciting consistent assessments of the standard deviation between experts is a lack of clear understanding of the sources of variation represented by the random variation in ground motion. Conceptually, a ground motion measure can be modeled as

$$\ln GM = a_o + f_1(m,r) + f_2(u_1, u_2 \ldots\ldots) + E$$

where f_1 (m, r) represents the dependence on m, r, f_2 (u_1 , u_2 .....) introduces the influence of the source and attenuation variables, e.g. stress drop, fault parameters, travel path parameters; and E represents stochastic and unmodeled variation. [Note: site effects are generally modeled separately, hence, are not included in the discussion.] An important issue is the inclusion of the source and attenuation variables, i.e., f_2 (u_1 , u_2.....). The inclusion of these variables affects the ground motion models in two ways:

1) It affects the values of the coefficients associated with m and r in f_1 (m, r)

2) It affects the statistical estimate of the standard deviation associated with the stochastic variation term E

Inclusion or non-inclusion of f_2 (u_1, u_2.....) varies between models. In addition, the extent to which the source and attenuation variables vary between data sets used to develop ground motion models and estimates of the standard deviation are likely to vary considerably. Also, LLNL's experience is that some experts are basing their bounds for the expected value on the ranges of these source and attenuation variables. That is, the variation in ground motion due to the variation in f_2 (u_1, u_2.....) is included in uncertainty. Is this the correct representation? If so, how can it be assured it is not included in the stochastic variation?

For example, consider stress drop, a source parameter. Three potential representations of variation in stress drop are:

1) Stress drop is a constant over location but its value is unknown

2) Stress drop is a physical variable which varies between locations, hence is a stochastic variable; its distribution is known

3) Stress drop is a physical variable, hence is stochastic; its distribution is unknown

In Model 1, the level of stress drop affects the level of ground motion, hence its expected value. Since its contribution to the ground motion is unknown, it can only be estimated with uncertainty. Hence, under the model, stress drop uncertainty contributes to uncertainty in the expected value of the ground motion measure. In Model 2, since stress drop is a stochastic variable, it contributes to the stochastic variation in the ground motion measure, i.e., it contributes to the standard deviation of the logarithm of the ground motion measure. In Model 3, stress drop contributes to both stochastic variation and uncertainty. The uncertainty in the expected value of the distribution of the stress drop contributes to the uncertainty in the expected value of the logarithm of the ground motion measure variability stress drop, identified by standard deviation, contributes to the stochastic variation of the ground motion measure; and its uncertainty contributes to the uncertainty in the standard deviation of the logarithm of the ground motion measure.

Overall, another lesson learned was:

Lesson 6: There is a definite need to identify and clearly understand the various sources of variation in ground motion and to partition these sources into those that contribute to uncertainty in the expected value and those that contribute to stochastic variation and, hence, the standard deviation.

This suggests that a meaningful exercise would be to have a small select group interact on the problems of ground motion variation. Perhaps, such a discussion could lead to a clearer understanding and a consensus assessment of the standard deviation representing stochastic variation.

On additional lesson came out of the workshop with the panel on expert elicitations. It was their recommendations that the ground motion information derived from experts be aggregated prior to combining it with seismicity information in the seismic hazard calculations. Thus, assuming the lognormal distribution and basing the elicitation on the expected value and standard deviation as a function of m, r, the lesson learned was:

Lesson 7: Individual joint probability distributions for the expected value and standard deviation, as a function of m, r should be combined to create an aggregate joint probability distribution as a function of m, r.

This recommendation leaves an open issue-how to create the aggregated joint probability distribution as a function of m, r.

APPENDIX E

EMPIRICAL SOURCE/THEORETICAL PATH MODELING METHOD

by
Dr. Norman Abrahamson

E.1 INTRODUCTION

The empirical source/theoretical modeling method for predicting strong ground motions (Somerville and Saikia proponents) has been described in several papers (Wald et al., 1988; Somerville et al., 1991; and Cohee et al., 1991) but these papers do not provide a full description of the method as it is now used. This write-up provides a more complete description of the current state of the method.

This method has also been called the semi-empirical source function method. The terminology for this method has been a source of confusion in the past. In this write-up, I've used a terminology that differs from Somerville, but I think it is easier to follow.

In general terms, the semi-empirical source method computes the ground motion from finite faults. The basic methodology for estimating mainshock ground motions by summing ground motions from small events is similar to other finite-fault methods. The fault is divided into discrete sub-fault elements. The ground motion for each sub-fault element is estimated by summing the ground motions from a number of subevents with appropriate time lags. Large scale asperities are introduced by varying the slip distribution over the fault surface (sub-fault elements). The mainshock motion is then computed by scaling and lagging the motions from these sub-fault elements to simulate the propagation of the rupture over the fault surface.

The details of computing the subevent motions and the sub-fault element motions is the main difference between this method and other finite-fault methods. Conceptually, the method is a generalization of the empirical Greens function (EGF) method.

In the EGF method, recordings from small earthquakes distributed over the source zone and recorded at the site of interest are used to represent the Green's functions including the sub-event source, wave propagation, and site-specific response effects. The ground motion for a

larger earthquake is computed by summing the EGFs with the appropriate time delays and scaling to represent the mainshock source rupture process. The strength of this method is that the site specific path and site effects are included directly.

In the ideal case, the hypocenters of the small earthquakes used as EGF are distributed such that they cover all of the sub-fault elements. Also, the EGF should have the same focal mechanism as the mainshock. The main drawback to this method is that most sites for which we want to estimate ground motion have few if any recordings of small earthquakes and the earthquakes do not cover the entire fault rupture surface.

The empirical source function/theoretical path (ESF/TF) method addresses this short coming of the EGF method by providing a procedure for transporting EGFs from a well recorded earthquake to different sites and source mechanisms. The method provides a means of transporting the stochastic information in the EGF to other sites and sources while accounting for the deterministic effects of differences in the site, crust (path), and source mechanisms. A key assumption of the method is that the unmodeled effects in the 0-15 km distance range apply equally to all phases at all distances. This assumption is discussed in more detail in the summary.

E.2 STEPS IN THE EMPIRICAL SOURCE FUNCTION METHOD

As an outline, the steps involved in the empirical source function method are described below.

1. Develop a set of empirical source functions.
   - 1a. Select a well recorded small earthquake for use as EGFs.
   - 1b. Remove the first order effects of the wave propagation from the EGFs. This gives a set of "reduced" EGFs.
   - 1c. Decompose the reduced EGFs into SH, SV, and P waves on the vertical, radial, and transverse components and classify each wavelet by its theoretical radiation pattern amplitude. This gives a set of empirical source functions.

2. Compute the motions for a subevent for the new source and site. (This step is repeated for each sub-fault element and for each wave type).

   2a. Compute the theoretical GF for the new site.

   2b. Compute the theoretical radiation pattern

   2c. Select an empirical source function with a radiation pattern amplitude that is similar to the theoretical valued computed in step 2b.

   2d. Convolve the selected empirical source function with the theoretical GF from step 2a.

   2e. Apply a receiver correction to account for the effect of the incidence angles and velocity structure on the partitioning of the waves onto the vertical, transverse and radial components.

3. Compute the sub-fault element ground motions

   3a. Estimate the mainshock and subevent rise-times.

   3b. Compute the number of subevent "firings" for each sub-fault elements from the ratio of the mainshock rise-time over the subevent rise-time.

   3c. Lag the subevent ground motions by the subevent rise-time (with some randomness in the lag times) and sum the lagged ground motions.

4. Compute the mainshock ground motions

   4a. Develop a slip distribution for the finite fault and select a hypocenter location.

   4b. Scale the sub-fault ground motions by the slip amplitude for the given sub-fault element (scaling is normalized such that the total moment is equal to the mainshock moment).

4c. Lag the subevent ground motions to account for the rupture velocity (with some randomness in the lag times).

4d. Sum the lagged and scaled ground motions from the sub-fault elements.

These steps are described in more detail below.

E.2.1 Develop the Set of Empirical Source Functions

Before the method can be used, the set of empirical source functions need to be developed. This is the major overhead involved in this procedure and makes the procedure more difficult to use, however, it only needs to be done once for each set of EGF.

Select a small earthquake that is well recorded in the near source region. A requirement is that this small earthquake must have a reliable estimate of the moment and the focal mechanism. (To have confidence is using the method, the recorded ground motions should be able to be modeled. If the waveforms cannot be modeled accurately, then the concept of breaking the ground motion down into its basic components and the recombining them in a different way based on understanding the source is not appropriate.)

The EGFs are then modified to remove the first order effects of the wave propagation. The theoretical Green's function is computed for each site that recorded the small earthquake. The theoretical Green's function could be deconvolved from the recorded empirical Green's function (e.g. Jacob and Horton method), however, due to zeros in the theoretical spectrum, this deconvolution is often unstable. Since the EGF are recorded at close distances (within about 1-2 source depths), the direct waves will dominate the GF. To capture the first order effects of the wave propagation, only the direct wave is used in the theoretical GF calculation. These theoretical Green's functions are quite simple; they are typically close to a step function. The deconvolution can be approximated by dividing the EGF by the amplitude of the step function, G_0. This amplitude is computed from the ratio of the maximum amplitude of the EGF convolved with the theoretical Green's function to the maximum amplitude of the EGF. That is

$$G_0 = \frac{\max[S(t) * G(t)]}{\max[S(t)]}$$

where S(t) is the EGF and G(t) is the theoretical GF for the desired wave type (P, SV, or SV waves). At this point, we have a set of reduced empirical Green's functions.

The reduced EGFs at each recording site are separated into P-wave and S-wave time windows and then decomposed into SH, SV, and P wavelets on the transverse, radial, and vertical components. The three components from the EGF lead to 5 wavelets: SH_t, SV_z, SV_r, P_z, P_r.

Each wavelet is then classified by its expected radiation pattern amplitude (see Figure 1). The expected radiation pattern amplitude is the theoretical value for the double couple source. The classification is done using the absolute value of the amplitude of the expected radiation pattern (e.g. between 0 and 1). The sign of the radiation pattern is noted as well for later use (to allow the correct polarity to be included). This gives a set of empirical source functions (ESF).

From this point on, the ESFs from a single site are no longer kept together. That is, each ESF is treated independently and is just classified by the expected radiation pattern amplitude. This is a key difference from the EGF method which keeps the three components together. By separating the components, the procedure can be used to estimate ground motions for focal mechanisms other than the mechanism of the small earthquake used for the EGF. This allows the method to transport the EGFs to other source mechanisms.

The term empirical source function is used here because the dominate features in the wavelets should be due to the source; however, the ESF do contain other effects than just the source. For example, since only the direct wave amplitude is used to remove the wave propagation effects, any complexities, such as scattering will still be present in the ESF.

Receiver Correction

The partitioning of the waves into the horizontal and vertical components depends on the angle of incidence of the waves. In general, this angle may be different for the desired site than for the site that recorded the EGF due to differences in the velocity structure at the sites. To account for this difference, a receiver correction is applied to the ESF. This correction is approximated by the ratio of the theoretical whole-space receiver functions which results in the following relations:

$$P_z' = \frac{1}{2}\left(\frac{\alpha_1}{\alpha_2}\frac{\cos i_2}{\cos i_1}\right)P_z + \frac{1}{2}\left(\frac{\alpha_1}{\alpha_2}\frac{\cos i_2}{\cos i_1}\right)P_R$$

$$P_R' = \frac{1}{2}\left(\frac{\alpha_1}{\alpha_2}\frac{\sin i_2}{\cos i_1}\right)P_z + \frac{1}{2}\left(\frac{\alpha_1}{\alpha_2}\frac{\sin i_2}{\sin i_1}\right)P_R$$

$$SV_Z' = \frac{1}{2}\left(\frac{\beta_1}{\beta_2}\frac{\sin i_2}{\sin i_1}\right)SV_z + \frac{1}{2}\left(\frac{\beta_1}{\beta_2}\frac{\sin i_2}{\cos i_1}\right)SV_R$$

$$SV_R' = \frac{1}{2}\left(\frac{\beta_1}{\beta_2}\frac{\cos i_2}{\sin i_1}\right)SV_z + \frac{1}{2}\left(\frac{\beta_1}{\beta_2}\frac{\cos i_2}{\cos i_1}\right)SV_R$$

$$SH'_T = \left(\frac{\beta_1}{\beta_2}\frac{\sin i_2}{\sin i_1}\right)SH_T,$$

where a_1, b_1, and i_1 are the P and S velocities and incidence angle at the site at which the empirical GF was recorded and a_2, b_2, and i_2 are similar parameters at the site of interest.

E.2.2 Subevent Ground Motions

To compute the ground motions from a subevent, the theoretical radiation patterns for the P, SH, and SV components are computed for each sub-fault element. Using the set of ESF as a library, the ESF whose radiation pattern amplitude is similar to the desired radiation pattern amplitude is selected (Figure 2). Specifically, a weighting function, given by a normal distribution centered at the desired radiation pattern amplitude is used to assign a weight to each ESF. The standard deviation of the weighting function is about 0.1 radiation pattern amplitude units. The weights are normalized such that they sum to unity, then the distribution of ESF is then sampled using these weights.

In initial applications of this model, the ESF with the radiation pattern amplitude closest to the desired amplitude was selected (e.g. it was given weight of 1 and all others were given a weight of zero). A drawback of this simpler approach is that if there were several ESF with similar radiation pattern amplitudes then one may be sampled much more often then the others. Consider, for example if three ESF had similar radiation pattern values, then the one in the middle would almost never be selected. Using a weighting function makes the resulting ground motion simulations less sensitive to the set of ESF used. Using a weighting function also allows different ESF to be selected for a given sub-fault element which provides an additional source of randomness.

The ESF are then convolved with theoretical GF computed for the new site using the generalized rays method (Helmberger and Harkrider, 1978). Only the direct P and S waves and the primary reflections from each layer below the source are included in most applications of the model, however, more complete GF could be computed if desired. (For example, in the EUS, more rays are needed to build up LG waves.)

After applying the receiver function correction discussed earlier, we have the ground motions at the site from the subevent. We then need to combine the subevent ground motions to estimate the sub-fault element ground motions and then combine the sub-fault element ground motions to estimate the mainshock ground motions.

E.2.3 Estimation of Sub-Fault Ground Motions

The sub-fault element ground motion is computed by lagging and summing a number of subevent ground motions.

The number of subevents summed in each sub-fault element is given by the ratio of the mainshock and subevent rise-times. The subevent rise time is estimated as part of the modeling of the subevent that was needed to determine its moment and mechanism. The mainshock rise-time is estimated from empirical relations developed by Somerville (1991):

$$\log_{10} \text{Rise} - \text{Time(sec)} = -8.76 + \frac{1}{3} \log_{10} M_o$$

The number of subevents per sub-fault element, N_{sub}, is given by

$$N_{sub} = RT \frac{RT_{MS}}{RT_{sub}}$$

The sub-fault element ground motions are computed by summing the lagged The delay time for the ith subevent is given by

$$LagTime_i = (i-1)RT_{sub} + \varepsilon$$

where e is a random variable from a normal distribution with mean 0 and standard deviation of $RT_{sub}/6$. The stochastic component to the time lags is included to avoid building up periodicities in the ground motion. The amount of variability was determined by trial and error during initial calibration of the method.

For each of the N_{sub} ESF required to be summed, a separate sampling of the ESF library is made. Therefore, the N_{sub} ESF used to estimate the sub-fault element ground motion are not necessarily the same.

E.2.4 Estimation of Mainshock Ground Motions

A stochastic component is included in the slip velocity at a point and in the rupture velocity to simulate the complexities in the rupture dynamics.

Large scale asperities are introduced by varying the slip distribution over the fault surface. The slip distribution is developed in the wavenumber domain. The Fourier amplitude of the slip distribution is modeled by two Butterworth filters (along strike and down dip). The corner wavenumbers of the filters were estimated from 12 events (Somerville, 1991) with estimated slip models and are give by:

$$\ln kcx = 6.08 - 1.6M$$

$$\ln kcy = 6.69 - 1.6M$$

where kcx is the corner wavenumber along strike and kcy is the corner wavenumber downdip. The number of poles for both filters is 1.4. The phase angles are computed from tapered noise that is uncorrelated at high wavenumbers and but are partially correlated at low wavenumbers. The tapers along the edges and down-dip were also developed from the analysis of the 12 events (Somerville, 1991).

The hypocenter is randomly located in the bottom half of the rupture plane, excluding 10% of the rupture length at each end.

The rupture velocity is taken as 80% of the shear-wave velocity at the hypocenter. The rupture time for each fault element is determined from the average of the time at which the rupture first reaches and last exists the element: $(t_a + t_b)/2$ in Figure 3. A stochastic component is also included in the rupture time for each element to simulate the complexities in the rupture dynamics. The stochastic component is a random sample from a normal distribution with mean 0 and standard deviation of $(t_b - t_a)/6$.

Scale factor for each sub-fault element are computed based on the ratio of the mainshock and subevent moments and the slip distribution. The scale factor the sub-fault element ij is given by

$$\mathrm{Scale}_{ij} = \frac{M_o^{MS}}{N_{sub} M_o^{sub}} \frac{\mathrm{Slip}_{ij}}{\sum_{i=1}^{nx} \sum_{j=1}^{ny} \mathrm{Slip}_{ij}}$$

where N_{sub} is the number of subevents per sub-fault element; nx and ny are the number of sub-fault elements along strike and along dip, respectively; slip_{ij} is the slip distribution; M_o^{MS} and M_o^{sub} are the seismic moments for the mainshock and subevent, respectively.

Using these scale factors and lag times, the sub-fault element ground motions are summed to give the mainshock ground motion.

E.3 SUMMARY

The empirical source function method is a generalization of the EGF method that allows it to be applied to regions and source mechanism for which there are insufficient data to use the EGF

method. A consequence of this generalization, is that the method is much more complex than the EGF method.

The strengths and weaknesses of the method are outlined below.

Strengths

- Ability to transfer EGF to other regions and sources

  The ability to transfer EGF to other regions and sources is the main strength of the method. This feature makes the method practical to use for most engineering problems.

- Empirical representation of the radiation pattern

  There is still disagreement about the degree to which the theoretical radiation pattern should be included in ground motion simulations at moderate frequencies. Some procedures include the theoretical radiation pattern at all frequencies, others use a "water level" approach, and others use a fixed constant. The empirical source function method avoids this issue by incorporating an empirical representation of the radiation pattern.

- Tested against EUS and WUS data

  The model has been tested against recorded earthquake ground motions in both the EUS and the WUS. As part of these tests, the model bias and modeling uncertainty (aleatory uncertainty) have been estimated. The model generally shows unbiased predictions of the data over the frequency band of 2-30 Hz.

Weaknesses

- Difficult to Use

  This model is much more difficult to use than other methods. The development of the ESF takes a substantial effort.

- Large number of source parameters required

  There are many more source parameters required compared to a simple model such as the stochastic model. Properly treating the variability and correlations between theses source parameters is difficult.

- Some site effects are folded into the ESF

  The detailed site response is not removed from the EGF. Therefore, some of the site response effects remain in the ESF and are incorporated in the predicted ground motions for a new site.

- Sensitive to the selection of the event and recordings to use as EGF

  The selection of the event used for the EGF can have a significant effect on the ground motions. The source parameters of the selected event (e.g. stress-drop) are assumed to apply to the new region and/or new source.

E.4 REFERENCES

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APPENDIX F

CHARACTERIZATION OF UNCERTAINTY IN GROUND-MOTION PREDICTIONS

by

Gabriel R. Toro

F.1 INTRODUCTION

This appendix expands on the characterization of uncertainty in ground-motion that was presented in Section 5.5. The presentation begins with an illustration of the various types of uncertainty, by considering a simplified setting and then moving to a more realistic setting. This is followed by an illustration of the characterization of uncertainty in the context of various physical and empirical ground-motion models, and how the quantification of parametric uncertainty depends on the application. This is followed by an example showing the steps in the quantification of uncertainty for a stochastic ground-motion model. Finally, this appendix provides examples showing the effect of aleatory and epistemic ground-motion uncertainties on the calculated hazard.

F.2 UNCERTAINTY CHARACTERIZATION: SIMPLIFIED SETTING

Consider first the hypothetical situation in which there are thousands of records from earthquakes in the region of interest, all having the magnitude (m_x), same distance (r_x), and same site category (s_x) for the prediction at hand. Given these data, we can compute the true value of the mean ln[ground-motion amplitude] at a certain frequency as

$$\ln[Amplitude]_{\text{true mean}} = \frac{1}{N}\sum_{i=1}^{N} \ln[Amplitude]_{\text{observed},\, i} \qquad \textbf{(F-1)}$$

where N is the number of records. One can also compute the true standard deviation associated with aleatory uncertainty (which is due to aleatory variations in all source, path, and site factors other than region, magnitude, distance, and site category) from the observed scatter as

$$\sigma_{\ln[Amplitude],\text{aleatory}} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} \left(\ln[Amplitude]_{\text{observed},\, i} - \ln[Amplitude]_{\text{true mean}}\right)^2} \qquad \textbf{(F-2)}$$

Assume also that we have a deterministic predictive model (e.g., a physical model, a stochastic model[1], or an empirical attenuation function) of the form:

$$\ln[Amplitude]_{\text{pred}} = f(m, r, \text{ site category; } \boldsymbol{P}) \qquad \textbf{(F-3)}$$

where $\boldsymbol{P}$ is a vector of explicit model parameters (e.g., stress drop, focal depth, slip distribution, etc.) and that we know the parameter values $\boldsymbol{P}_i$ for each record. Because the predictive model does not include all physical processes and parameters affecting ground motions, the predicted amplitude for a given record will likely differ from the observed amplitude, even if we have perfect knowledge of the parameters $\boldsymbol{P}_i$ for that event. Moreover, the predictive model may have a bias (i.e., a tendency to over- or under-predict observations), so that the mean of the predictions from all events may differ from the true mean value given by Equation F-1. The bias in the predictive model can be evaluated by comparing observations and predictions for the available recordings for the same magnitude, distance, and site category of interest; i.e.,

[1]We consider "stochastic" ground-motion models (e.g., Hanks and McGuire, 1981; Boore, 1983) as deterministic models, because they are typically used to predict only the mean value of ln[amplitude].

$$\mu = \frac{1}{N}\sum_{i=1}^{N}\left(\ln[Amplitude]_{\text{observed, } i} - f(m_x, r_x, s_x;\ \boldsymbol{P}_i)\right) \tag{F-4}$$

or

$$\mu = \ln[Amplitude]_{\text{true mean}} - \frac{1}{N}\sum_{i=1}^{N} f(m_x, r_x, s_x;\ \boldsymbol{P}_i) \tag{F-5}$$

Knowing the model bias, we can construct a bias-corrected model[2]

$$\tilde{f}(m_x, r_x, s_x;\ \boldsymbol{P}_i) = f(m_x, r_x, s_x;\ \boldsymbol{P}_i) + \mu \tag{F-6}$$

By considering the unbiased model, it is possible to decompose the aleatory uncertainty given by Equation F-2 into two parts, as follows:

a) A **parametric** portion, representing scatter that can be explained in terms of the model parameters in vector $\boldsymbol{P}$ (e.g., some events have high stress drop, some have low stress drop).

b) A **modeling** portion, representing those physical processes not explicitly included in the deterministic model (e.g., crustal heterogeneity, P waves).

In terms of this decomposition, Equation F-2 is re-written as[3],

[2]Here, we assume that the bias is the same for all magnitudes, distances, site conditions, and values of $\boldsymbol{P}$. We will return to this issue later.

[3]We assume that the predictive model's dependence on the parameters in vector $\boldsymbol{P}$ is correct.

$$\sigma_{\ln[Amplitude],\text{aleatory}} = \sqrt{\begin{array}{l} \frac{1}{N}\sum_{i=1}^{N}\left(\bar{f}(m_x, r_x, s_x; \boldsymbol{P}_i) - \ln[Amplitude]_{\text{true mean}}\right)^2 + \\ \frac{1}{N}\sum_{i=1}^{N}\left(\ln[Amplitude]_{\text{observed},\,i} - \bar{f}(m_x, r_x, s_x; \boldsymbol{P}_i)\right)^2 \end{array}} \quad \textbf{(F-7)}$$

where the first summation represents aleatory parametric uncertainty and the second summation represents aleatory modeling uncertainty. Assuming that we know the distribution of $\boldsymbol{P}$ in our data set, the parametric term may be computed analytically as an expectation over the parameter values, obtaining

$$\sigma_{\ln[Amplitude],\text{aleatory}} = \sqrt{\begin{array}{l} E_{\boldsymbol{P}}\left[\left(\bar{f}(m_x, r_x, s_x; \boldsymbol{P}) - \ln[Amplitude]_{\text{true mean}}\right)^2\right] + \\ \frac{1}{N}\sum_{i=1}^{N}\left(\ln[Amplitude]_{\text{observed},\,i} - \bar{f}(m_x, r_x, s_x; \boldsymbol{P}_i)\right)^2 \end{array}} \quad \textbf{(F-8)}$$

At this point, we can make several observations about aleatory uncertainty and its partition into parametric and aleatory uncertainty.

1. The value of the aleatory uncertainty given in equations F-2 and F-8 is determined by the physics of seismic sources and wave propagation and by our choice of ground-motion measure and explanatory variables. Given a choice of ground-motion measure and explanatory variables, there is nothing arbitrary about the aleatory uncertainty. There are only three ways to change the value of the aleatory uncertainty, as follows: (1) by changing the ground-motion measure (e.g., switching from spectral acceleration to average spectral acceleration over a frequency band), (2) by changing the explanatory variables (e.g., using a different magnitude scale, adding source depth as an explanatory variable), or (2) by re-defining the distribution of the parameters in $\boldsymbol{P}$ (e.g., deciding that we are only going to consider ground motions coming from thrust earthquakes). In practice, one may obtain different estimates of aleatory uncertainty

(as we will see later), due to limitations in the data or deficiencies in the model. In principle, however, the aleatory uncertainty for given m_x, r_x, and s_x is fixed.

2. The partition between aleatory-parametric and aleatory-modeling uncertainty is model-dependent. If one reduces the scatter between observations and predictions by making the model more complete, one introduces new parameters in the model. Unless these parameters are known a priori for future earthquakes, there will be an increase in parametric uncertainty and the total aleatory uncertainty will be maintained. A reduction in modeling uncertainty may be beneficial, nonetheless, if it allows the incorporation of site-specific information through an updated (typically narrower) site- or region-specific distributions of $\boldsymbol{P}$.

3. The above discussion assumes that the predictive model's dependence on the parameters in vector $\boldsymbol{P}$ is correct. If the model exaggerates the effect of a parameter, both terms in Equation F-8 become inflated, and the quantity in Equation F-8 is larger than that in Equation F-2.

In reality, the available ground-motion data are limited. The number of available records for the magnitude, distance, and site category of interest (i.e., m_x, r_x, s_x) is small at best. Assume, for the moment, that we have a small number n of records for (m_x, r_x, s_x) . We can apply an equation analogous to Equation F-4 (but with the smaller sample size) to estimate the model bias; i.e.,

$$\hat{\mu}=\frac{1}{n}\sum_{i=1}^{n}\left(\ln[Amplitude]_{\text{observed},\ i}-f(m_x,r_x,s_x;\ \boldsymbol{P}_i)\right) \qquad \textbf{(F-9)}$$

but this estimate of the bias has statistical uncertainty because n is small. The resulting uncertainty in

$$\tilde{f}(m_x,r_x,s_x;\ \boldsymbol{P}_i)=f(m_x,r_x,s_x;\ \boldsymbol{P}_i)+\hat{\mu} \qquad \textbf{(F-10)}$$

is epistemic modeling uncertainty.

Limitations in the data also introduce a parametric component of epistemic uncertainty in physical ground-motion models: we do not know the true distributions of model parameters $\boldsymbol{P}$, particularly their central tendencies. (e.g., we do not know the median stress drop for the region of interest). Thus, epistemic parametric uncertainty arises when we compute the mean ln-amplitude as

$$\ln[Amplitude]_{pred.\ mean} = E_{\boldsymbol{P}}\left[\tilde{f}(m_x, r_x, s_x;\ \boldsymbol{P}_i)\right] \qquad \textbf{(F-11)}$$

using uncertain distribution parameters for $\boldsymbol{P}$. Returning to the example of stress drop, the extent of this uncertainty depends on the uncertainty in the median stress drop and on the sensitivity of $f(m_x, r_x, s_x;\ \boldsymbol{P})$ to stress drop.

There is also epistemic uncertainty associated with the estimated $\sigma_{\ln[\text{Ampl.}],\text{aleatory}}$ because the modeling uncertainty is estimated using a small number of records and because there is statistical uncertainty about the distribution of $\boldsymbol{P}$ (particularly their standard deviations).

In practice, the data are so limited that one is required to pool data from multiple magnitudes, distances, and site categories, in order to estimate the bias and the aleatory modeling uncertainty. In doing this, there is the implicit assumption that the predictive model $f(m,r,\text{site category};\ \boldsymbol{P})$ is equally good, and has the same bias, for the magnitudes, distances, and site categories represented in the data as for (m_x, r_x, s_x). This assumption introduces additional epistemic uncertainty, especially when there are few data near (m_x, r_x, s_x). This epistemic uncertainty can be incorporated in two ways, as follows: (1) by considering alternative models, and (2) by allowing the bias and aleatory modeling uncertainty to be magnitude-,distance-, or site-dependent.

This partitioning of aleatory uncertainty into its parametric and modeling components is not necessary, but some investigators consider it useful when working with physically based

models. One advantage of physical models and the parametric/modeling partition presented here is that one can use a variety of data sets, possibly from different regions, thus alleviating the problems caused by the absence of data at (m_x, r_x, s_x). If one is developing a ground-motion model for a region with limited data, one can use strong-motion data (coming mostly from California) to estimate the bias and aleatory modeling uncertainty. One can also use regional or teleseismic seismograph data to estimate the distribution of model parameters such as stress drop and anelastic attenuation, and then use the model to calculate the associated parametric uncertainties. The example application to be illustrated in Section F.4 will illustrate this process in more detail. If, on the other hand, data at or near (m_x ,r_x ,s_x) are abundant in the region of interest, empirical methods provide a more direct method for the characterization of ground motion and its uncertainty. Another advantage of physical models and the parametric/modeling partition is that it allows the incorporation of site-specific information in the form of site- or region-specific distributions for the parameters in ***P***.

F.3 ILLUSTRATIONS OF PARAMETRIC AND MODELING UNCERTAINTY

The examples that follow illustrate the definition of parametric and modeling uncertainties for various ground-motion models. These models are used to predict ground-motion in the usual manner required for seismic-hazard analysis (i.e., using magnitude, distance, and possibly site conditions as the only explanatory variables). The models are presented in decreasing order of physical detail. For the sake of simplicity, site effects are not considered in this discussion.

F.3.1. Extended-Source Models.

Extended-source models contain a kinematic representation of the generation of seismic energy along the rupture surface and a model of wave propagation through the crust (typically assuming a flat-layered crustal structure). A description of these models is given in Appendix E. Examples of this kind of models are given by Wald et al. (1988) and Herrmann and Jost (1988). Here, unlike the above two references, we consider the case in which the model is used to predict ground-motions as a function of moment magnitude and distance, rather than the situation where the location of the site relative to the rupture (or at least to the

fault) is fixed.

The following are parameters that are explicitly included in the physical ground-motion model:

1. Source Parameters: rupture dimensions*, slip distribution, hypocentral location, rupture velocity*, rise time*, slip time-function*, rake angle;
2. Geometry: rupture location, azimuth of site relative to rupture;
3. Wave Propagation: Crustal S-wave velocity structure (typically 1-D), anelastic attenuation (Q)*;

Those parameters that are treated as varying randomly from event to event or from site to site contribute to parametric uncertainty. In order to quantify the contribution of a parameter to the aleatory uncertainty in the predicted ground motions, one must first specify the parameter's probability distribution (aleatory). More precisely, one must specify the joint probability distributions of all such parameters, given magnitude and distance. Uncertainty in the specification of these parameters, due to incomplete data or alternative interpretations of the data, contributes to epistemic parametric uncertainty.

Those parameters that are present in the model but are assumed constant or are assumed to be deterministic functions of the explanatory variables and of other parameters, do not contribute to parametric uncertainty. Any deficiencies in these assumptions will contribute to modeling uncertainty and are captured by comparing predictions to observations (to the extent that the data used to quantify modeling uncertainty covers a wide enough range of conditions). The asterisks in the above list indicate those parameters that were treated as constant or deterministic by Wald et al. (1988).

Physical phenomena that are not included in the model (e.g, site effects, complexity of energy release at the source, non-uniform rupture velocity, deviation from a flat-layered crust, wave scattering due to small-scale crustal heterogeneity) also contribute to modeling uncertainty and

are captured by comparing predictions to observations.

F.3.2. Point-Source Stochastic Models.

Point-source stochastic models use a simple frequency-domain representation of seismic energy release at the source. The representation of wave propagation may explicitly include the effect of crustal velocity structure (e.g., Ou and Herrmann, 1990), or it may consist of a more simplified representation (Herrmann, 1985). An example of this model is the EPRI (1993) ground-motion model, which forms the basis for this example. As in the above example, we consider the case in which the model is used to predict ground-motions as a function of magnitude (moment magnitude or m_{Lg}) and horizontal distance.

The following parameters are specifically included in the point-source stochastic ground-motion model:

1. Source Parameters: seismic moment, stress drop, asperity depth (i.e., depth at which the point source is located);

2. Geometry: horizontal distance to asperity;

3. Wave Propagation: Crustal S-wave velocity structure (typically 1-D), anelastic attenuation (Q), site kappa;

In the EPRI study, all parameters in the above list (except crustal velocity structure) were treated as uncertain. The effect of crustal velocity structure is captured as modeling uncertainty (to the extent that the data used to quantify modeling uncertainty samples the variations in crustal structure within the study region).

The effects of those parameters that appear in the extended-source model but do not appear in the stochastic point-source model (e.g., slip distribution, rake angle, rupture velocity, rupture location, site azimuth, etc.) are captured as modeling uncertainty.

Physical phenomena that are not included in this model or the extended-source model (e.g, complexity of energy release at the source, non-uniform rupture velocity, deviation from a flat-layered crust, wave scattering due to small-scale crustal heterogeneity) are also captured as modeling uncertainty.

F.3.2. Empirical Attenuation Equations.

In most cases, the functional form of the attenuation equation is based on physical considerations. Thus, the difference between empirically derived attenuation equations and the physical models described earlier may not be as large as it first appears (the main difference relates to how parameters are interpreted and estimated; i.e., which data are used and how they are used).

In an empirical attenuation equation, the empirically derived coefficients of the attenuation equation take the role of parameters. They have no aleatory uncertainty, however, because they are assumed to be the same for all events.

The empirically derived coefficients have epistemic uncertainty, representing statistical uncertainty associated with sample size. The statistical uncertainty in the coefficients is routinely calculated as part of the regression calculations. The calculated statistical uncertainty is typically very small, however, and is not representative of the true epistemic uncertainty. This is likely the result of ignoring correlations in the data and of under-parameterization. In practice, additional epistemic uncertainty is introduced by considering attenuation equations developed by various investigators, who use somewhat different data sets (which may differ in their data-selection criteria or in their interpretations of the data), functional forms, and fitting procedures.

If the attenuation equation contains explanatory variables other than magnitude and distance (e.g., depth to basement, average shear-wave velocity in the upper 30 m, soil category, style of faulting), which are not known with certainty for the seismic sources and site of interest, one must consider parametric uncertainty. To the extent that a parameter is constant (though, perhaps, unknown) for the site and seismic sources of interest, uncertainty in that parameter is

epistemic. To the extent that a parameter is expected to vary from event to event, uncertainty in that parameter is aleatory. As in physical models, there is a trade-off between modeling and parametric uncertainty: if a physical parameter is added, modeling uncertainty is reduced but parametric uncertainty is increased. The total uncertainty is reduced only when the parameter's distribution is narrowed.

Modeling uncertainty is characterized by the residual standard deviation obtained from the regression analysis. This modeling uncertainty contains both aleatory and epistemic components (though one may, at first thought, think it is all aleatory). Some of this uncertainty is associated with local site conditions (beyond the site characterization used in the attenuation equation) and with regional variations in crustal structure and in Q, and could be resolved with additional data. For instance, if one has ten or more strong-motion recordings at the site of interest, one should be able to obtain refined predictions for that particular site (with lower modeling uncertainty and with somewhat higher or lower median predictions), by combining the regional predictions from the attenuation equation and the site-specific observations. Also, one would not treat data from that site in the same way as data from other sites in the same region. In practice, however, this distinction between the aleatory and epistemic components of the residual standard deviation is difficult to make and the standard deviation is considered all aleatory.

F.3.3 Application-Dependent Nature of Parametric Uncertainty.

So far, we have seen how the probability distributions representing parametric uncertainty depend on the model being used (e.g., physical vs. stochastic vs. empirical). In addition, these distributions may also depend on the type of application being performed and on how the integration tasks are divided between the ground-motion analyst and the seismic-hazard analyst. All these issues affect the calculated uncertainty. These issues are best explained by means of several examples.

Consider, as a first example, the application of an extended-source model to develop fault-specific attenuation equations for a site in which the fault-site geometry is fairly well known (e.g., the San Andreas fault and a site in the San Francisco peninsula). The ground-motion

analyst will know the fault dip (to within 10 to 20 degrees), style of faulting, on which side of the fault the site is located, and many other parameters. Thus, many of the parameters related to the site-fault geometry will be fixed or will have narrow distributions. The ground-motion analyst will still have to consider multiple locations of the rupture (as the independent variable) and multiple nucleation-point locations within that rupture[4] (as parameters to integrate over) and report amplitude and uncertainty as a function of magnitude and rupture location. The seismic-hazard analyst would integrate over magnitude and rupture location to obtain the hazard.

Consider now the application of the same extended-source model to the development of a generic attenuation equation (using distance to the rupture as the distance metric) for the same region where the site is located. The model parameters are the same as in the previous application, but the ground-motion analyst will have to integrate over more parameters or over wider distributions of these parameters. For instance, the ground-motion analyst will have to consider much wider distributions of dip angle and style of faulting, he will have to consider sites on either side of a dipping fault, etc. Because the seismic-hazard analyst wants results as a function of magnitude and rupture distance, he will have to integrate over all these parameters, and also over rupture location given rupture distance, to obtain a mean prediction and the associated epistemic and aleatory parametric uncertainties. Even though the modeling uncertainty is the same, the total uncertainty will be higher in the second example because the parametric uncertainty is higher.

Consider now the application of the same extended-source model to develop generic attenuation equations for CEUS (using m_{Lg} and hypocentral distance as explanatory variables). Now, because the ground-motion model does not use m_{Lg} or hypocentral distance directly as parameters), the ground-motion analyst must integrate over two more uncertain

[4]If there were two faults that contribute significantly to seismic hazard at the site, one strike-slip and the other thrust, it would be natural to use different distributions for a number of their parametric uncertainties. Thus, the traditional division of labor between ground-motion modeling (amplitude given M and R, irrespective of seismic source) and characterization of the seismic sources (joint distribution of M and R) may not be appropriate.

quantities: moment magnitude (for given m_{Lg}) and hypocentral distance (for given rupture location).

Finally, consider the EPRI (1993) study described below, where integration over depth was performed as part of the ground-motion modeling (depth is usually taken as fixed or integrated over in the seismic-hazard analysis). The result of this integration is increased parametric uncertainty at distances of 20 km or less (this will be seen in Figure F-9).

In all these cases, the uncertainty (particularly the aleatory uncertainty) will be different because the ground-motion analyst is having to integrate over different distributions of model parameters.

F.4. ESTIMATION OF UNCERTAINTY IN GROUND-MOTION MODELS

This section provides more details on how the various components of uncertainty are calculated in the context of physical models. The EPRI work on the stochastic model will be the basis for this presentation, with more general comments where appropriate.

F.4.1. Modeling Uncertainty.

Modeling uncertainty is quantified by comparing model predictions to actual observations. For each event and record modeled, one finds the values of the free model parameters (i.e., those model parameters without asterisks or obvious physical constraints in the above section) that minimize the sum of squared differences between predicted and observed amplitudes[5],

[5]It is typical to consider Fourier amplitudes, rather than spectral accelerations, in the minimization (inversion) process to determine the optimal parameter values, even though the engineering predictions are made for (pseudo) spectral acceleration. One reason for this is that the spectral acceleration at frequency f may be driven by energy at much lower frequencies.

summed over the frequency range of engineering interest. The sampling on frequency may be arithmetic or logarithmic, thereby giving more or less weight, respectively, to high frequencies. The optimal parameter values should, of course, be physically reasonable. Sometimes, independently derived parameter values are used. The amplitudes considered are log spectral accelerations over the frequency range of engineering interest.

Using the residuals $\varepsilon_{ij}(f)$ (observed–predicted amplitude at frequency f), one then obtains the model bias

$$\mu(f)=\frac{1}{n}\sum_{i\ (\text{events})}\sum_{j\ (\text{sites})}\varepsilon_{ij}(f) \qquad \textbf{(F-12)}$$

and the bias-corrected variance

$$\sigma_{\varepsilon}^{2}(f)=\frac{1}{n-1}\sum_{i\ (\text{events})}\sum_{j\ (\text{sites})}\left(\varepsilon_{ij}(f)-\mu(f)\right)^{2} \qquad \textbf{(F-13)}$$

where n is the number of records used in the process.

The EPRI (1993) characterization of modeling uncertainty used data in the magnitude-distance range of engineering interest, coming from a mixture of ENA and California earthquakes (i.e, Saguenay, Nahanni, Loma Prieta and Whittier Narrows). Figure F-1 shows the bias as a function of frequency for the EPRI stochastic model. It shows that the bias is essentially zero for frequencies above 3 Hz and negative (i.e., conservative) for lower frequencies. Because the bias was negligible or negative, the model predictions were not corrected for bias. Figure F-2 shows the aleatory modeling uncertainty (dashed line; labeled "Modeling Randomness"), which is estimated as $\sigma_{\varepsilon}(f)$.

The epistemic uncertainty of the EPRI model was computed from the bias and the site-to-site variance of the "D terms," which represent frequency-independent site terms obtained during the inversion process (further details and motivation for the D terms are provided in Section 3

of EPRI, 1993). Figure F-2 also shows the total modeling uncertainty (i.e., $[\text{aleatory}^2+\text{epistemic}^2]^{1/2}$, solid line; labeled "Modeling Randomness and uncertainty").

The computation of the modeling epistemic uncertainty merits discussion. Setting aside the D terms, one can say that the modeling epistemic uncertainty may be computed from the model bias, the statistical uncertainty in the bias, or both. An intuitive justification for using the bias as an indication of modeling epistemic uncertainty is that a large bias (whether positive or negative) detracts from the model's credibility (one may interpret this as a prior belief or expectation that the model bias would turn out to be zero or small). A problem with this argument is that it suggests that if the model over-predicts the data using one data set, it is not unlikely that it will under-predict the data by roughly the same amount if we use another data set. This approach suggests that one should not correct the model for bias.

Alternatively, one can take an empirical position and view the bias as a calibration constant to be determined from the data (with no meaning assigned to its actual value). Then, it follows that the modeling epistemic uncertainty should be calculated as the statistical uncertainty in the bias. Care should be taken, however, to account for correlation in the data when calculating the statistical uncertainty, because this correlation reduces the number of effective degrees of freedom[6]. This is the approach implied in Section F-2 and is perhaps the most widely accepted approach; it suggests that one should correct the model for bias.

F.4.1. Parametric Uncertainty

The quantification of parametric uncertainty in ground motions consists of two steps, as follows:

1. Quantification of the uncertainty (both aleatory and epistemic) in the model parameters.

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[6]For instance, considering the residual ϵ_{ij} as the sum of an inter-event and an intra-event component, all recordings from the same event will be correlated because they share the same value of the inter-event term. A similar situation arises with recordings at the same site from several earthquakes.

2. Propagation of uncertainties in model parameters into uncertainty in ground-motion amplitude. Again, this must be done for both aleatory and epistemic uncertainty.

The uncertainty in free model parameters is obtained from the "observed" values of these parameters in the events and recordings investigated. As with the calculation of modeling uncertainty, the process involves finding optimal values of the free model parameters, so that the best fit between model and observations is obtained (this is what seismologists call inverting for the parameters). Then, instead of focusing on the misfit between model and observations, one focuses on the event-to-event and site-to-site variation of the parameters.

The observed variation in the parameters (e.g., event-to-event variation in stress drop) is used to characterize the aleatory parametric uncertainty. The associated statistical uncertainty (e.g., uncertainty about the median stress drop in ENA) represents epistemic uncertainty. One should also characterize probabilistic dependencies, if indicated by the parameter observations. Because the parameters are not directly observed, but are inferred from an inversion, it may be necessary to consider the uncertainty associated with each "observation," and the correlations that arise when the inversion procedure has trouble resolving between two parameters.

Ideally, these calculations should be performed with the same data set used in the calculation of modeling uncertainty; this would guarantee that there is no double-counting of uncertainties. In practice, this is not always possible due to limitations in the availability of data, particularly for the magnitude-distance combinations that dominate seismic hazard. One often has to use different data sets to estimate different parameters, use independently determined parameter values, use subjective probability assessments, or a combination of these.

The EPRI (1993) study considered the following free model parameters: stress drop, asperity depth, anelastic attenuation (Q), and near-site anelastic attenuation (κ) (recall Section F.3.2). Different data sets were used to characterize uncertainty in stress drop, and κ. The characterization of Q used results from inversions, together with published results for the

region, and subjective weights.

The characterization of stress drop and its uncertainty considered the following two data sets:

1. Atkinson's (1993) data set of estimated high-frequency stress-parameter[7] values for 21 ENA main events (See Figure F-3). Estimates for events since 1982 were obtained by fitting model predictions of Fourier amplitude to the observed Fourier amplitudes from regional recordings. Estimates for earlier events used intensity data. The calculated logarithmic-mean stress drop is 120 bars (with a statistical uncertainty of $\times e^{\pm 0.16}$); the logarithmic standard deviation is 0.71.

2. Estimates of Brune stress drop[7] obtained by inverting near-source recordings from 12 earthquakes in ENA (Figure F-4). The calculated logarithmic-mean stress drop is 145 bars ($\times e^{\pm 0.16}$); the logarithmic standard deviation is 0.86. Neither data set shows a tendency towards stress drops increasing with moment magnitude.

The Atkinson (1993) data set is used to formulate the model predictions because the high-frequency stress parameter is more directly related to high-frequency ground motions and because this data set contains a better sampling of larger events. Recognizing that there are few events above magnitude 6 (these events have, in fact a lower median and lower scatter than the other events), the epistemic uncertainty in stress drop is taken to be higher for **M>6**, while keeping the total parametric uncertainty constant (see Figure F-5)[8].

The distribution of focal depth was constructed from several compilations of focal depth for

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[7]The high-frequency stress-parameter and the Brune stress drop represent two ways of calculating the stress drop $\Delta\sigma$ that appears in the stochastic model. The former is calculated by fitting only the flat high-frequency portion of the source spectrum above the "corner frequency"; the latter is calculated by fitting the Fourier spectrum over a wider range (this range is limited by noise and by instrument-response characteristics).

[8]This may be viewed as partially relaxing the assumption of magnitude-independent stress drop for the higher magnitudes. The reduction in aleatory uncertainty with increasing magnitude is consistent with the experience in California.

earthquakes in CEUS and in similar tectonic environments. Statistically significant differences were found between plate margins (portions of the crust near the continental/oceanic transition zone) and other areas of the stable-continental crust. The distribution used in the ground-motion simulations is based on the pooled data from both regions (Figure F-6).

Uncertainty in Q was specified by means of three alternative Q models for each geographic region (see Figure F-7), with equal weights. These models nearly cover the range of Q models in the literature.

The median value of κ for CEUS hard rock was estimated as 0.006 sec, obtained by fitting the observed shape of the normalized response spectrum at high frequencies. The associated uncertainty in $\ln(\kappa)$ was estimated as 0.4, based on 20 rock recordings from the Loma Prieta earthquake. Uncertainty in κ is conservatively represented by three equally likely values of 0.003, 0.006, and 0.012 (this discrete distribution has 50% higher uncertainty than estimated).

In the EPRI study, all uncertainty in depth, Q, and kappa is taken as aleatory[9]. This inconsistency does not introduce a large error because these parameters (with the exception of depth at short distances) have only a modest effect on the uncertainty in ground-motion amplitude at frequencies below 10 Hz (as we will show below).

The EPRI example shows how one can use a variety of data sources to characterize uncertainty in the parameters of a physical ground-motion model.

The propagation of parameter uncertainties into uncertainties in ground-motion amplitudes is

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[9]This assumption is equivalent to assuming that the ground-motions will be predicted for an ENA hard-rock site chosen at random; hence; site-to-site variability (within the same "hard-rock" classification), and regional variation in depth and Q are treated as aleatory. Within a strict perspective on epistemic and aleatory uncertainty, this would <u>not</u> be appropriate for a site-specific application. This is recognized in Section 9 of EPRI (1993). Section F-5 contains guidance for site-specific applications.

one of derived distributions. Because of the partition of uncertainty into its epistemic and aleatory components, the problem is actually one of two nested derived-distribution problems. If we represent the epistemic and aleatory portions by logarithmic means and a standard deviation, the problem is greatly simplified, as shown in Section 5.5.2.

It is useful to display the various contributions to aleatory and epistemic uncertainty. Figure F-8 shows the various contributions to aleatory uncertainty as a function of distance and magnitude, for spectral acceleration at 1 and 10 Hz. Depth is an important contributor to aleatory uncertainty at distances of 5 km or less. Stress drop and modeling uncertainty are equally important at small distances. Modeling uncertainty is more important for 1 Hz than for 10 Hz; stress drop is more important for 10 Hz than for 1 Hz. Q is of little importance at distances less than 100 km; κ is unimportant at all distances. Q and κ become more important at 25 Hz (not shown).

Similarly, Figure F-9 shown the contributions to epistemic uncertainty, as well as the total uncertainty, as a function of magnitude. The epistemic uncertainty is higher for higher magnitudes, due to the higher epistemic uncertainty in the median stress drop.

F.5. PARAMETRIC UNCERTAINTIES: SITE-SPECIFIC PERSPECTIVE

The characterization of parametric uncertainty adopted in the EPRI (1993) work described above, and in most other ground-motion studies, treats systematic intra-region geographic variation[10] in a parameter as aleatory uncertainty. This is done because the available data make it difficult to differentiate intra-region geographic variation from other, less predictable, forms of uncertainty. If one takes the perspective of a given site (which is the appropriate

[10]One example of this systematic intra-region variability would be a difference in geometric and anelastic attenuation between northern and southern California, which would cause an increase in the residual standard deviation obtained in regression studies. A similar situation arises for intra-category variation in relation to site response (e.g., variations in kappa among hard rock sites).

perspective in nearly all situations), the intra-region geographic variation becomes epistemic uncertainty because it can be reduced with the collection and analysis of data at a more local scale. These new data would be anticipated to yield parameter distributions that are tighter than the generic distributions used in the EPRI study and to have median values within the one-sigma ranges of the generic medians. These site-specific distributions would result in lower aleatory uncertainty and in median attenuation equations that are somewhat different from the generic EPRI results.

This section illustrates how site-specific data could be incorporated and used to derive new attenuation functions that reflect these site-specific data.

The availability of site-specific data (or, more generally, data collected at a smaller geographic scale) about a parameter will resolve some or all the epistemic uncertainty in the parameter. This will typically translate into smaller epistemic standard deviation and a median value that is different from the original median. In practice, the amount of site-specific data may not be large, so it may be best to combine the site-specific data and the generic distribution[11].

Focal Depth. Site-specific investigations of hypocentral depth would focus on the tectonic province where the site is located. Because the distribution of depth depends on the location of the site (margins vs. others), site-specific information on depth is always available (as long as one knows the coordinates of the site and its surrounding seismic sources). If the nearby seismic sources affecting the site are located in the coastal margin, one should use the depth distribution for margins. If they are located elsewhere in CEUS, one should use the depth

[11]If only the site-specific data are used, the associated statistical uncertainty may be very large because of the small sample size. On the other hand, one does not want to simply pool the generic and site-specific data, because the site-specific data are more relevant to the site. What one needs is a procedure that properly weights the site-specific and generic data. For instance, the site-specific data set should receive more weight if it shows less scatter or if its sample size is increased by gathering additional site-specific data. Appendix 6A of EPRI (1993) provides an example of combining site-specific and generic information, using a procedure that is loosely based on empirical Bayes methods.

distribution for "others" (see Figure F-10). If the site is near the boundary between the two regions, one should use the pooled distribution in Figure F-6. Statistical (epistemic) uncertainty arises at sites located in a margin because the data set is small.

Q. Site-specific investigations of Q would focus on a radius of 100 to 500 km around the site, with the choice of radius being dictated by the distances to the seismic source zones that contribute to seismic hazard at the site. The regionalizations by Singh and Herrmann (1983) and Gupta et al. (1989) provide a starting point for the development of site-specific values of Q. The following example uses results from these two studies to obtain site-specific estimates of Q for a site in south-eastern Wyoming. Figure F-11 shows the estimates of Q from these two studies (heavy line: Singh and Herrmann; error bars: Gupta et al). Also shown are the three Q models considered in the EPRI (1993) generic calculations (thin lines; given equal weights in the EPRI calculations). Based on these two results, which show values of Q above the median EPRI value, the weights for the three EPRI models are changed to [0.4 (higher Q model), 0.5 (middle), 0.1 (lower)]. The remaining uncertainty (i.e., the uncertainty represented by means of the updated weights) could be treated as aleatory.

Kappa. Site-specific investigations of κ would focus on the local geology of the site and should include any significant variations among locations (buildings) within the site. Information on κ might be obtained from local recordings obtained with a temporary seismograph network, from local measurements of near-surface shear-wave velocity (using, for example, the correlations between velocity and κ developed by Silva, 1991), from local measurements of anelastic attenuation, or from analogies with other sites with similar geology. Changes in κ as a result of site-specific information would affect the predicted amplitudes for high-frequency (> 10 Hz) ground motions and peak ground acceleration. Site-specific parameter information of this type would be incorporated by using the site-specific parameter distributions, instead of the generic distributions, in the propagation of parametric uncertainties. The result would be a new value of the median ground motions, and a likely decrease in the total parametric uncertainty ($[\text{aleatory}^2+\text{epistemic}^2]^{1/2}$). This decrease in parametric uncertainty would be due to a reduction in epistemic parametric uncertainty, but may be labeled as due to a decrease in aleatory parametric uncertainty because of the

difficulty in separating geographical variations (which are epistemic) from aleatory uncertainty.

F.6. EFFECT OF GROUND-MOTION UNCERTAINTY ON HAZARD RESULTS

In most modern seismic hazard studies, aleatory and epistemic uncertainties (in magnitudes, locations, and ground-motion amplitude) are treated separately in the calculations and displayed separately in the results. Aleatory uncertainty is displayed by the shape of the hazard curves. Epistemic uncertainty is displayed by the spread among the fractile hazard curves. (If the epistemic uncertainty is zero, all fractile hazard curves, and the mean curve, coincide.)

This section shows typical hazard results and how these are affected by the epistemic and aleatory uncertainties in ground motions. We present results obtained using the EPRI/SOG (EPRI, 1986, 1988) methodology and inputs, but the observed trends are valid in general. We show results for both PGA and 1-Hz PSV for a New England site (we observed the same general trends for a midwestern site located in a low-seismicity region approximately 500 km away from the New Madrid source zone).

Figures F-12 and F-13 show the effect of the aleatory uncertainty (σ) on the mean and fractile results (without changing the epistemic uncertainty). The thick lines represent results obtained using an aleatory σ of 0.5 (natural log units) for both PGA and 1 Hz. The thin lines represent results obtained using an aleatory σ of 0.6 for PGA (this used to be the rule-of-thumb value) and 0.76 for 1-Hz (Boore and Joyner, 1988).

Results for PGA indicate little difference for hazards of 10^{-4} or greater (the region used for setting design spectra). Differences become important (though not dominant) for the lower hazards that are important in seismic PRA studies. Results for 1 Hz indicate important differences, even near 10^{-4}. This is a result of the higher aleatory σ (other results, not shown here, indicate that we would have obtained the same effect if we had used 0.76 for PGA).

Another related issue is the trade-off between epistemic and aleatory uncertainties (i.e., what happens to the calculated hazard if some contributor to uncertainty is mis-labeled and put in the wrong bin?). One can prove that the mean hazard is unchanged and that the median hazard increases[12], if the aleatory σ is increased while keeping the total (aleatory+epistemic) uncertainty in ground-motions constant.

These results show the importance of proper quantification of aleatory and epistemic uncertainty in ground-motion predictions. Differences greater than 0.1 lead to significant differences in calculated hazard, even for the amplitudes considered in setting design levels. Because epistemic and aleatory uncertainties are treated differently in making design and retrofit decisions, and because the median hazard is sometimes the preferred central measure of hazard due to its stability, it is also important to allocate uncertainties in the proper category.

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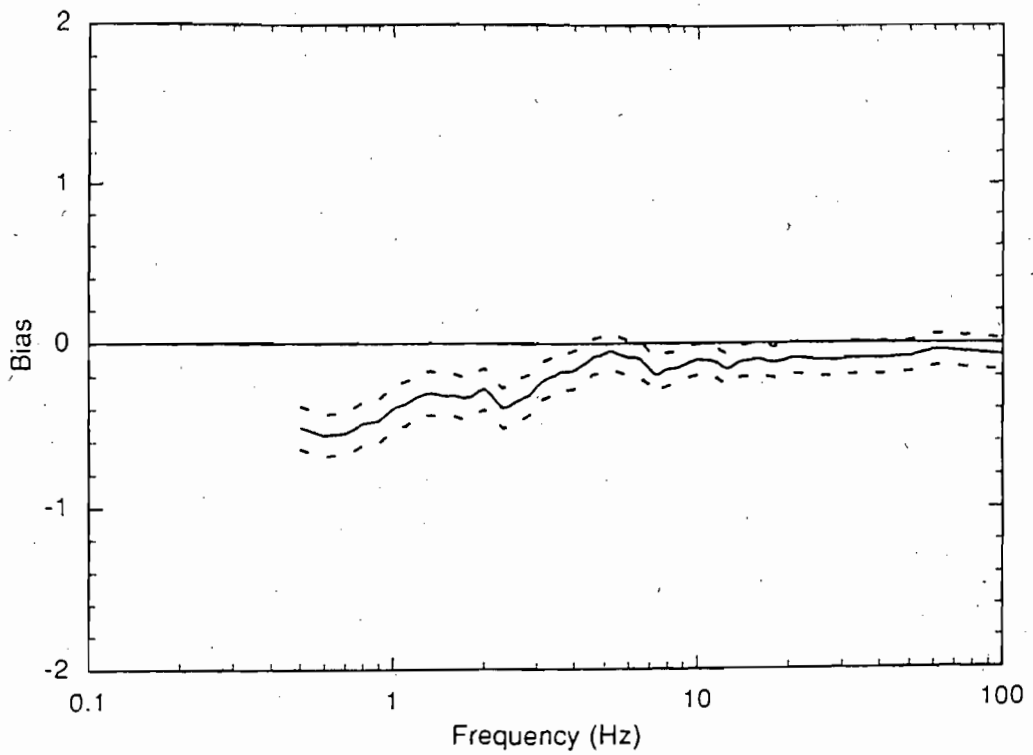


Figure F-1. Modeling bias for the EPRI (1993) stochastic model, obtained using 61 recordings from four events. Dashed lines indicate 90% confidence limits.

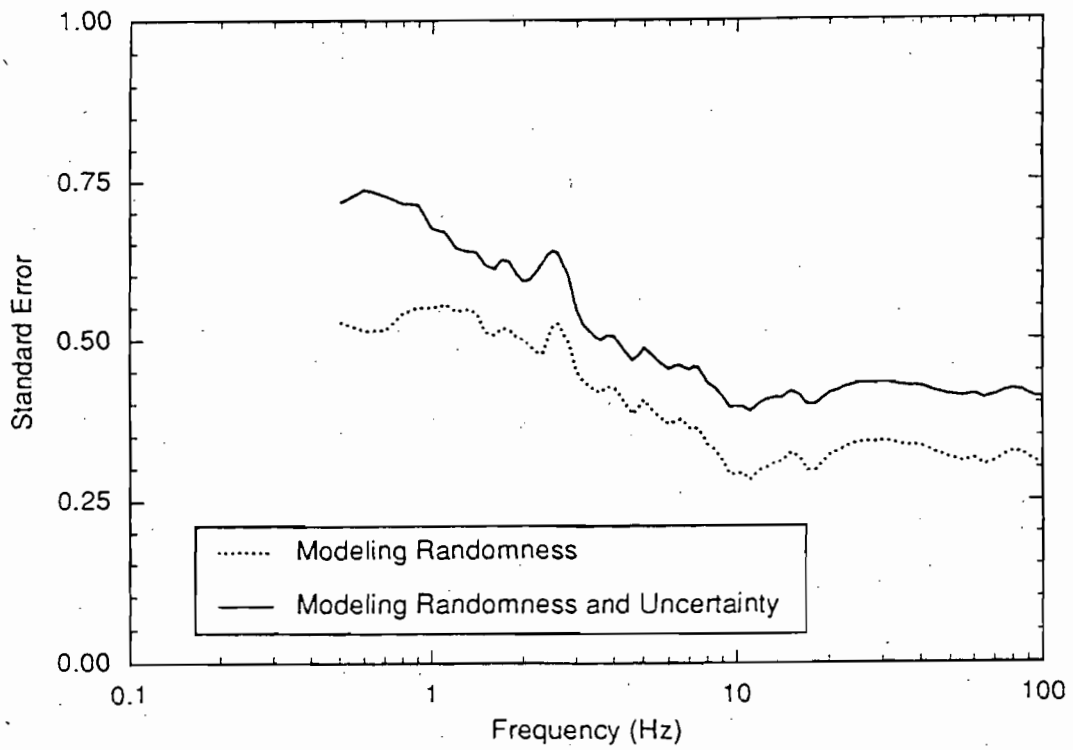


Figure F-2. Modeling uncertainty for the EPRI (1993) stochastic model, obtained using 61 recordings from four events. Dashed line: indicates the modeling aleatory uncertainty; solid line: total modeling uncertainty (aleatory+epistemic).

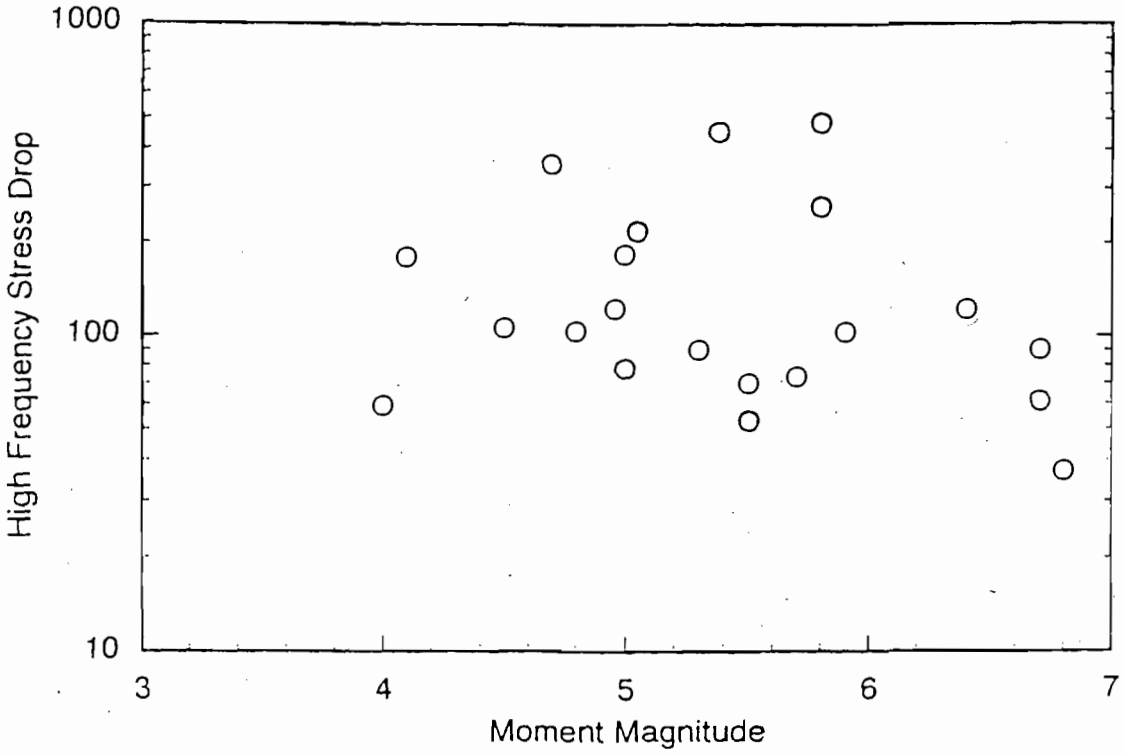


Figure F-3. High-frequency stress parameters (values are modified from Atkinson, 1993). Source: EPRI (1993, vol. 5).

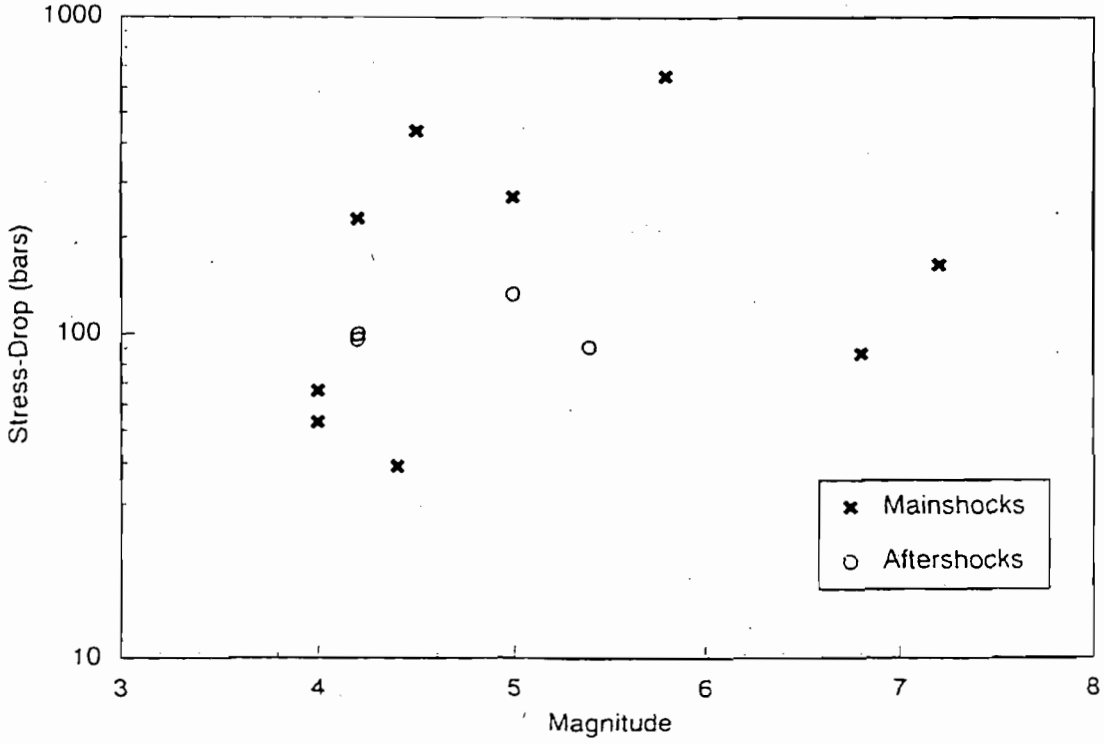


Figure F-4. Brune stress drops for stable continental regions estimated by inversion of the Fourier amplitude spectrum.

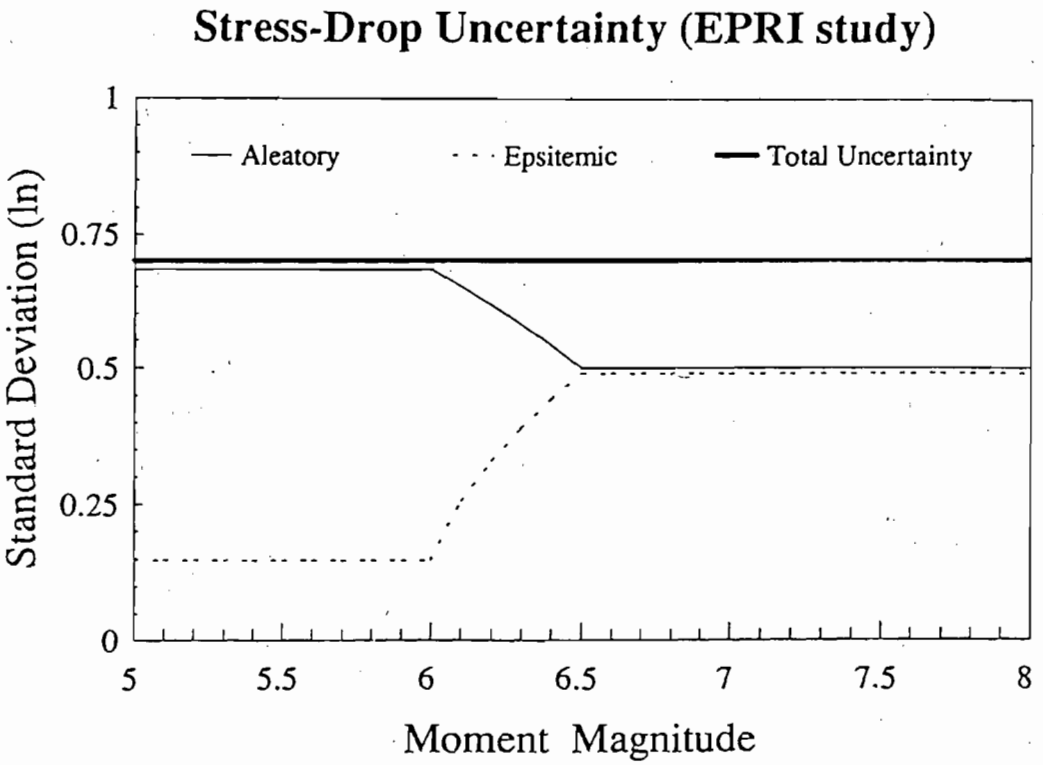


Figure F-5. Aleatory and epistemic uncertainty in stress drop in the EPRI (1993) study. Modified from Toro et al. (1995).

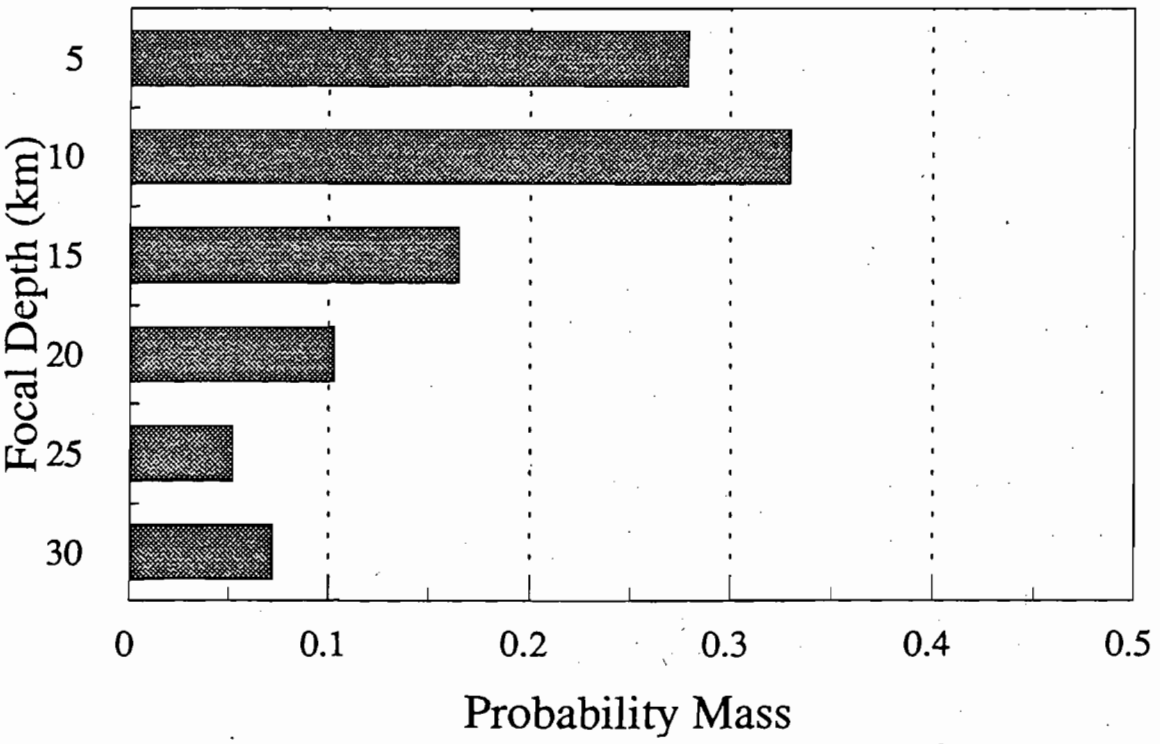


Figure F-6. Distribution of focal depth (aleatory) in the EPRI (1993) study. Source: Toro et al. (1994).

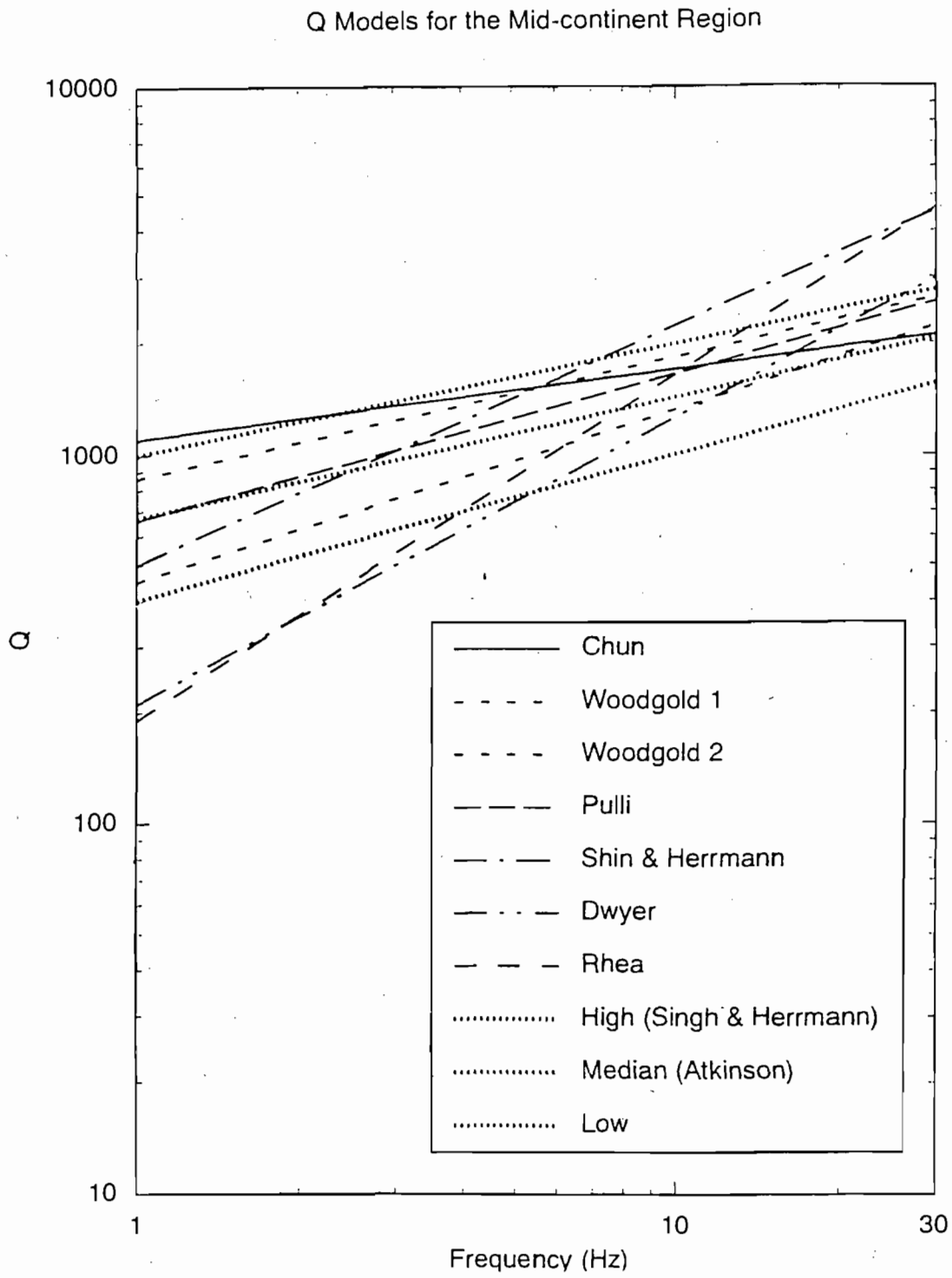


Figure F-7. Representation of Q in the mid-continent region and its aleatory uncertainty in the EPRI (1993) study. The Q models shown as dashed lines are given equal weights.

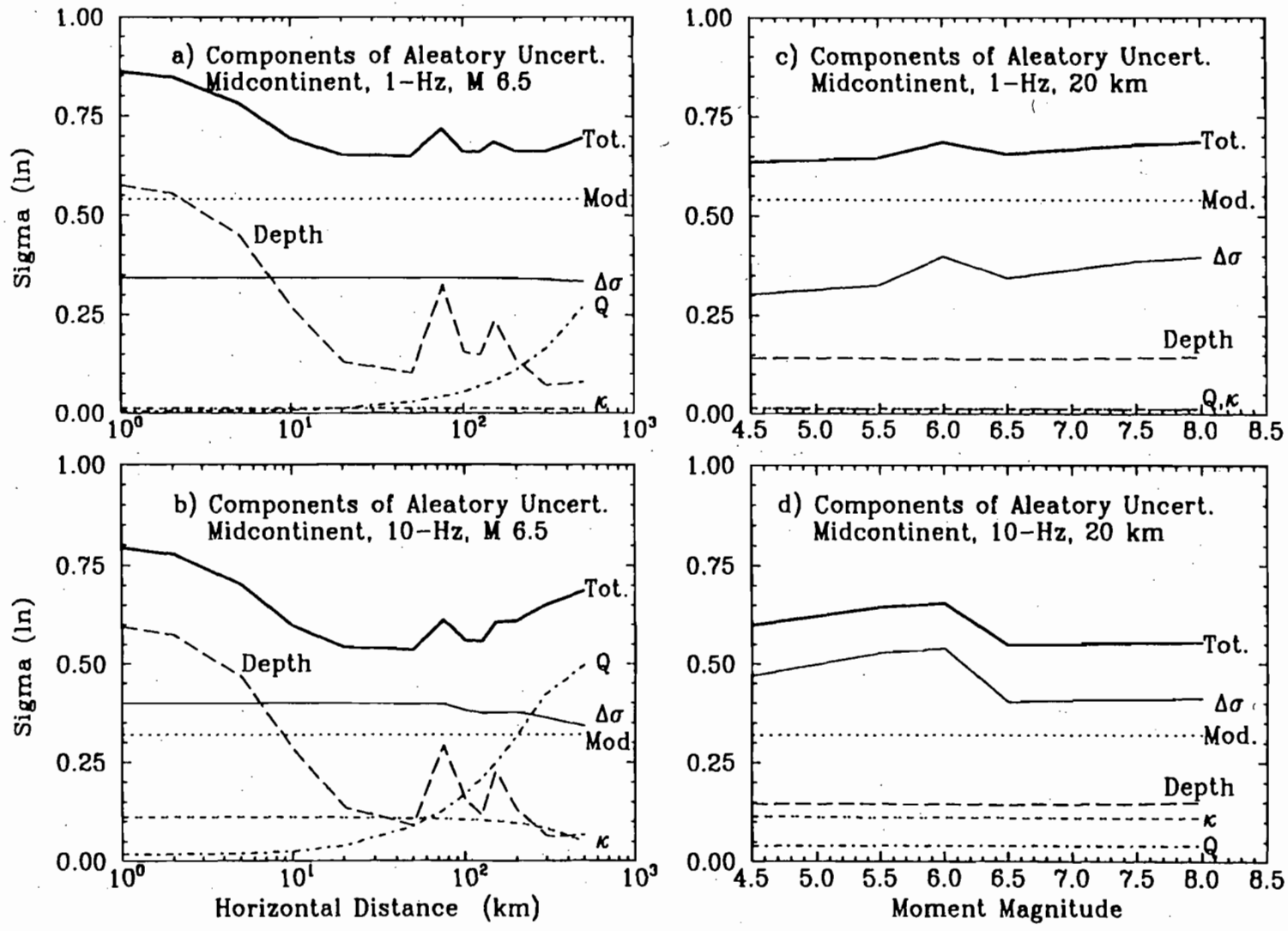


Figure F-8. Contributions to aleatory uncertainty in ground motion predictions from the EPRI (1993) study. Modified from Toro et al. (1995).

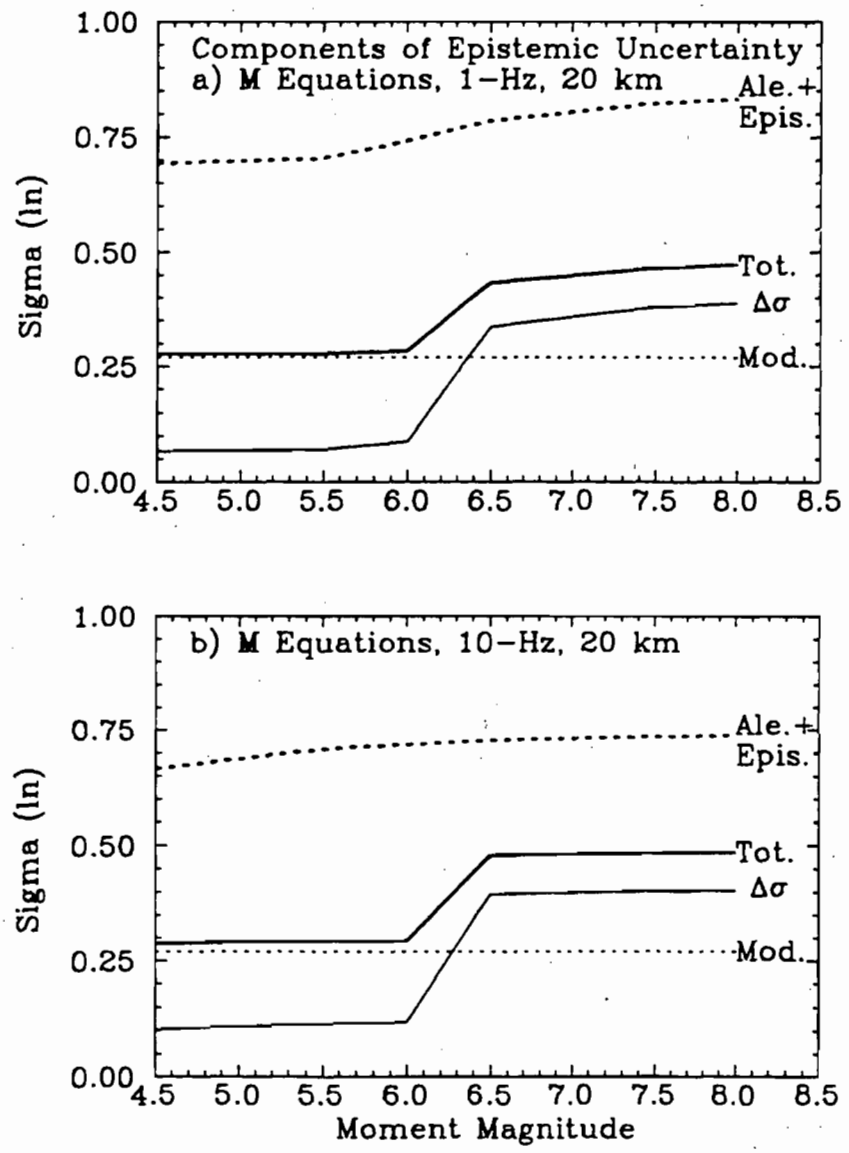
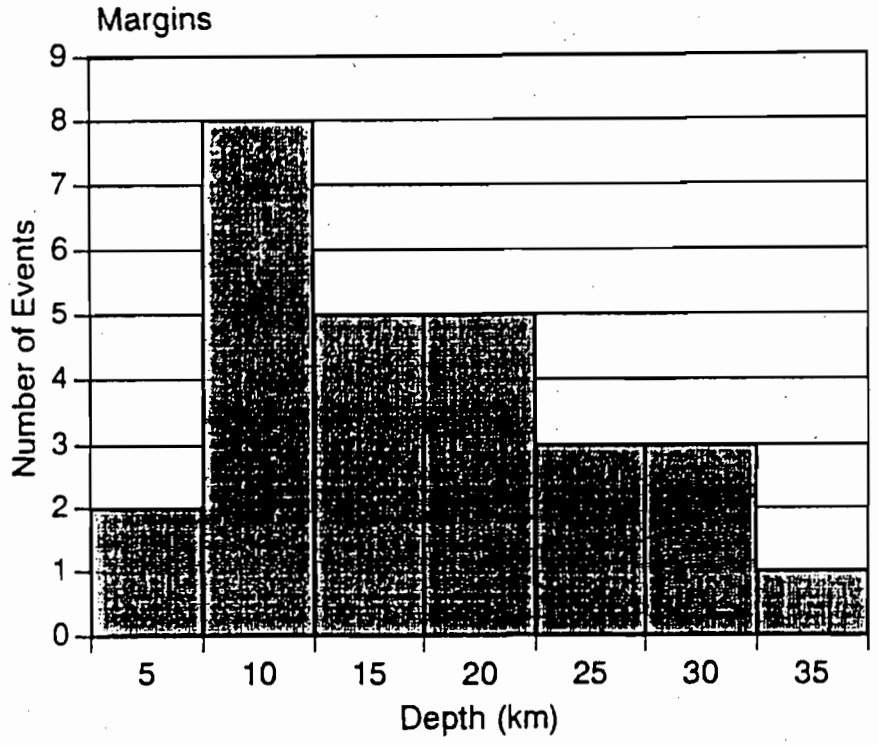


Figure F-9. Contributions to epistemic uncertainty in ground-motion predictions from the EPRI (1993) study. Modified from Toro et al. (1995).



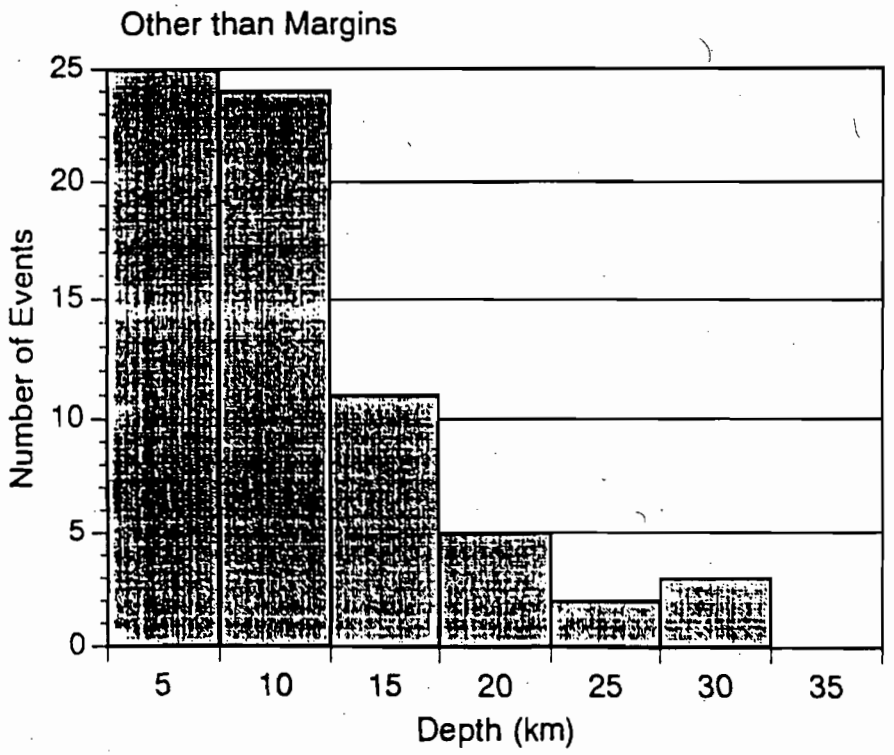


Figure F-10. Depth distribution model for margins and non-margins based on the combined eastern North America, Africa, and Australia data set. This depth distribution model is considered in the regression analysis in Section 9. Source: EPRI (1993).

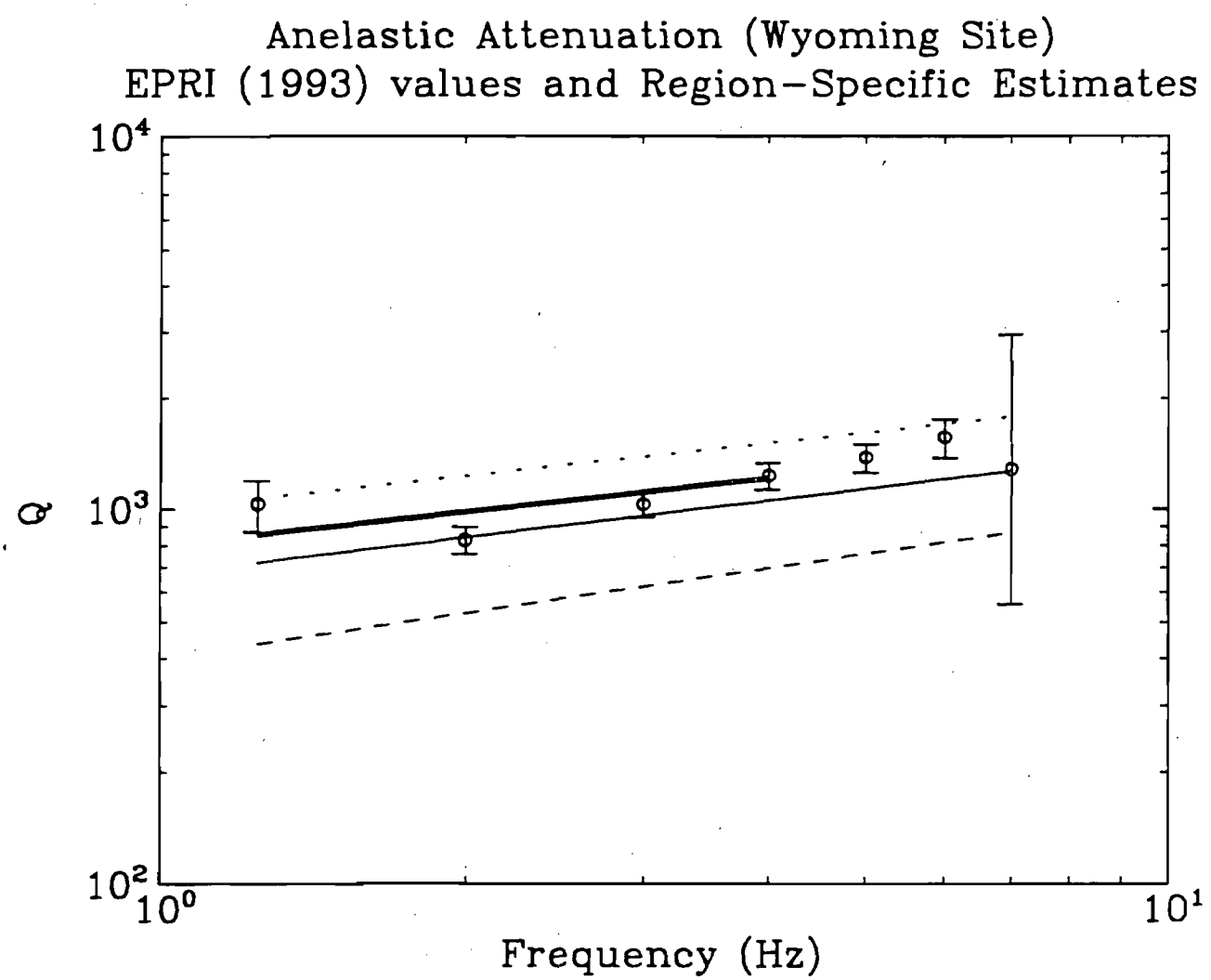


Figure F-11. Example on the use of site-specific (in this case region-specific) information on Q. The site specific data comes from Gupta et al. (1989, error bars) and Singh and Herrmann (1983, heavy solid line). Also shown are the three Q models considered in the EPRI (1993) generic calculations (thin lines; given equal weights in the EPRI calculations). Based on the site-specific data, the weights are changed to 0.4 (dots), 0.5 (solid), and 0.1 (dashed).

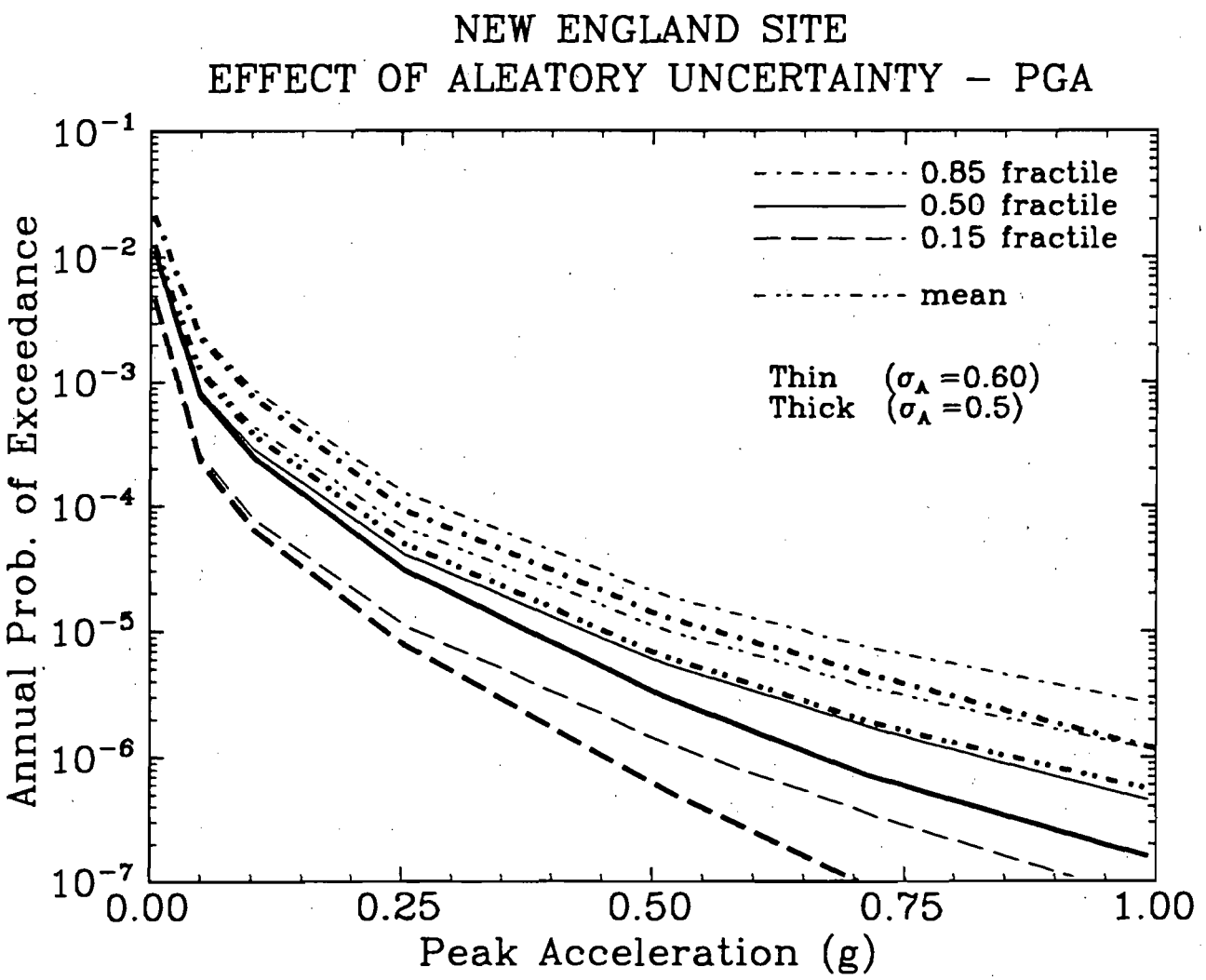


Figure F-12. Sensitivity of calculated seismic hazard to aleatory uncertainty in ground motions; results for PGA. The epistemic uncertainty is kept constant.

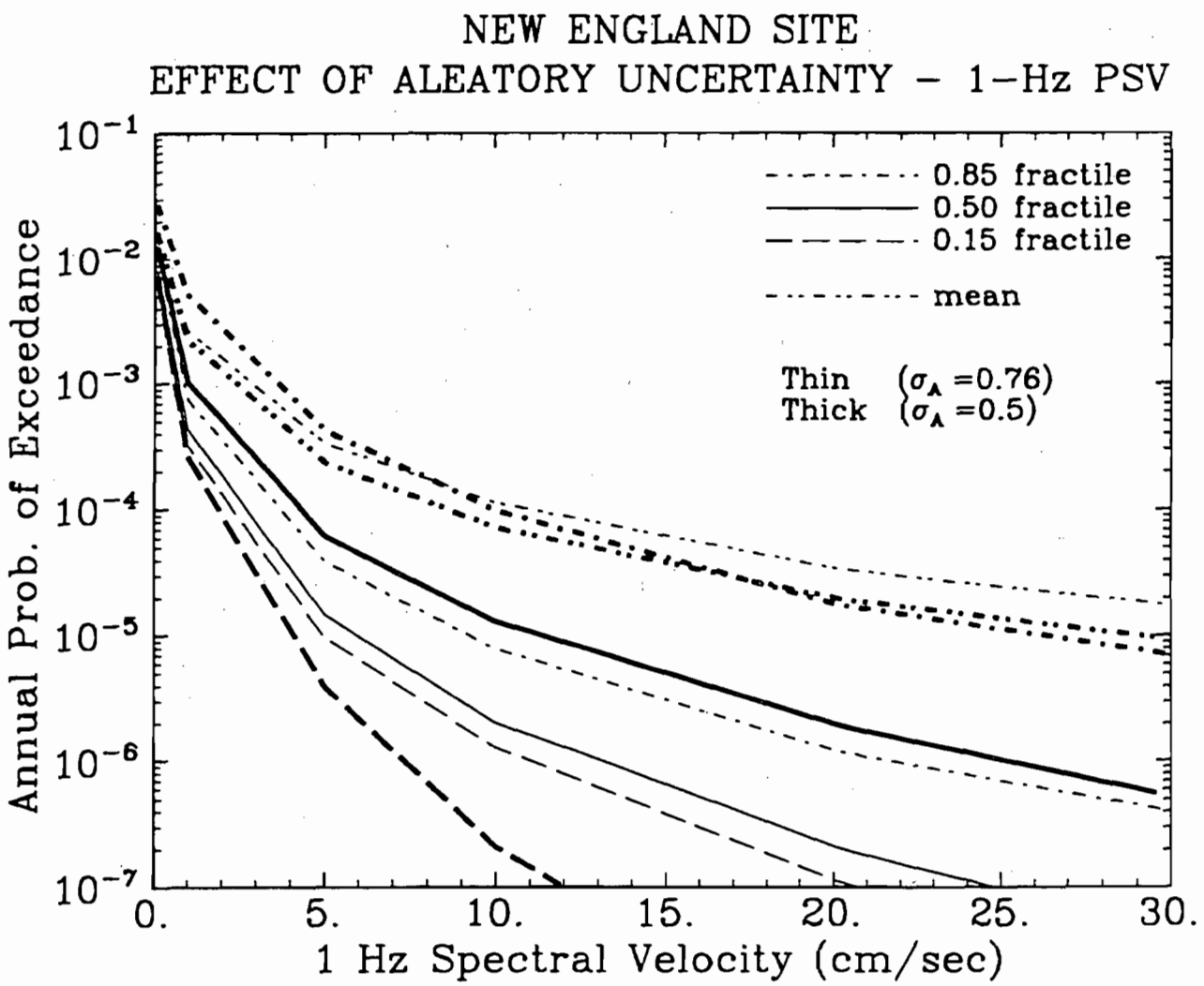


Figure F-13. Sensitivity of calculated seismic hazard to aleatory uncertainty in ground motions; results for 1-Hz spectral velocity. The epistemic uncertainty is kept constant.

APPENDIX G

SIGNIFICANT PARAMETERS IN SEISMIC HAZARD CALCULATIONS

by

Robin K. McGuire

G.1 INTRODUCTION

A significant amount of effort must go into seismic hazard analysis to obtain meaningful results, and this effort should be used in the most efficient way possible. To this end, it is important to examine what parameters contribute significantly to seismic hazard, and to determine when changes in those parameters make significant differences to the imputed hazard. The identification of important parameters can then be made on an informed basis so that maximum effort can be guided toward evaluating those parameters that make the most difference to the hazard.

The evaluation of which parameters lead to significant changes in the hazard is ultimately the responsibility of the analyst. However, guidelines can be drawn based on generic analyses so that the initial allocation of resources and effort can be made in a reasonable way. Without this guidance, a full seismic hazard analysis would have to be made at each site, including quantification of parameter uncertainties, to evaluate which parameters are most significant. If this is done, all of the effort to quantify parameter uncertainties has already been completed.

The real benefit in considering which parameters contribute to significant changes in hazard comes from being able to concentrate on the evaluation (both in the sense of the best estimate and of the uncertainty) of important parameters while neglecting, or treating in a crude fashion, other parameters that are not significant or are only marginally significant. Thus consideration of significant parameters involves both an evaluation of what drives the seismic hazard in the sense of the best-estimate hazard, and what contributes significantly to uncertainties in hazard. To these ends we formulate a procedure to guide the evaluation of which parameters deserve the most scrutiny. We also present generic results that document the changes in hazard that result from

varying certain parameters, so that initial concentrations of effort can be decided upon in an informed way.

These results will be useful to guide the efforts of earth scientists providing inputs to seismic hazard analyses. Such scientists may have little experience with probabilistic seismic hazard calculations, and without guidance may expend significant effort making interpretations and estimating parameters that matter little. Using the guidelines developed here will allow concentration on the inputs that matter most, resulting both in more efficiency and in a better estimate of seismic hazard.

G.2 DEFINITION OF SIGNIFICANT CHANGE

What is of most concern is the relative influence that one model or parameter has on the hazard, compared to other models and parameters. Given the finite limits of resources, scope, and time that all seismic hazard projects have, concentration should be placed on those interpretations that have the most influence. However, it also is useful to think in terms of absolute changes in hazard, for example to make decisions on whether to include or exclude certain models. Even though the contribution of these models might be low on a relative scale, if they would influence the hazard at an absolute level greater than some threshold, a case can be made that they should be studied and included in the seismic hazard computations.

Decisions regarding seismic hazard inputs can be divided into two types:

1. Should certain models and parameters be included in the calculations? In other words, should the underlying concepts be modeled at all, or should they be ignored? An example is the modeling of seismic sources that are successively farther and farther away from the site of interest. At some point a distant source will not contribute significantly to the hazard and should be ignored.
2. Should certain models and parameters have their uncertainty quantified? In this context a model or parameter may be required to evaluate the seismic hazard, but uncertainty in that model or parameter may or may not contribute to the uncertainty in seismic hazard.

For example, the host source for a site might dominate the seismic hazard, but (particularly for high frequency measures of ground motion) the maximum magnitude might not be a critical parameter in the calculations. Thus, while a maximum magnitude is needed, quantifying its uncertainty does not change the best estimate of seismic hazard nor the uncertainty in hazard. This does not relieve the analyst of the responsibility of making an accurate, defendable estimate of the maximum magnitude; indeed, the assessment that parameter uncertainty would not contribute to seismic hazard uncertainty depends on an accurate assessment of the parameter to start with.

Given the above two types of applications, guidelines can be offered on the levels of change in seismic hazard that would be significant. These guidelines are stated in terms of hazard calculations (annual frequencies of exceedence), which can be examined as a direct output of the seismic hazard analysis, but have their basis in the ground motion associated with a chosen annual frequency level. The two are related through the following:

$$\Delta \text{ Ground Motion} \simeq (\Delta \text{ Seismic Hazard})^{-1/S}$$

where Δ is the multiplicative factor by which the ground motion or seismic hazard changes, and S is the slope of the hazard curve in a log-log plot at the ground motion level of interest. For example, if the slope of the seismic hazard curve is -3 (a typical value), a parameter change that causes the hazard to change by a factor of 1.3 will cause the ground motion at the initial annual frequency of exceedence to change by a factor of 1.09. The relationship is approximate because the slope of the hazard curve changes as a function of ground motion amplitude.

Guidelines for decisions regarding models and parameters in the seismic hazard analysis are as follows. These are based on a slope of -3 for the hazard curve, and should be adjusted for the site-specific slope once it is determined from preliminary analyses.

<u>Guideline A.</u> To determine models and parameters to include, contributions to hazard must be included so that not more than 3% of the hazard (annual frequency of exceedence) is missing. As a practical matter, of course, what we are trying to find is the total hazard, so we can only take 3% of the total calculated hazard and compare it to the remainder that

might not be modeled. For example, if five sources together indicate a hazard of X at a site for a given ground motion amplitude, we are justified in neglecting other sources if together they contribute less than 3% of X at that amplitude. The rationale here is that we want the ground motion for a chosen annual frequency of exceedence to be accurate to at least 1%; with a slope of -3 in the hazard curve, this translates to the above criterion.

Guideline B. To determine models and parameters whose uncertainty should be quantified, the squared variation in hazard of the models and parameters whose uncertainty is being neglected must not exceed 10% of the total squared variation in hazard. For example, if the squared variation in hazard from models and parameters whose hazard is quantified is Y, the estimated squared variation from other models and parameters must not exceed 10% of Y. The rationale is that, if the squared variation in hazard is accurate to 10%, the standard deviation will be accurate to 5%, and the associated change in ground motion will be accurate to better than 2% (assuming a slope of -3 in the hazard curves). This means that the 85th percentile ground motion for a given annual frequency of exceedence should be accurate to 2%.

An example of the application of these guidelines is given in the next subsection.

G.3 FORMAT FOR EVALUATING SIGNIFICANT CHANGES IN HAZARD

A format is presented here wherein decisions regarding the important models, parameters, and uncertainties can be determined for a seismic hazard analysis, in order to ensure that the most critical elements are included. It should be emphasized that a proper seismic hazard analysis involves some iteration between models, earth scientists providing inputs, and results, so that assurance of the validity of results is reached based on the site-specific calculations. The format and guidelines offered here should be used as a tool in that evaluation process, not as a substitute for it.

Table G-1 lists models and parameters that should be considered when evaluating which to include and which uncertainties to model. In most cases for each primary parameter there is a second

critical parameter that is important in governing the importance of the first. For example the depth distribution of earthquakes may be important for the host source for a site, where earthquakes can occur directly under the site. The depth distribution is not important if the source lies several hundred km from the site.

A format for evaluating the importance of models and parameters in the hazard calculations is presented in Table G-2. Column (1) indicates the source (fault or area) being considered, and Column (2) lists the models or parameters considered for that source. All of the models and parameters identified in Table G-1 should in general be considered, unless they are not relevant to a specific application.

A preliminary seismic hazard calculation should be performed using first estimates of each model and parameter, and using first estimates of uncertainties. At the preliminary stage this calculation can use single estimates of each model and parameter, as long as uncertainties have been quantified in a preliminary fashion so that a reasonable estimate of the mean value can be derived. The hazard level (annual frequency of exceedence) for each source is listed in Column (3); it is repeated for each parameter being evaluated for each source. Thus for example Column (3) in Table G-2 lists "H_1" after each parameter for source 1.

Column (4) indicates the partial derivative of the hazard with respect to each parameter for each source. In a preliminary evaluation this can be obtained from the results presented in the next subsection; in a final seismic hazard calculation sensitivity studies should be used to determine these partial derivatives. Again this illustrates the iterative nature of the analysis: the evaluation of model and parameter importance should be made at several different levels of detail and accuracy during the analysis, to guide later analyses.

Column (5) of Table G-2 lists the uncertainty of each parameter, as provided by earth scientists or other analysts providing input to the application. These should be represented as standard deviations of each parameter's uncertainty, in the units of that parameter. For example, the

standard deviation of M_{max} should be listed in magnitude units. (Exceptions are discussed in Section G.5 below.)

The uncertainty in hazard caused by each parameter is calculated in Column (6) as the product of Columns (3), (4), and (5). This gives, for each entry, the amount that the hazard is expected to vary as a result of the absolute level of hazard, the sensitivity of hazard to that parameter, and the level of uncertainty in that parameter. Large contribution to the uncertainty in hazard requires three things: (a) that the source be a major contributor to hazard, (b) that the calculated hazard be sensitivity to a particular parameter, and (c) that that parameter be uncertain to a significant degree. Column (6) is an approximation to the standard deviation in hazard caused by uncertainties in that parameter. Column (7) of Table G-2 transforms the values of Column (6) into contributions to the variance in hazard by squaring the entries.

The guidelines offered above for determining significant contributions to hazard can be followed by deriving the sums shown in the last row of Table G-2. The first sum, in Column (3), shows the total hazard for the chosen ground motion amplitude. Guideline A can be applied by comparing the hazard contributed by each source (H_i) to the summation of the H_i's. The second sum, at the bottom of Column (7), shows the sum of the variances for the individual entries in Column (7). The individual contributions for each source and parameter can be compared to this sum to determine their level of significance, using Guideline B.

Column (8) in Table G-2 is included to indicate whether that source and parameter will be included in the uncertainty modeling. When a source is disregarded because it contributes little to the hazard, of course none of its parameters need be specified (except to the extent needed for documentation. When a model or parameter of a source is treated without uncertainty (because its contribution to uncertainty is small), a best estimate value of that parameter still needs to be specified so that hazard calculations can be made.

The format described here allows objective decisions to be made on which models and parameters to include in a seismic hazard calculation and for which models and parameters uncertainty is important to include. The format can be applied at several levels in the analysis, for example:

- at the screening stage, when preliminary decisions must be made on the sources to include in the analysis. Here first estimates of models and parameters would be used, with partial derivatives obtained from general results such as presented in the next subsection, and general estimates of parameter uncertainties (e.g. taken by analogy from other regions) can be used.

- at the draft calculation stage, when assurance is sought that the predominant contributors to seismic hazard and its uncertainty have been included. Here site-specific sensitivities of hazard should be used to obtain the partial derivatives, along with draft assessments of parameter uncertainties.

- at the project documentation stage, when final interpretations are available and it is necessary to document the decisions regarding including and excluding various models and parameters. Here again, site-specific studies of seismic hazard should be used to obtain the partial derivatives needed for the format.

Adopting a format such as that illustrated here will provide assurance that the significant contributions to seismic hazard have been included in the analysis.

G.4 EXAMPLES OF SEISMIC HAZARD SENSITIVITIES

Examples of the sensitivity of seismic hazard calculations to various seismic source models and parameter values are presented in this subsection. The objective of these calculations is to create a data set of sensitivity calculations that can be used for preliminary screening and to develop first-cut partial derivatives as required by the guidelines described in the previous subsection. Sites are selected that are subject to seismic hazard from realistic representations of seismic sources in

the eastern U.S. and California. While we believe the sensitivity calculations to be valid and useful, they are not a substitute for site-specific calculations.

Three groups of sites are studied here. Group A sites lie to the east of the New Madrid fault system in the central Mississippi embayment (see Figure G-1). This source has a large maximum magnitude ($M_{max} = 7.5$). Group B sites lie within and to the west of a large area source in eastern Massachusetts (see Figure G-16); this source has a moderate maximum magnitude ($M_{max} = 6.3$). Group C sites are a set of sites that lie to the east of the Hayward fault in California (see Figure G-27). This fault has a moderate-to-high maximum magnitude ($M_{max} = 7.0$). The representations of the sources for groups A and B are taken from the EPRI (1989) study of seismic hazard in the central and eastern U.S. The parameters of the Hayward fault are taken from recent studies of California faults, their activity rates and maximum magnitudes.

The attenuation equations used for the sensitivity studies in the eastern Column (groups A and B) are those of the recent EPRI-sponsored study of ground motions in the eastern Column (EPRI, 1993). For the California example (Group C) the attenuation equations of Joyner and Boore (1993) and Campbell (1993). In this application only the median rock ground motion equations were used, as all that is required is a reasonable attenuation equation that shows the effects of source geometries and source parameters.

The seismic hazard was calculated at each site in the group, both for base-case estimates of parameters and for variations of those parameters. Results are presented graphically, showing the original calculated hazard and the change in hazard as the parameters are varied from the base case. Figure G-2a is an example of the sensitivity of hazard to changes in beta, the parameter of the exponential magnitude distribution that is equal to the Richter b-value times ln(10). The top figure shows the calculated hazard at the string of sites, and the bottom figure shows the percentage change in hazard, for distances of 0 to 500 km from the New Madrid fault. In these calculations all other parameters have been fixed at their best-estimate values. The density of site locations is higher closer to the fault where more precision is required because the seismic hazard and its sensitivity may change more quickly with distance.

Figure "a" in each group shows the sensitivities for a spectral level corresponding to a PGA of 0.1g, and Figure "b" in each group is similar but for a spectral level corresponding to a PGA of 0.3g. (For Group C sites in California the PGA levels used are 0.3g and 0.6g, respectively, recognizing the generally higher level of seismic design that applies in California.) The order of the figures is as follows:

Figures G-2 through G-8: Group A sites, 10 Hz.
Figures G-9 through G-15: Group A sites, 1 Hz.
Figures G-17 through G-21: Group B sites, 10 Hz.
Figures G-22 through G-26: Group B sites, 1 Hz.
Figures G-28 through G-34: Group C sites, 10 Hz.
Figures G-35 through G-41: Group C sites, 1 Hz.

Individual interpretations are warranted for each of the figures in an actual application where decisions must be made on retaining or disregarding certain models and parameters. The following general conclusions regarding the sensitivities can be stated:

1. Sensitivity to beta is moderate, and it decreases at small source-to-site distances (less than 25 km).
2. Sensitivity to the depth distribution is negligible except at small source-to-site distances (less than 50 km).
3. Sensitivity to whether an exponential or characteristic magnitude distribution is used depends on whether a slip rate constraint or a seismicity constraint is used to fix the rate of activity. If a slip rate constraint is used, the maximum sensitivity occurs for very close or very distant sites. If a seismicity constraint is used, calculations at all distances are sensitive to the choice of model.
4. Sensitivity to maximum magnitude is largest at large source-to-site distances. It increases with ground motion amplitude, and is largest when the mean M_{max} value is lower. (The sensitivity is greater when the mean M_{max} is 6.0 or 6.5 than when the mean M_{max} is 7.5 or

7.8. Note when comparing Figures G-6a and G-7a [and other figures] that the range of M_{max} values in Figure G-7a is 1.2 units whereas it is 0.6 units in Figure G-6a.)

5. Uncertainty in fault location causes a moderate sensitivity for most sites for high frequencies, and less sensitivity at low frequencies. For source areas this applies to sites located outside the source, but especially sites near the source border.

Note that on Figures G-17 through G-26, sites located at distances less than 80 km are inside the source boundaries, so the hazard is more-or-less constant (particularly for sites at distances indicated as less than 50 km, which are well within the source borders).

The lower curve on each plot can be used to calculate partial derivatives of hazard to use in the format recommended above. An example of this application is given in the next section. For a particular site, determine the distance to the relevant source and pick a change in the parameter value that represents one sigma in the uncertainty distribution. For example, for M_{max} this might be 0.2 magnitude units, and for a site located 65 km from an area source boundary Figure 19b indicates a sensitivity of +50% for a decrease of 0.2 units in M_{max} from 6.0 to 5.8. (A site located 65 km from the source boundary is plotted at 150 km on Figure 19b.) In general the larger of an increase or a decrease in the subject parameter should be used. With a sensitivity of +50%, the partial derivative is calculated as $\ln(1.50)/0.2 = 2.03$. This partial derivative can be used in Table G-2.

G.5 EXAMPLE APPLICATION

An example is presented next to show how the sensitivity plots of the previous section can be used in conjunction with Table G-2 to check Guidelines A and B. A hypothetical mid-continent site is chosen that is 200 km from a major fault (called Fault F), is located 50 km inside one source (called Source H, the host source) with a low maximum magnitude, and is located 100 km from the border of another source (called Source Z) with a moderate maximum magnitude. For this example the plots for Group A and Group B sites, presented in the previous section, are used to determine the sensitivities.

Table G-3 lists the critical parameters for each of the three hypothetical sources. These parameters have been chosen for illustration and are not meant to represent any particular source, including the New Madrid fault. For Fault F we use Figures G-2 through G-15 at a distance of 200 km (the distance of the fault from the site) to determine sensitivities. For Source H we use Figures G-17 through G-26 at a distance of 30 km (the point marked "*" on Figure G-16, which is 50 km inside the source) to determine sensitivities. For Source Z we also use Figures G-17 through G-26 but at a distance of 190 km (the point marked "+" on Figure G-16, which is 100 km outside the source). Also, we assume that the hazard from Source Z is twice that shown on Figures G-17 through G-26, because of the assumed activity rate of Source Z (Table G-3).

The parameter evaluation is carried out using the relevant figures as described above. For this example we describe the calculations of entries in Table G-2 for Source H, but the other sources are evaluated in a similar way. The calculated values for all sources are summarized in Table G-4 for 10 Hz spectral acceleration corresponding to a ground motion of 0.3g.

Hazard levels H_i. The hazard level is read from the top of Figure G-17b as 1.4×10^{-4} at 35 km. This goes in Column (3) of Table G-4.

Activity rate. A figure is not used for activity rate because hazard is directly proportional to this parameter. Therefore we can calculate Column (4) in Table G-4 using a factor of 2 (the standard deviation) as

$$\partial(\ln[\text{Hazard}])/\partial p = 0.69/2 = 0.35$$

β. The bottom of Figure G-17b indicates that changing β by 0.5 changes hazard by 20%. Thus

$$\partial(\ln[\text{Hazard}])/\partial p = 0.18/-0.5 = -0.36$$

Here the negative sign means that the hazard increases as β decreases, and vice versa.

Depth. The bottom of Figure G-18b is used for assessment of the effects of depth. Here the sensitivity may not be symmetrical, so we compute the two alternative depth changes separately:

3 km depth, sensitivity is a factor of +7%:

$$\partial(\ln[\text{Hazard}])/\partial p = 0.068/-2 = -0.034$$

10 km depth, sensitivity is a factor of -22%:

$$\partial(\ln[\text{Hazard}])/\partial p = -0.248/5 = -0.050$$

The negative sign here again means that the hazard increases as the depth decreases, and vice versa. The average of these sensitivities, -0.042, is used in Table G-4.

M_{max}. Figure G-19b (bottom) is used for this sensitivity. This plot shows that changing M_{max} by 0.3 units changes the hazard by 25%. Thus

$$\partial(\ln[\text{Hazard}])/\partial p = 0.223/0.3 = 0.744$$

Distance to source border. Figures G-21a and G-21b show very low sensitivity to changes in the border location for a site well inside the source, as would be expected. Thus

$$\partial(\ln[\text{Hazard}])/\partial p = 0$$

These values are shown in Column (4) of Table G-4. Column (5) lists the uncertainties in parameters, which are in most cases the standard deviations. Where discrete alternatives exist among choices, such as for the magnitude distribution on the fault, it is acceptable (and conservative) to indicate "alt." under Column (5) and treat this with a value of unity. Column (6) shows the product of Columns (3), (4), and (5), and Column (7) shows the square of Column (6).

Totals are shown for Columns (3) and (7). Under Column (3), the total hazard is indicated as 1.45E-4. Checking the values for individual sources, we see that Source H (hazard of 1.4E-4) contributes 96.6% of the total. Thus Source H alone does not meet Guideline A (inclusion of 97% of the hazard), so we should include the next highest contributor to hazard, Source Z. Fault F contributes less than 0.5% to the total hazard, so it is excluded ("N" is inserted in the Column (8) of Table G-4).

Checking the contribution to variance, the total of the contributions in Column (7) is 1.15E-8, and two parameters contribute 92% of that total. These are the rate and M_{max} uncertainties for Source H. The β uncertainty for Source H contributes another 5.5% to the total variance. Following Guideline B, we select rate and M_{max} for Source H to have the uncertainty quantified, and indicate for the remaining parameters in both Sources H and Z that only best estimates need be modeled. (As a practical matter, if the rate uncertainty is being quantified for a source, it would usually be

little additional work to quantify the β uncertainty. Since this would result in 97% of the total uncertainty being included, it would ordinarily be done.)

Several points are worth mentioning for this example. First, examining lower structural frequencies (e.g. 1 Hz) or lower amplitudes of ground motion usually results in more sources and parameters being included than 10 Hz. Second, for discrete alternatives (e.g. the characteristic vs. exponential magnitude distribution for Fault F), it is usually acceptable to show the change in ln[hazard] as the change in hazard when changing from one parameter assumption to the other, and to treat the parameter change as unity. This will work as long as the base case choice is more conservative than the alternative. Finally, the standard deviation of activity rate in Table G-3, and the sensitivity to activity rate in Table G-4 (Column (4)), are treated as factors on the mean rate. This leads to the same result as treating the standard deviation and sensitivity in units of events per year.

G.6 SUMMARY

Appendix G has presented typical sensitivity studies that show the relationship between calculated hazard and parameter changes. These studies are for common values of parameters and for a range of site locations with respect to seismic sources. They can be used as guidance to determine the most critical sources and parameters to concentrate on in a seismic hazard assessment, both for inclusion in the calculations and for uncertainty quantification.

References

EPRI (1989). Probabilistic seismic hazard evaluations at nuclear plant sites in the central and eastern United States: resolution of the Charleston earthquake issue. Electric Power Research Inst. Rept NP-6395, Palo Alto, April.

EPRI (1993). Guidelines for determining design basis ground motions. Electric Power Research Inst. Rept. 102293, Palo Alto, November.

TABLE G-1

MODELS AND PARAMETERS FOR CONSIDERATION

Primary Model or Parameter	Other Critical Parameter
Source or fault location	Distance to source boundary or fault.
Depth distribution	Distance to source boundary or fault.
Maximum magnitude	Best estimate of m_{max} (8 is different from 6).
Magnitude distribution (exponential vs. characteristic)	Contribution of that source/fault: designation of slip rates or activity rates.
Activity rate	(none)
b-value	Best estimate of m_{max}.
Homogenous vs. spatially-varying seismicity	Location of site relative to average rate.
Correlation of source parameter uncertainty	Specific parameter and correlation model.
Correlation of source activity	Range of activities and correlation.

TABLE 2

FORMAT FOR SOURCE AND PARAMETER EVALUATION

(1) Source	(2) Parameter (p)	(3) Hazard*	(4) $\partial\{\ln[\text{Hazard}]\}/\partial p$**	(5) Unc. in p***	(6) Uncert. due to p (6)=(3)·(4)·(5)	(7) Contribution to variance $(6)^2$	(8) Include (y/n)
1	Mmax	H_1					
1	depth	H_1					
"	.	H_1					
"	.	H_1					
2	Mmax	H_2					
2	depth	H_2					
		H_2					
		H_2					
Total		$\sum_i H_i$				$\sum_i (4)_i^2$	

* From preliminary hazard calculations
** From task 3 sensitivity results
*** From seismicity expert

TABLE G-3

EXAMPLE PARAMETERS FOR HYPOTHETICAL SOURCES

Parameter	Fault F	Source Q	Source Z
Mean activity rate	10^{-3}/yr*	10^{-3}/yr+	$2x10^{-3}$/yr**
S.D. of activity rate	factor of 1.2	factor of 2	factor of 2
Mean β	2.0	2.7	2.7
S.D. of β	0.2	0.5	0.5
Base Case Depth Dist.	2-20 km	5 km	5 km
Alternative Depth Dist.	8-30 km	3 or 10 km	3 or 10 km
Base Case Mag. Dist.	char.	exp.	exp.
Alternative Mag. Dist.	exp.	--	--
Mean m_{max}	7.5	6.0	6.0
S.D. of m_{max}	0.4	0.3	0.3
Mean dist. to source/border	200 km	50 km (inside)	100 km (outside)
S.D. of dist. to source/border	5 km	10 km	10 km

* Equivalent to the rate used to calculate sensitivities for Group A sites.
\+ Equivalent to the rate used to calculate sensitivities for Group B sites.
** Equivalent to two times the rate used to calculate sensitivities for Group B sites.

TABLE G-4

SOURCE AND PARAMETER EVALUATION FOR EXAMPLE PROBLEM

(1) Source	(2) Parameter P	(3) Hazard	(4) ∂/ln[Hazard]/ ∂p	(5) unc. in p	(6) unc. due to p	(7) cont. to var.	(8) include* (Y/B.E./N)
F	act. rate	5E-7	0.35	1.2	2.1E-7	4.4E-14	N
	β	5E-7	1.11	0.2	1.1E-7	1.2E-14	N
	depth	5E-7	0.01	alt.	5.0E-9	2.5E-17	N
	mag. dist.	5E-7	7.7	alt.	3.8E-6	1.5E-11	N
	m_{max}	5E-7	0.97	0.4	1.9E-7	3.8E-14	N
	distance	5E-7	0.045	5	1.1E-7	1.3E-14	N
H	act. rate	1.4E-4	0.35	2	9.8E-5	9.6E-9	Y
	β	1.4E-4	-0.36	0.5	-2.5E-5	6.3E-10	B.E.
	depth	1.4E-4	-0.042	2.9	-1.7E-5	2.9E-10	B.E.
	m_{max}	1.4E-4	0.744	0.3	3.1E-5	9.6E-10	Y
	distance	1.4E-4	0	10	0	0	B.E.
Z	act. rate	5E-6	0.35	2	1.7E-6	2.9E-12	B.E.
	β	5E-6	1.00	0.5	-1.2E-6	1.4E-12	B.E.
	depth	5E-6	-0	2.9	0	0	B.E.
	m_{max}	5E-6	2	0.3	1.5E-6	2.3E-12	B.E.
	distance	5E-6	-.049	10	-1.2E-6	1.4E-12	B.E.
		$\sum H_i$ = 1.45E-4				$\sum$ = 1.15E-8	

* Y = include parameter uncertainty, B.E. = include parameter best estimate, N = exclude source

Line Source (EUS)

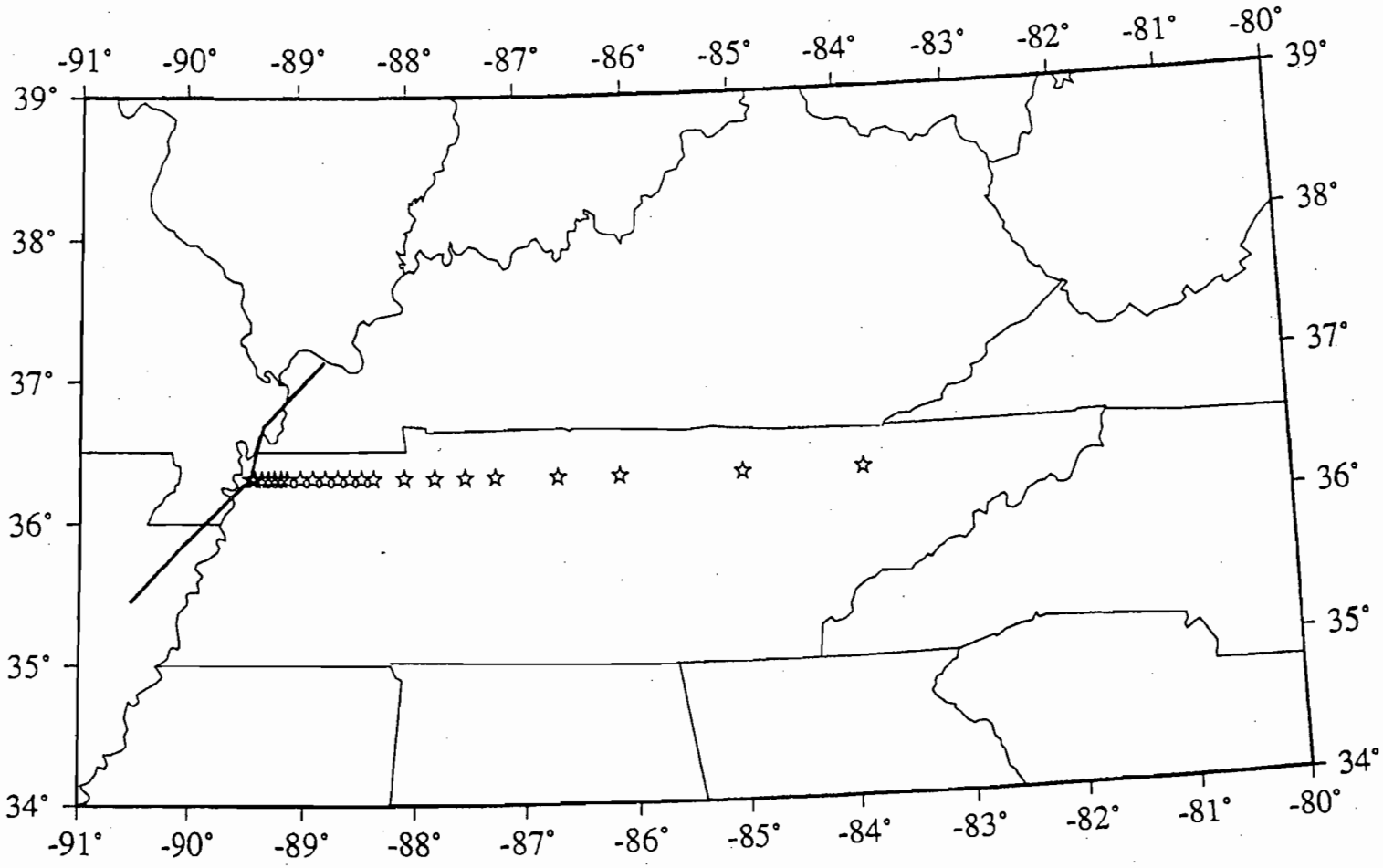
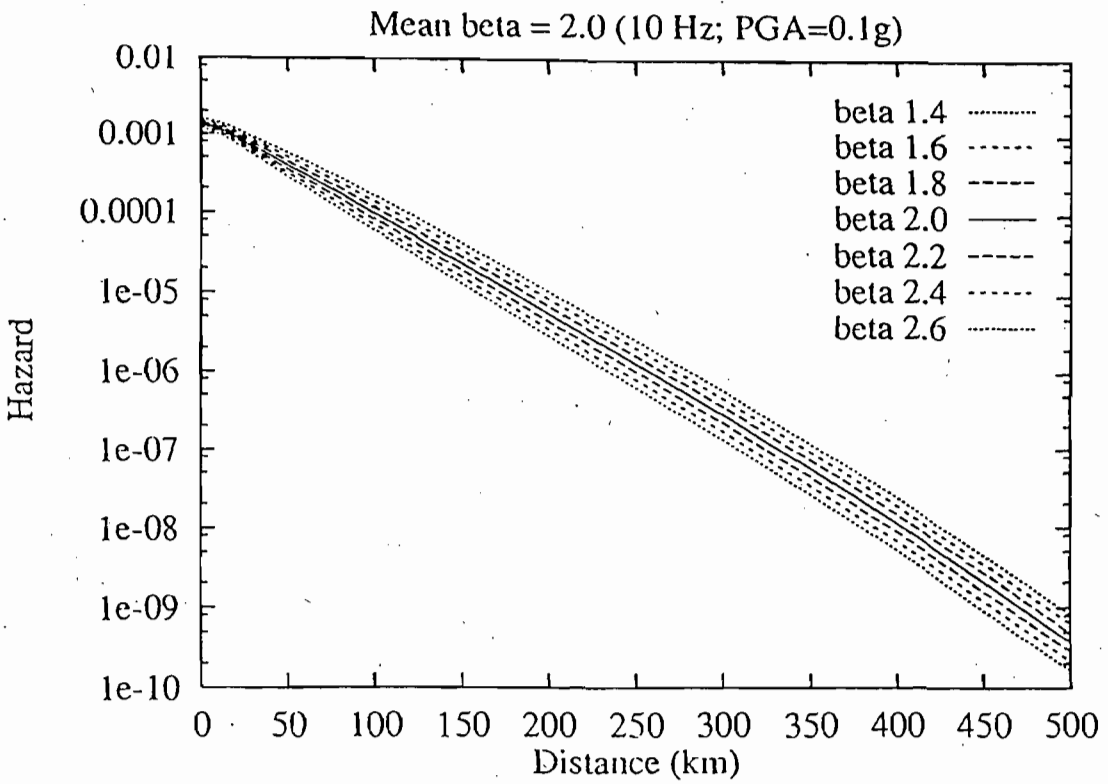


Figure G-1. Configuration of Group A sites with line source.



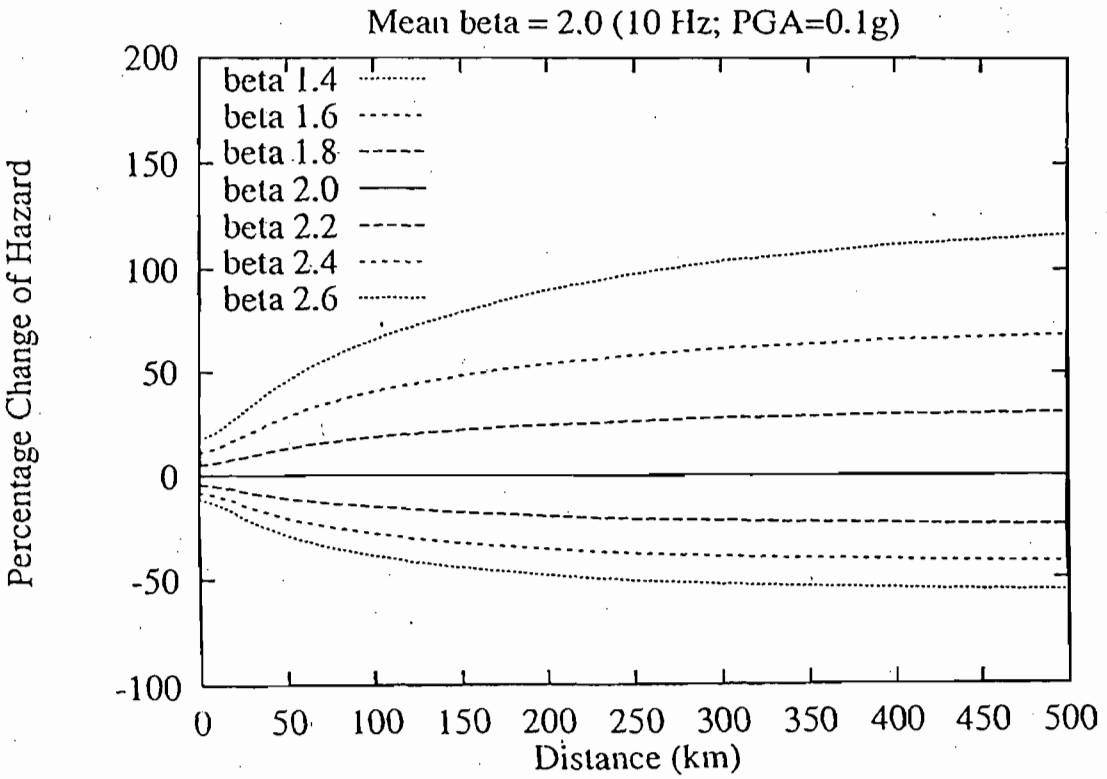
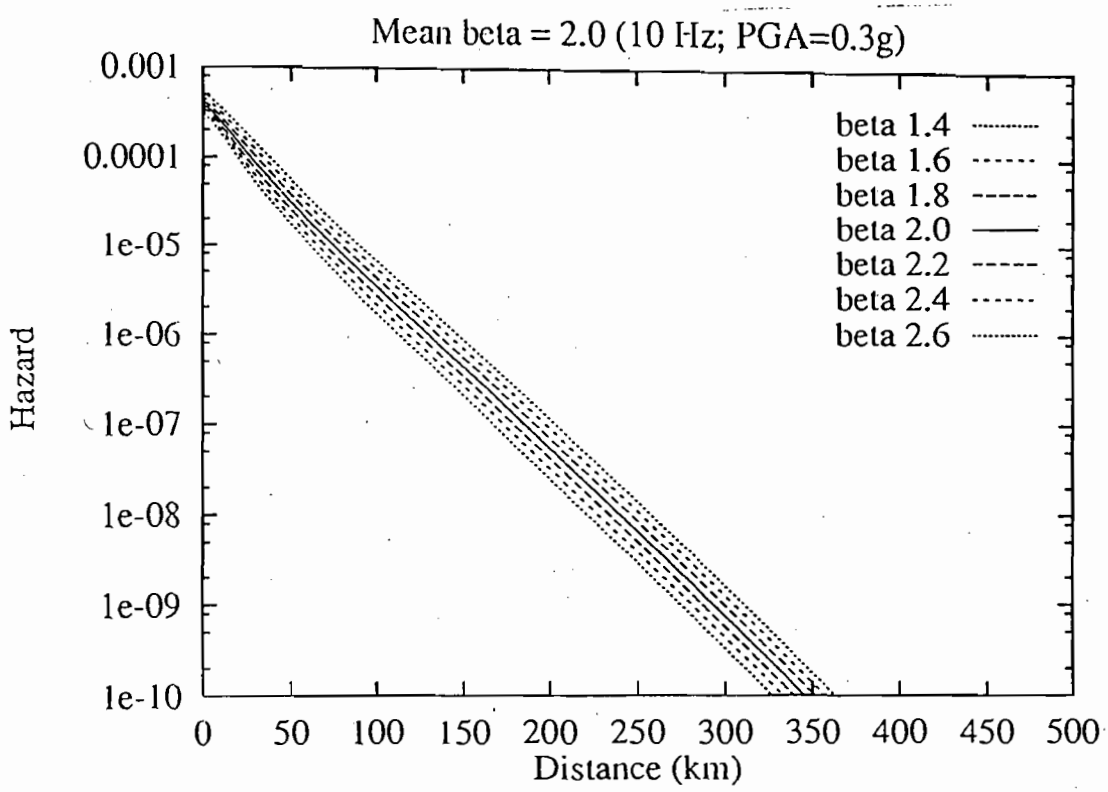


Figure G-2a. Sensitivity of 10 Hz hazard to beta for PGA = 0.1g, Group A sites.



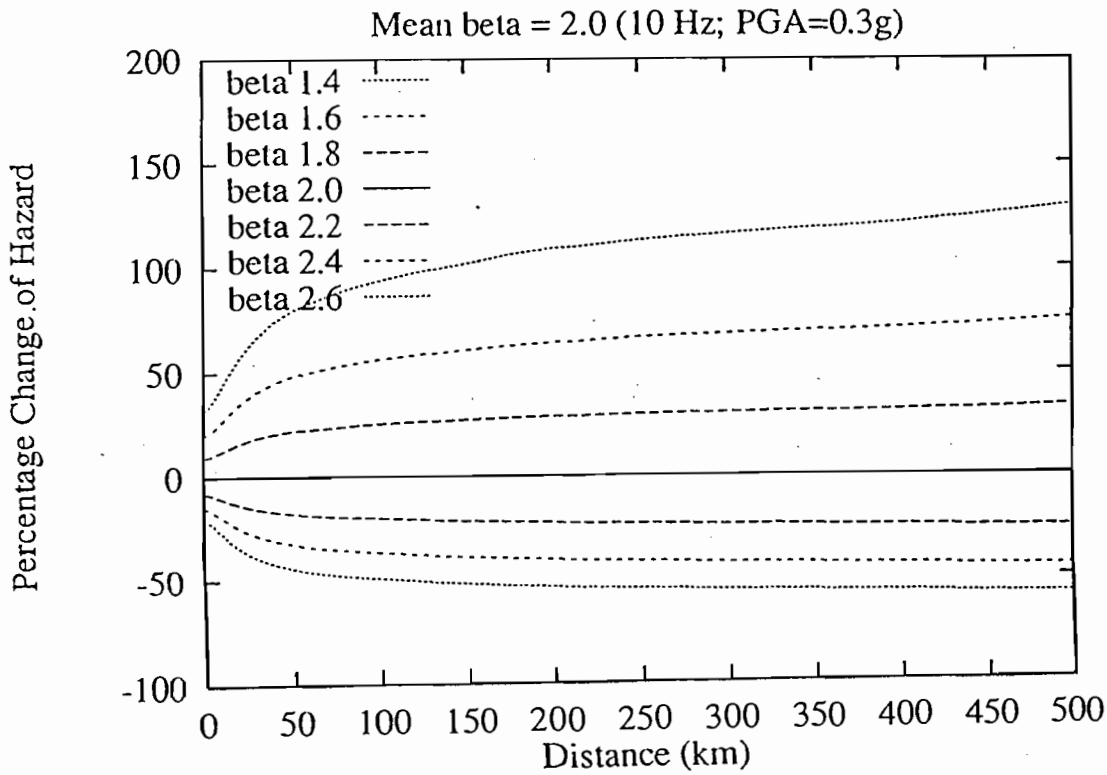
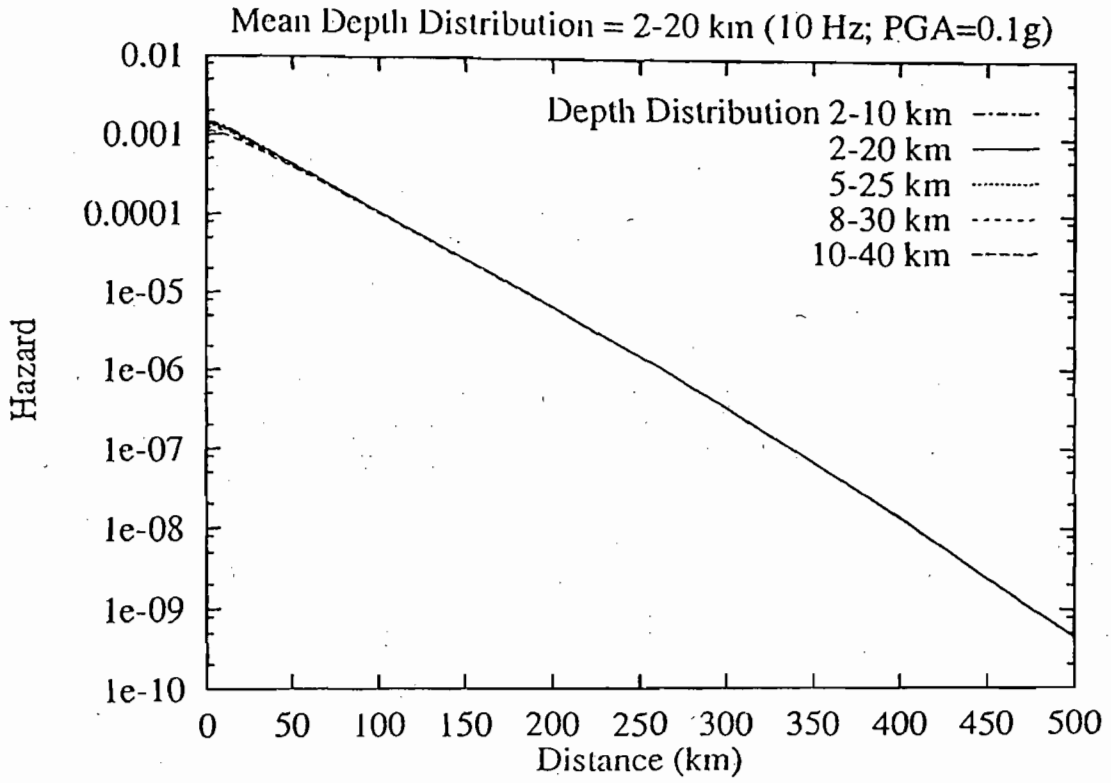


Figure G-2b. Sensitivity of 10 Hz hazard to beta for PGA = 0.3g, Group A sites.



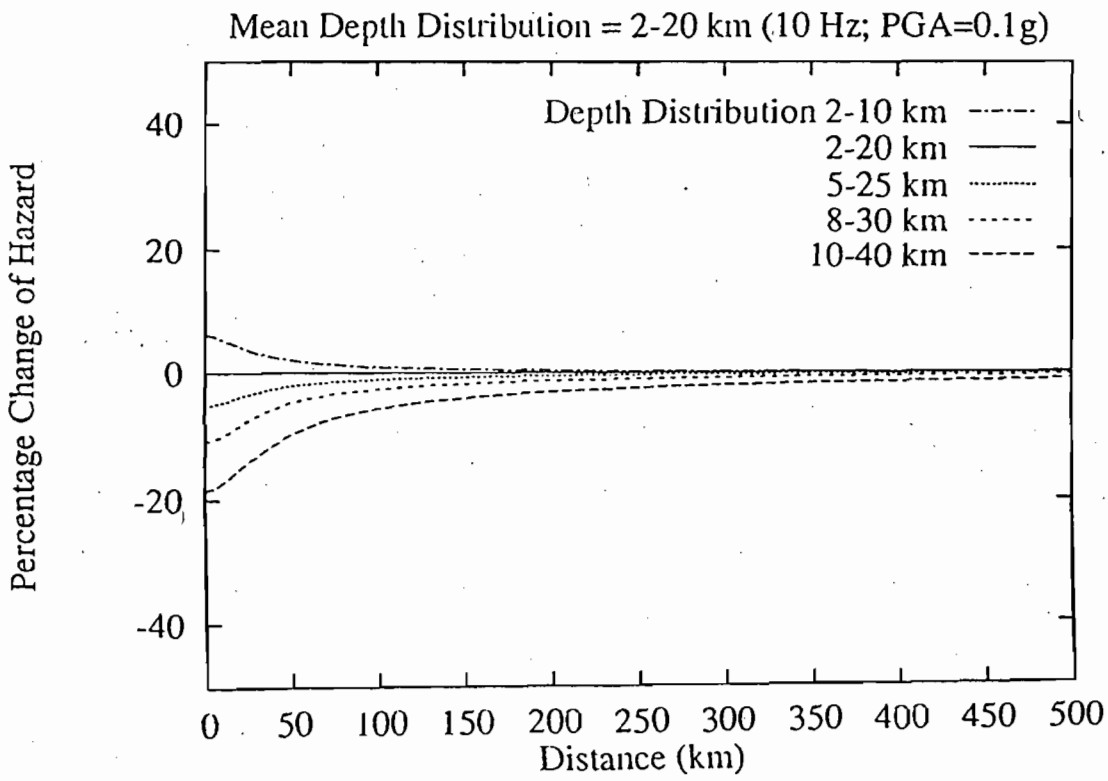
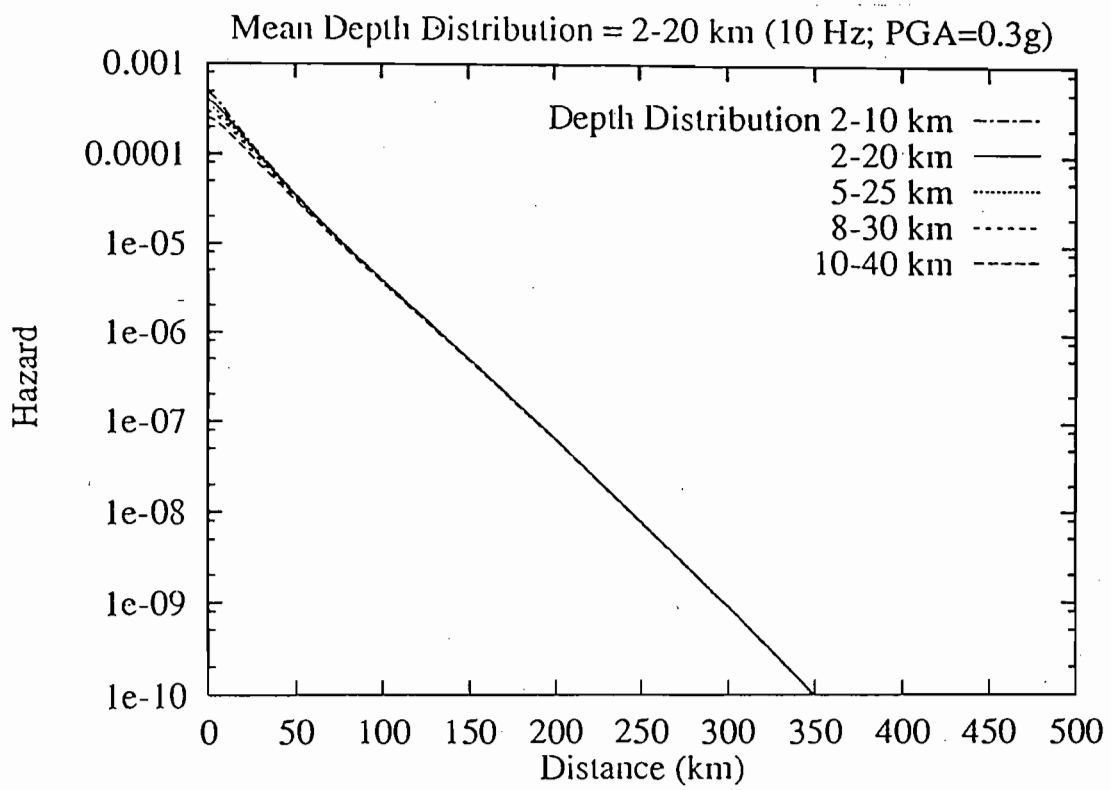


Figure G-3a. Sensitivity of 10 Hz hazard to depth distribution for PGA = 0.1g, Group A sites.



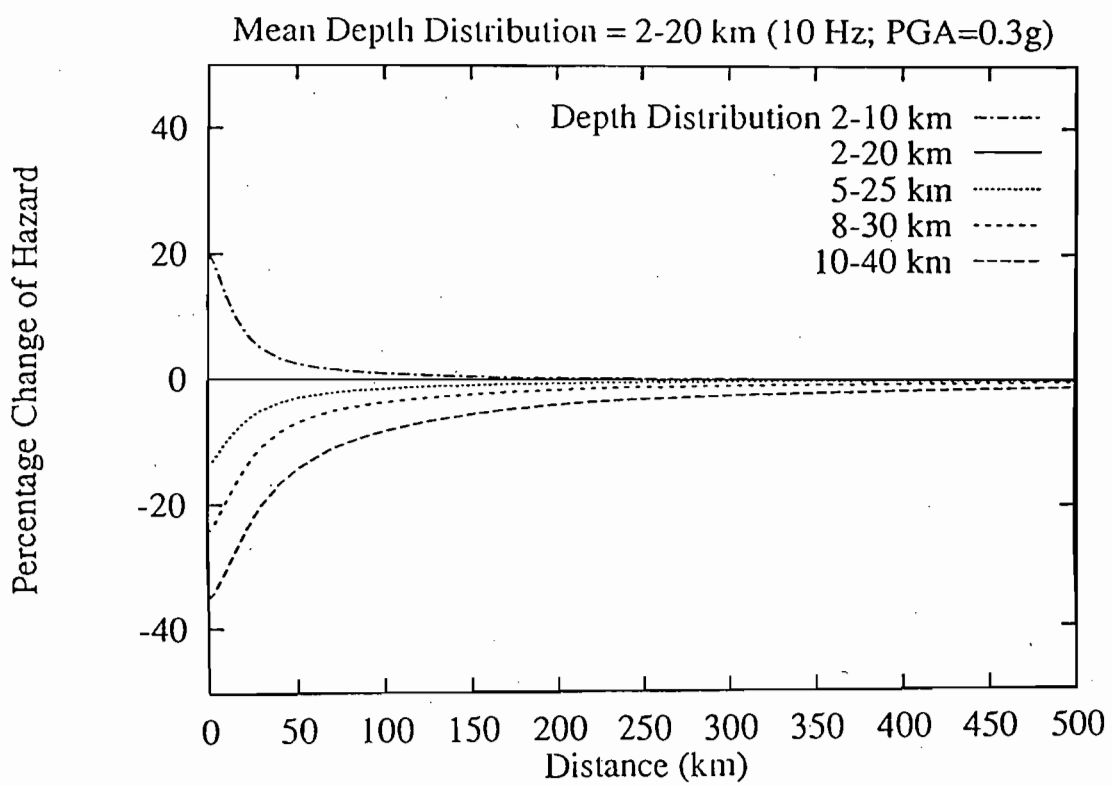
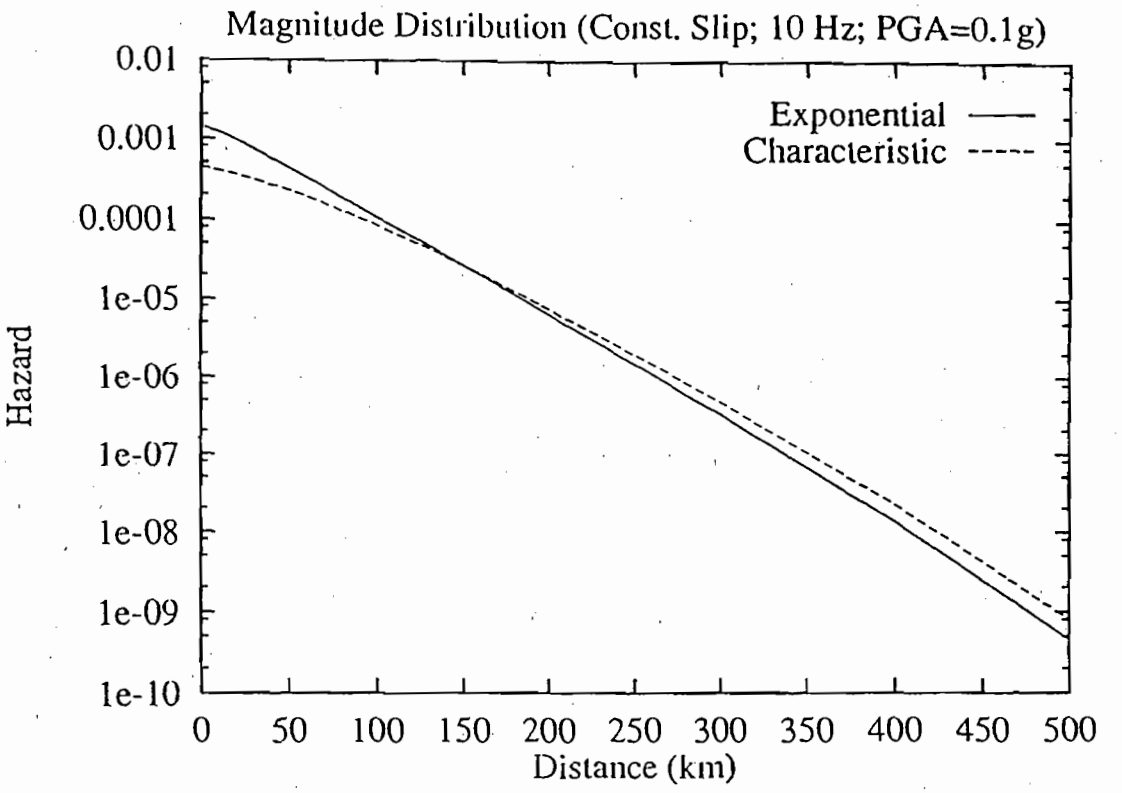


Figure G-3b. Sensitivity of 10 Hz hazard to depth distribution for PGA = 0.3g, Group A sites.



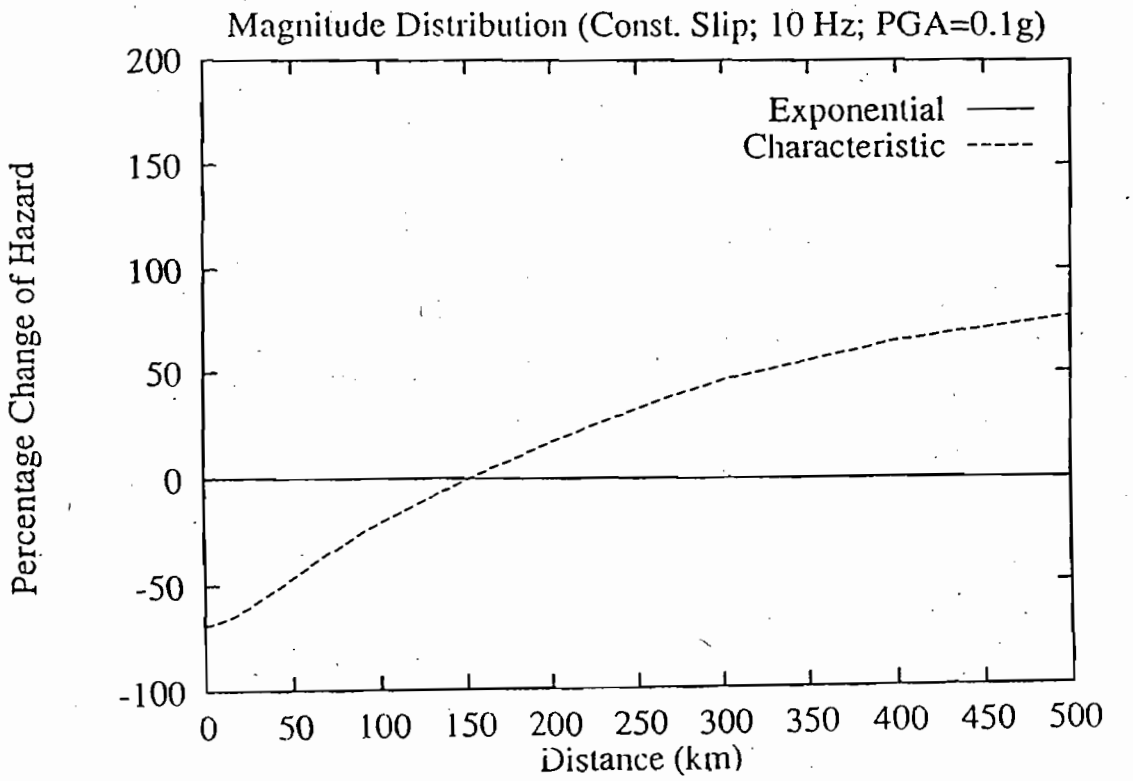
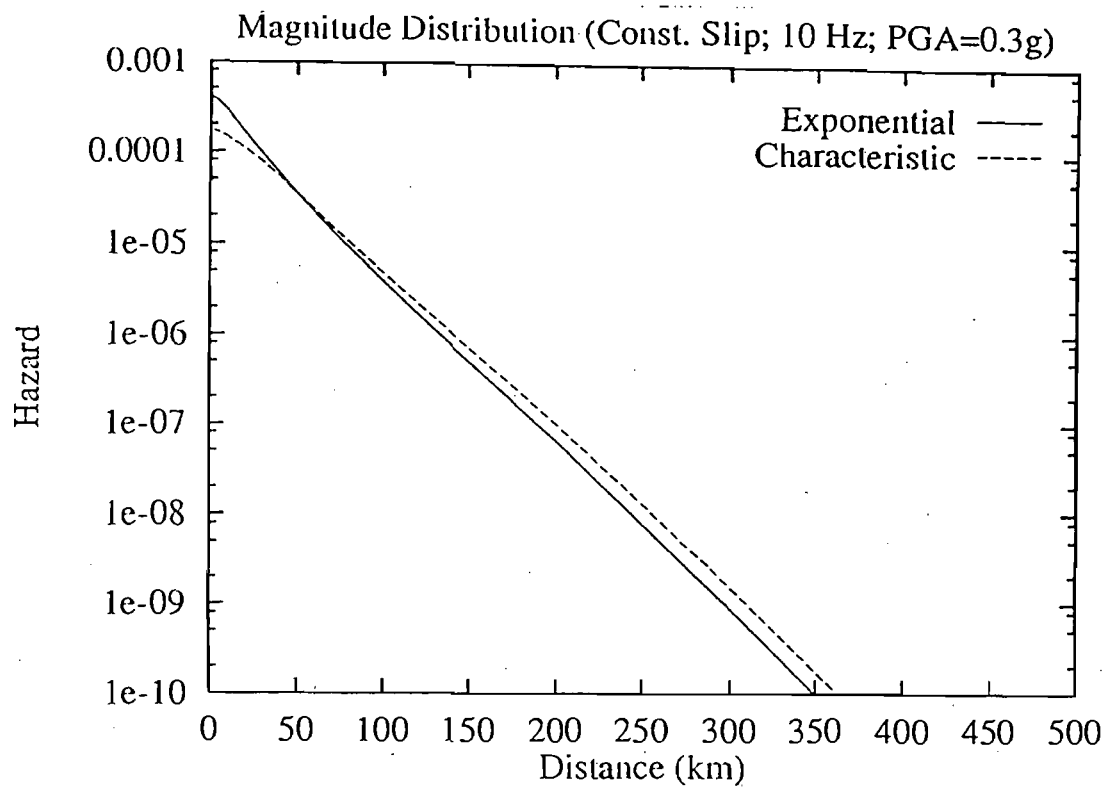


Figure G-4a. Sensitivity of 10 Hz hazard to magnitude distribution (with constant slip assumption), PGA = 0.1g, Group A sites.



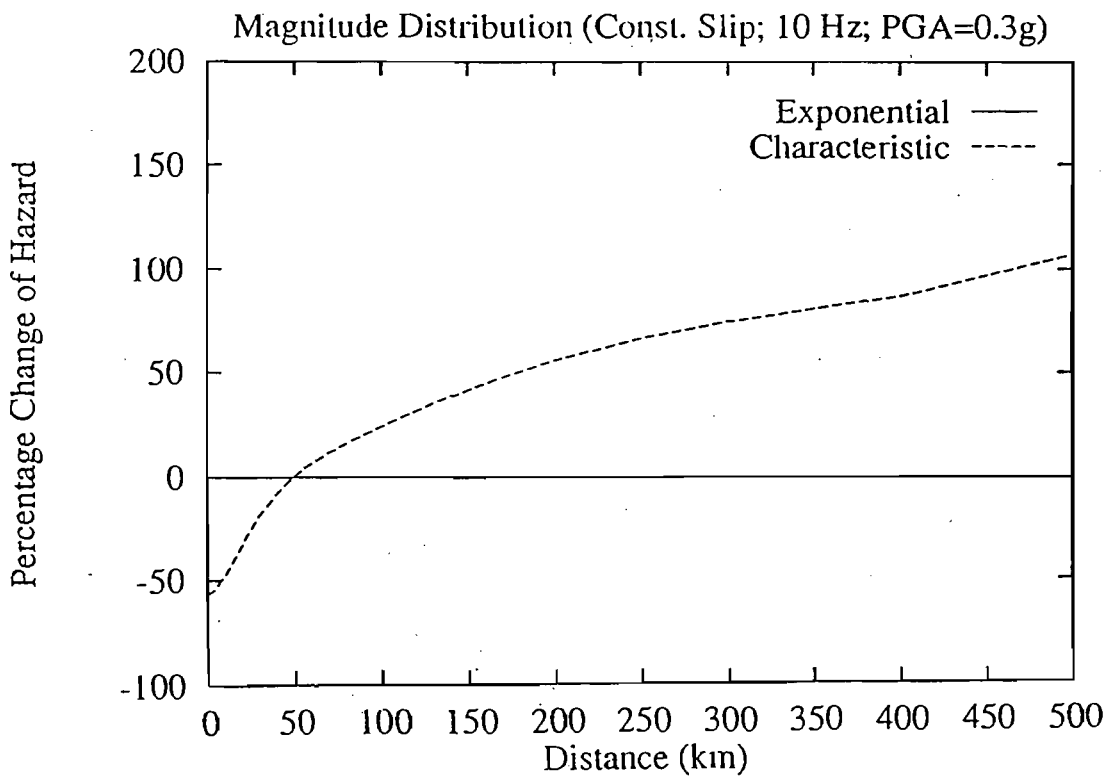
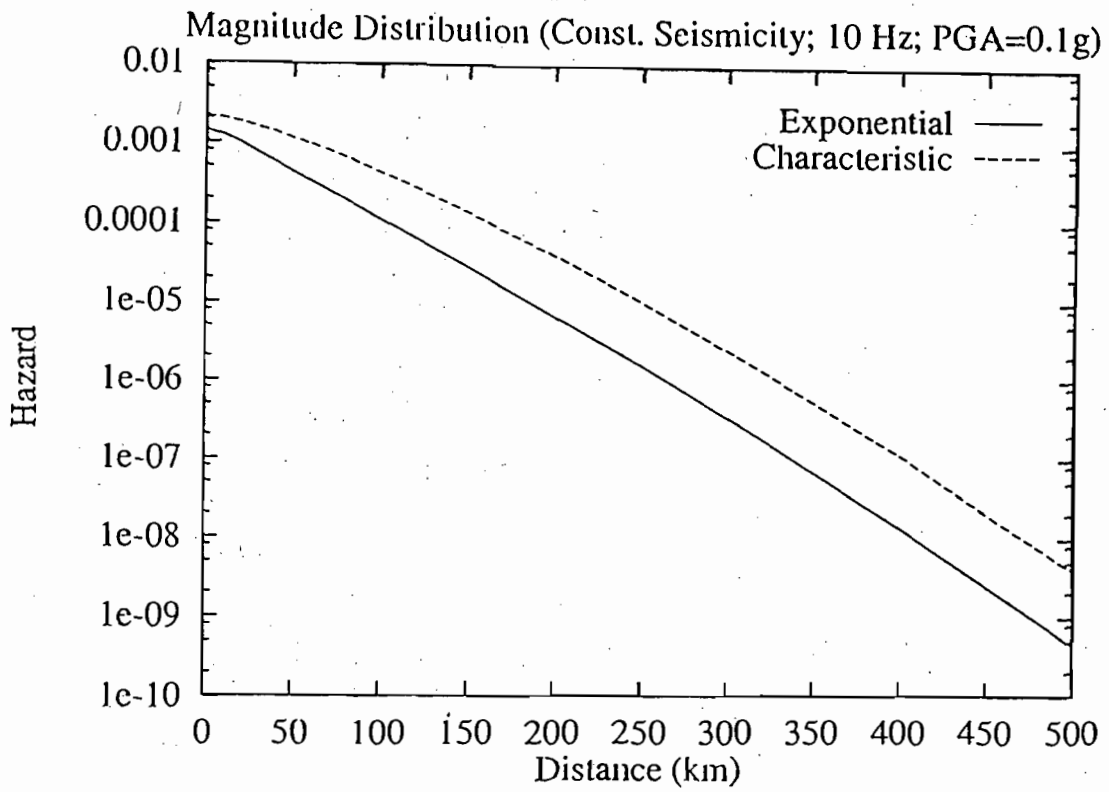


Figure G-4b. Sensitivity of 10 Hz hazard to magnitude distribution (with constant slip assumption), PGA = 0.3g, Group A sites.



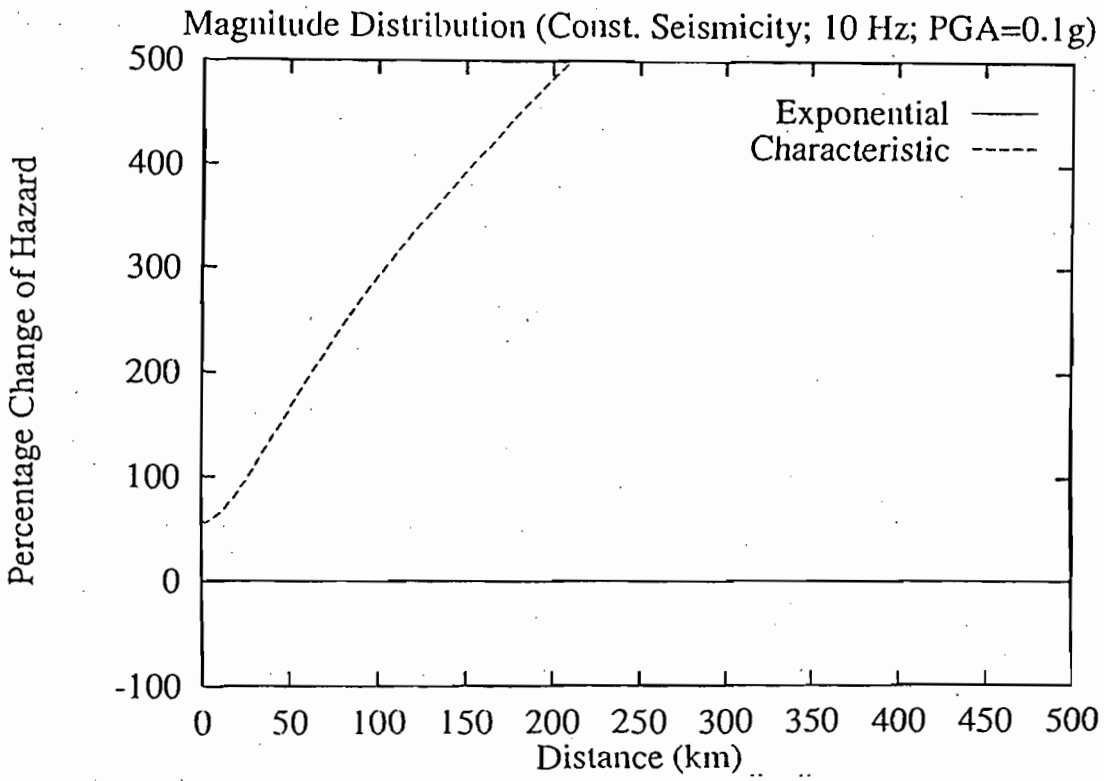
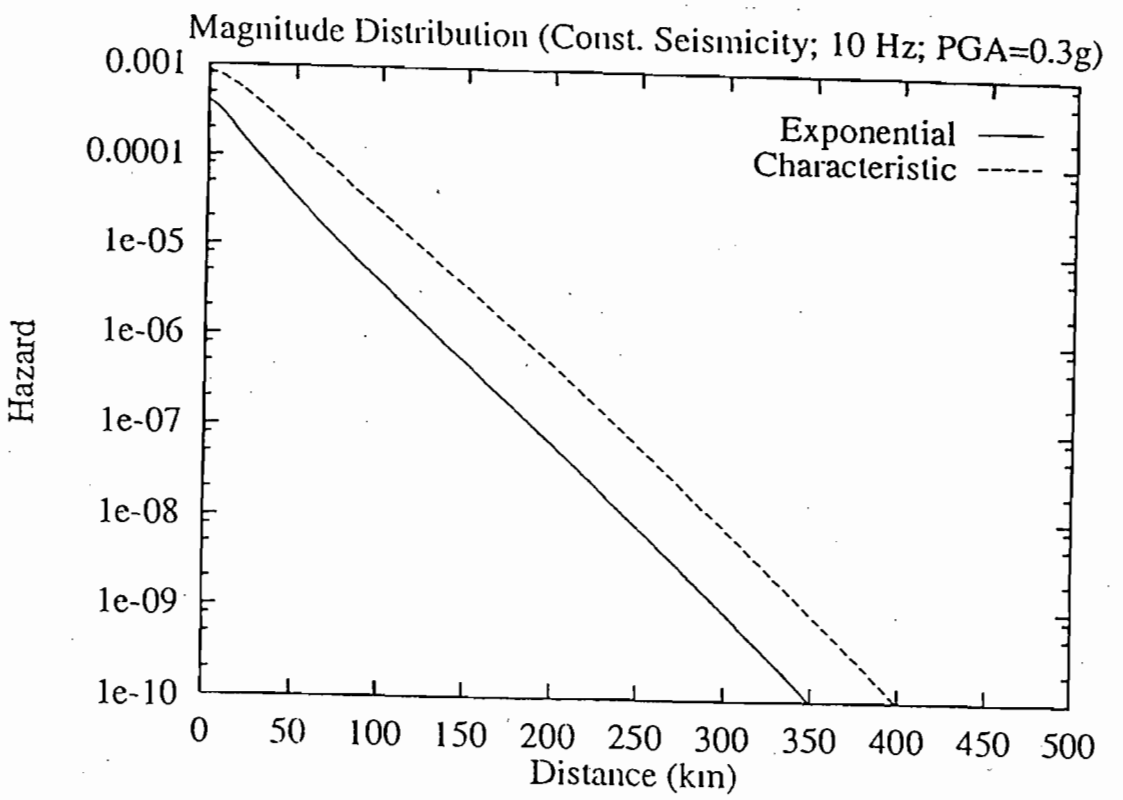


Figure G-5a. Sensitivity of 10 Hz hazard to magnitude distribution (with constant seismicity assumption), PGA = 0.1g, Group A sites.



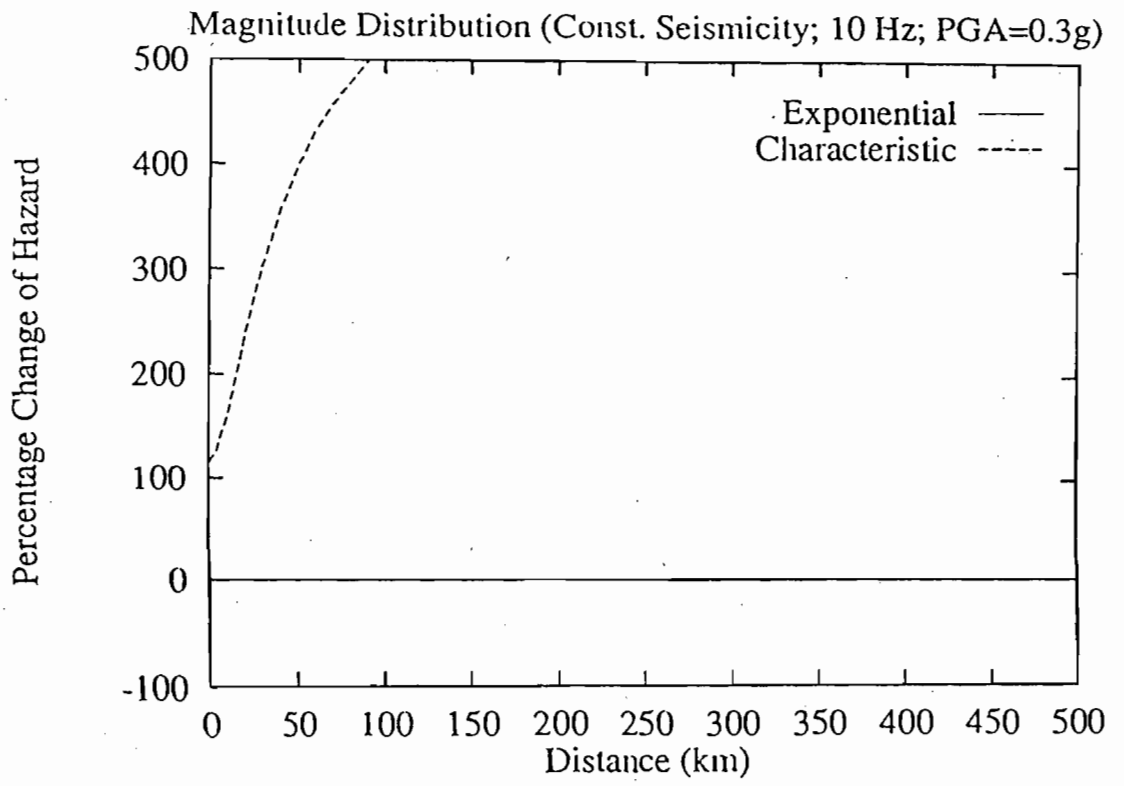
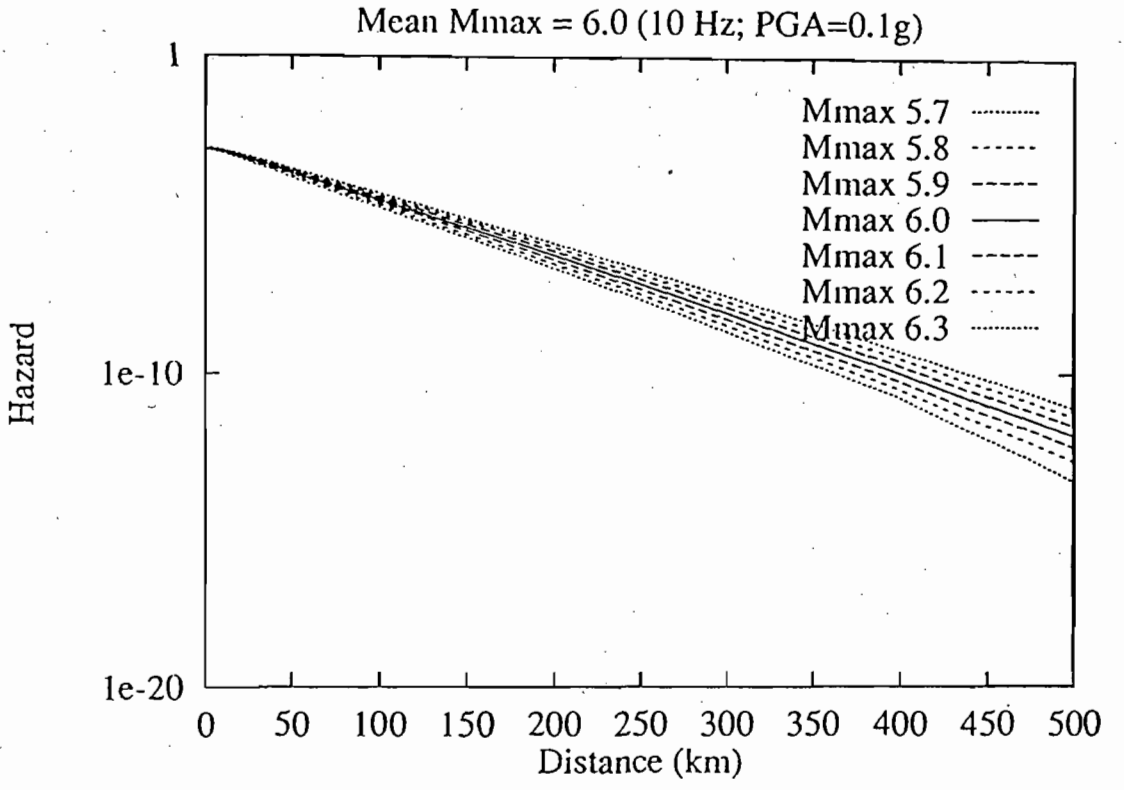


Figure G-5b. Sensitivity of 10 Hz hazard to magnitude distribution, (with constant seismicity assumption), PGA = 0.3g, Group A sites.



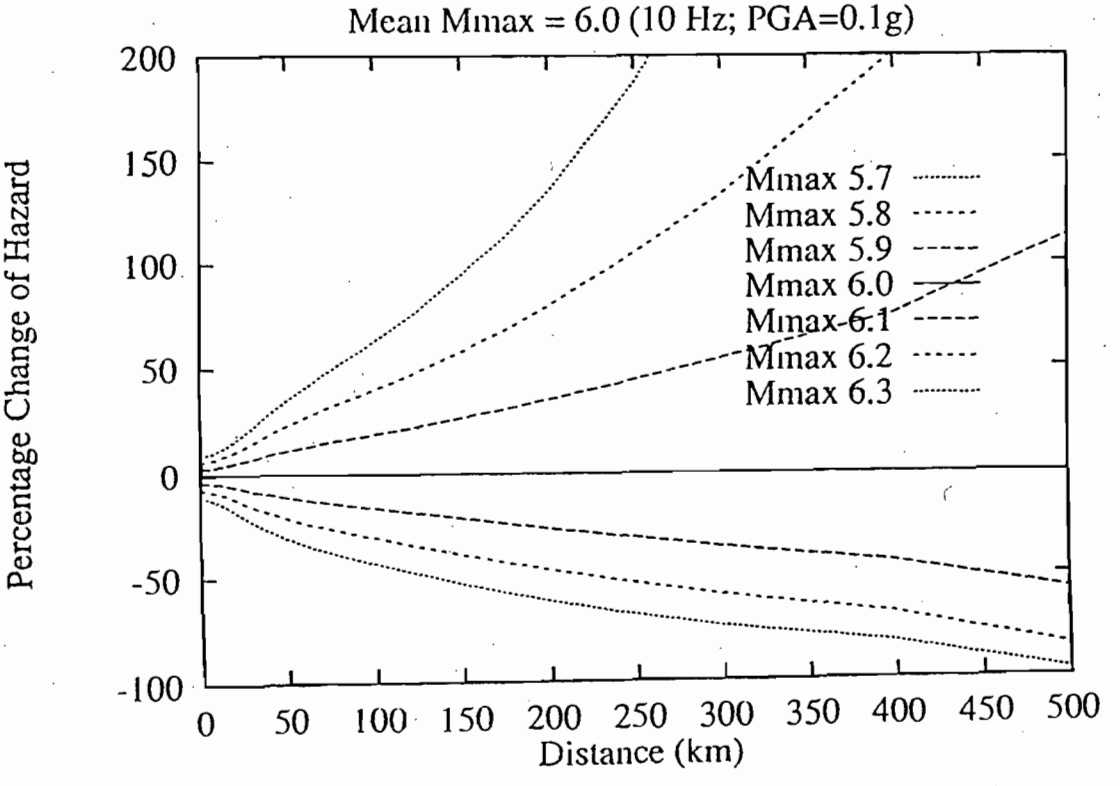
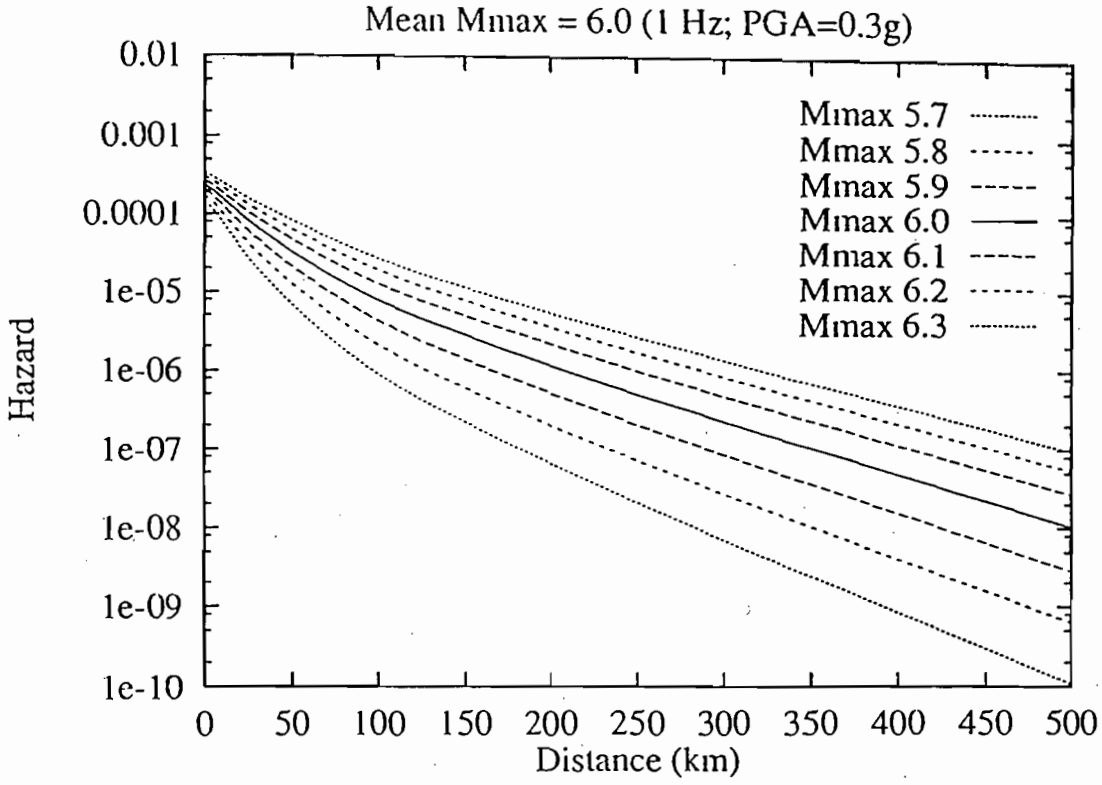


Figure G-6a. Sensitivity of 10 Hz hazard to m_{max} = 6.0, PGA = 0.1g, Group A sites.



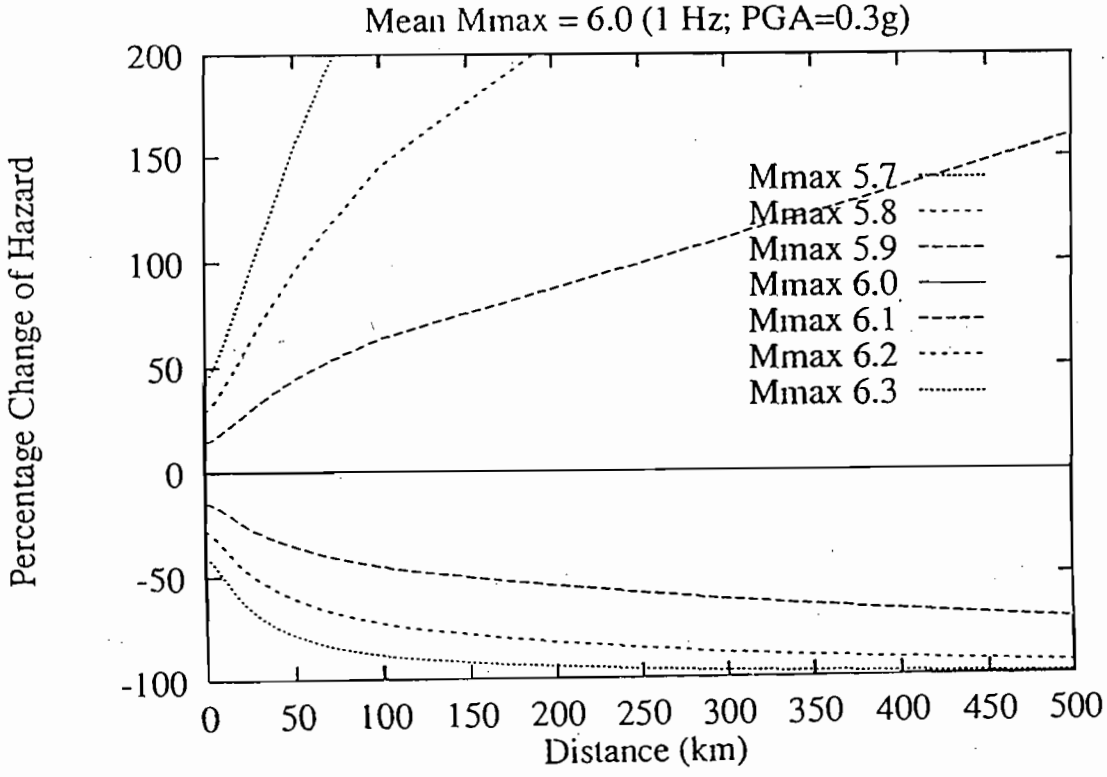
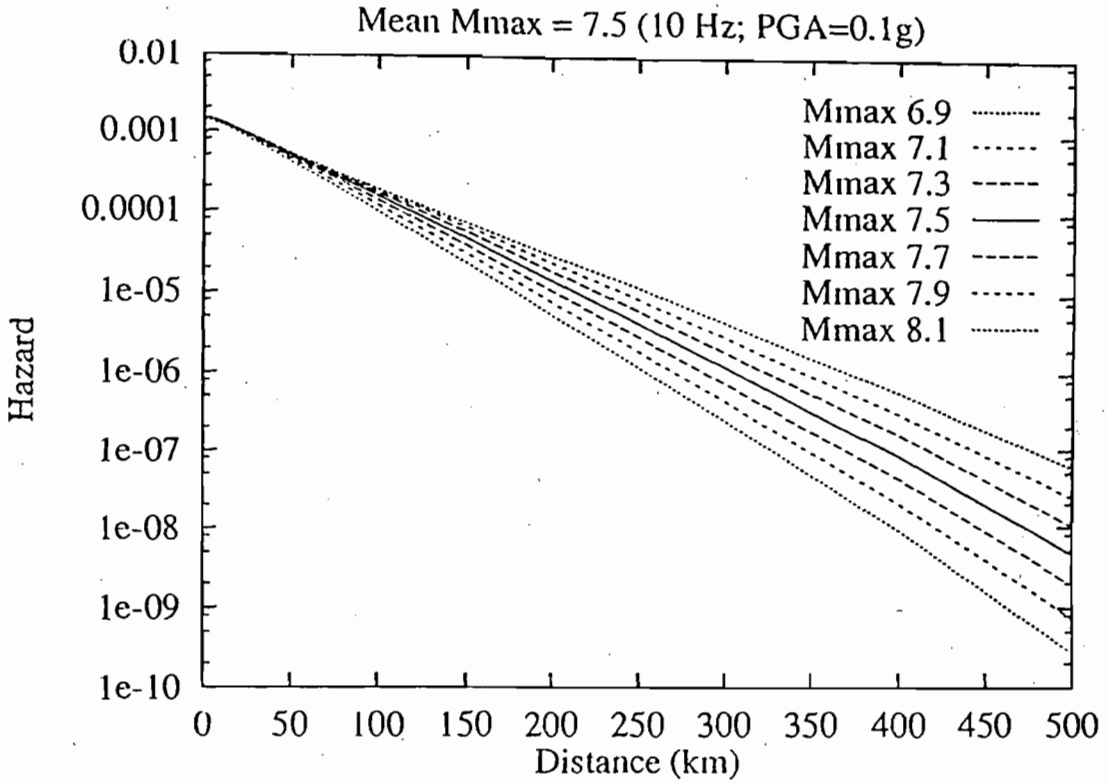


Figure G-6b. Sensitivity of 10 Hz hazard to m_{max} = 6.0, PGA = 0.3g, Group A sites.



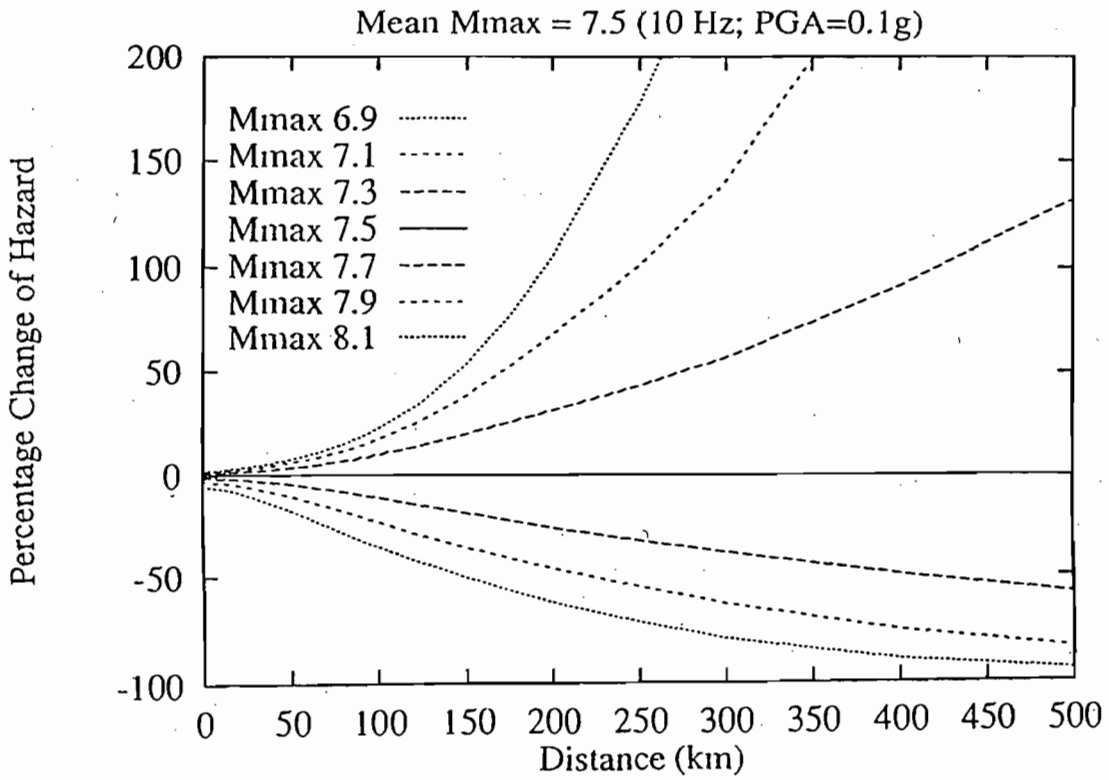
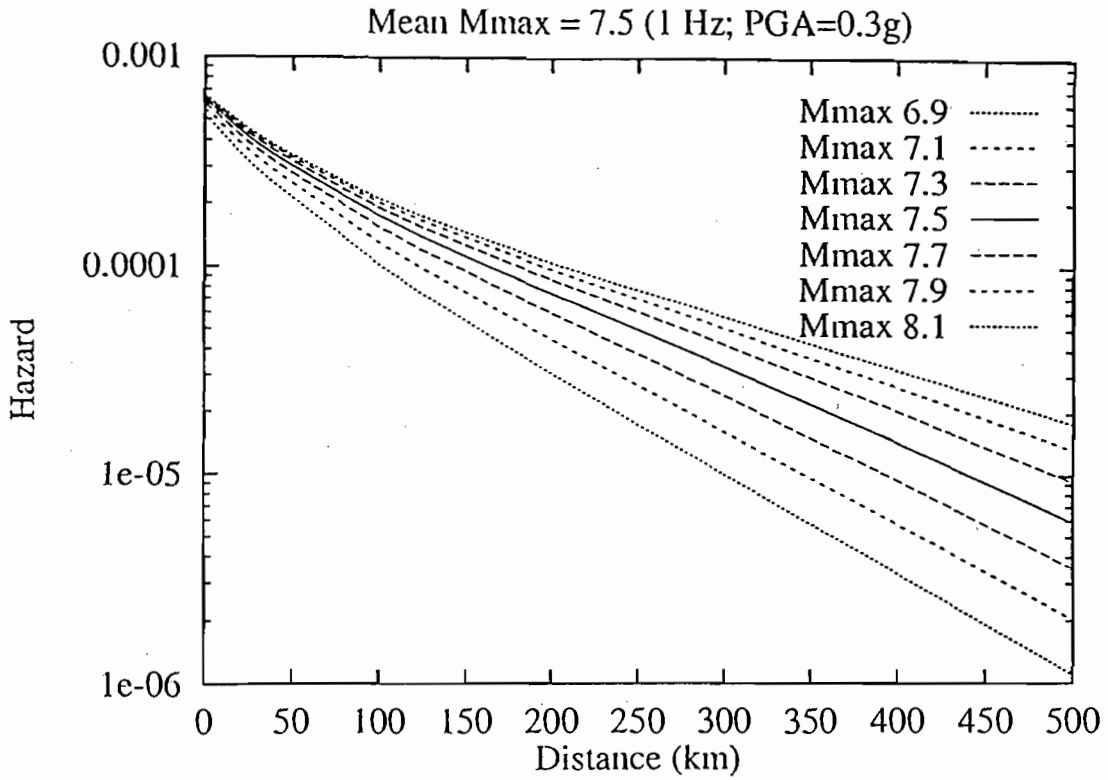


Figure G-7a. Sensitivity of 10 Hz hazard to m_{max} = 7.5, PGA = 0.1g, Group A sites.



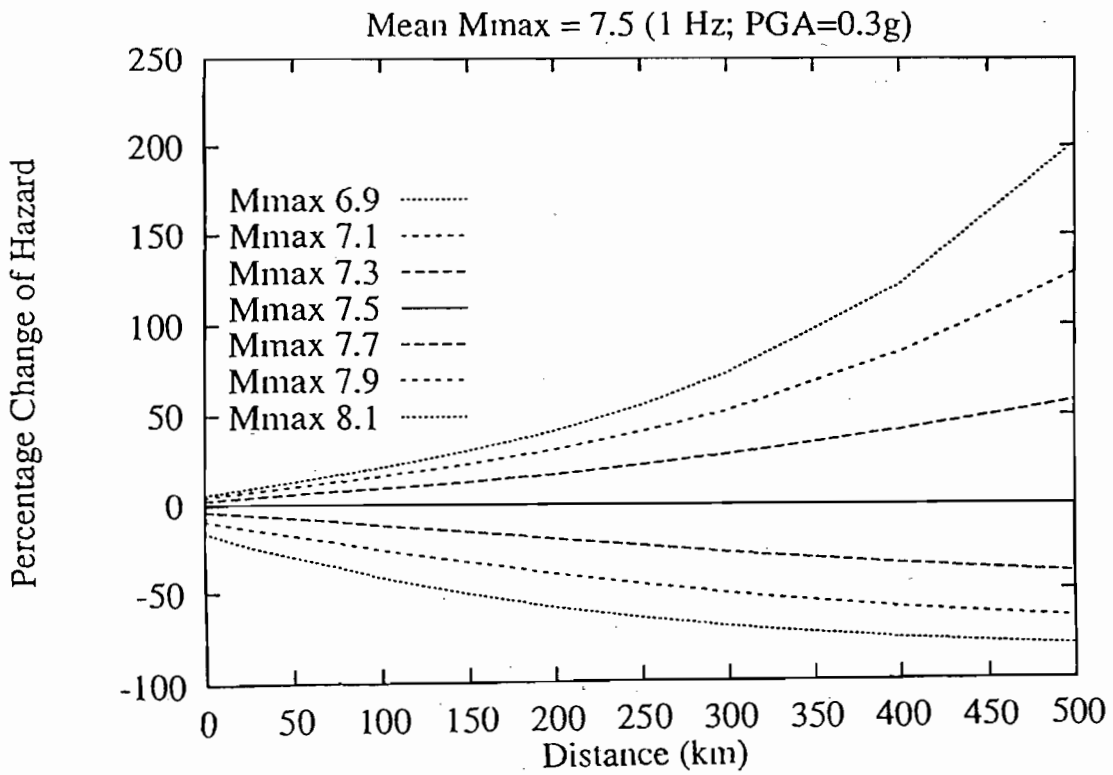
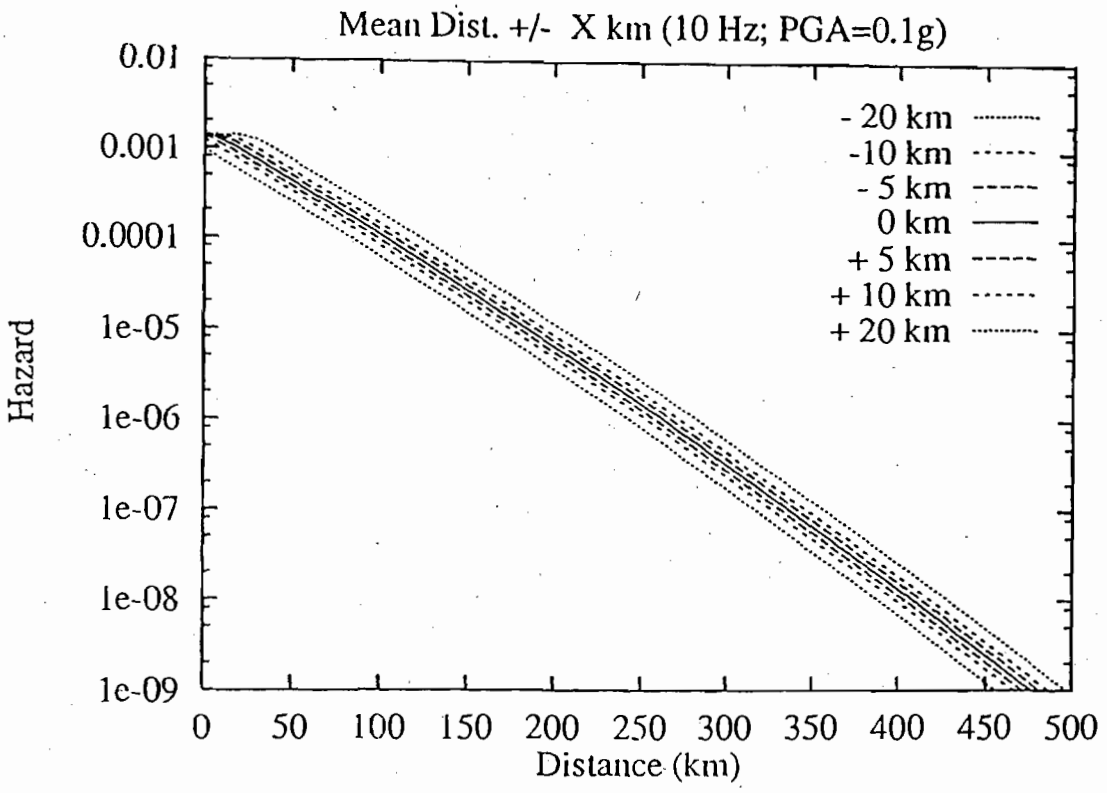


Figure G-7b. Sensitivity of 10 Hz hazard to m_{max} = 7.5, PGA = 0.3g, Group A sites.



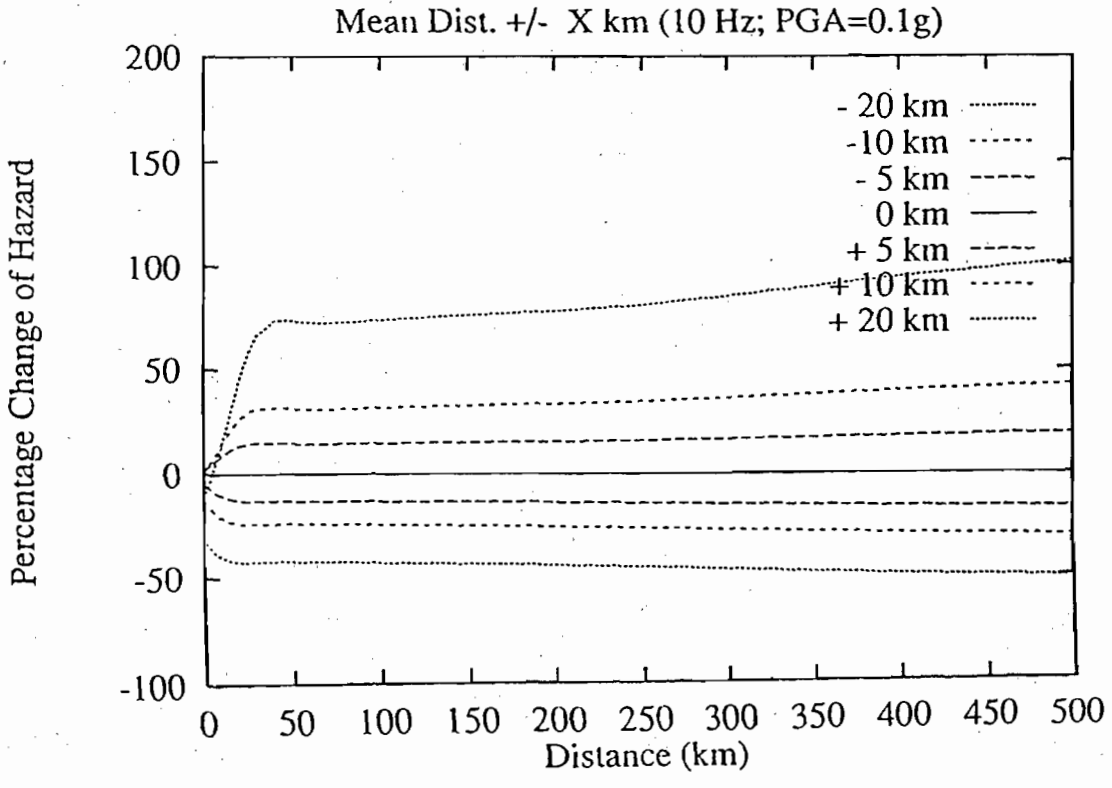
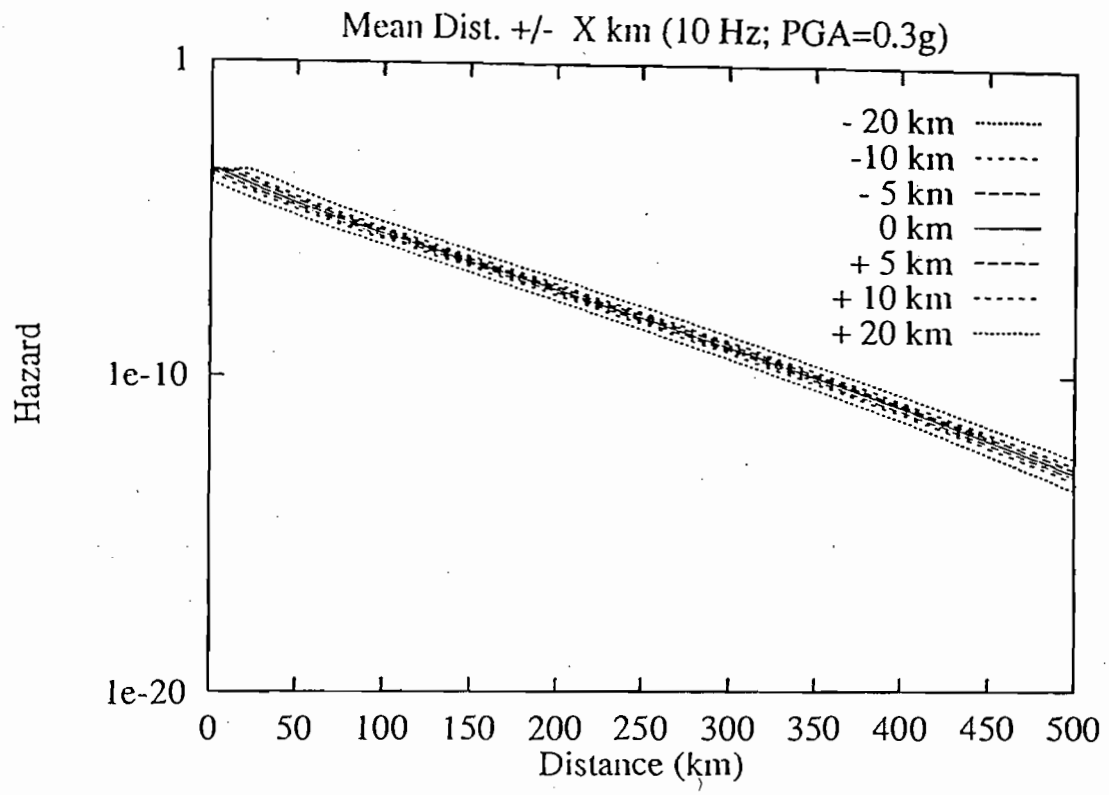


Figure G-8a. Sensitivity of 10 Hz hazard to distance from fault, PGA = 0.1g, Group A sites.



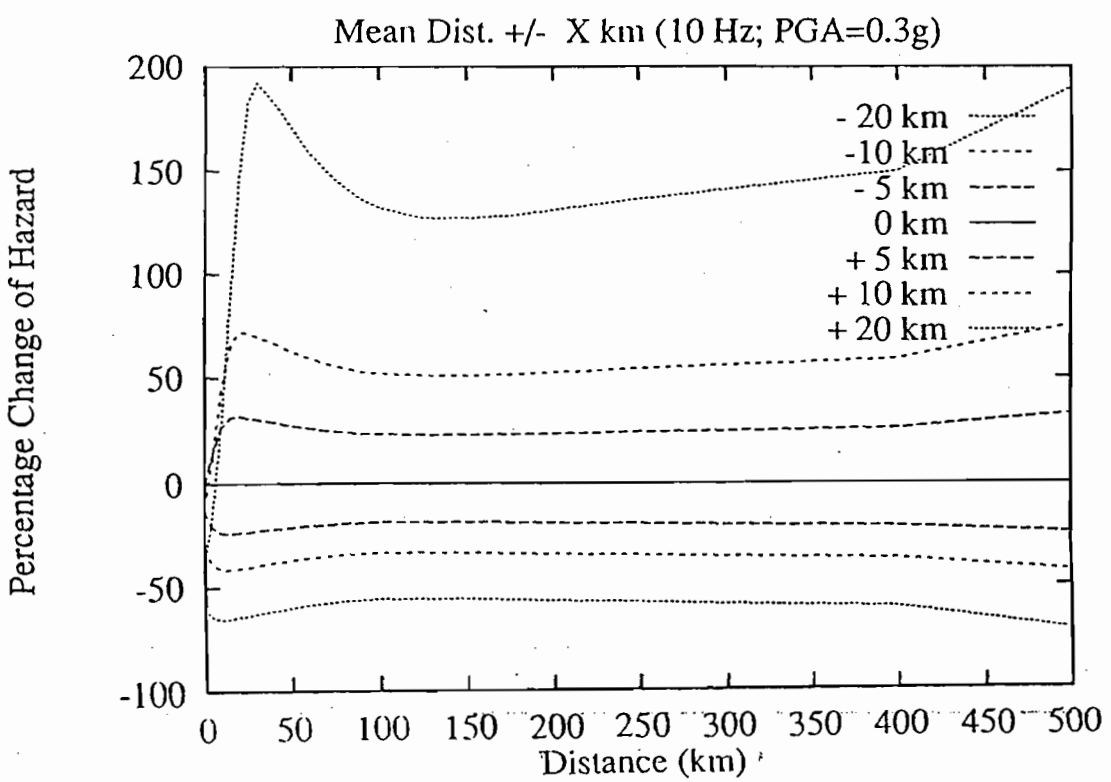
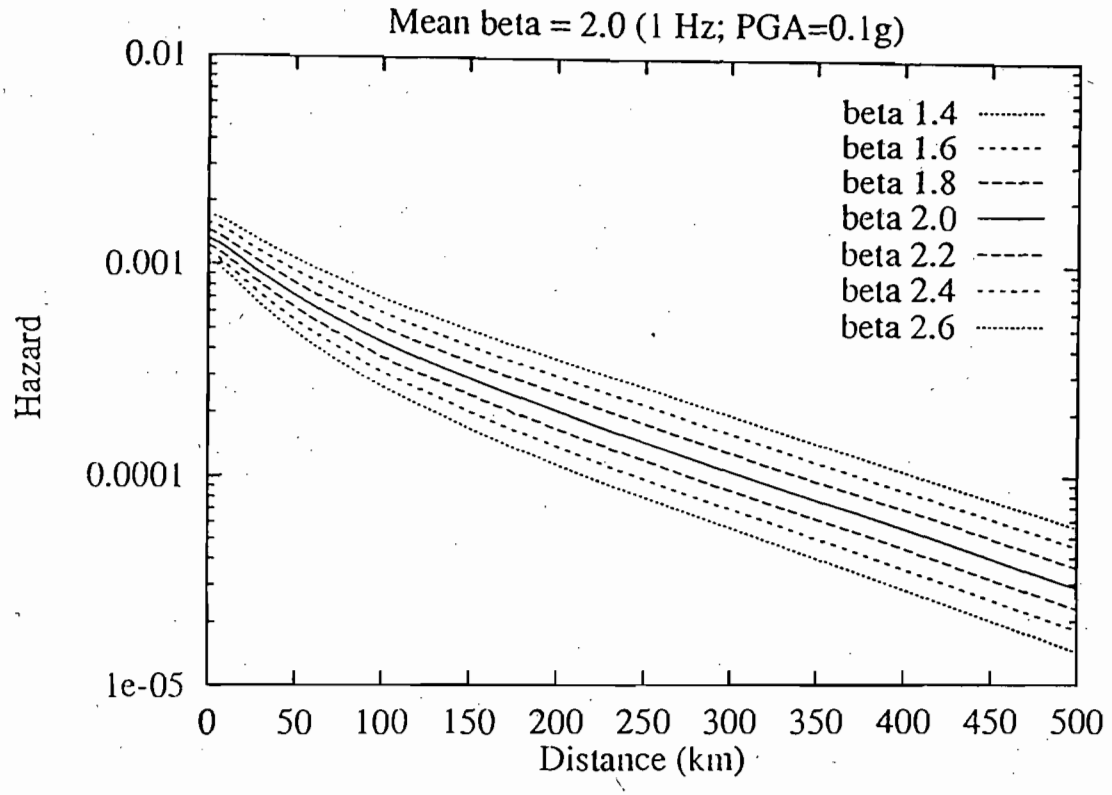


Figure G-8b. Sensitivity of 10 Hz hazard to distance from fault, PGA = 0.3g, Group A sites.



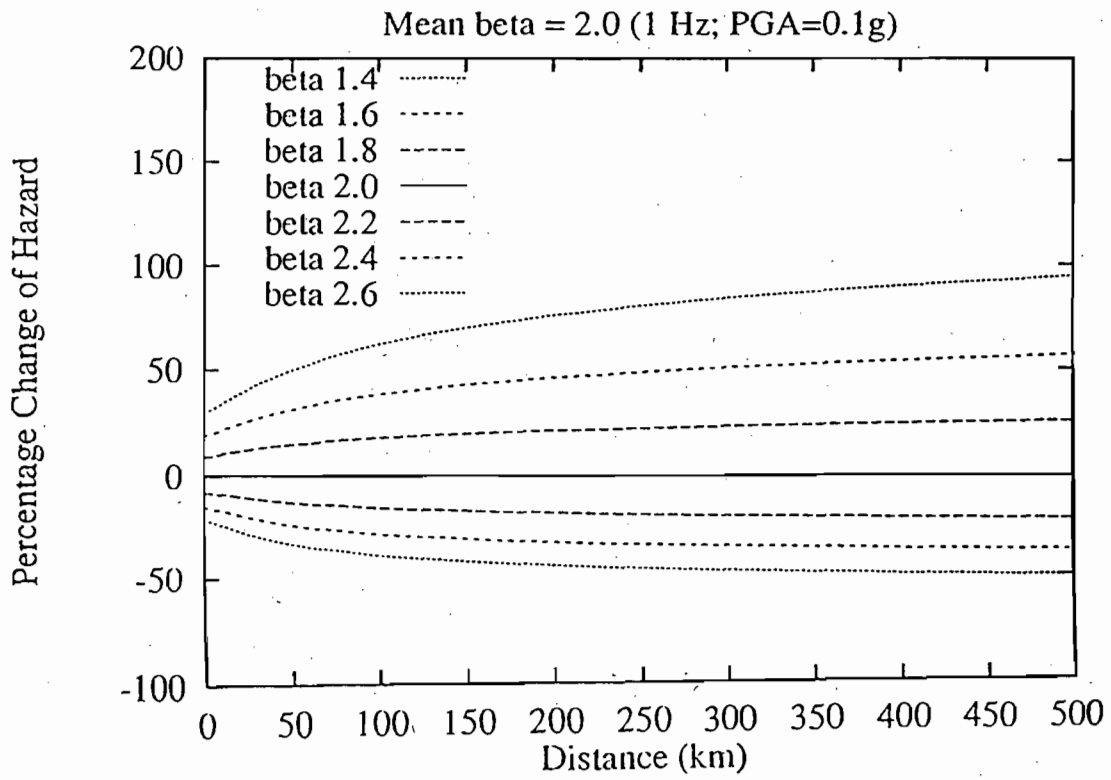
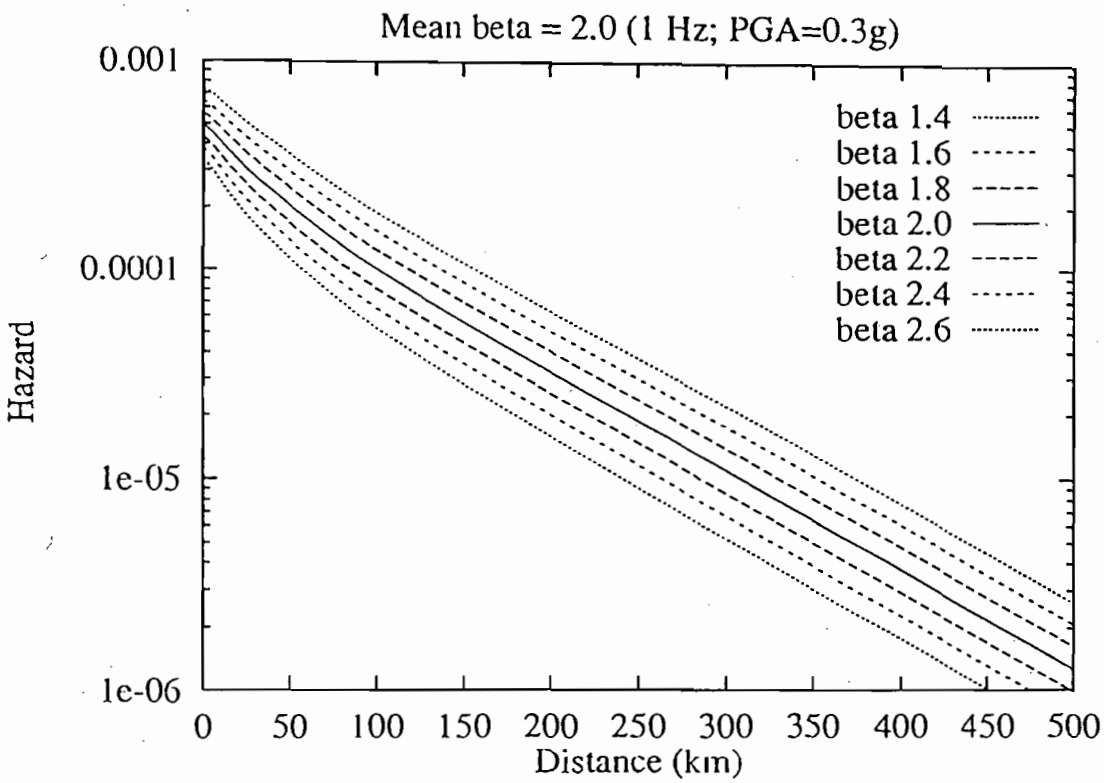


Figure G-9a. Sensitivity of 1 Hz hazard to beta for PGA = 0.1g, Group A sites.



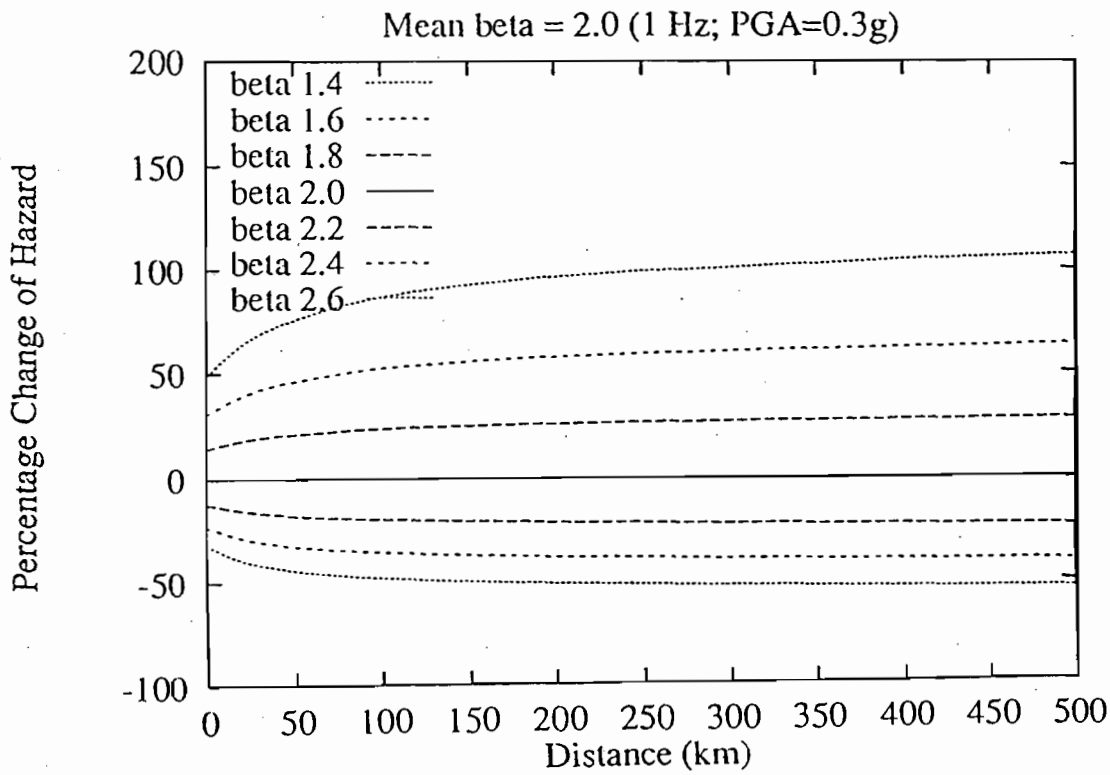
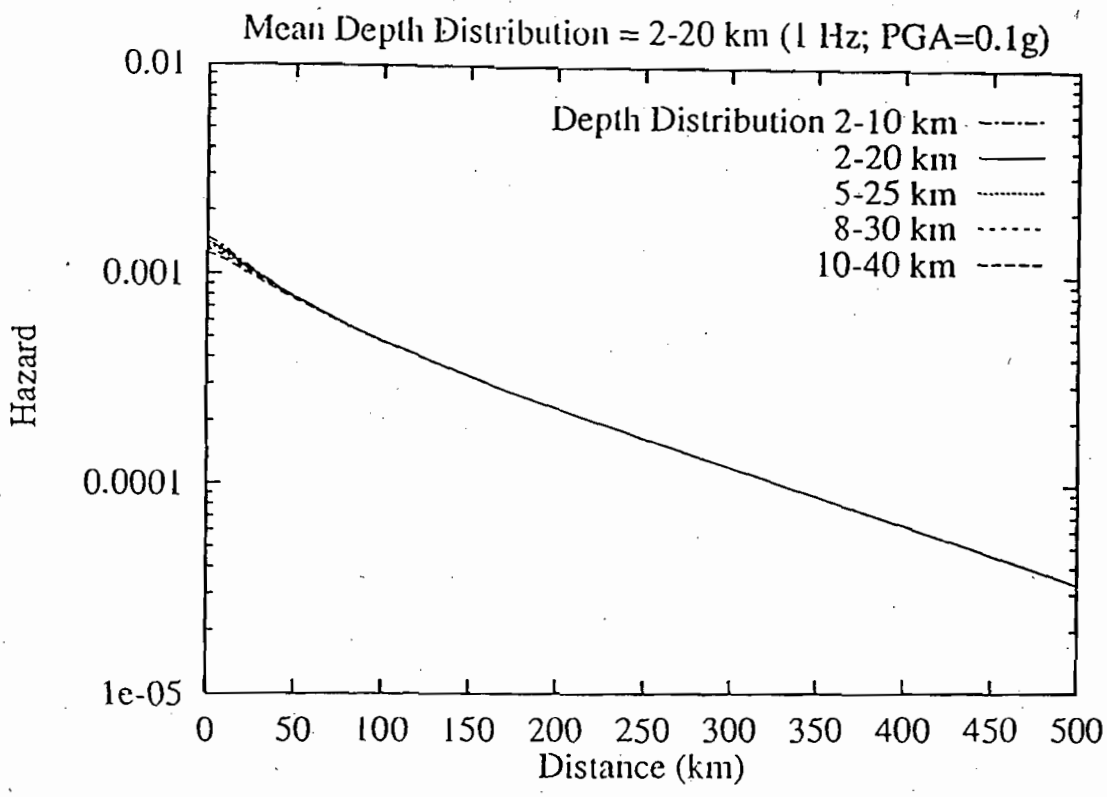


Figure G-9b. Sensitivity of 1 Hz hazard to beta for PGA = 0.3g, Group A sites.



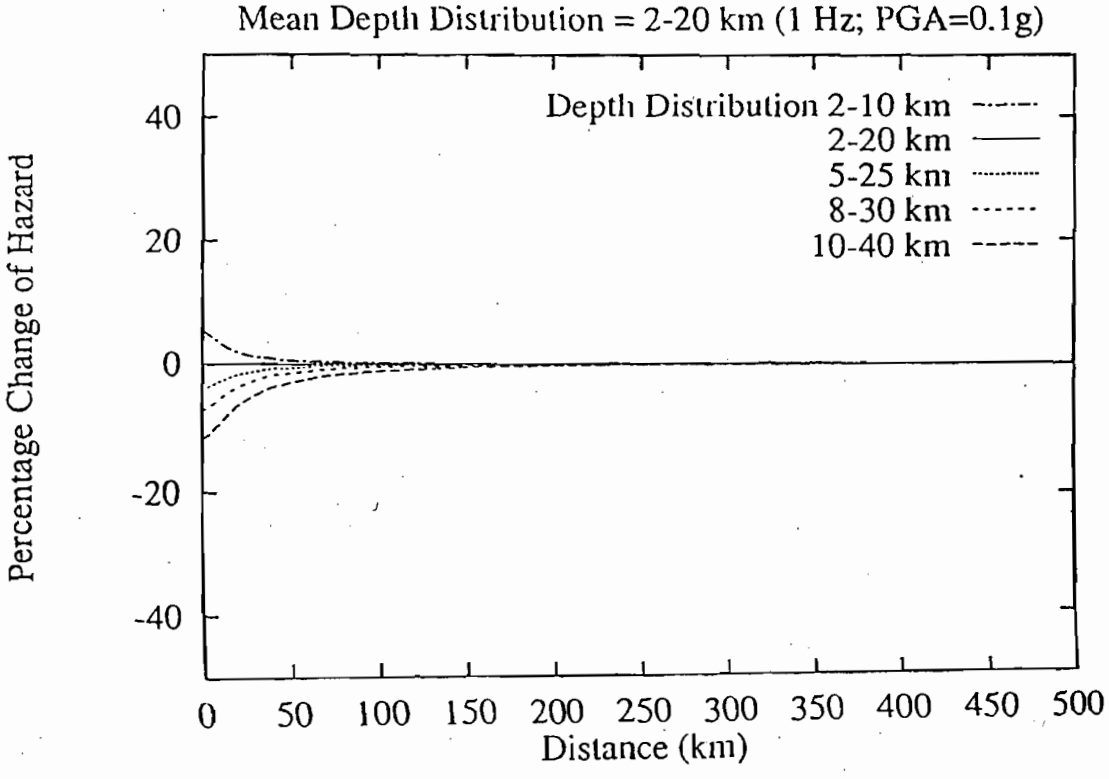
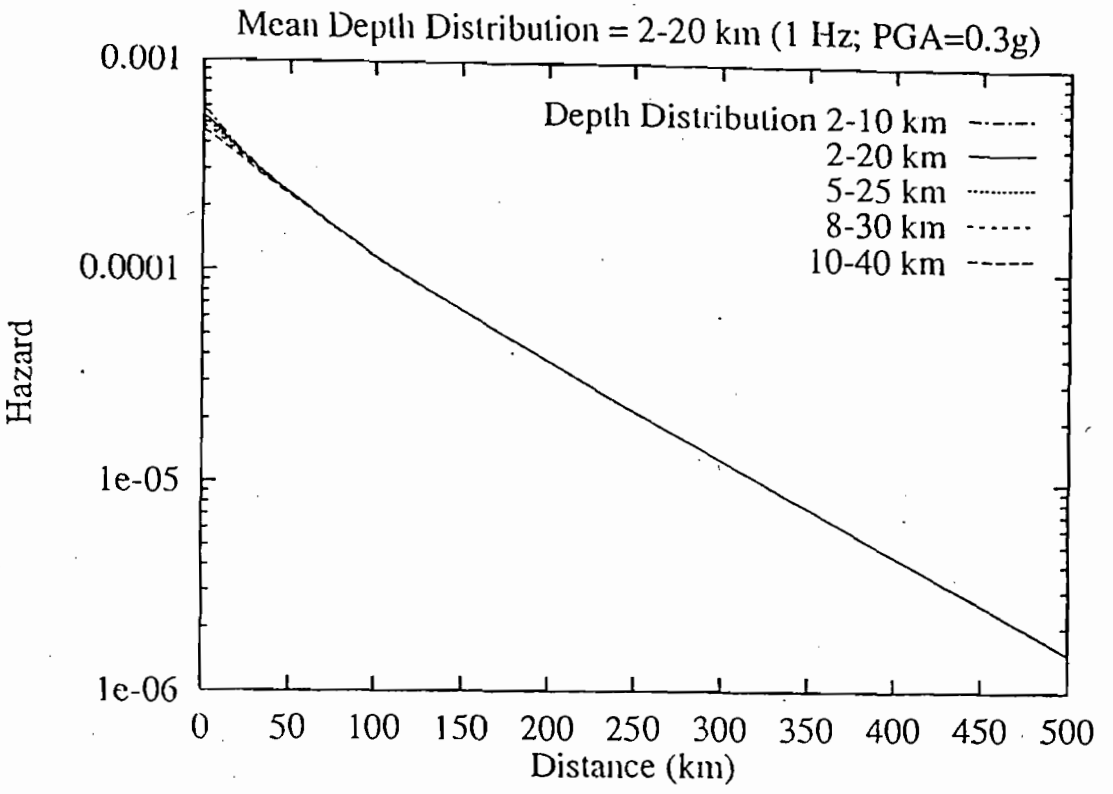


Figure G-10a. Sensitivity of 1 Hz hazard to depth distribution for PGA = 0.1g, Group A sites.



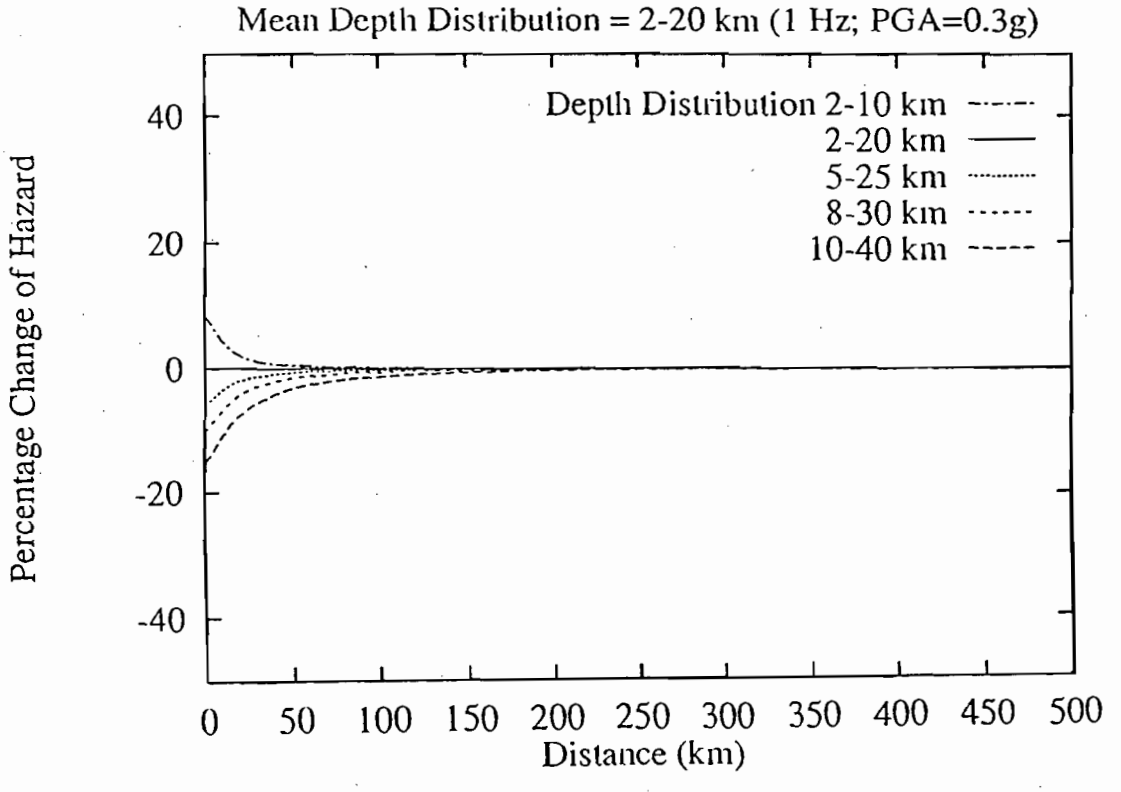
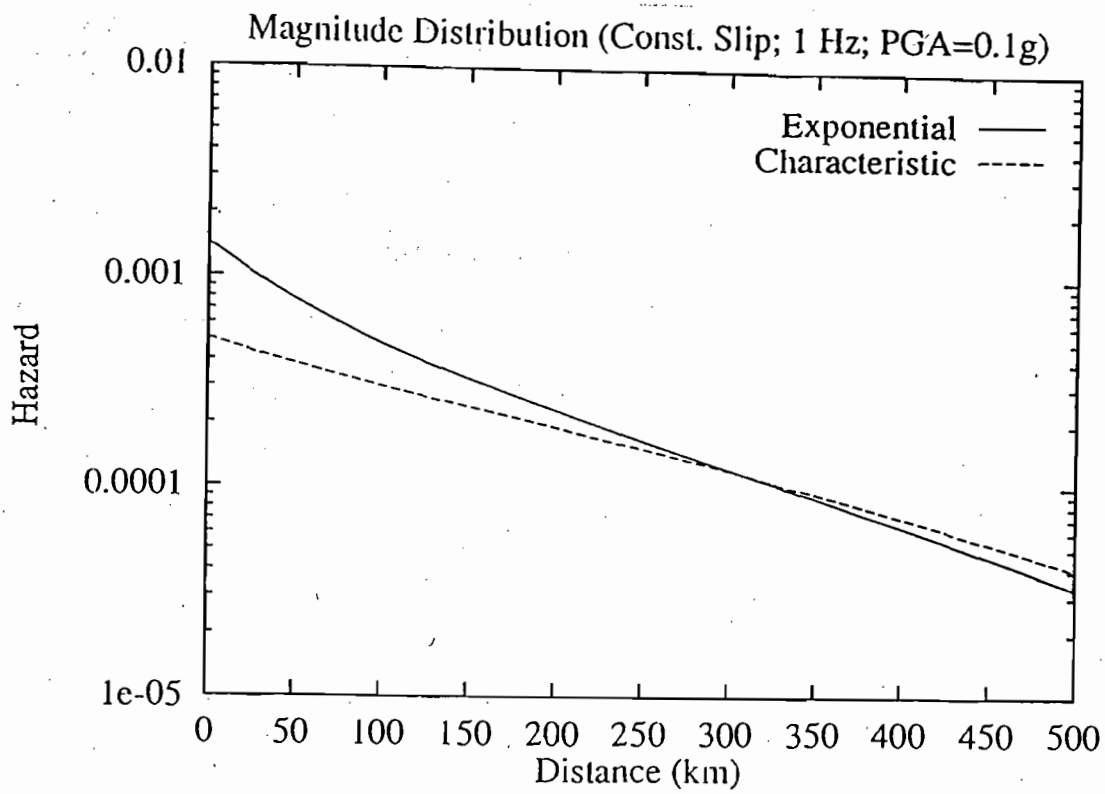


Figure G-10b. Sensitivity of 1 Hz hazard to depth distribution for PGA = 0.3g, Group A sites.



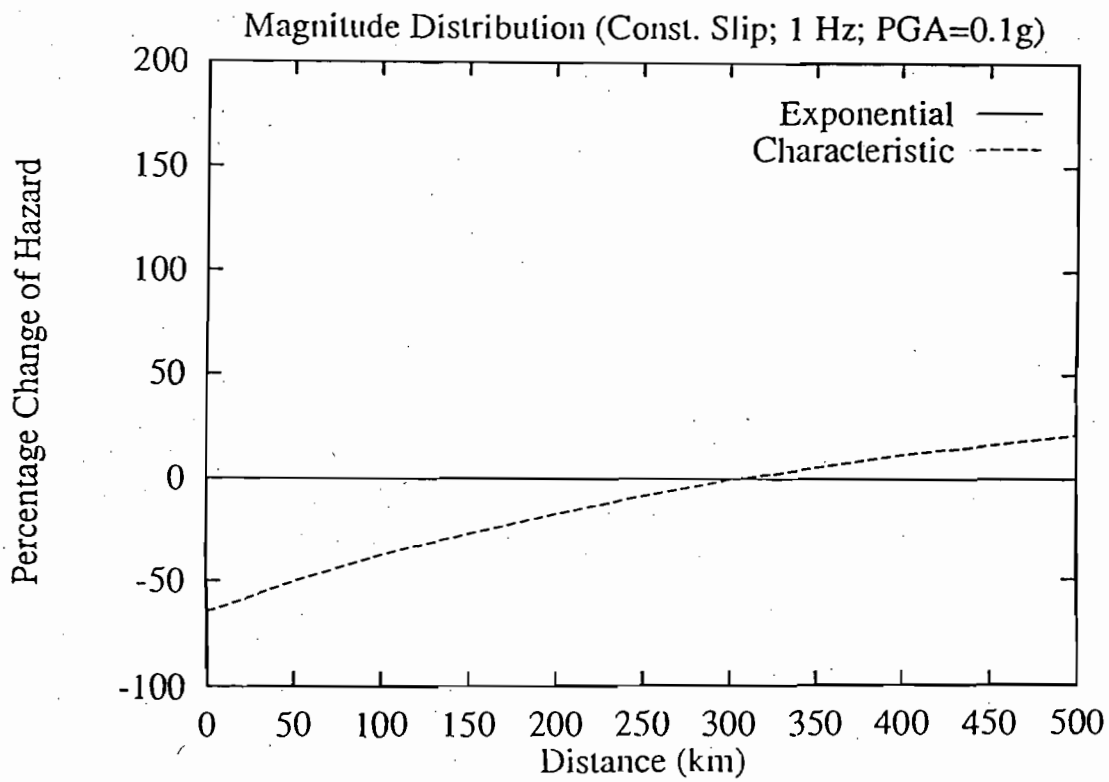
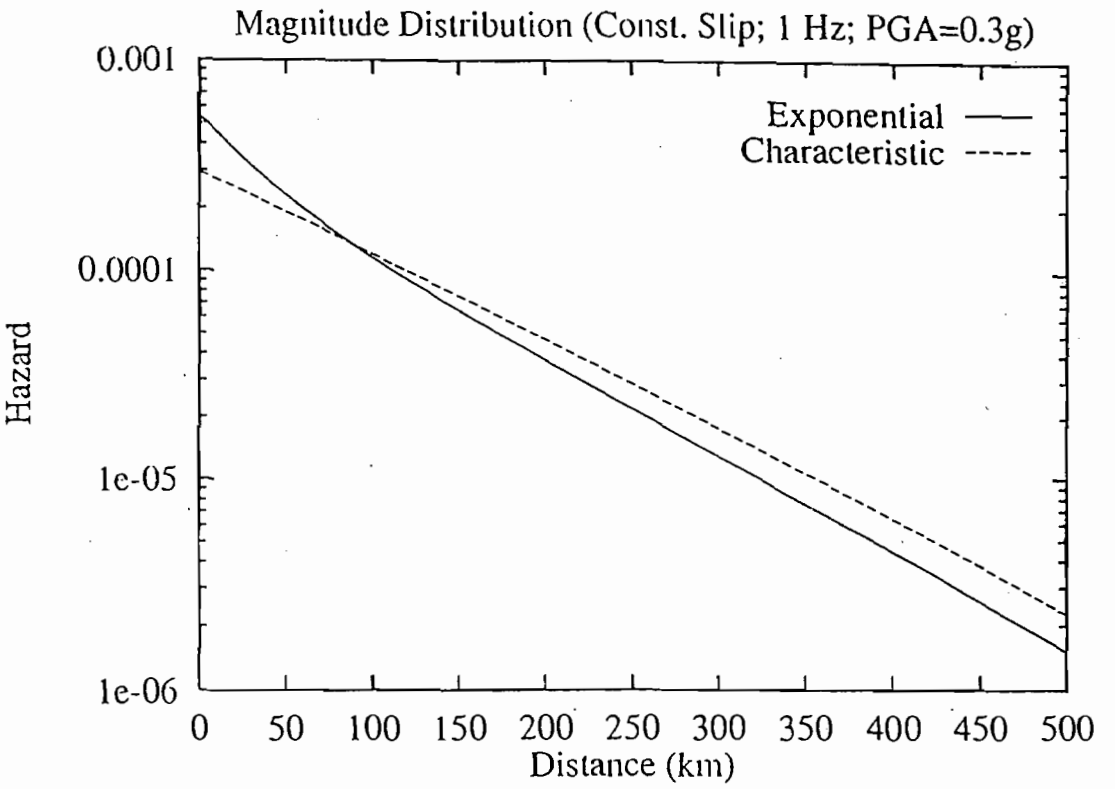


Figure G-11a. Sensitivity of 1 Hz hazard to magnitude distribution (with constant slip assumption), PGA = 0.1g, Group A sites.



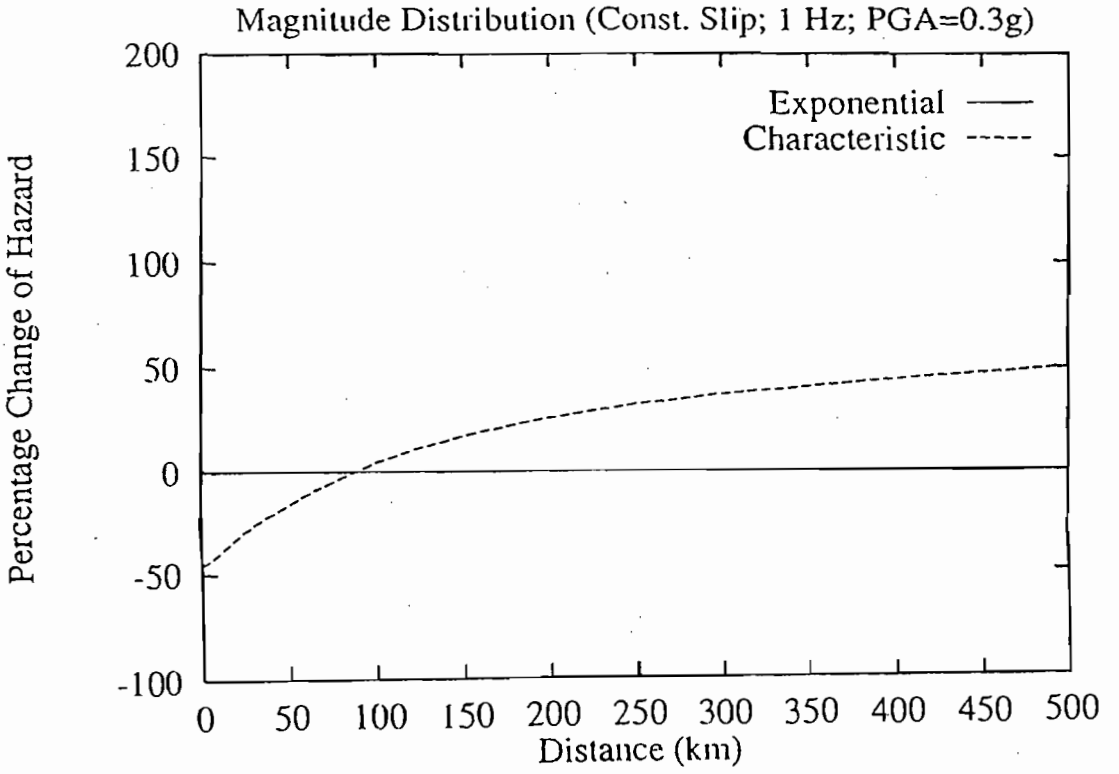
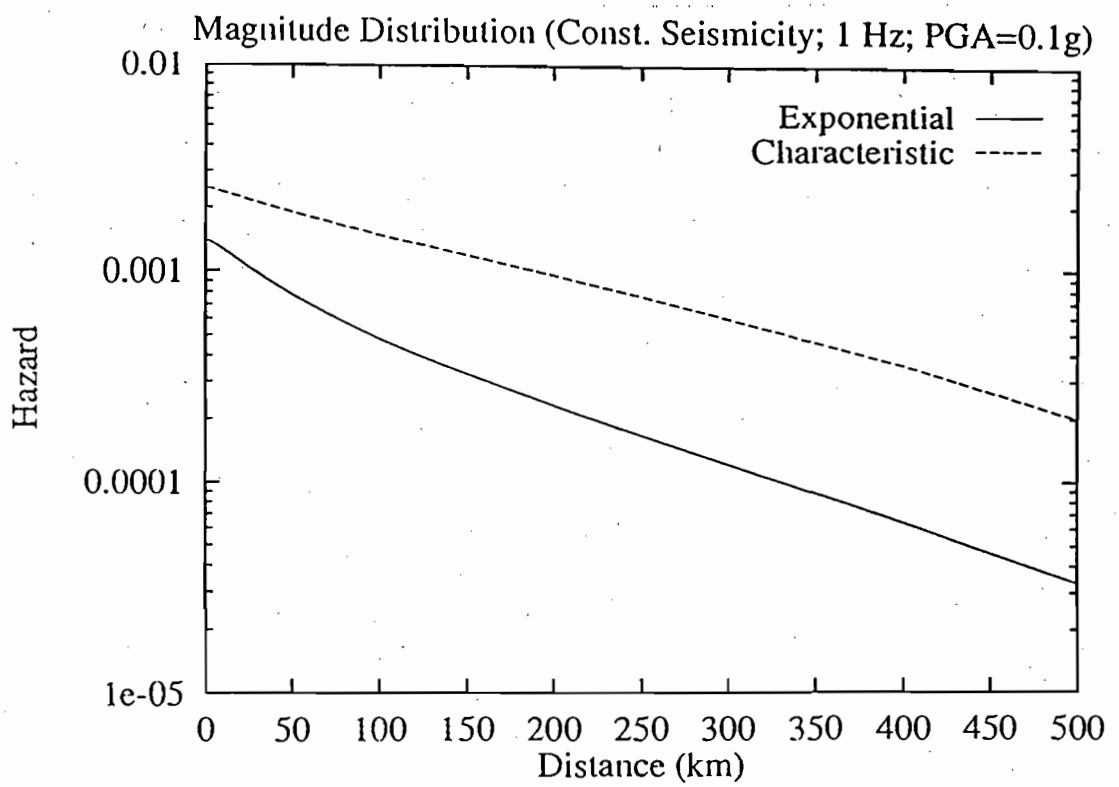


Figure G-11b. Sensitivity of 1 Hz hazard to magnitude distribution (with constant slip assumption), PGA = 0.3g, Group A sites.



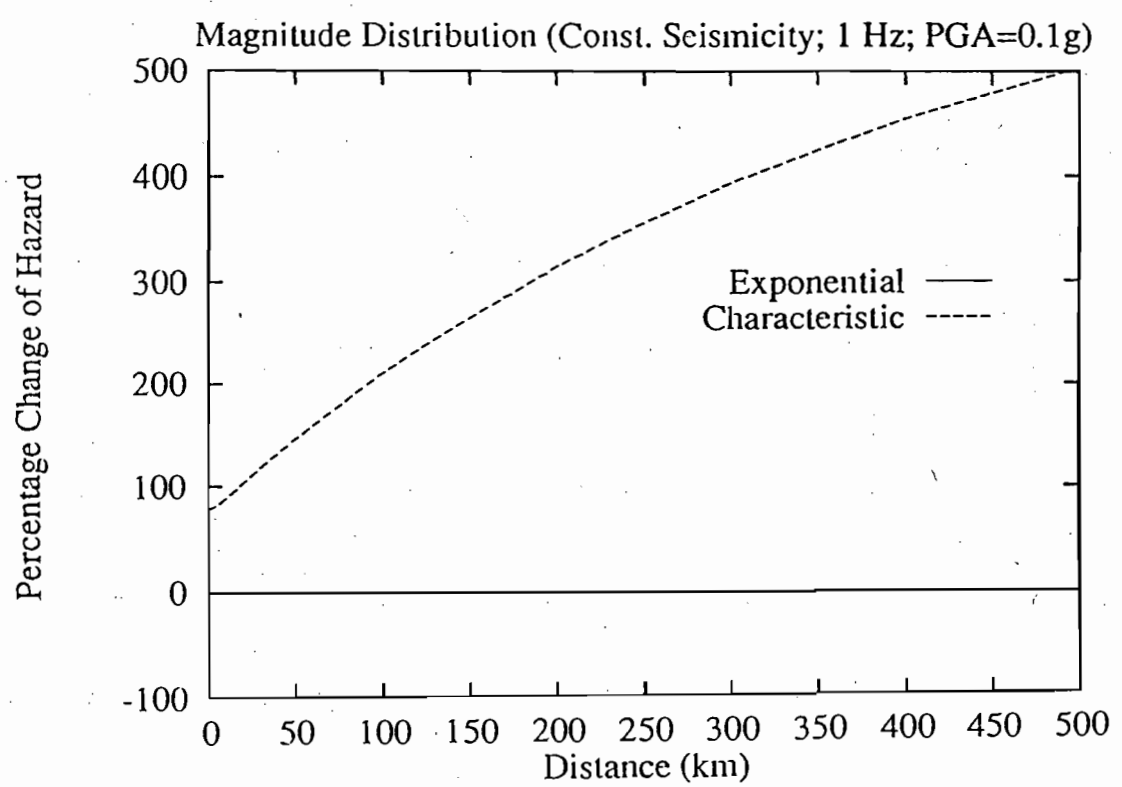
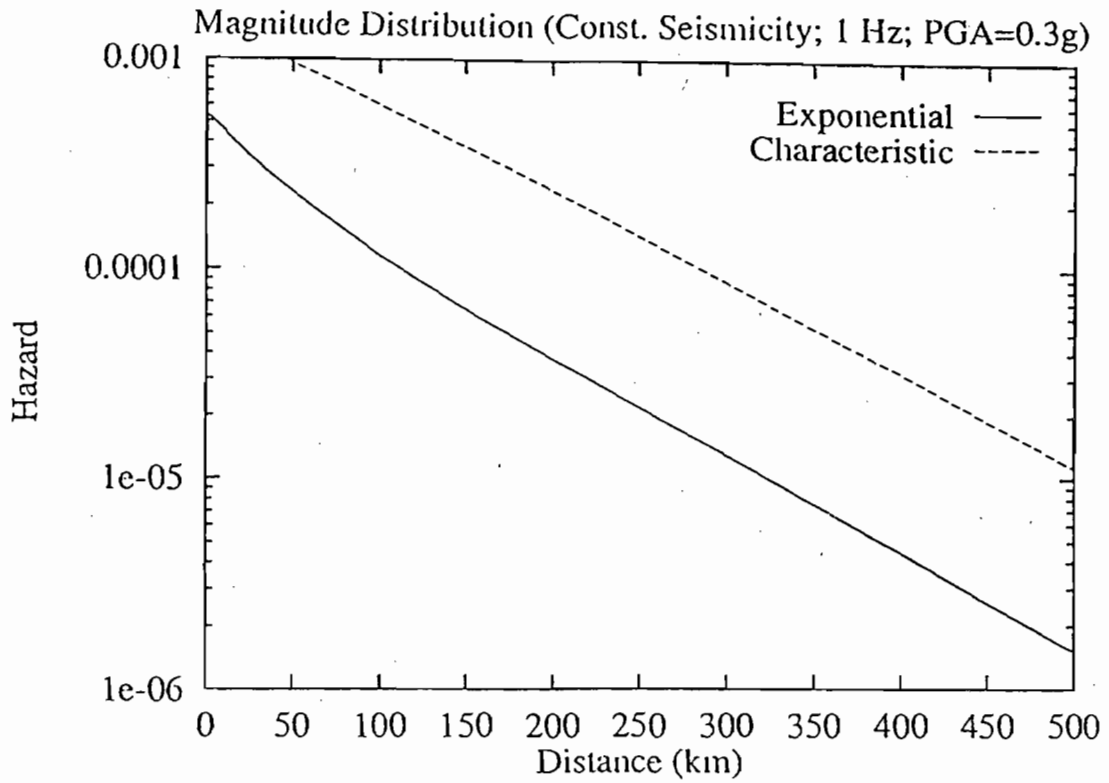


Figure G-12a. Sensitivity of 1 Hz hazard to magnitude distribution (with constant seismicity assumption), PGA = 0.1g, Group A sites.



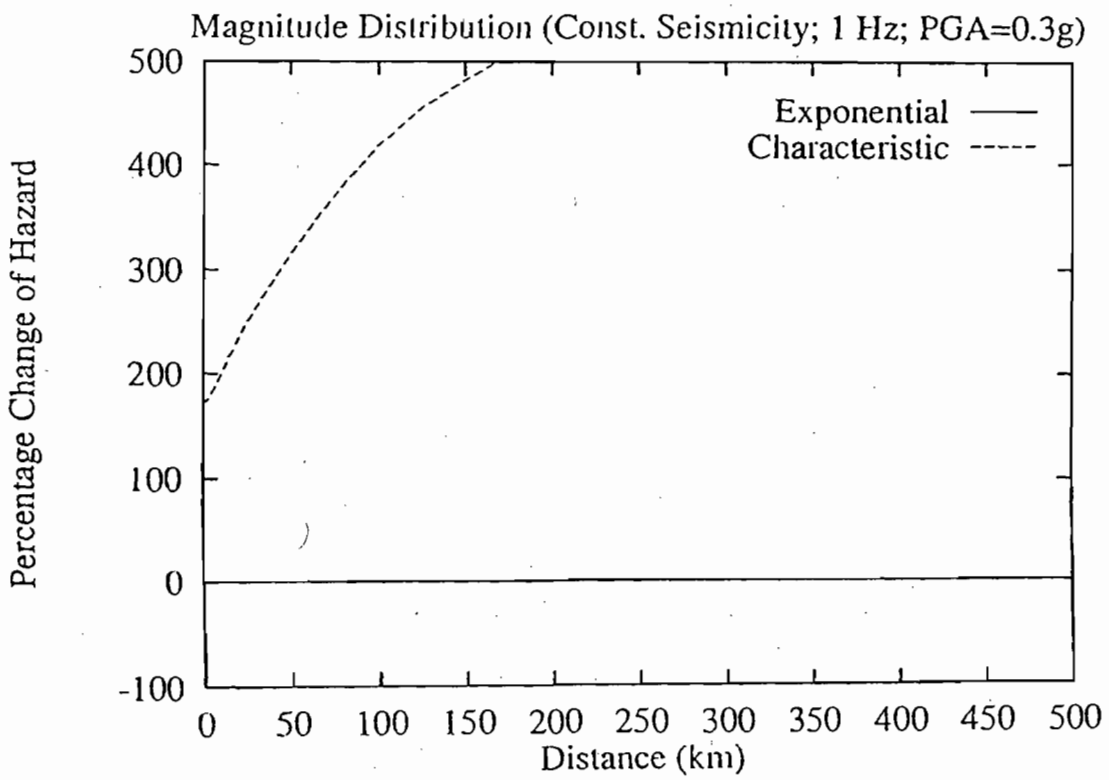
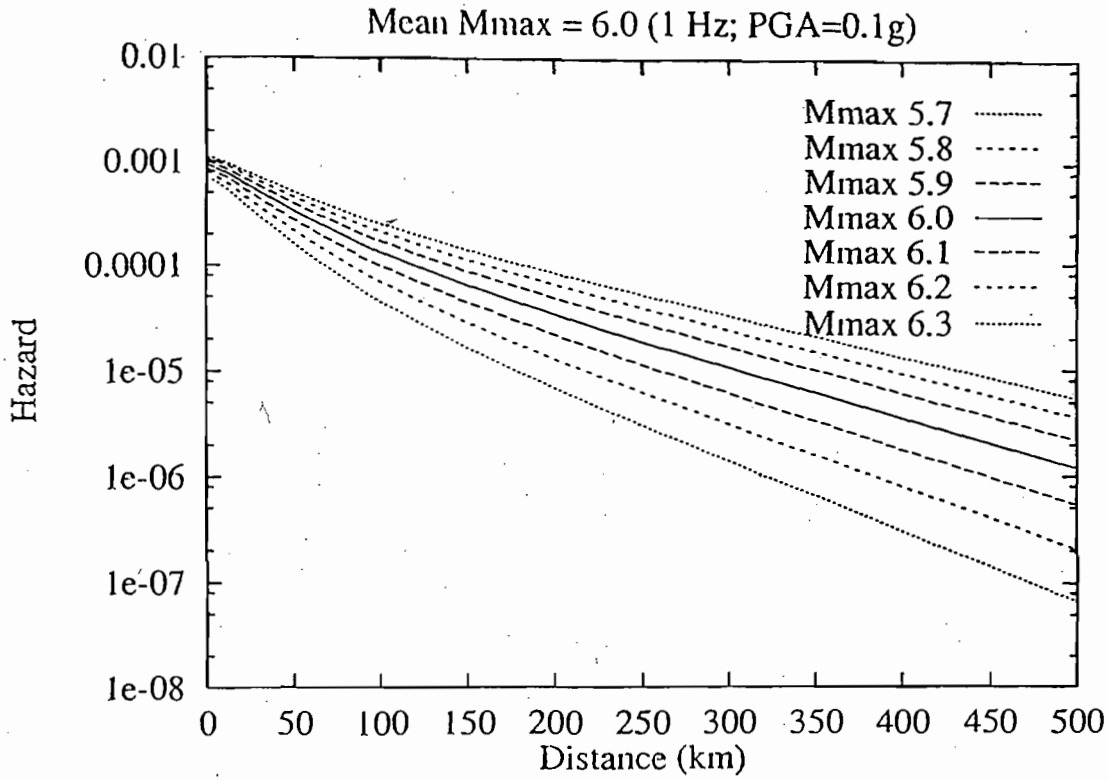


Figure G-12b. Sensitivity of 1 Hz hazard to magnitude distribution (with constant seismicity assumption), PGA = 0.3g, Group A sites.



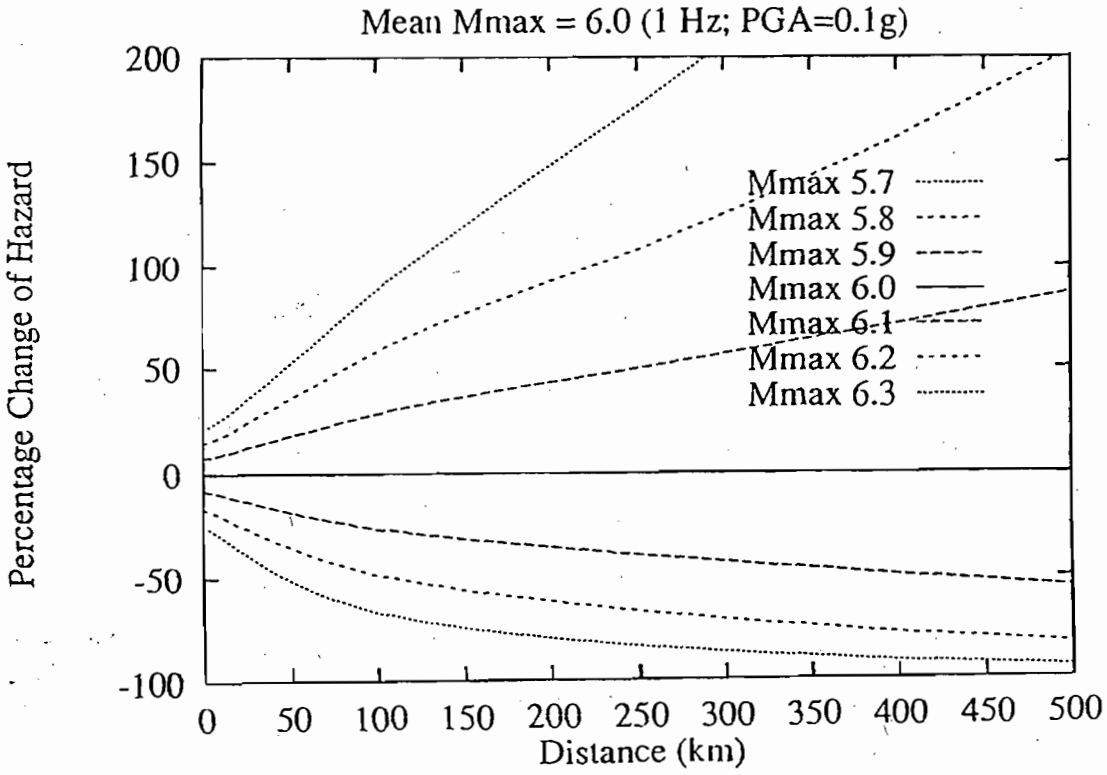
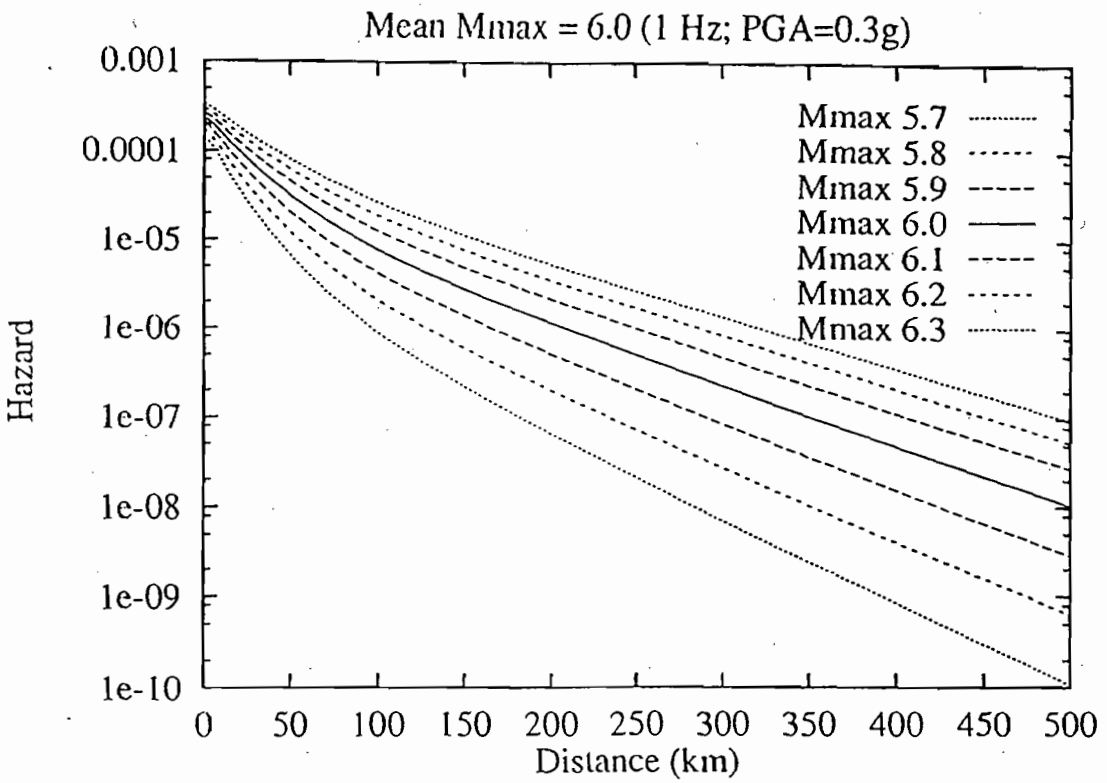


Figure G-13a. Sensitivity of 1 Hz hazard to m_{max} = 6.0, PGA = 0.1g, Group A sites.



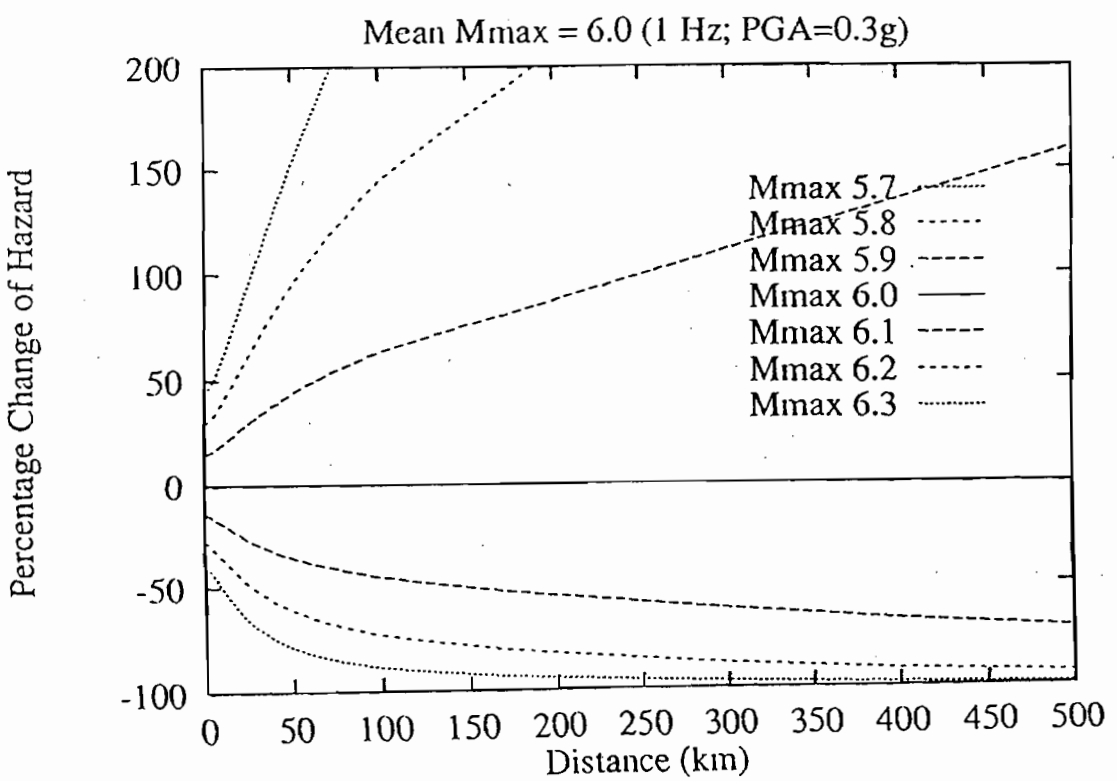
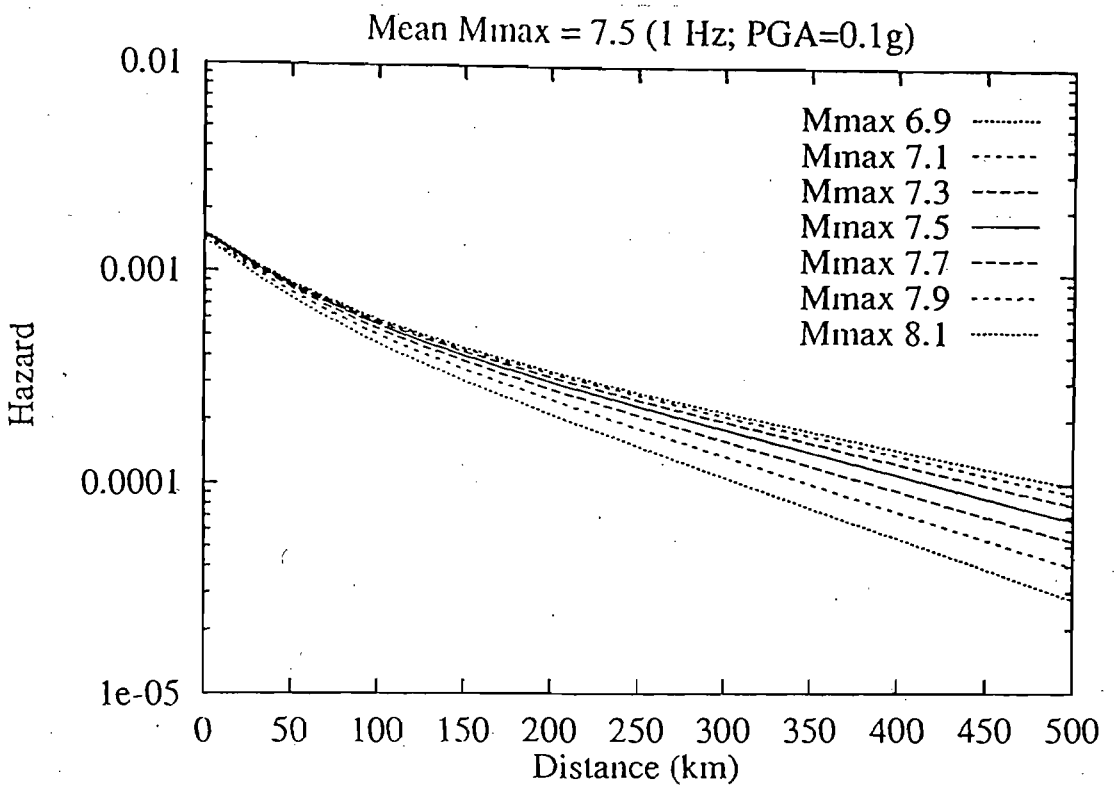


Figure G-13b. Sensitivity of 1 Hz hazard to m_{max} = 6.0, PGA = 0.3g, Group A sites.



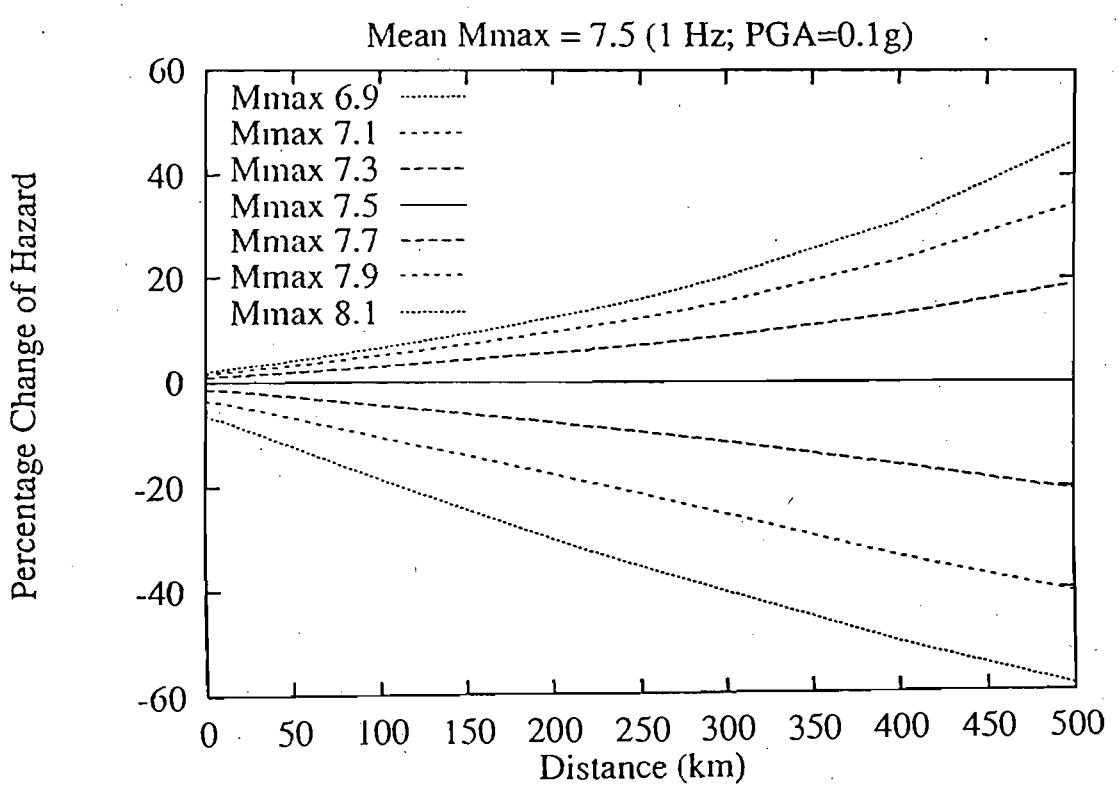
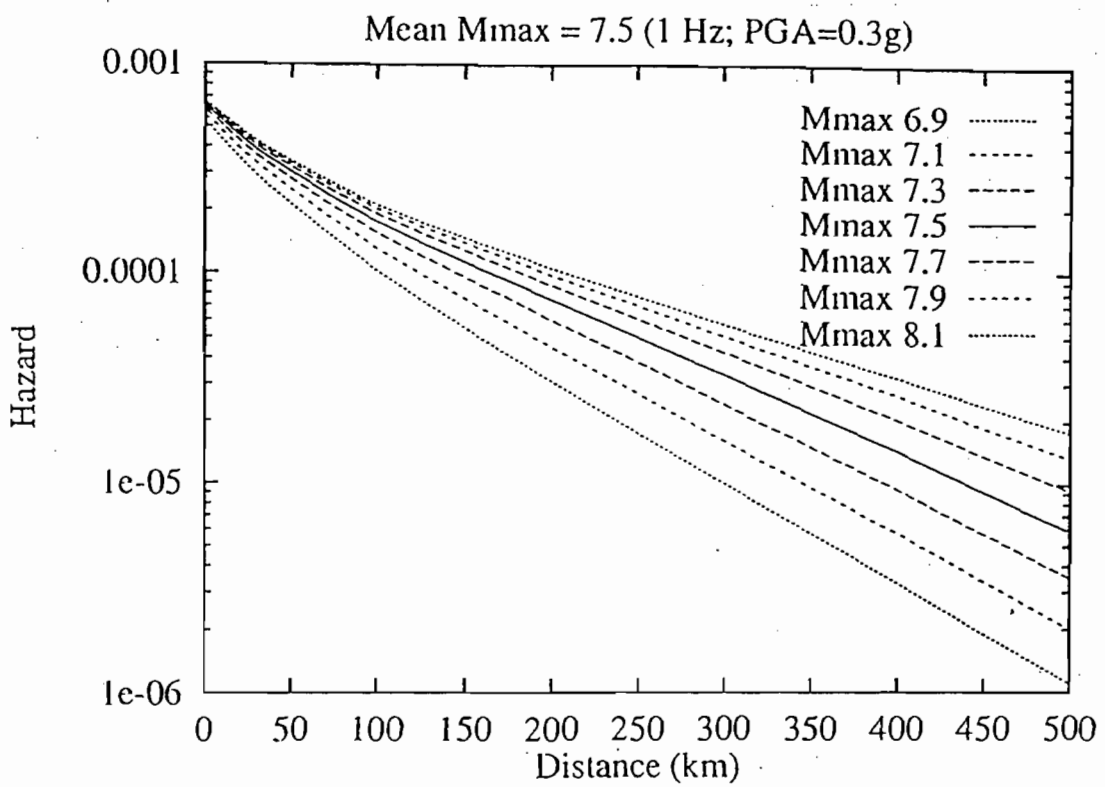


Figure G-14a. Sensitivity of 1 Hz hazard to m_{max} = 7.5, PGA = 0.1g, Group A sites.



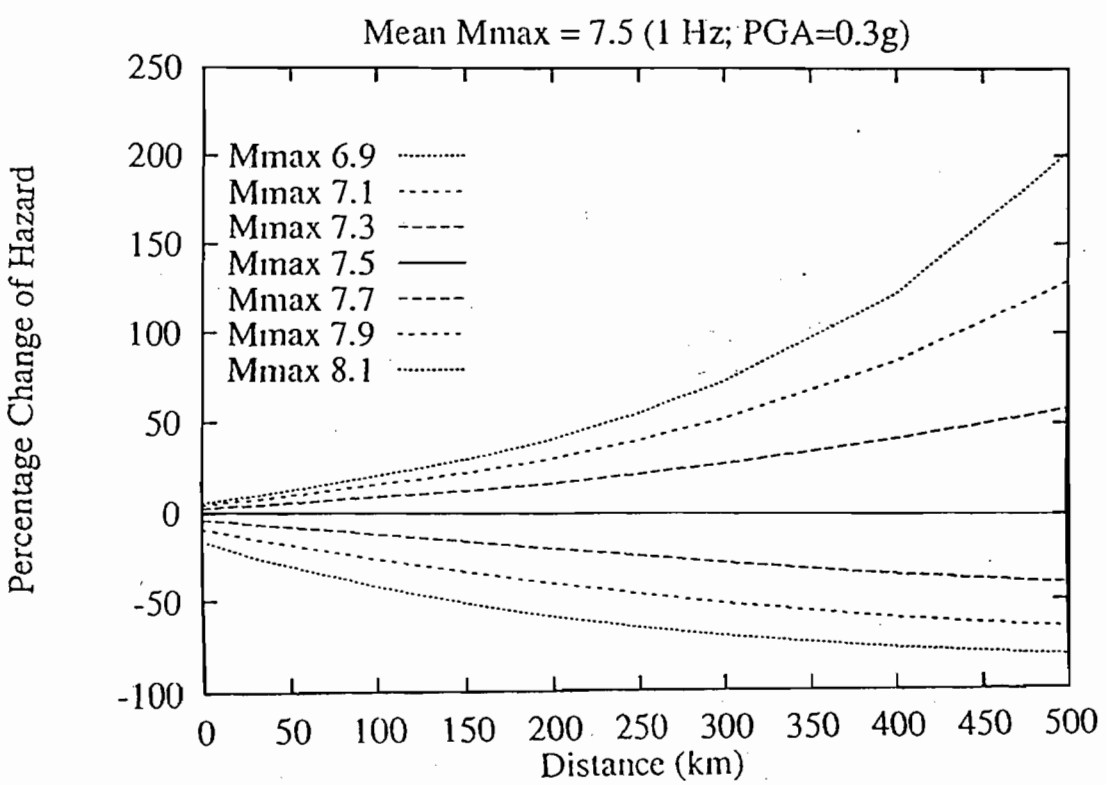
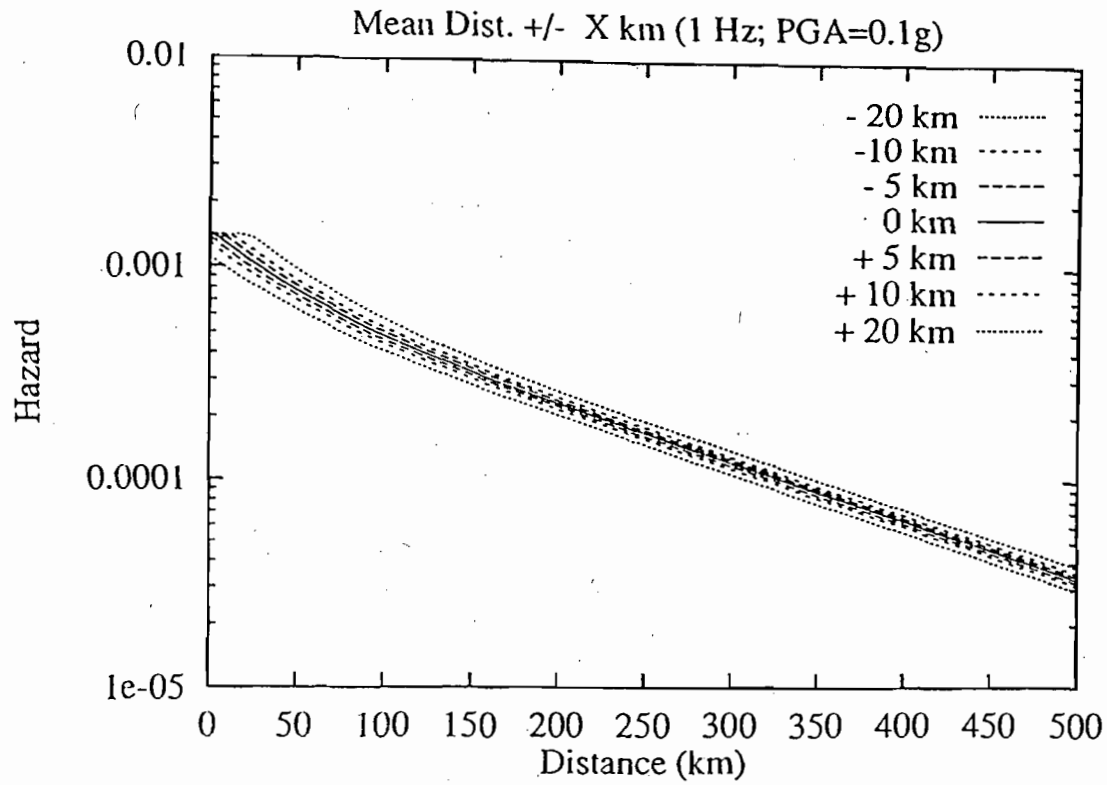


Figure G-14b. Sensitivity of 1 Hz hazard to m_{max} = 7.5, PGA = 0.3g, Group A sites.



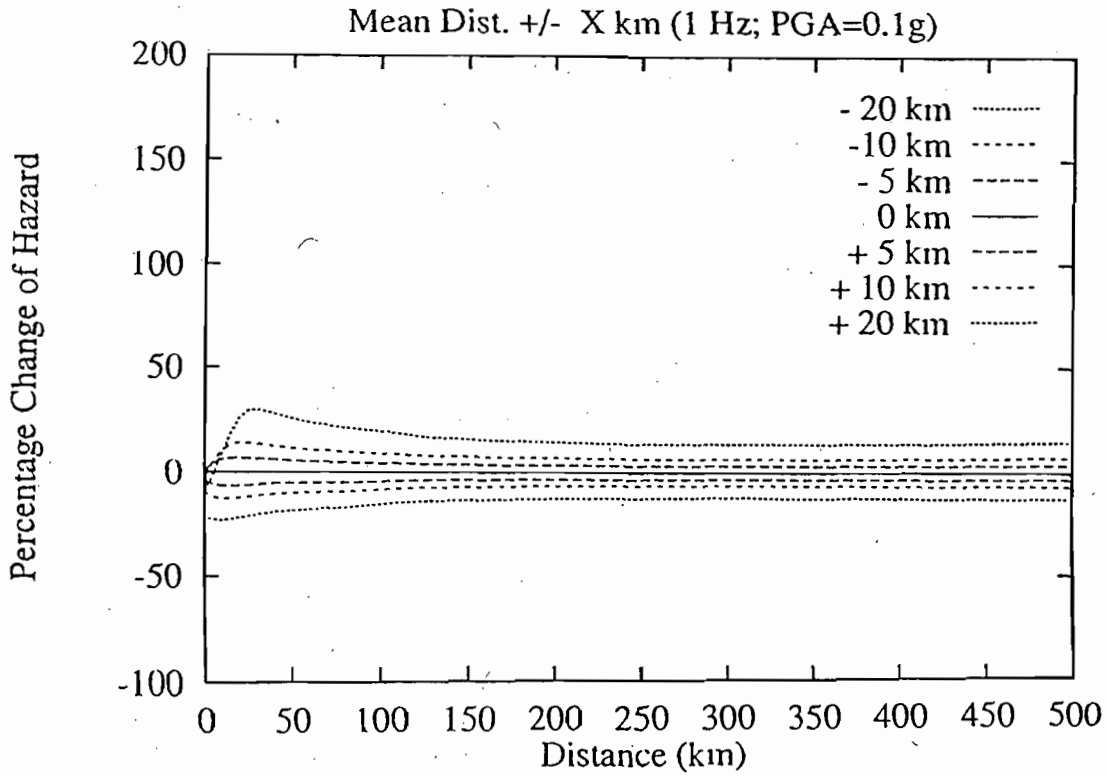
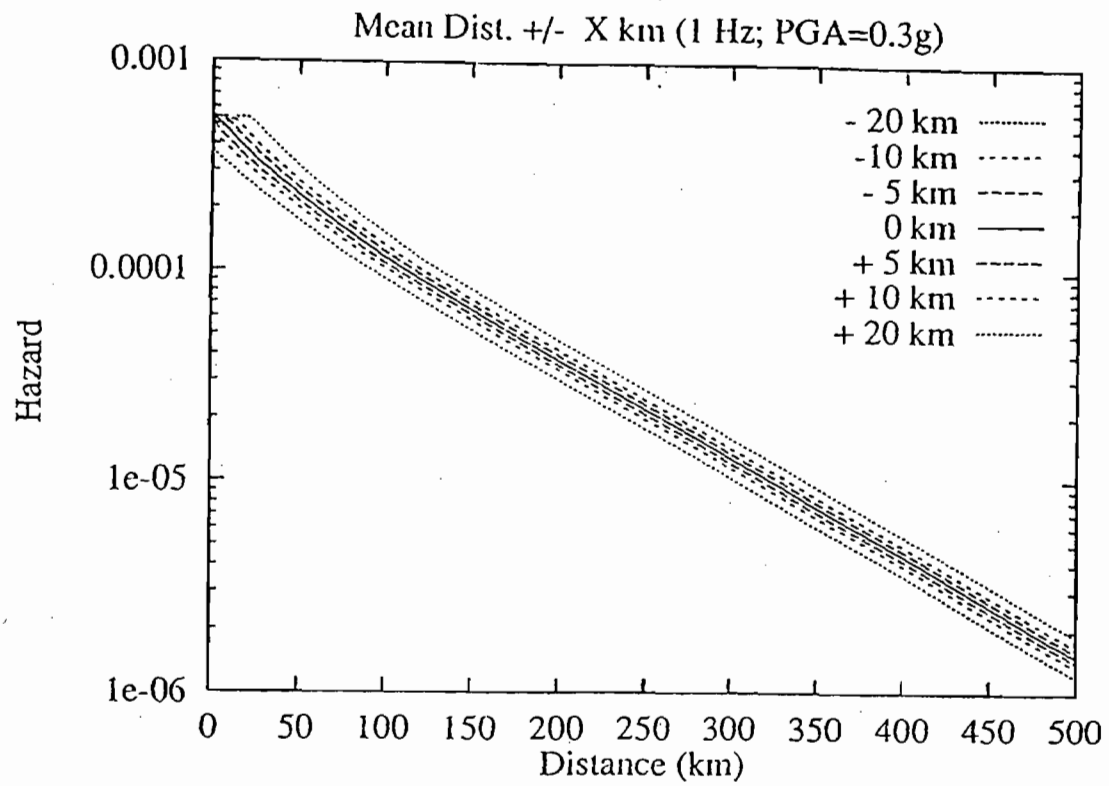


Figure G-15a. Sensitivity of 1 Hz hazard to distance from fault, PGA = 0.1g, Group A sites.



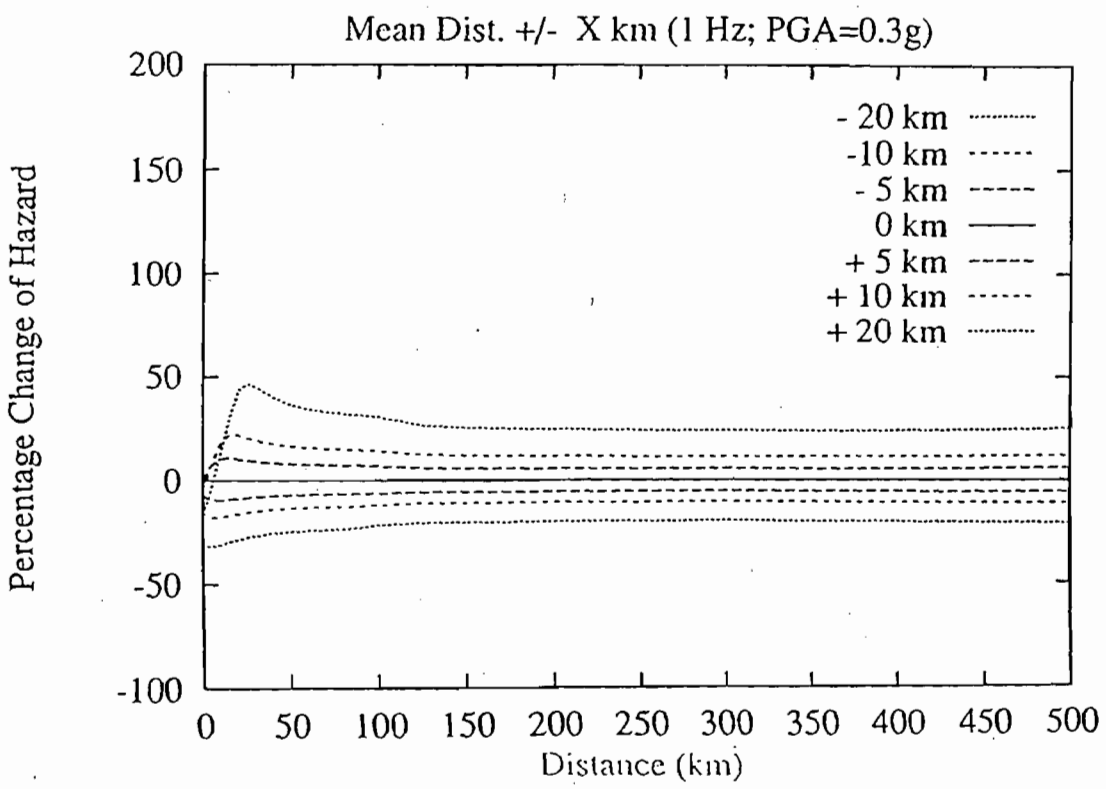


Figure G-15b. Sensitivity of 1 Hz hazard to distance from fault, PGA = 0.3g, Group A sites.

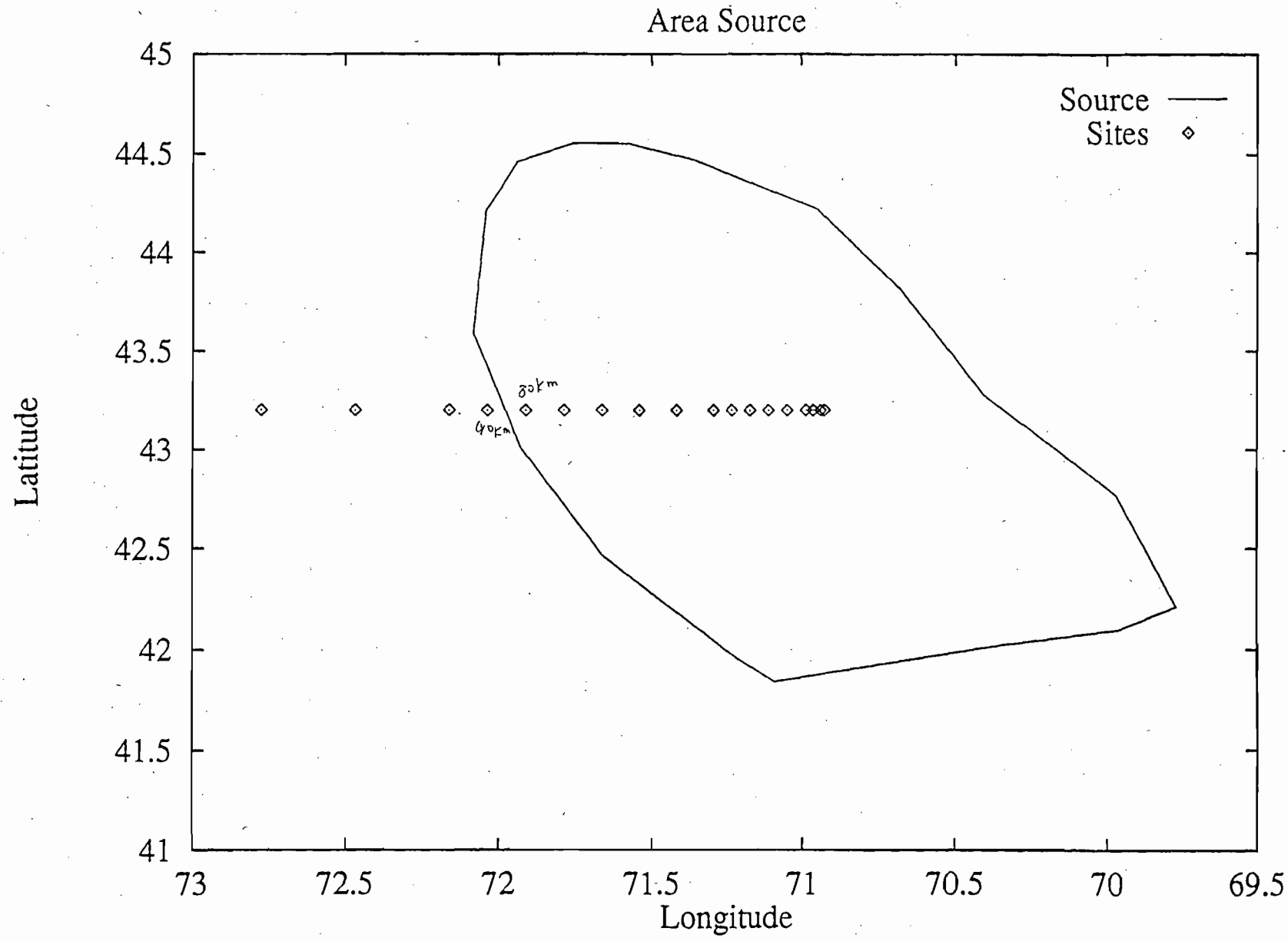
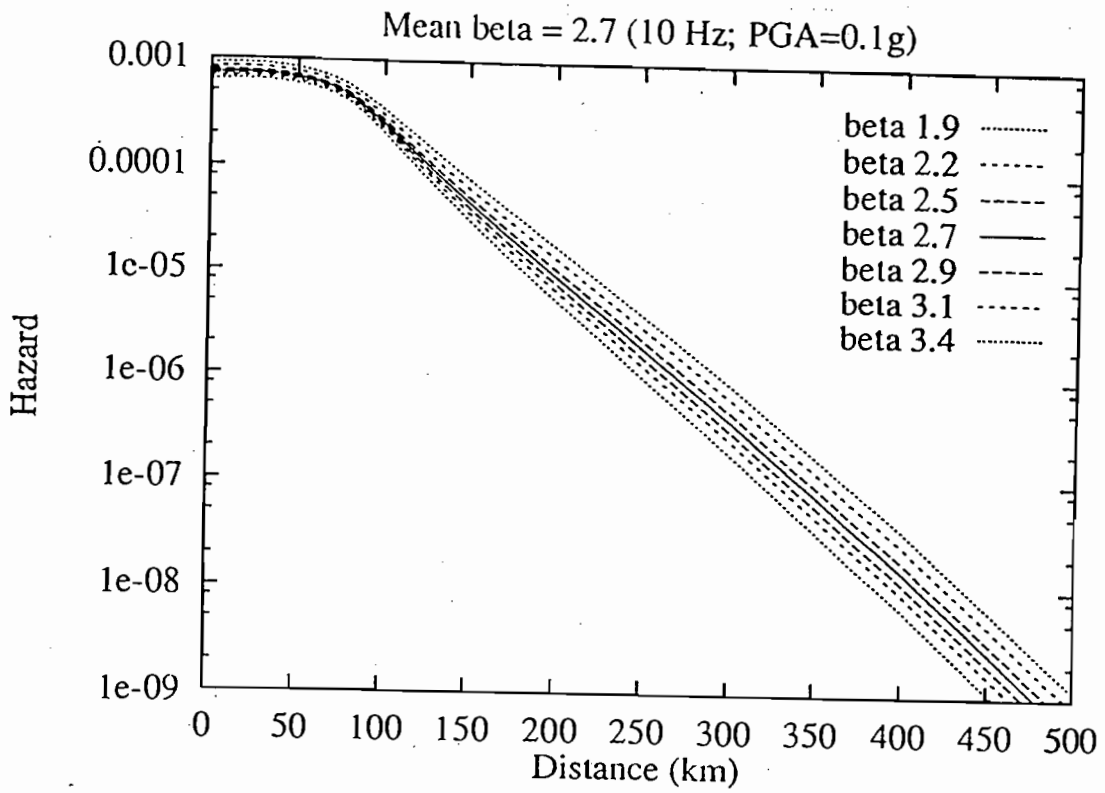


Figure 16. Configuration of Group B sites with line source.



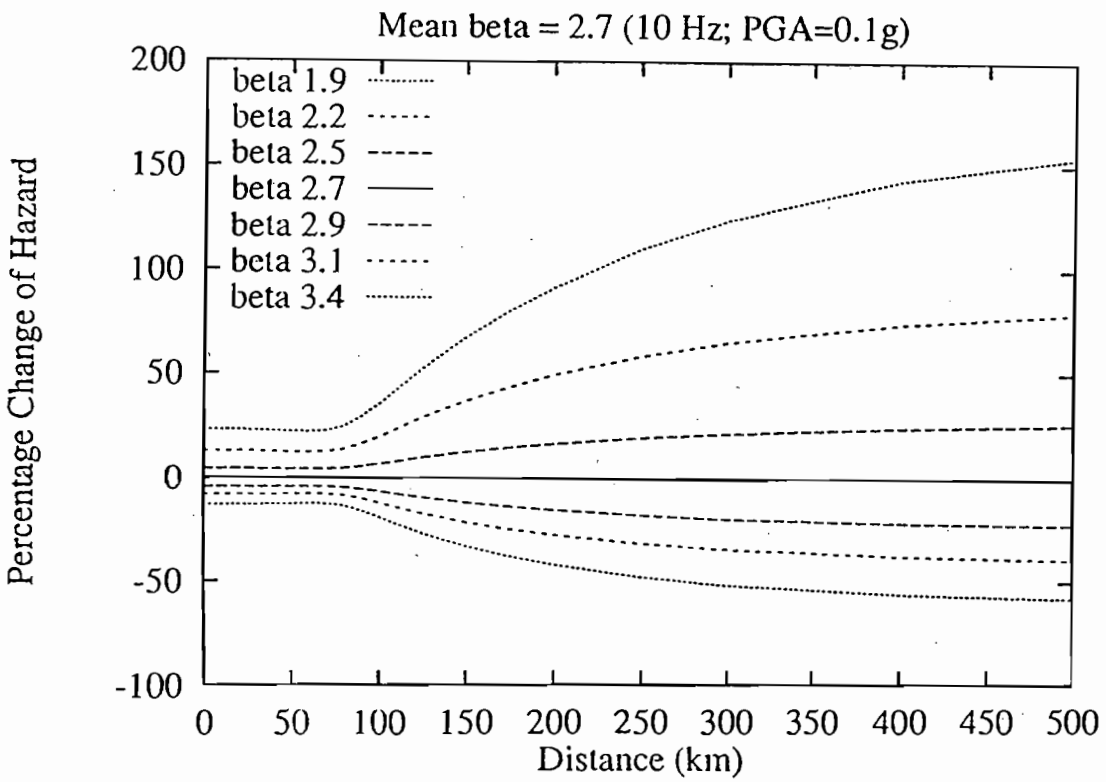
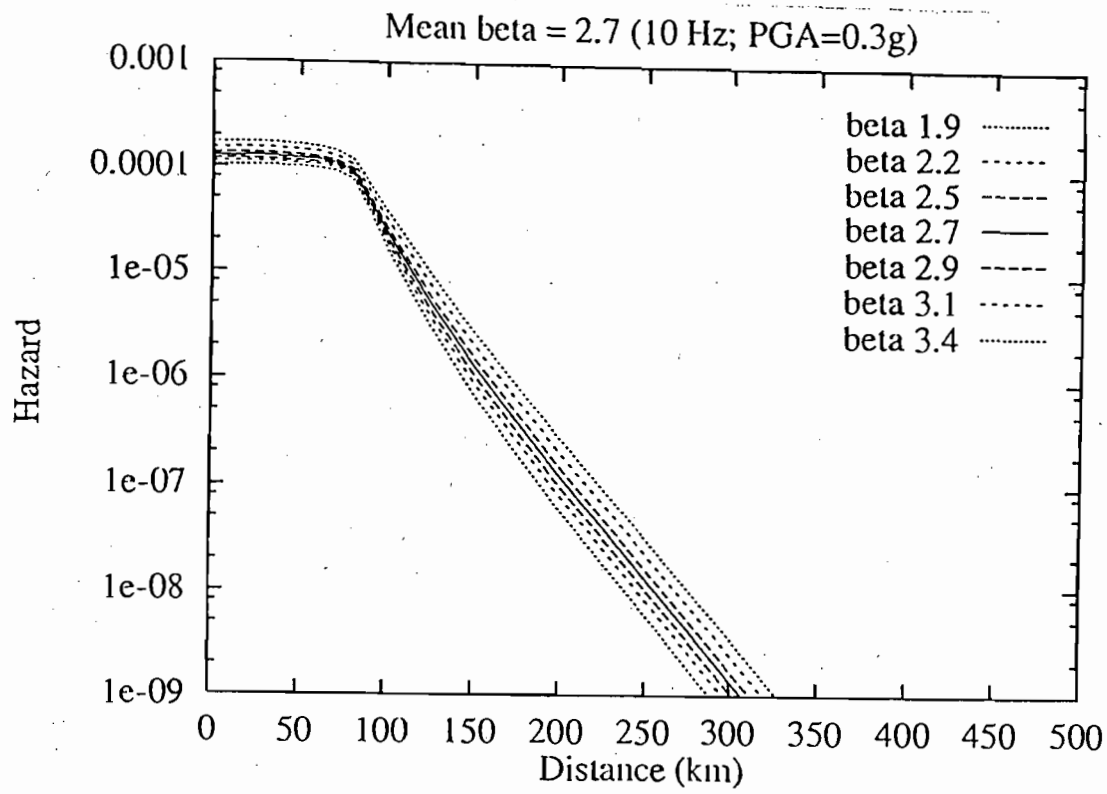


Figure G-17a. Sensitivity of 10 Hz hazard to beta for PGA = 0.1g, Group B sites.



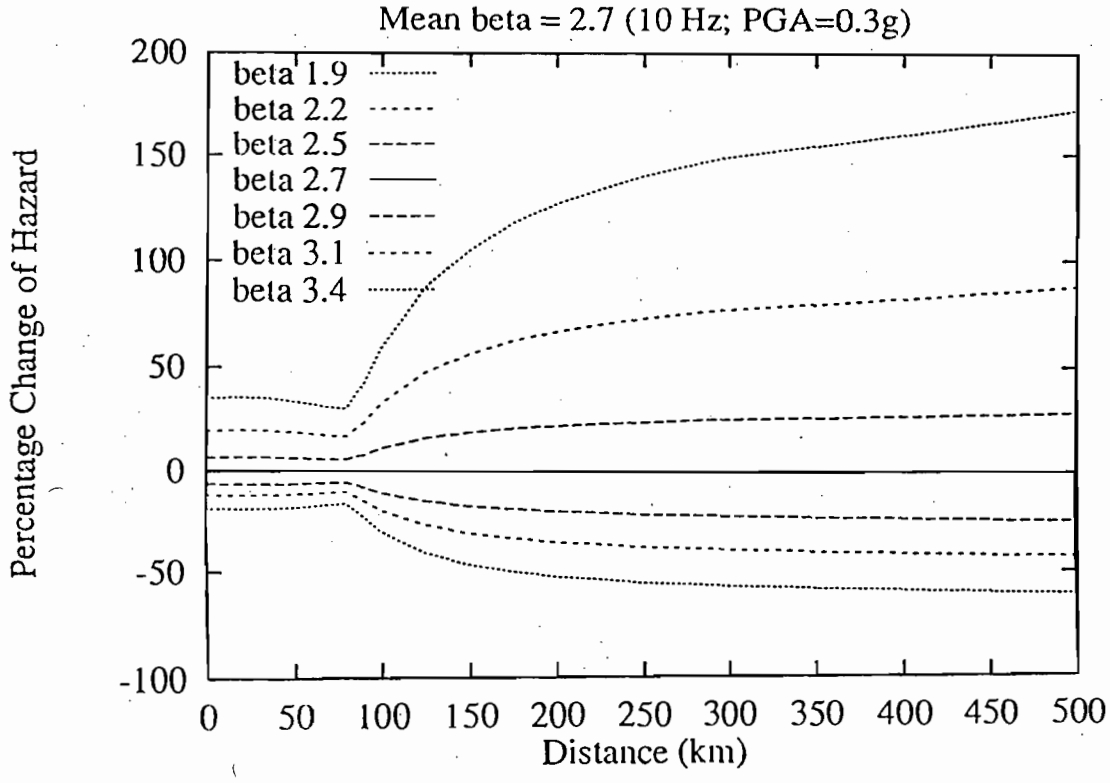
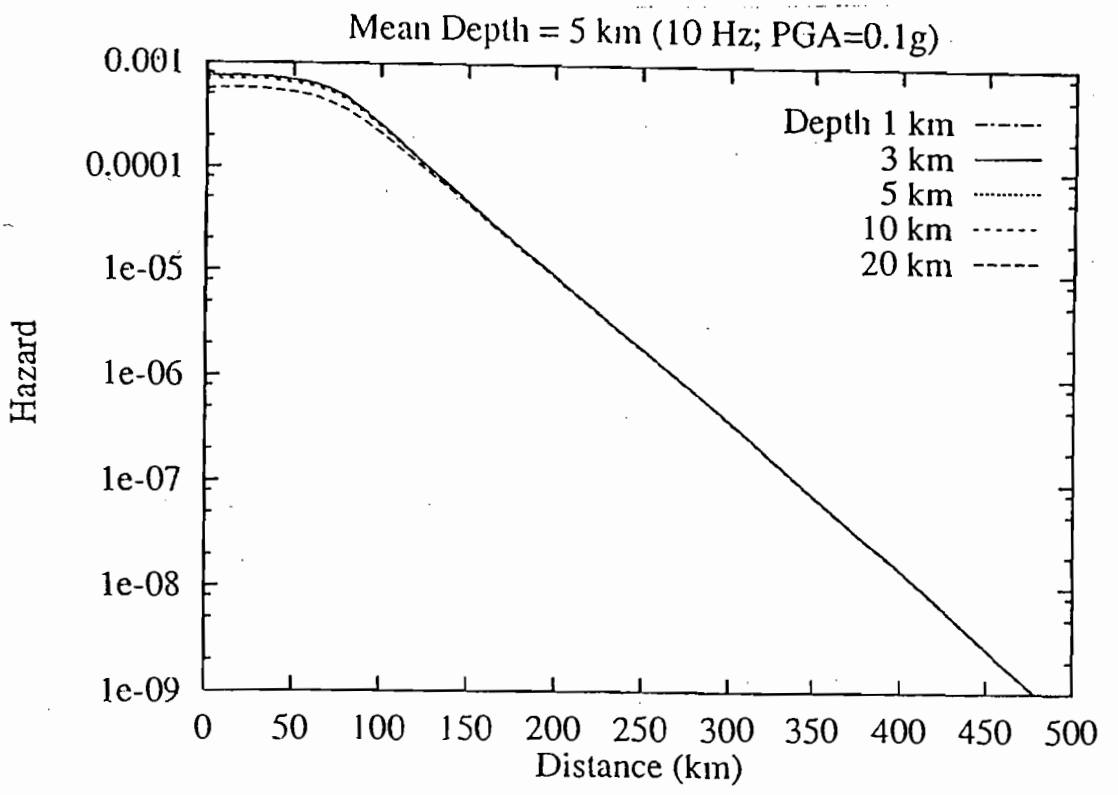


Figure G-17b. Sensitivity of 10 Hz hazard to beta for PGA = 0.3g, Group B sites.



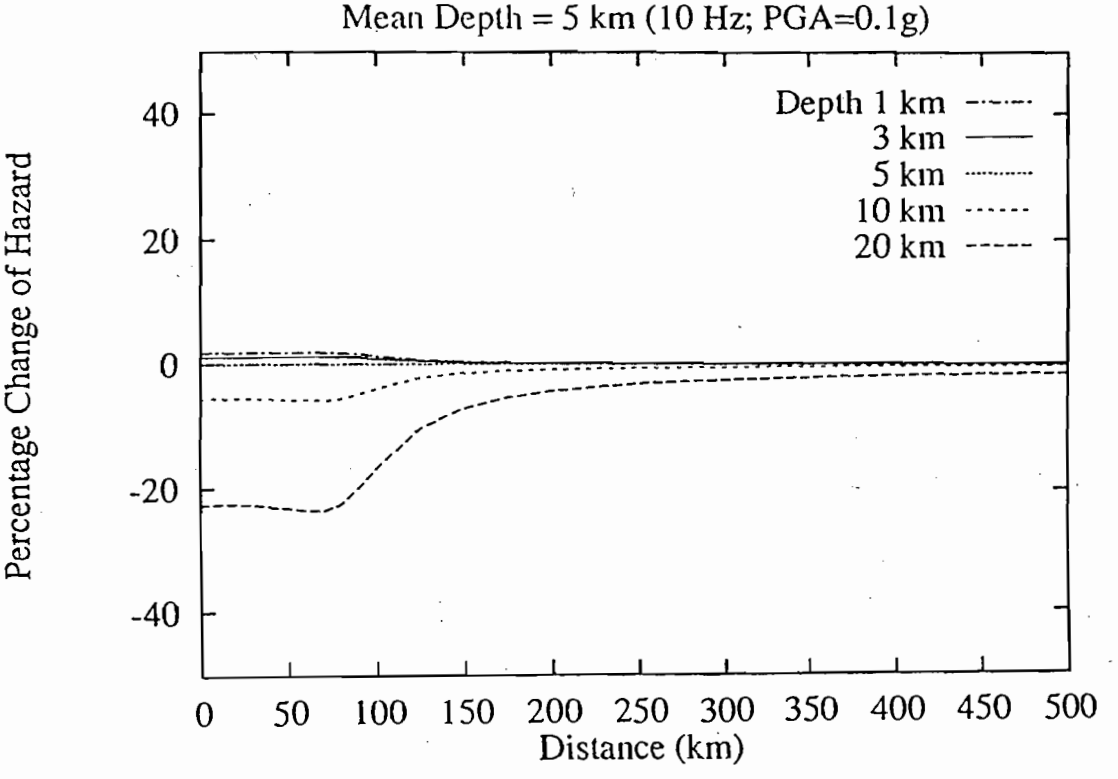


Figure G-18a. Sensitivity of 10 Hz hazard to depth distribution for PGA = 0.1g, Group B sites.

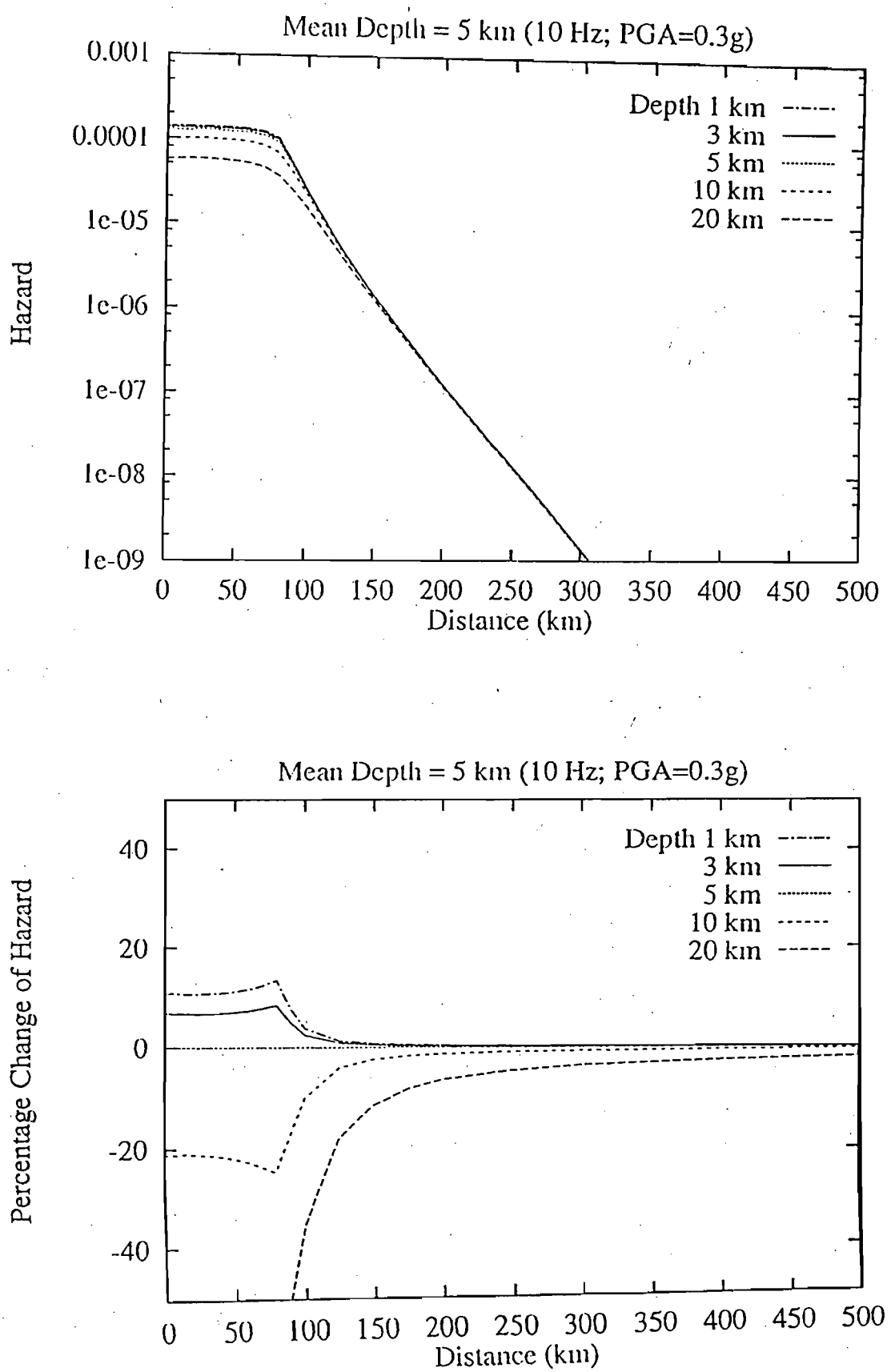
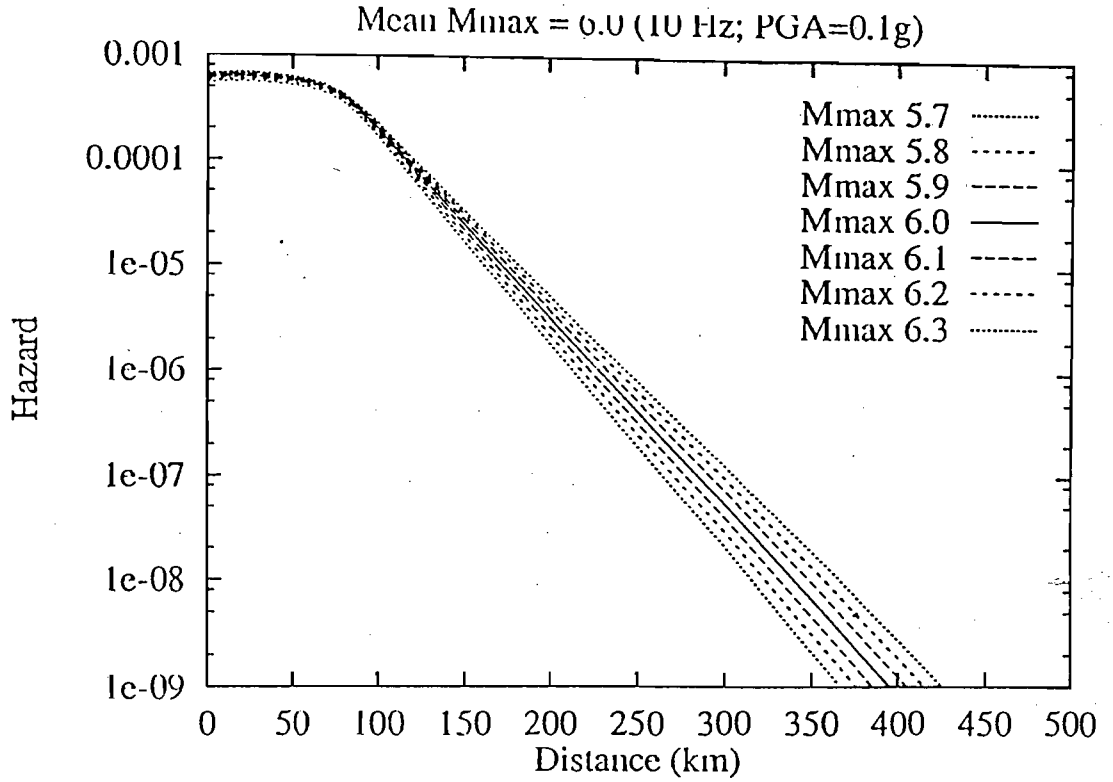


Figure G-18b. Sensitivity of 10 Hz hazard to depth distribution for PGA = 0.3g, Group B sites.



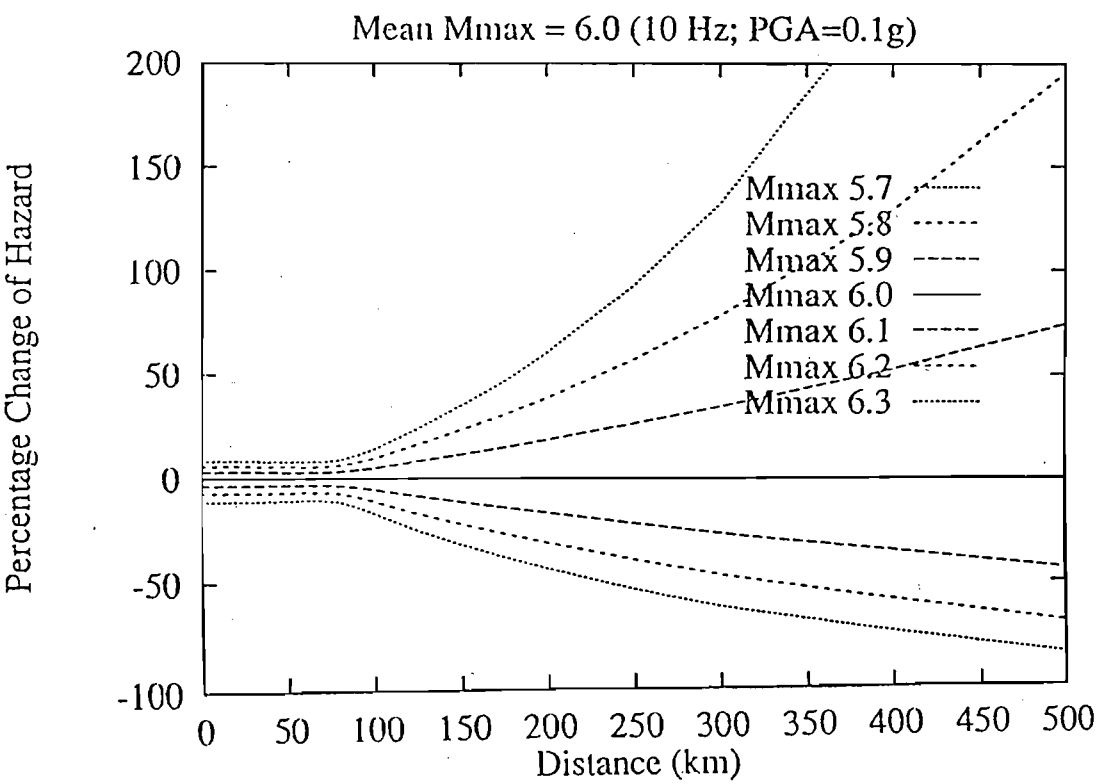
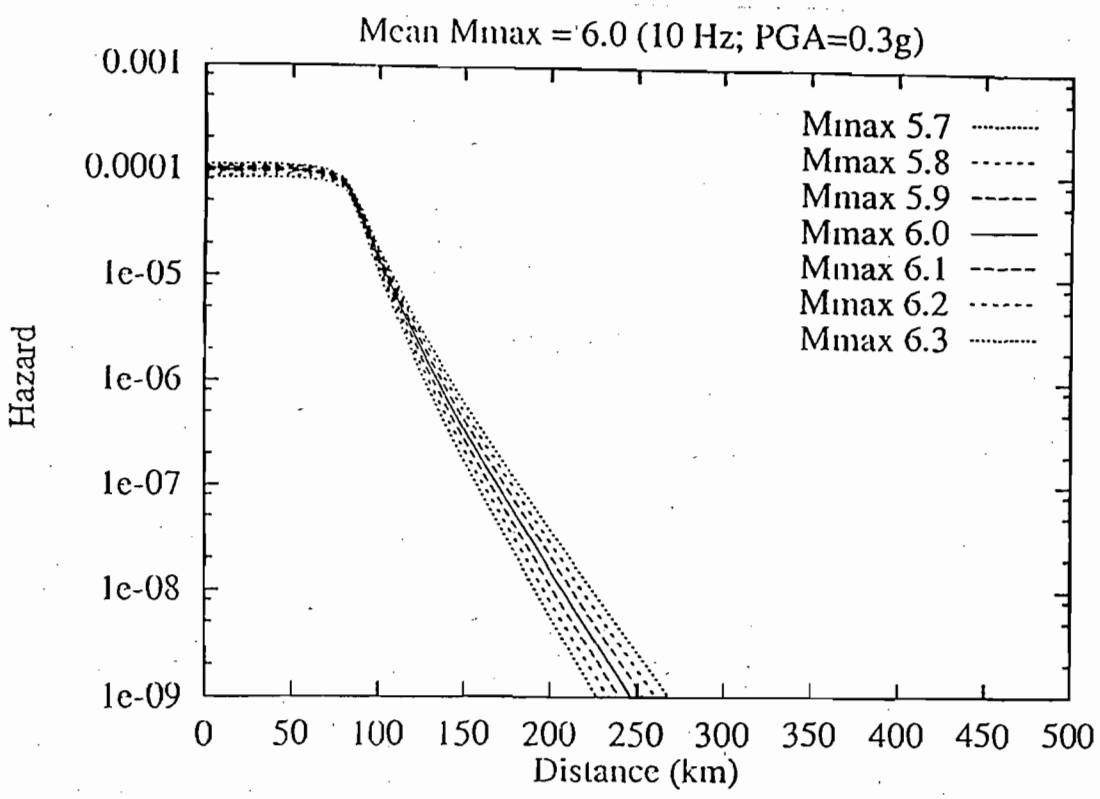


Figure G-19a. Sensitivity of 10 Hz hazard to m_{max} = 6.0, PGA = 0.1g, Group B sites.



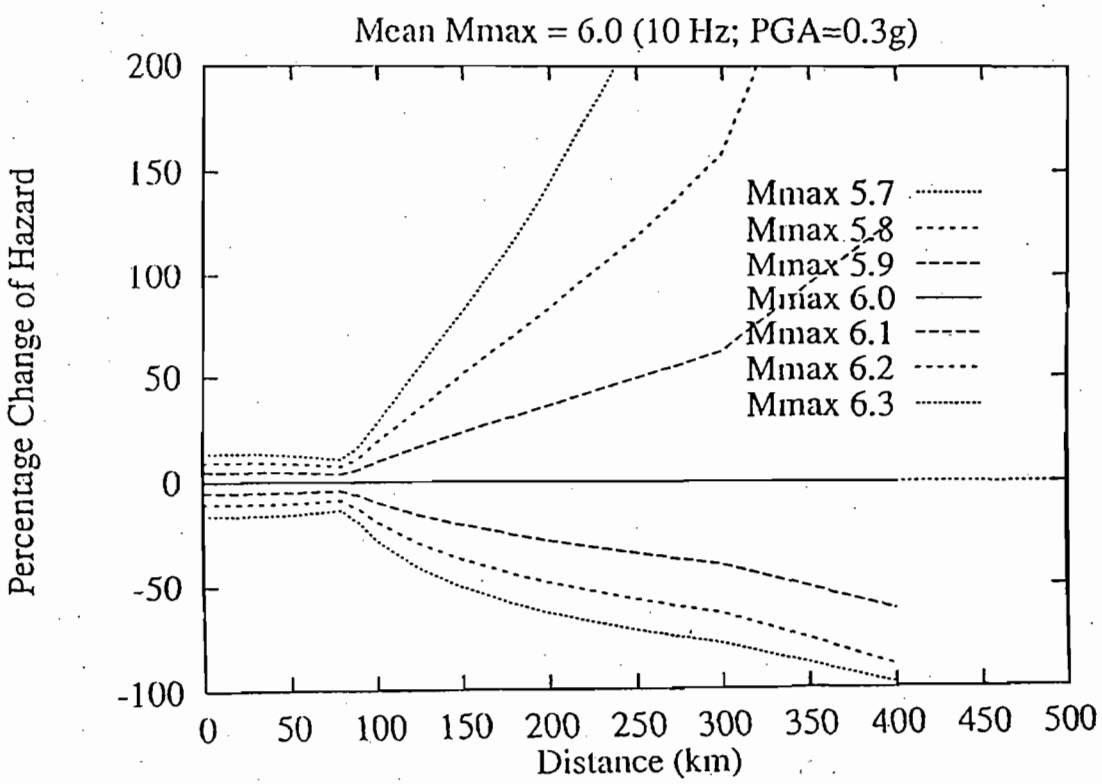
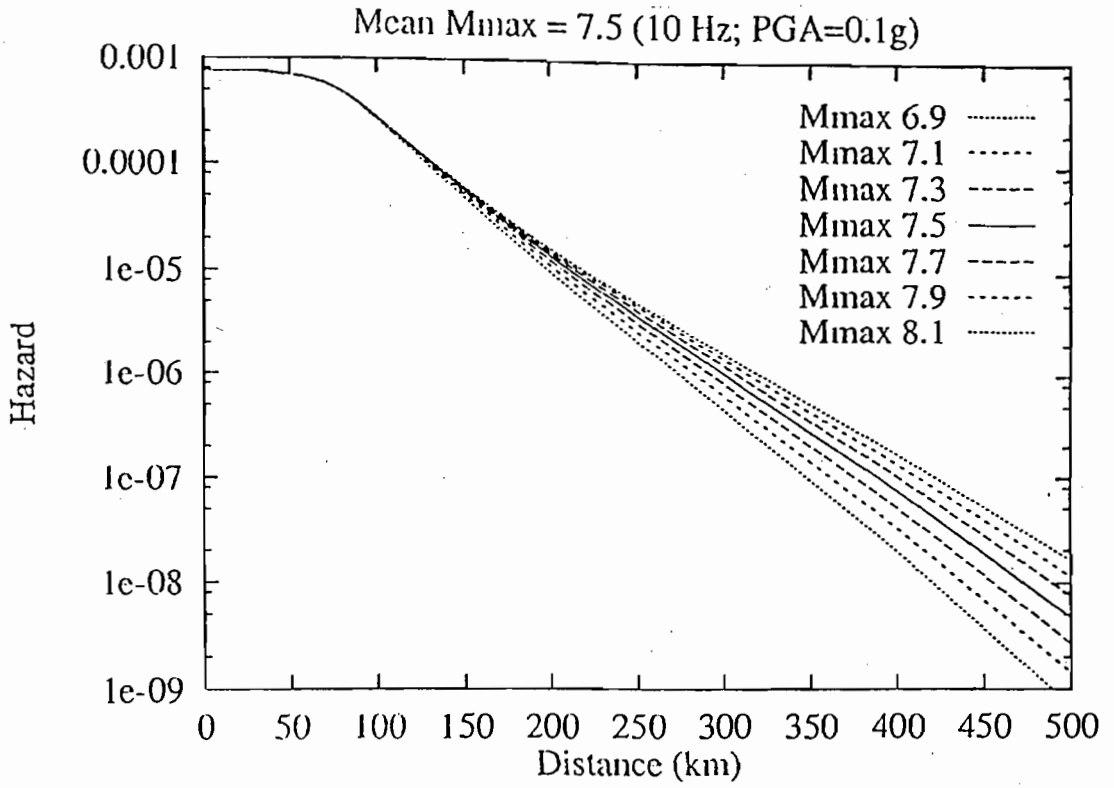


Figure G-19b. Sensitivity of 10 Hz hazard to m_{max} = 6.0, PGA = 0.3g, Group B sites.



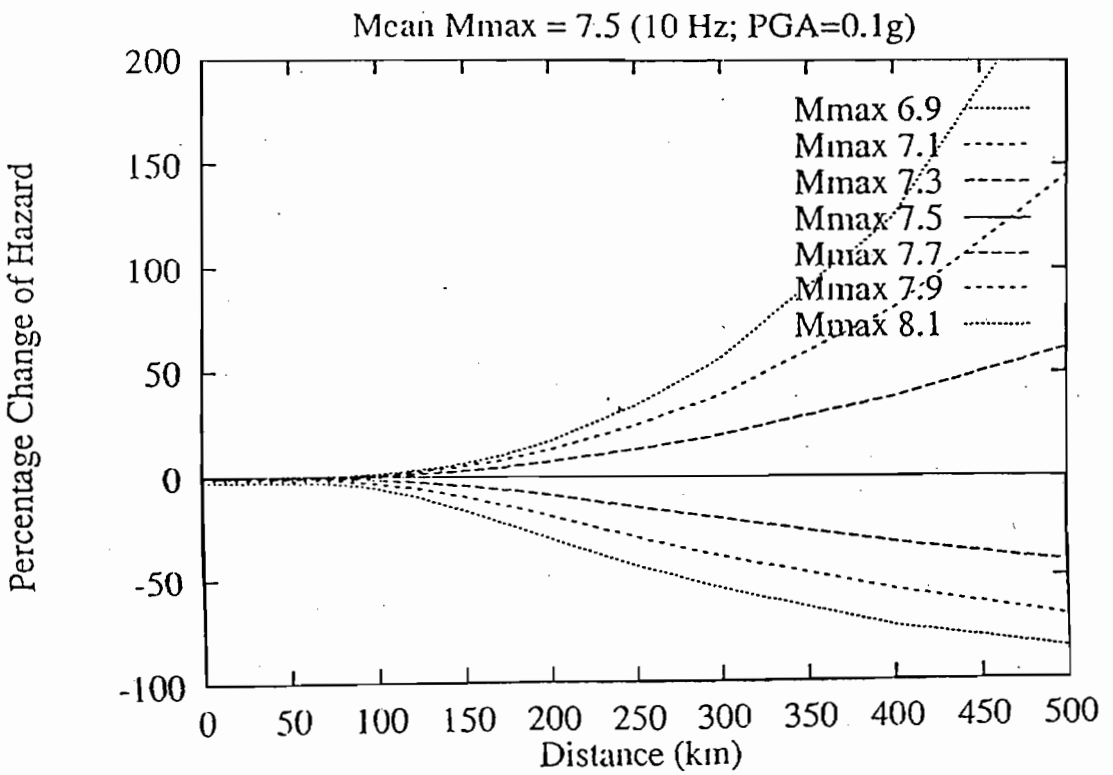
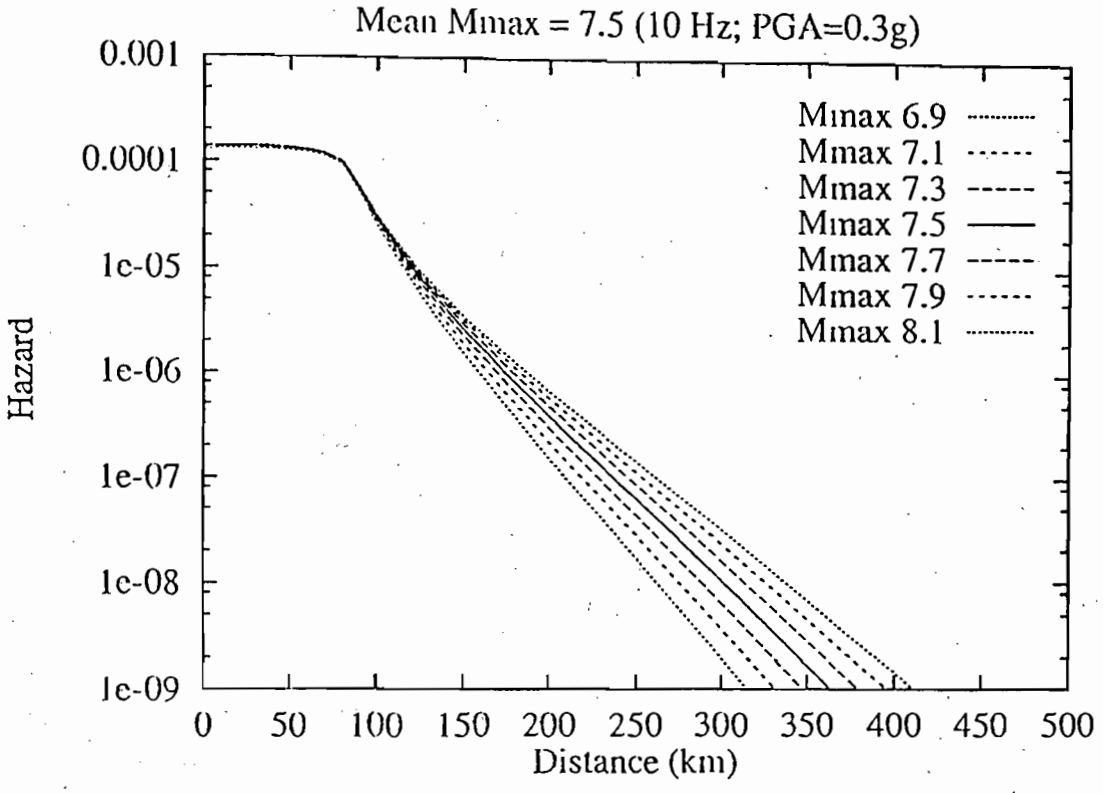


Figure G-20a. Sensitivity of 10 Hz hazard to m_{max} = 7.5, PGA = 0.1g, Group B sites.



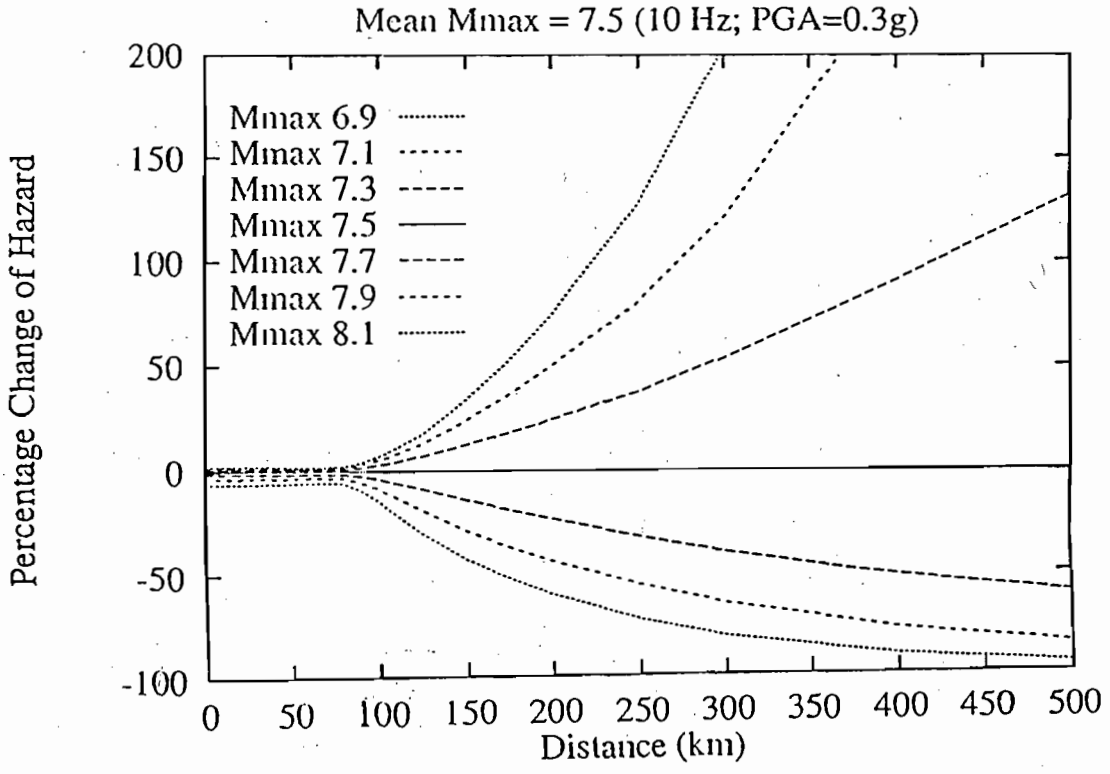
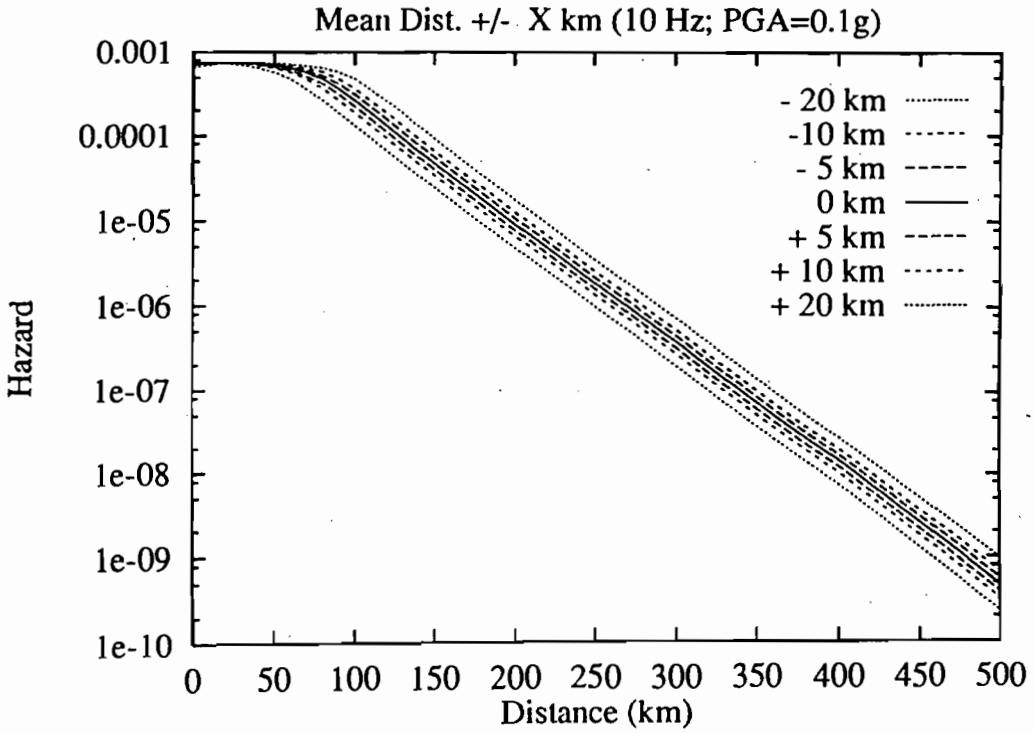


Figure G-20b. Sensitivity of 10 Hz hazard to m_{max} = 7.5, PGA = 0.3g, Group B sites.



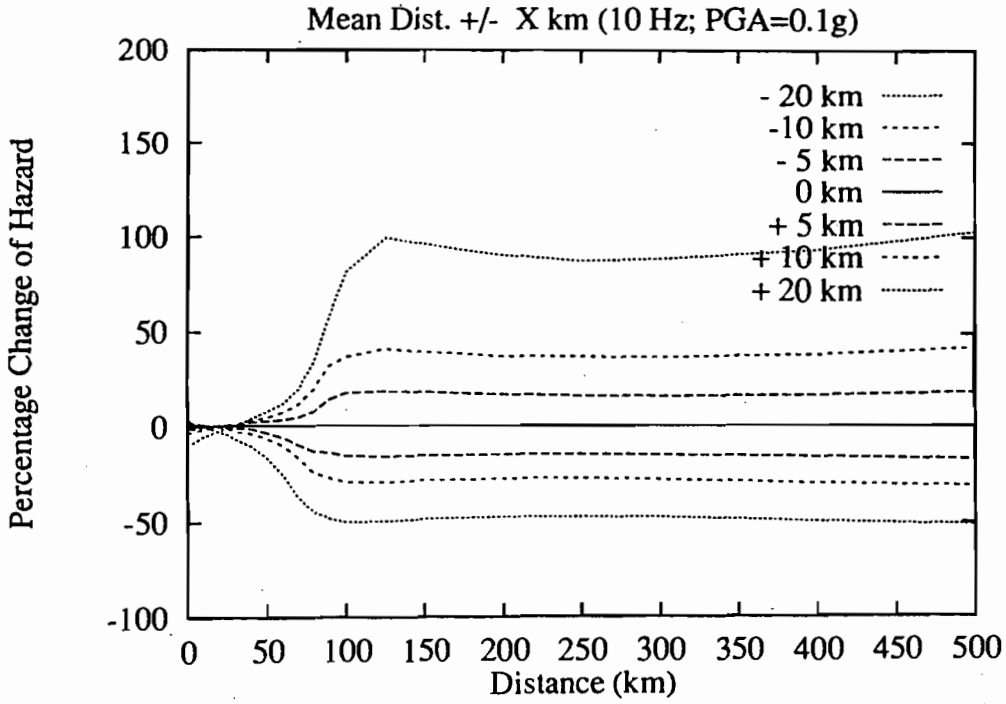
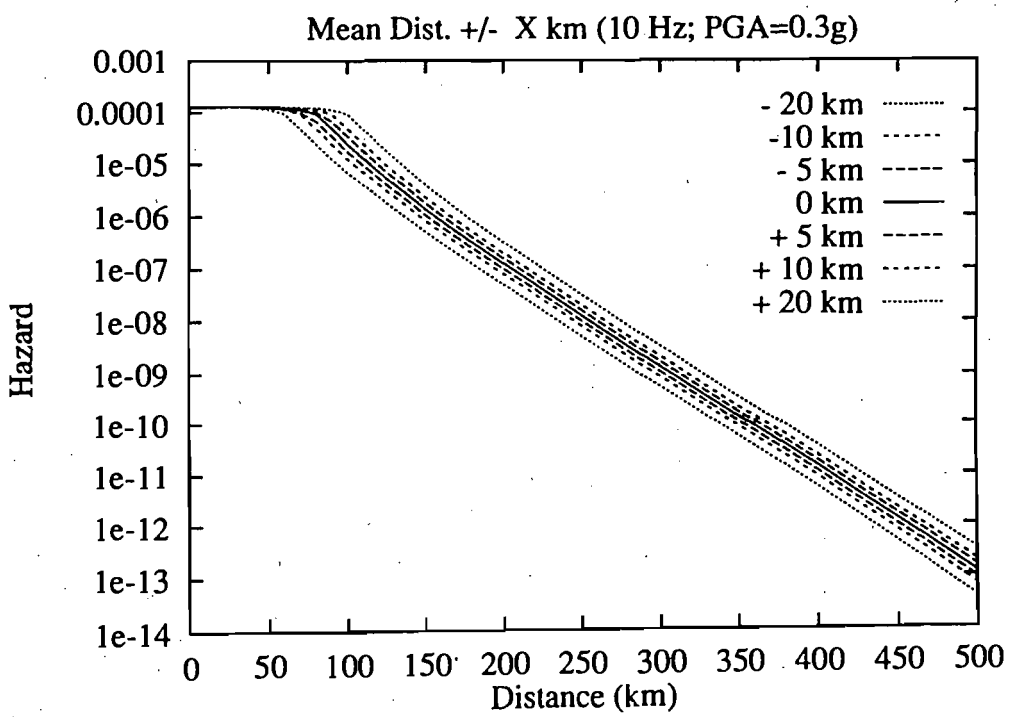


Figure G-21a. Sensitivity of 10 Hz hazard to distance from fault, PGA=0.1g, Group B sites.



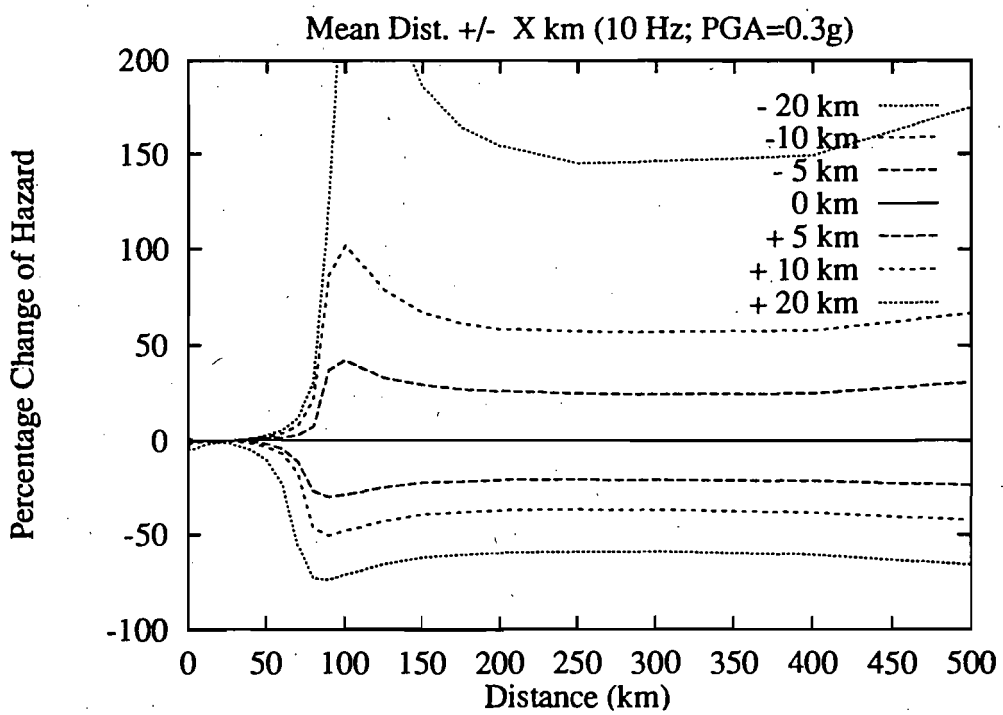
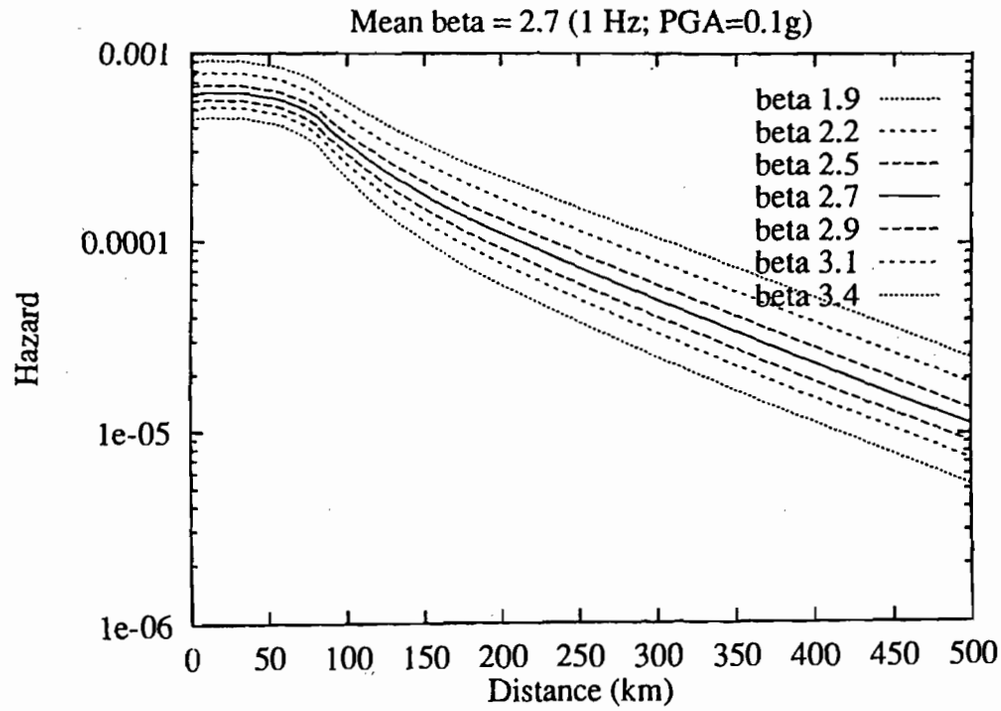


Figure G-21b. Sensitivity of 10 Hz hazard to distance from fault, PGA=0.3g, Group B sites.



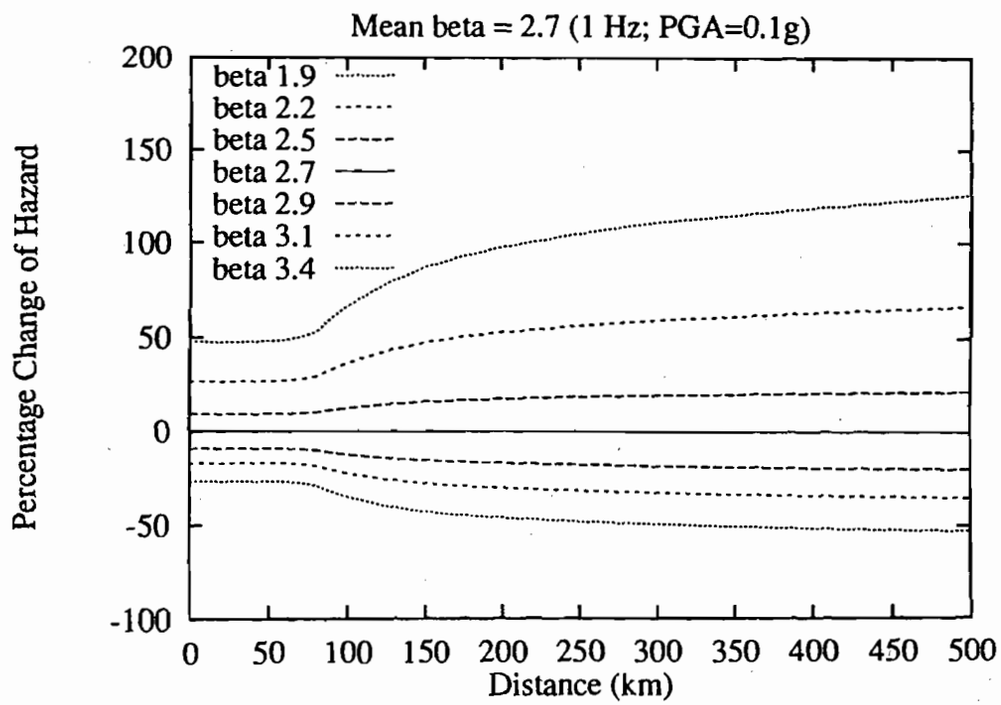
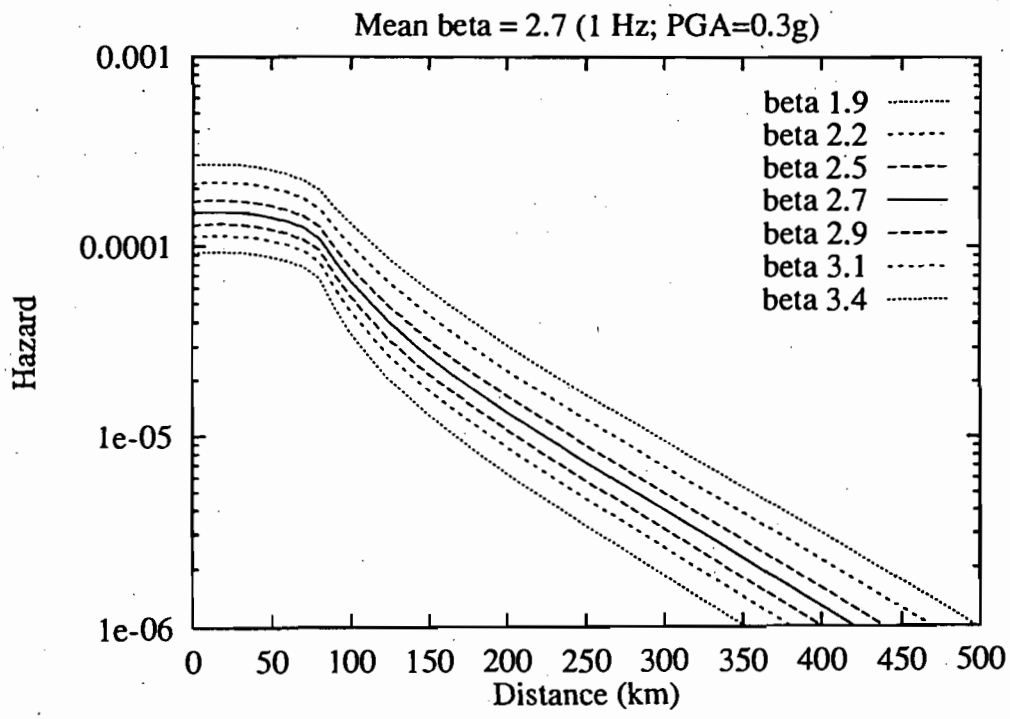


Figure G-22a. Sensitivity of 1 Hz hazard to beta for PGA=0.1g, Group B sites.



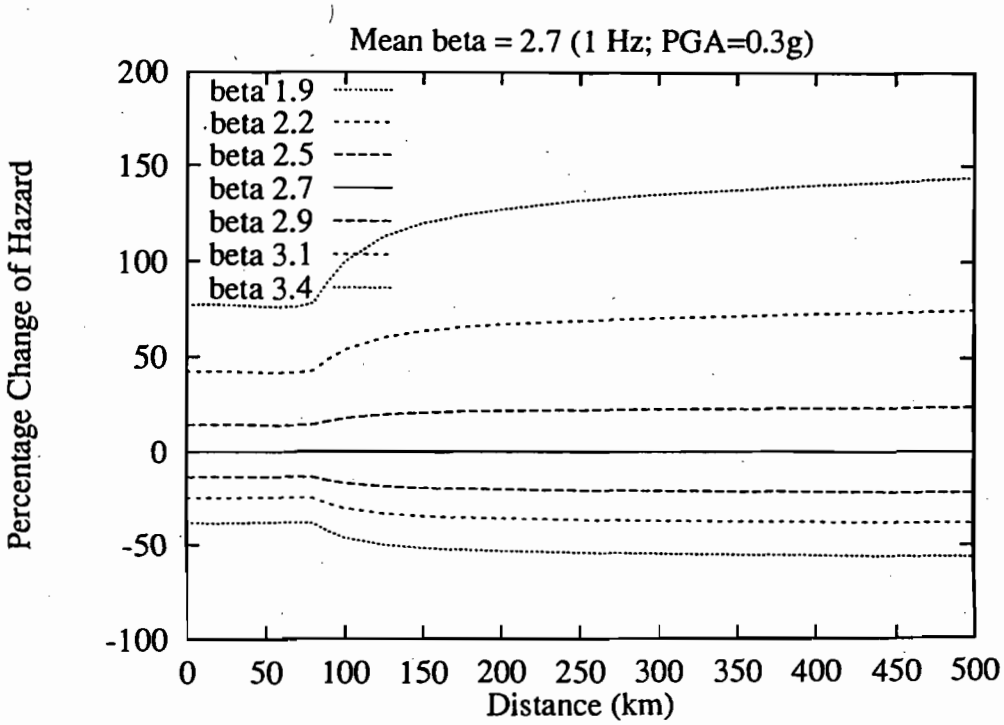
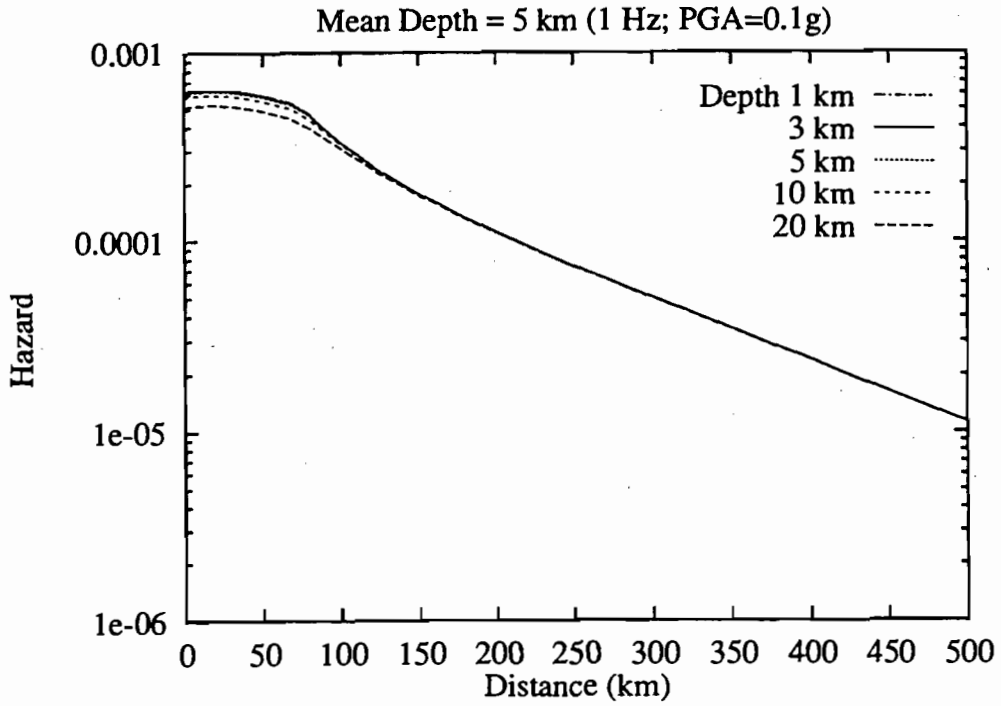


Figure G-22b. Sensitivity of 1 Hz hazard to beta for PGA=0.3g, Group B sites.



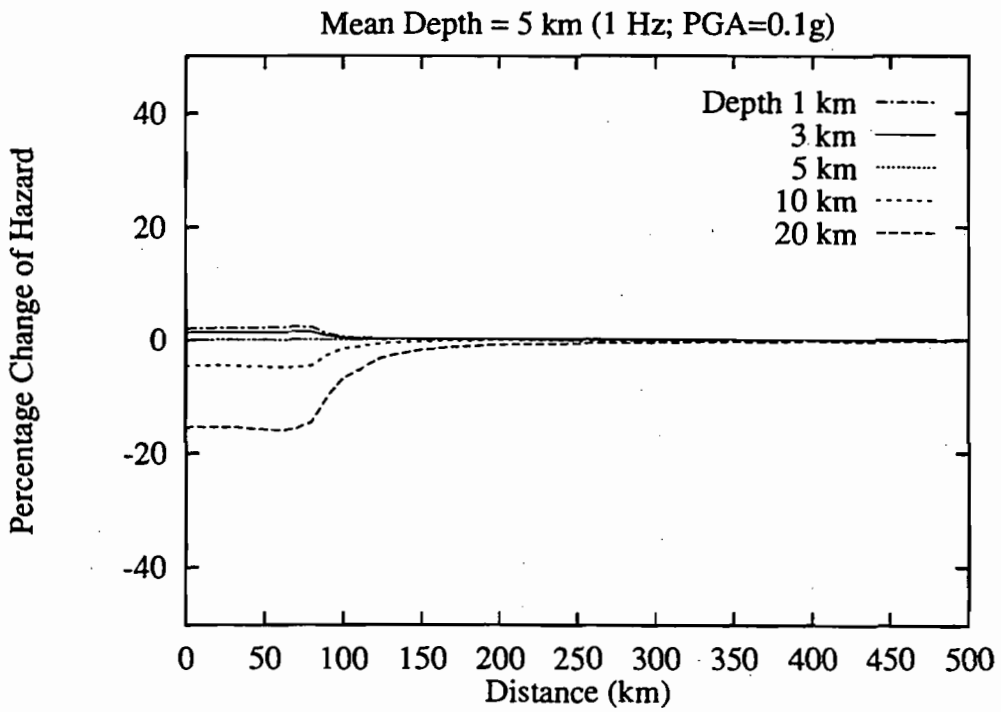
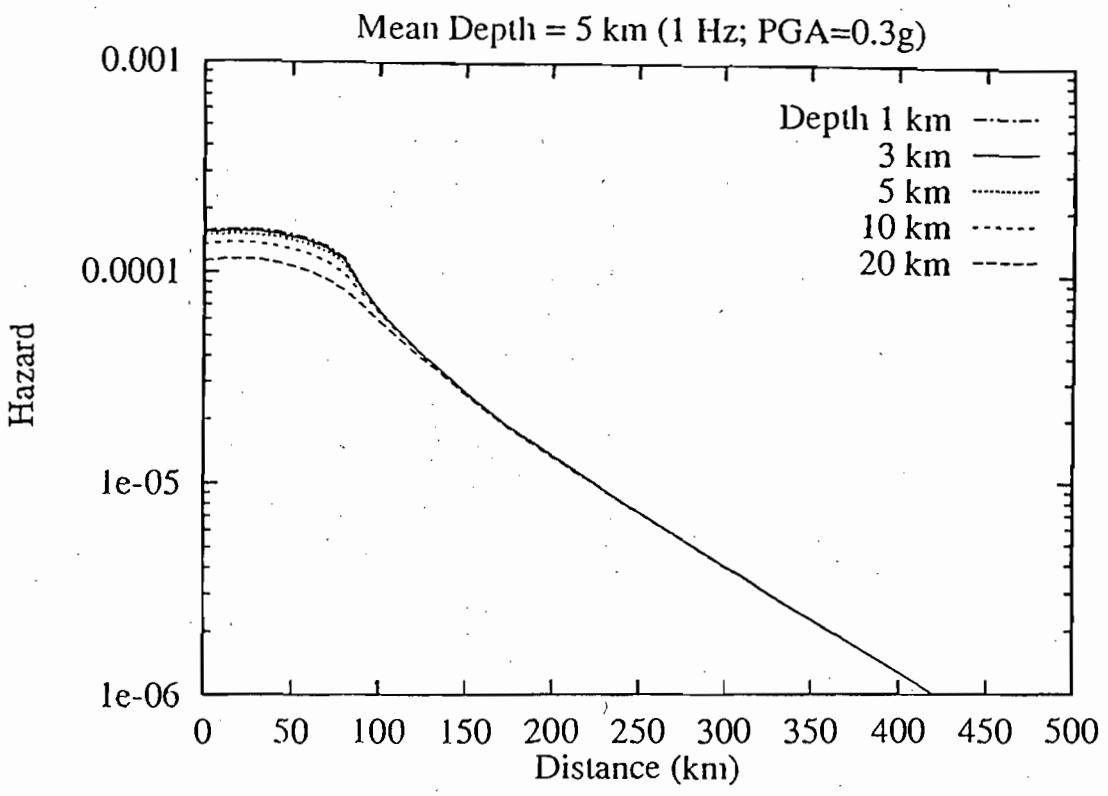


Figure G-23a. Sensitivity of 1 Hz hazard to depth distribution for PGA=0.1g, Group B sites.



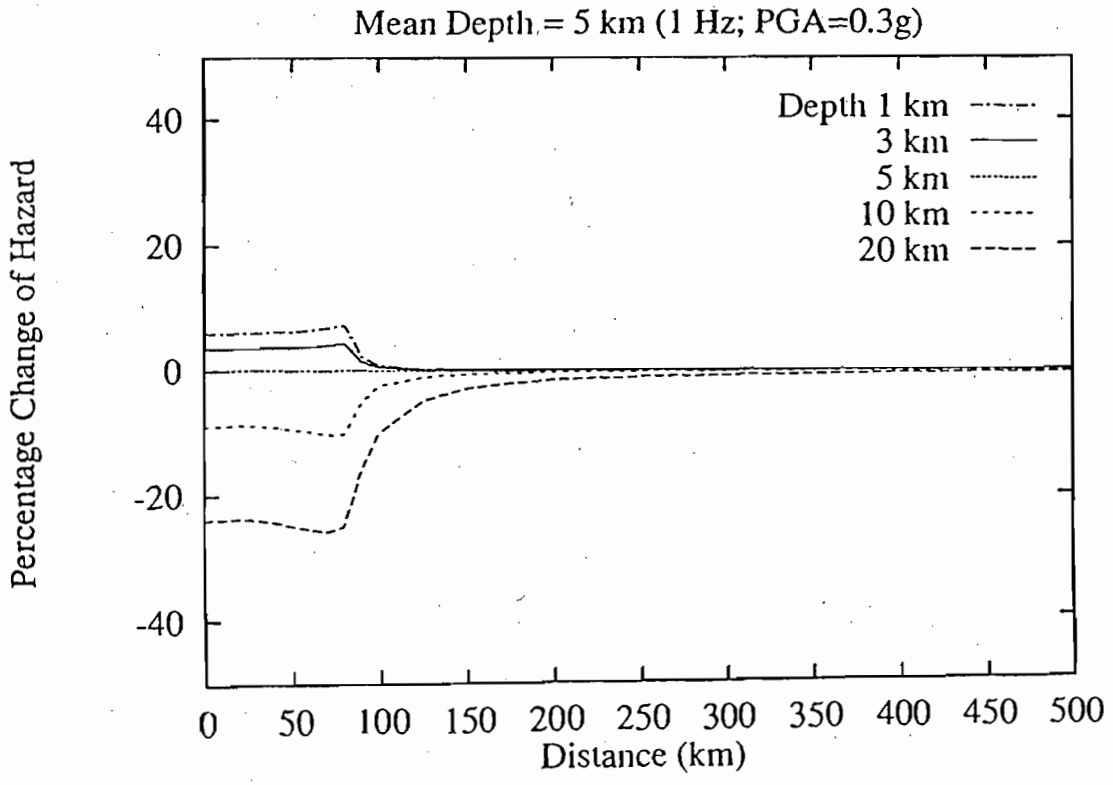
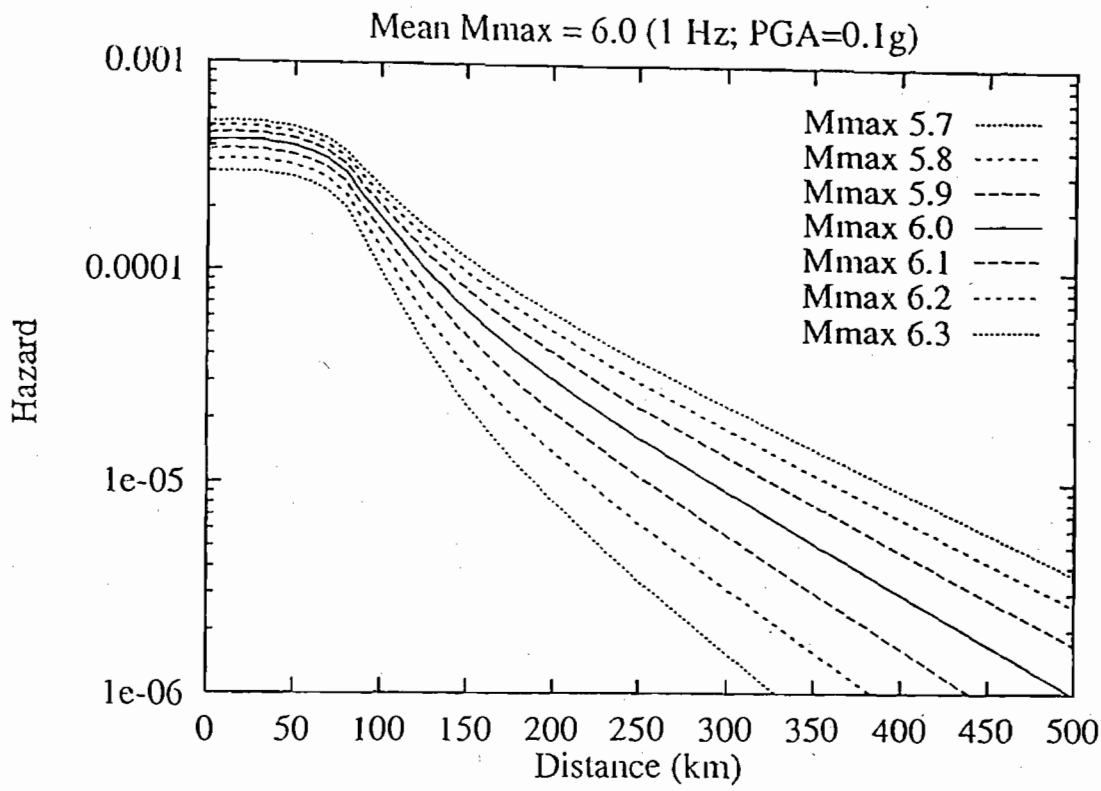


Figure G-23b. Sensitivity of 1 Hz hazard to depth distribution for PGA = 0.3g, Group B sites.



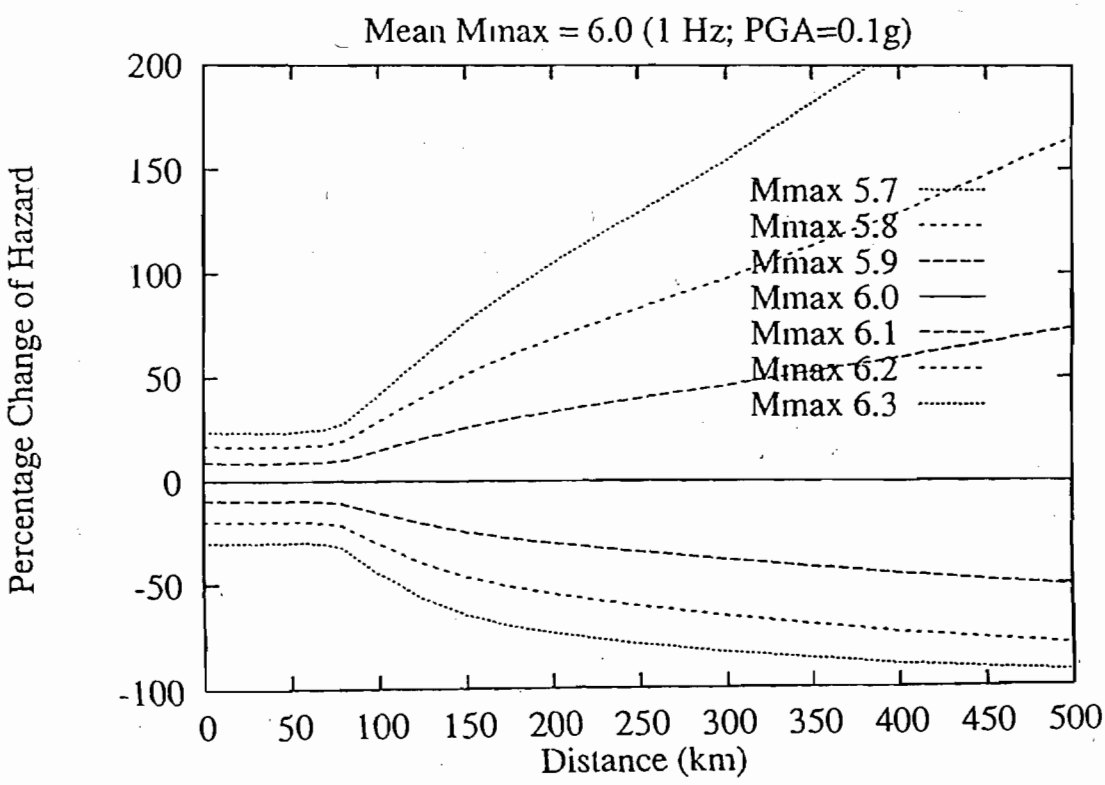
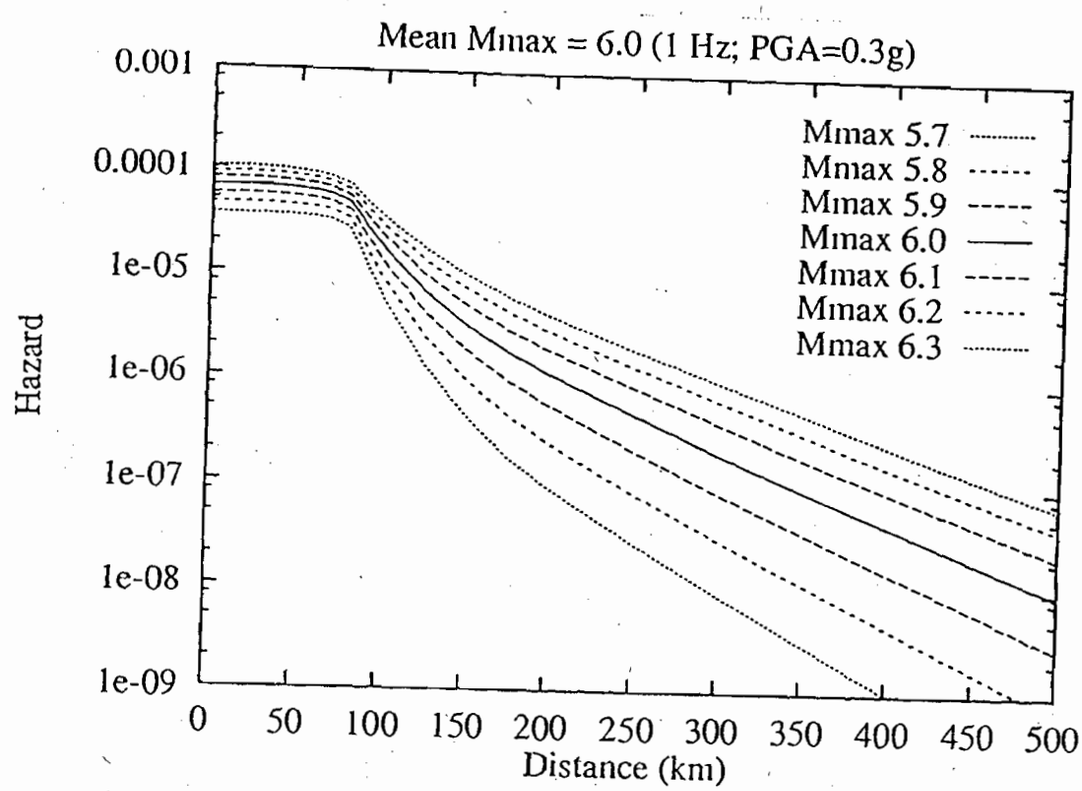


Figure G-24a. Sensitivity of 1 Hz hazard to m_{max} = 6.0, PGA = 0.1g, Group B sites.



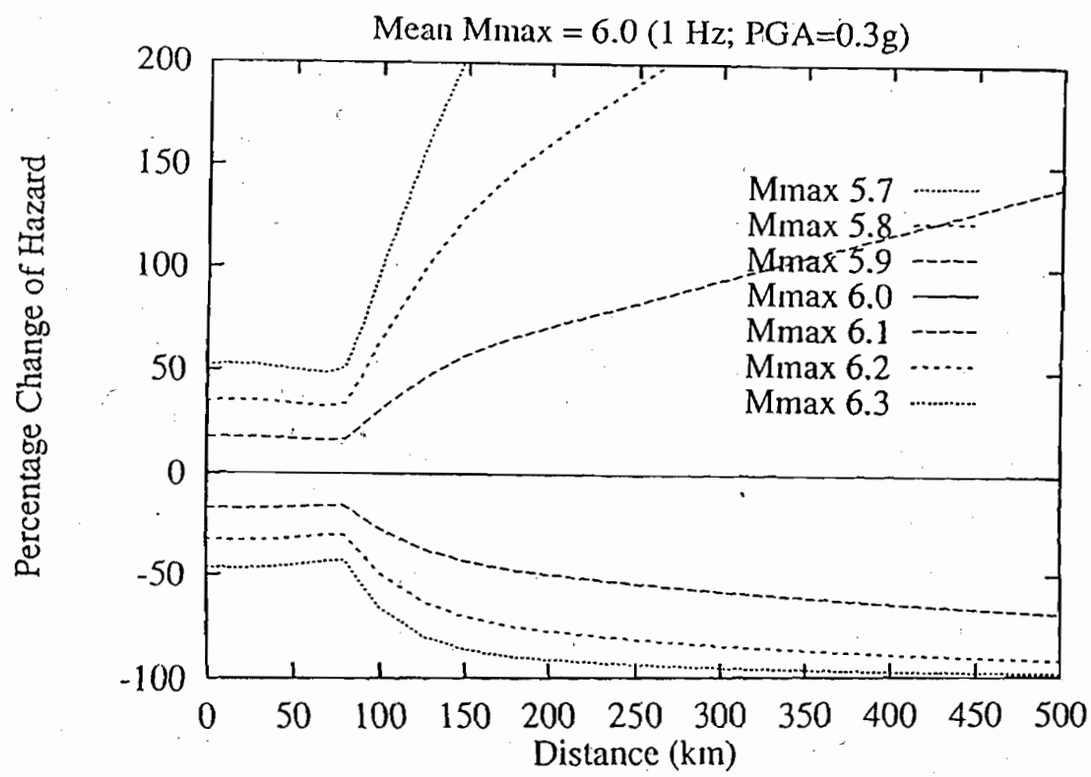
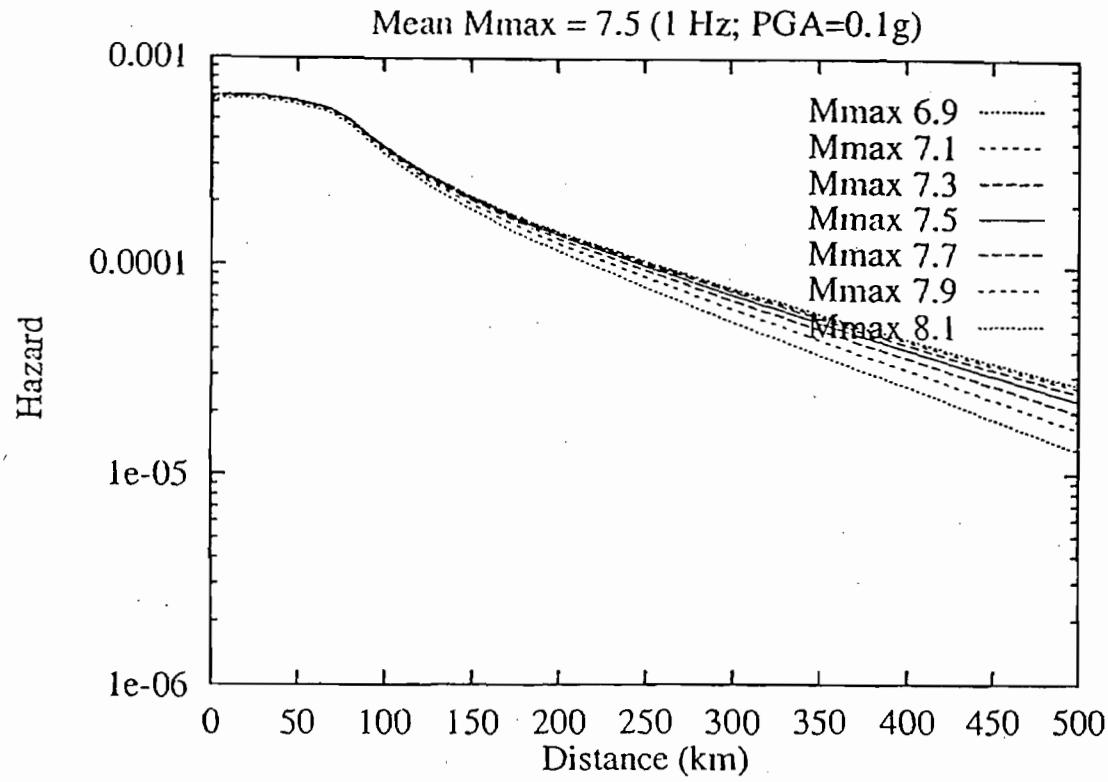


Figure G-24b. Sensitivity of 1 Hz hazard to m_{max} = 6.0, PGA = 0.3g, Group B sites.



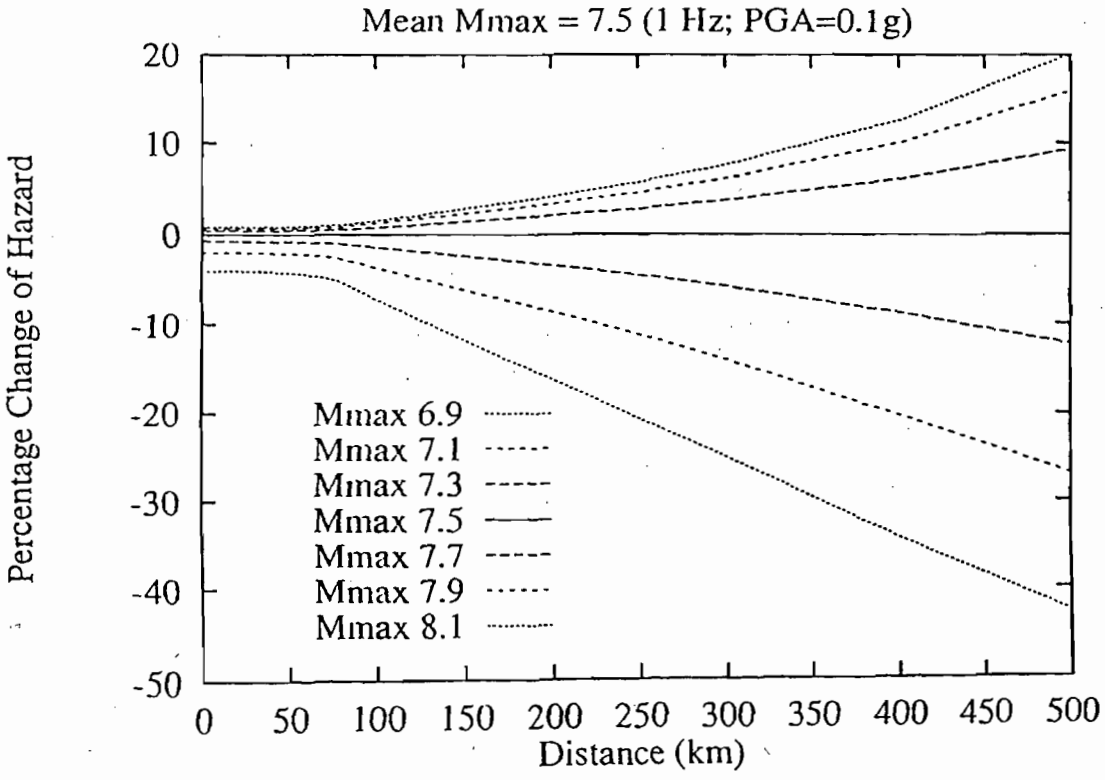
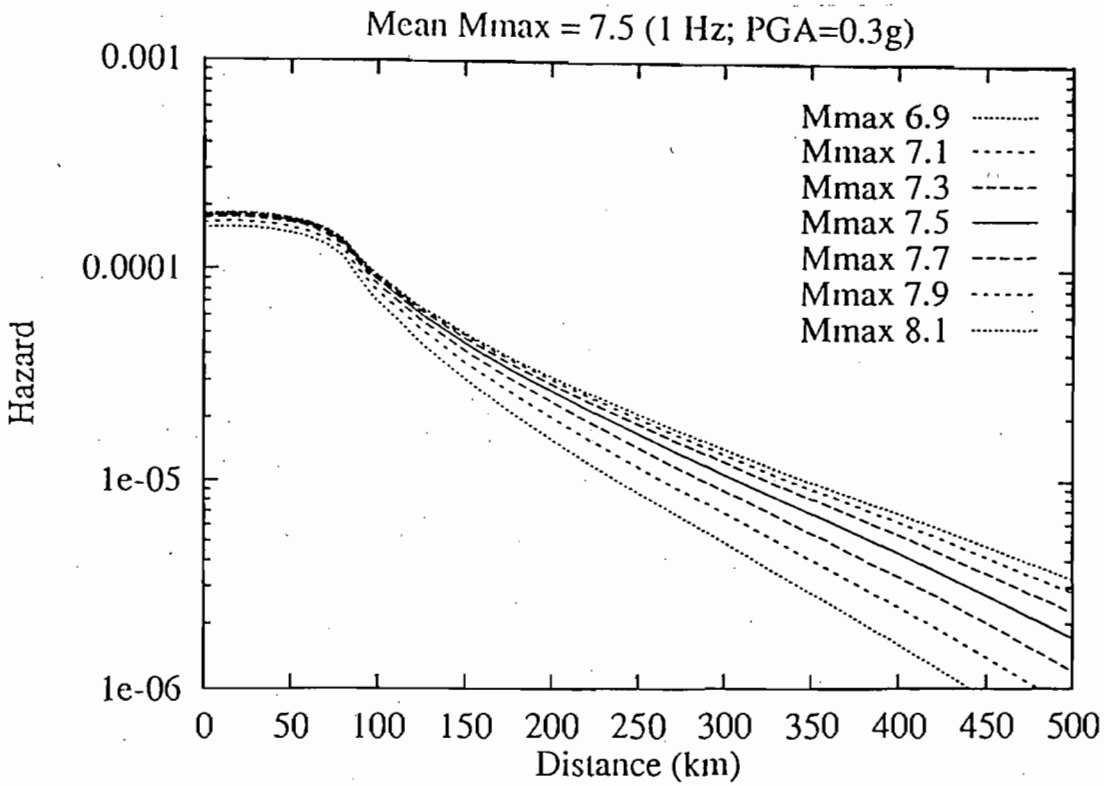


Figure G-25a. Sensitivity of 1 Hz hazard to m_{max} = 7.5, PGA = 0.1g, Group B sites.



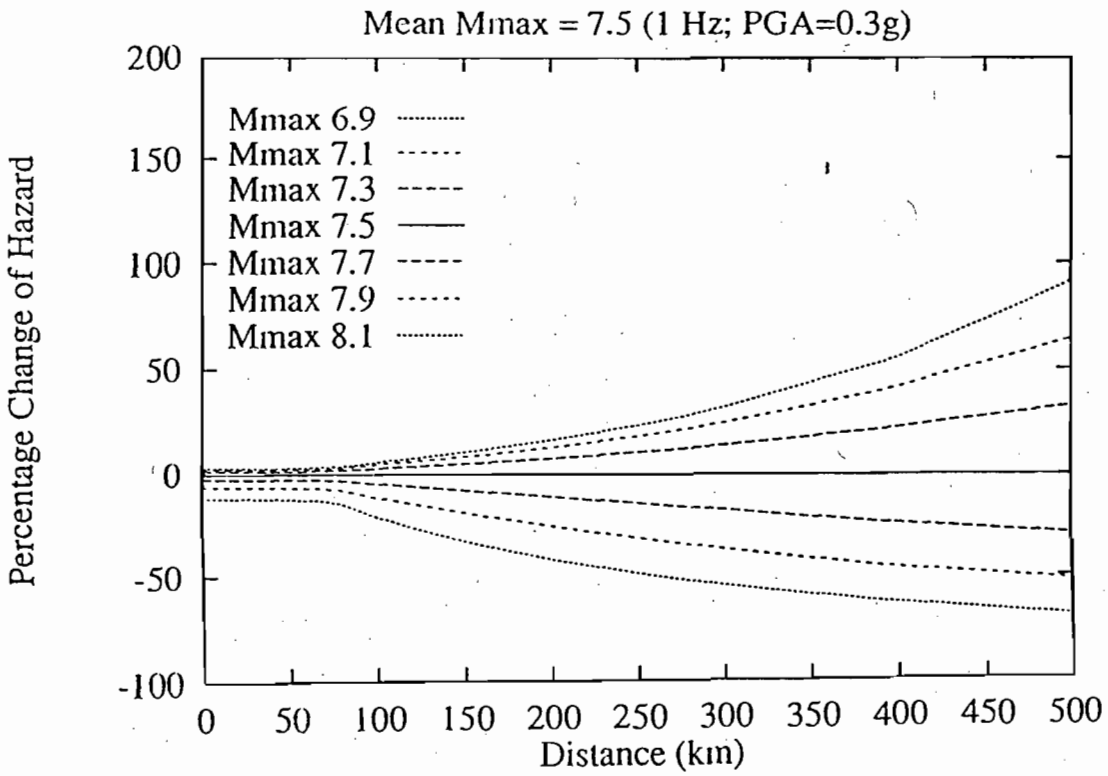
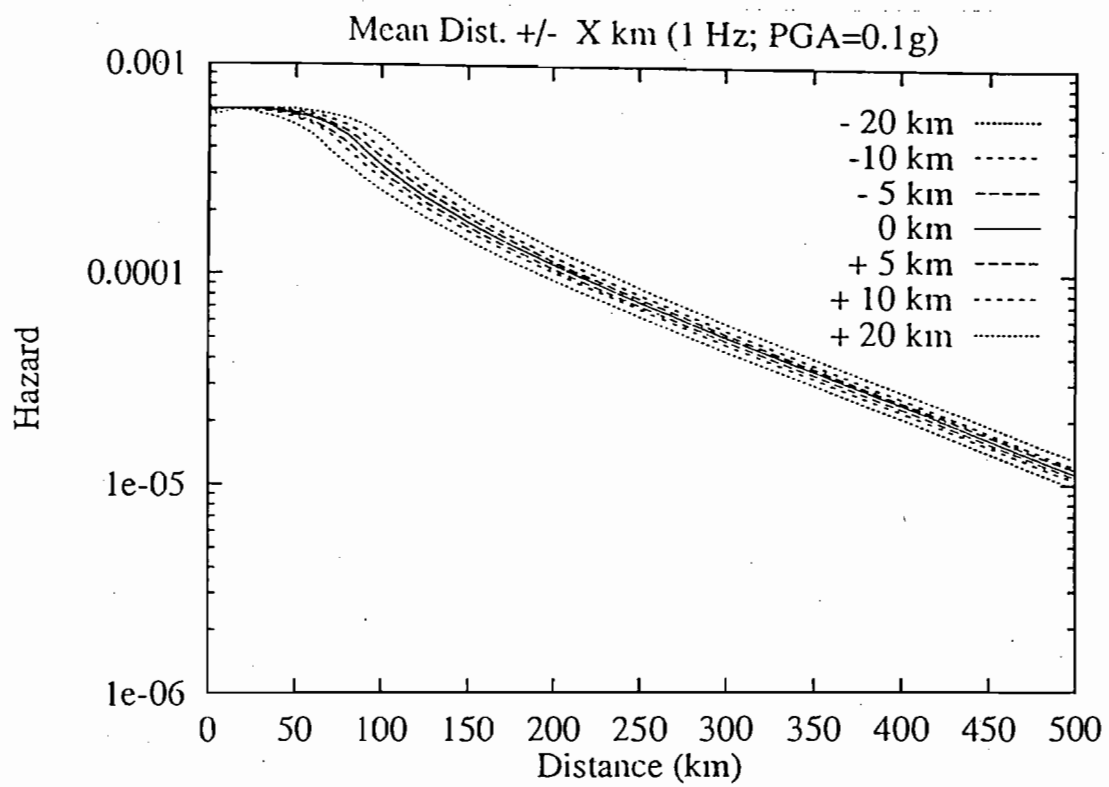


Figure G-25b. Sensitivity of 1 Hz hazard to m_{max} = 7.5, PGA = 0.3g, Group B sites.



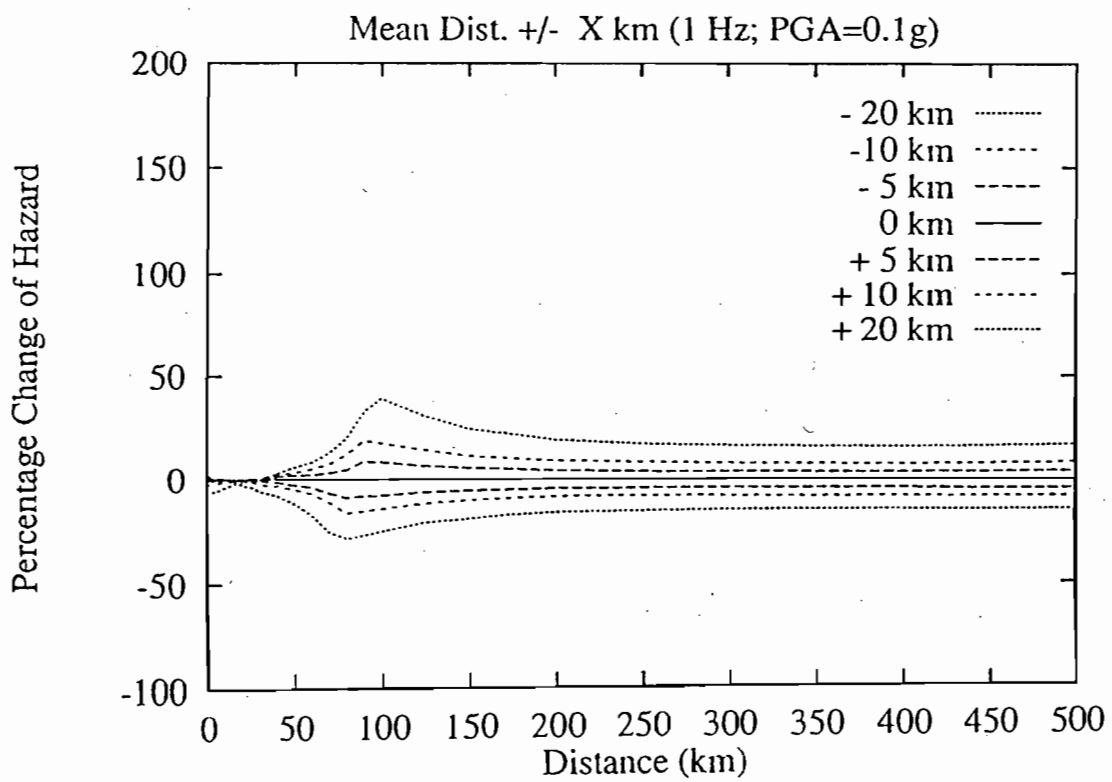
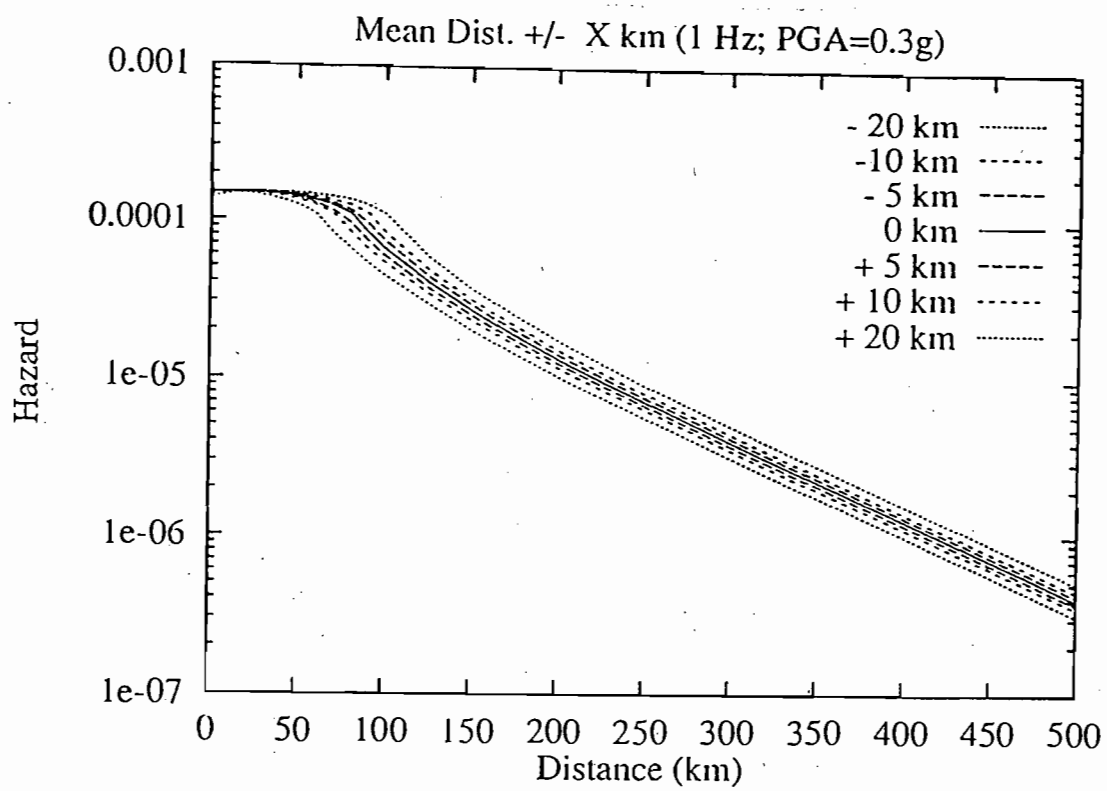


Figure G-26a. Sensitivity of 1 Hz hazard to distance from fault, PGA = 0.1g, Group B sites.



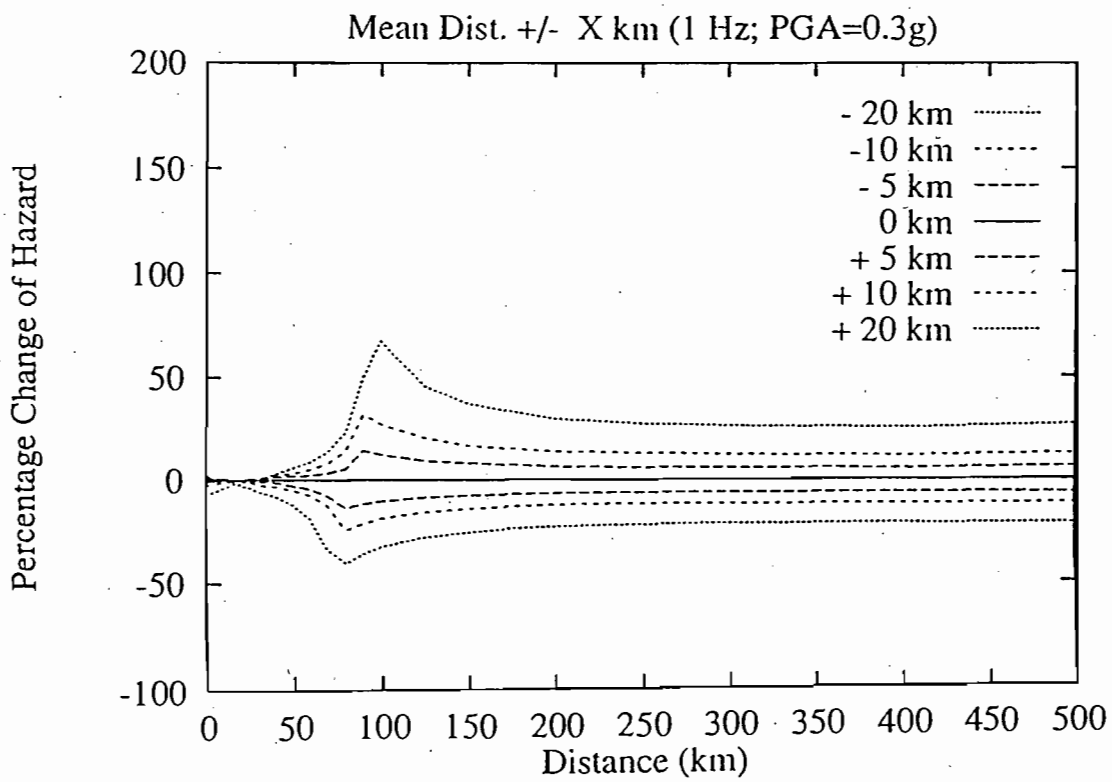


Figure G-26b. Sensitivity of 1 Hz hazard to distance from fault, PGA = 0.3g, Group B sites.

Line Source (WUS)

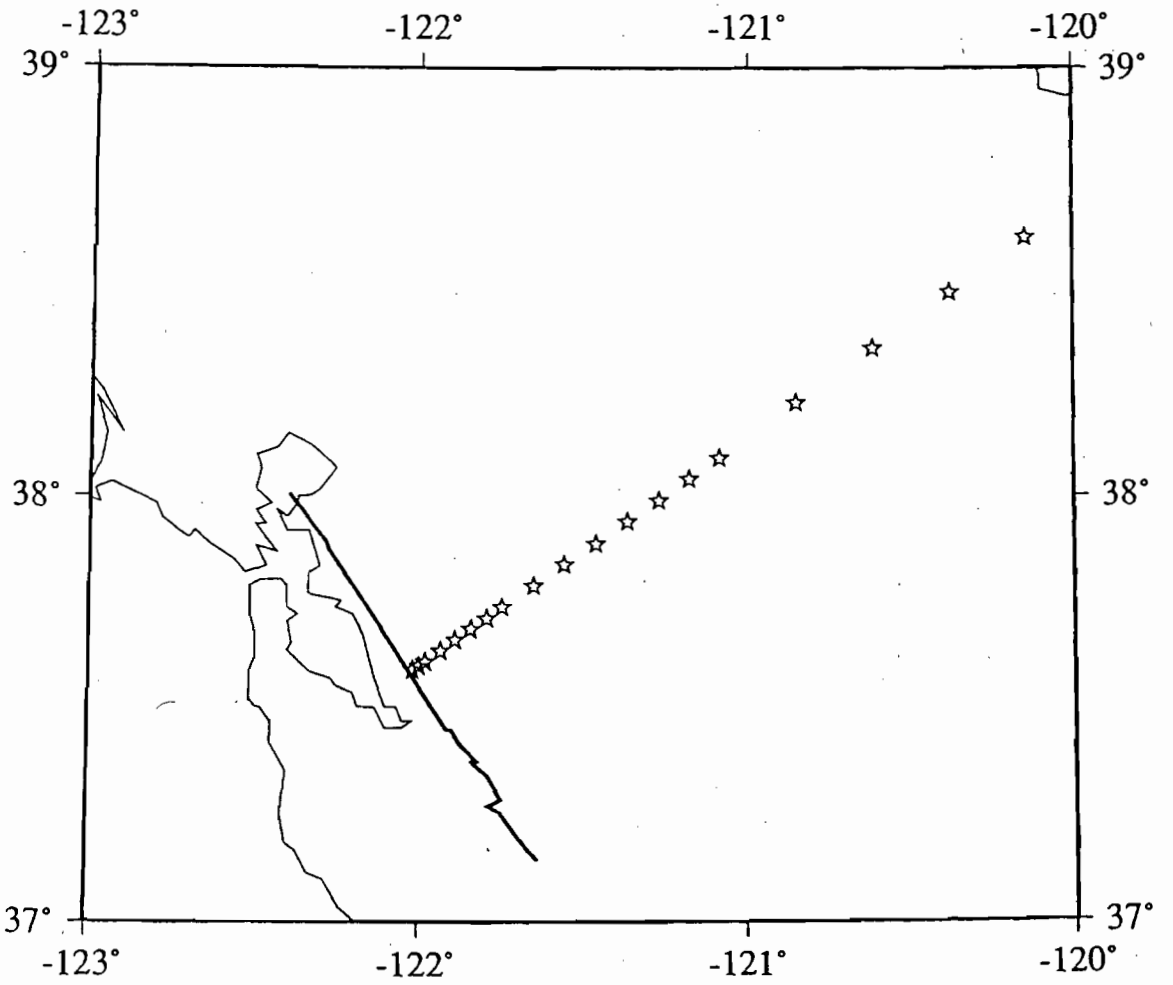
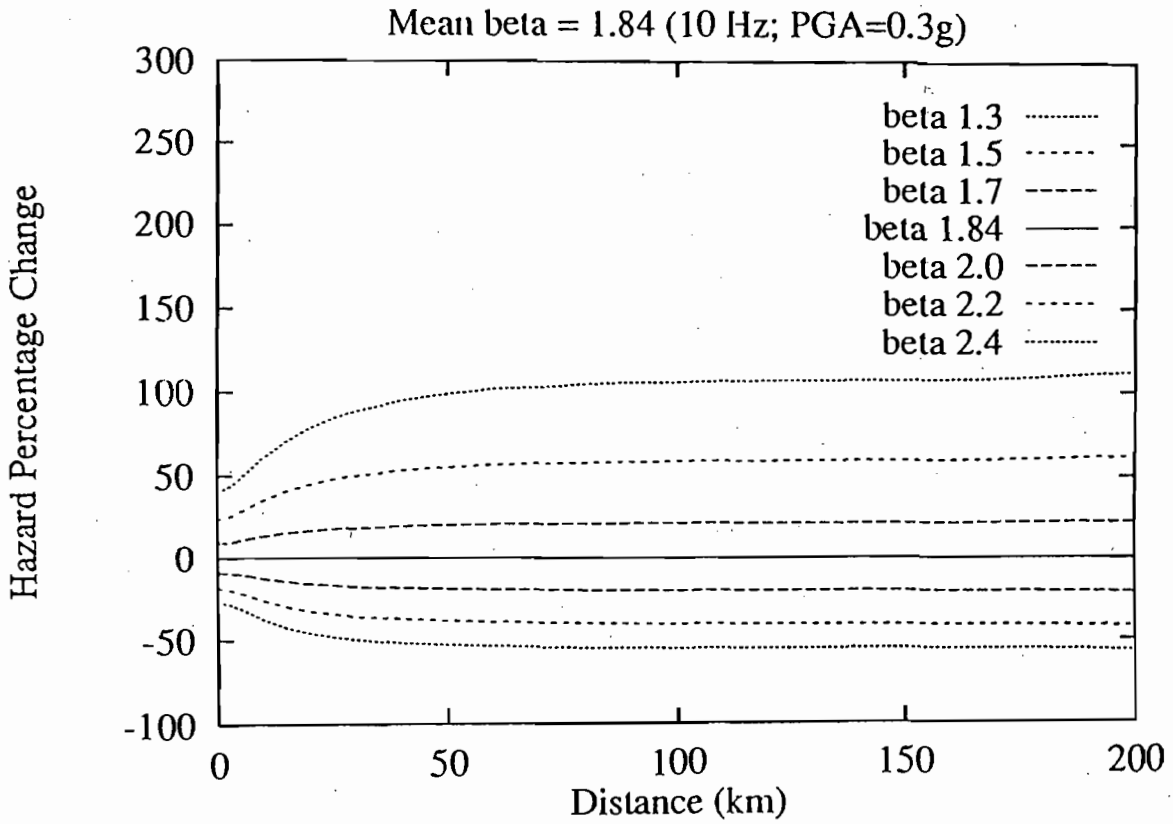


Figure G-27: Location of Group C sites with respect to Hayward fault.



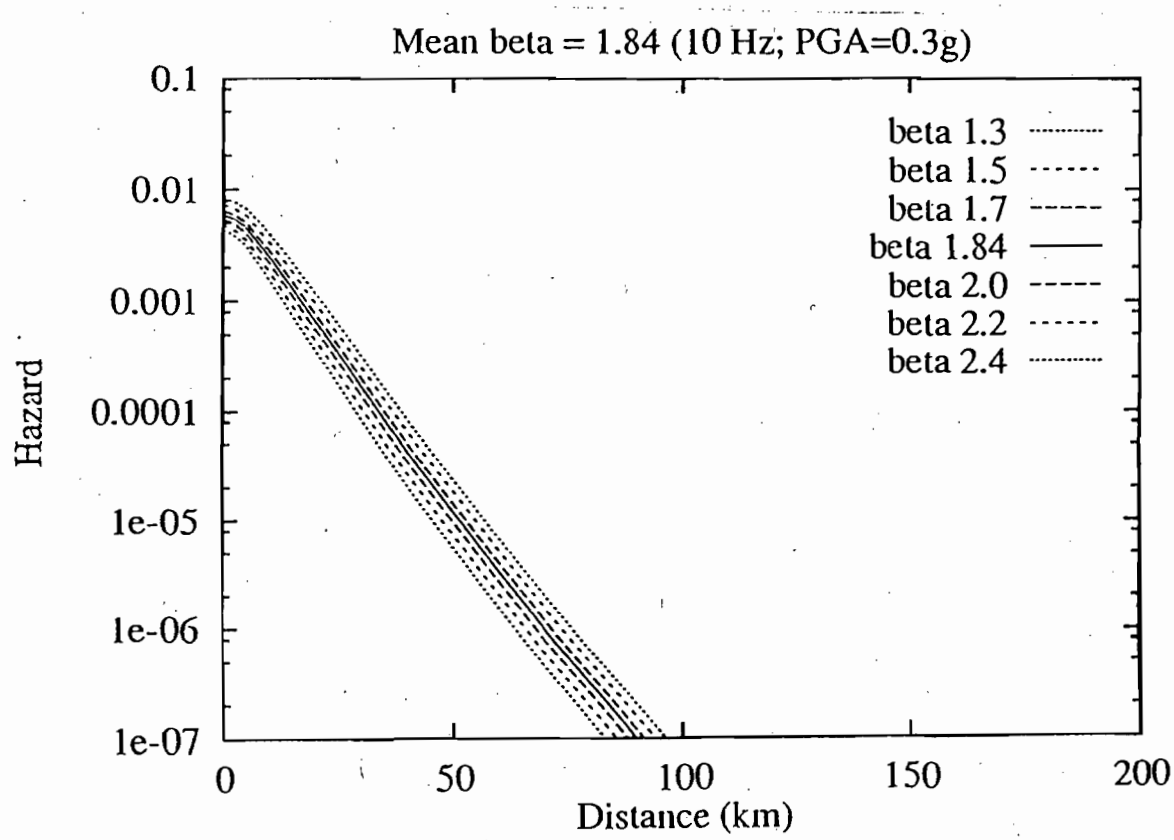
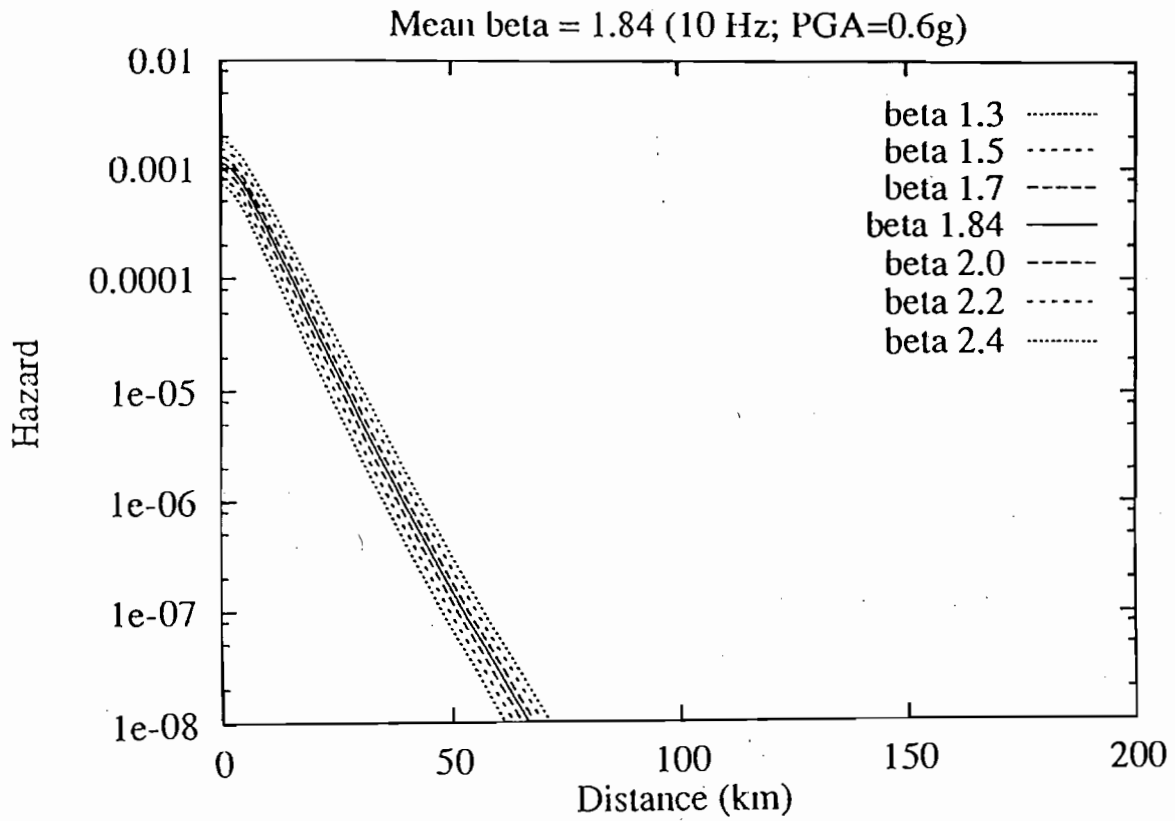


Figure G-28a. Sensitivity of 10 Hz hazard to beta for PGA = 0.3g, Group C sites.



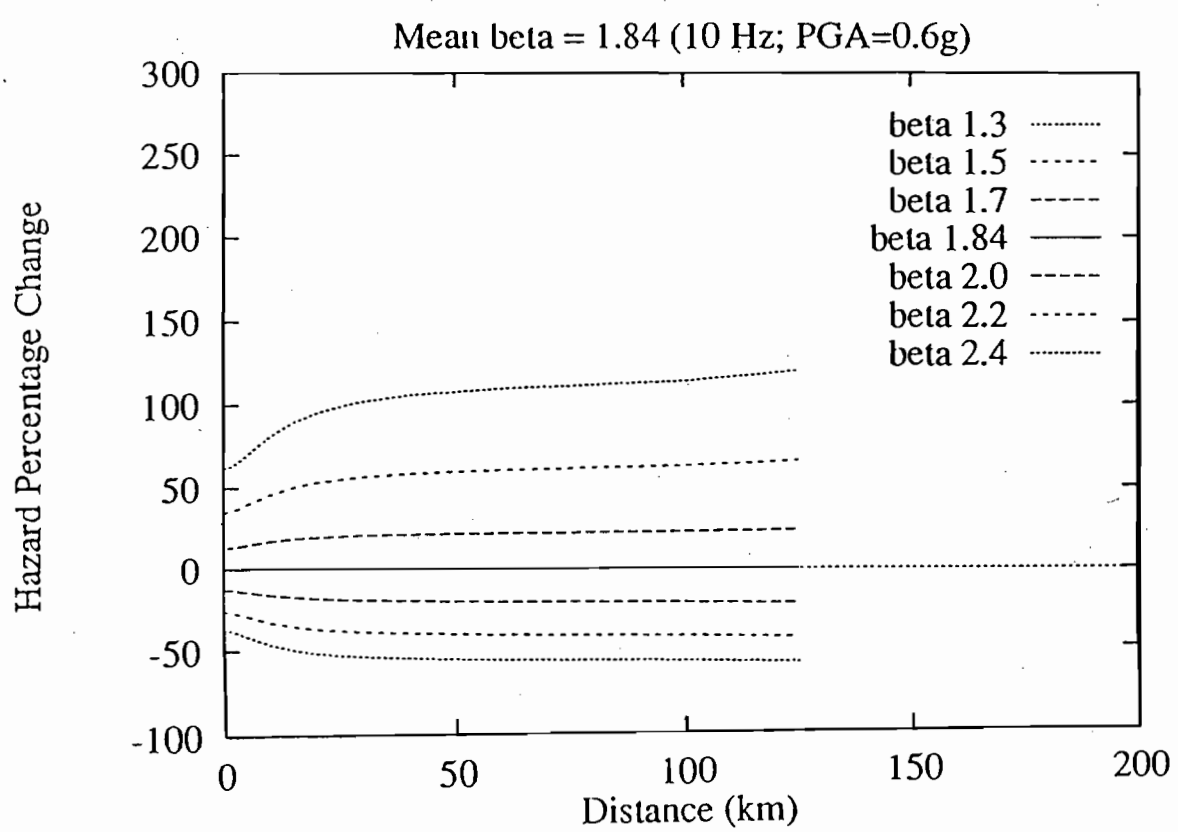
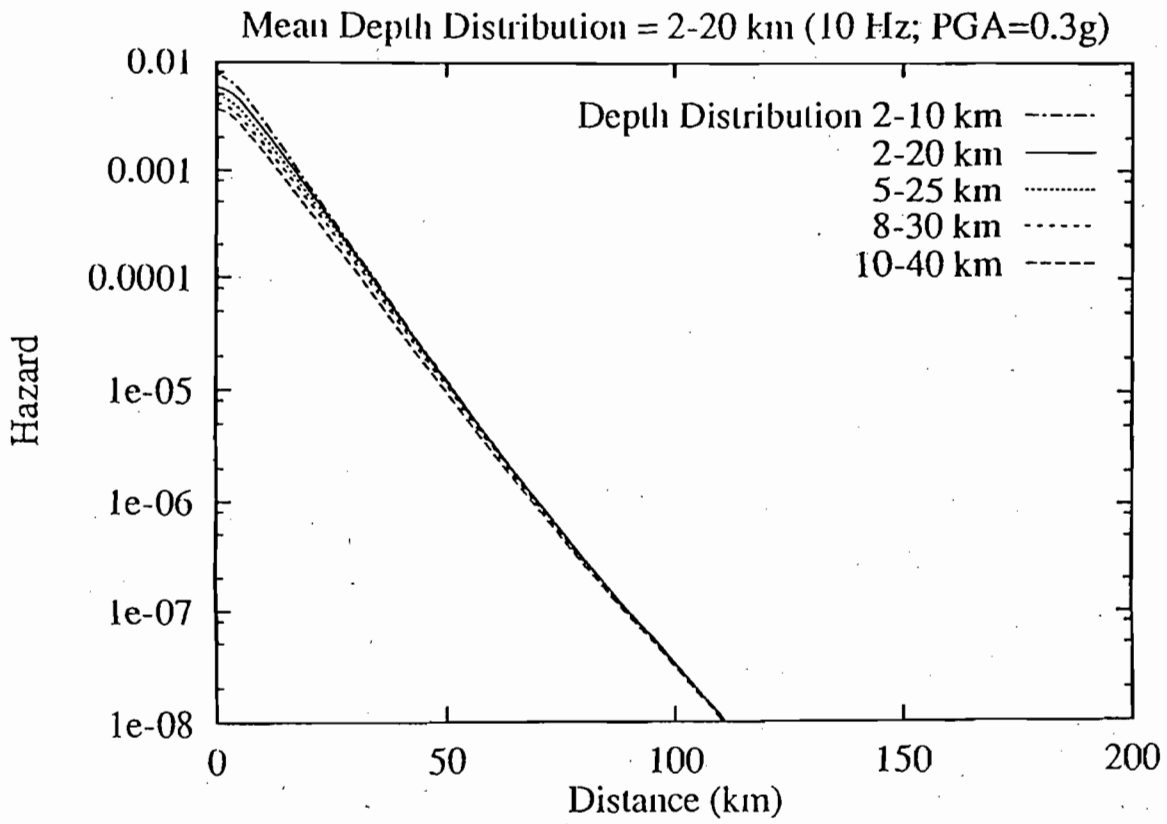


Figure G-28b. Sensitivity of 10 Hz hazard to beta for PGA = 0.6g, Group C sites.



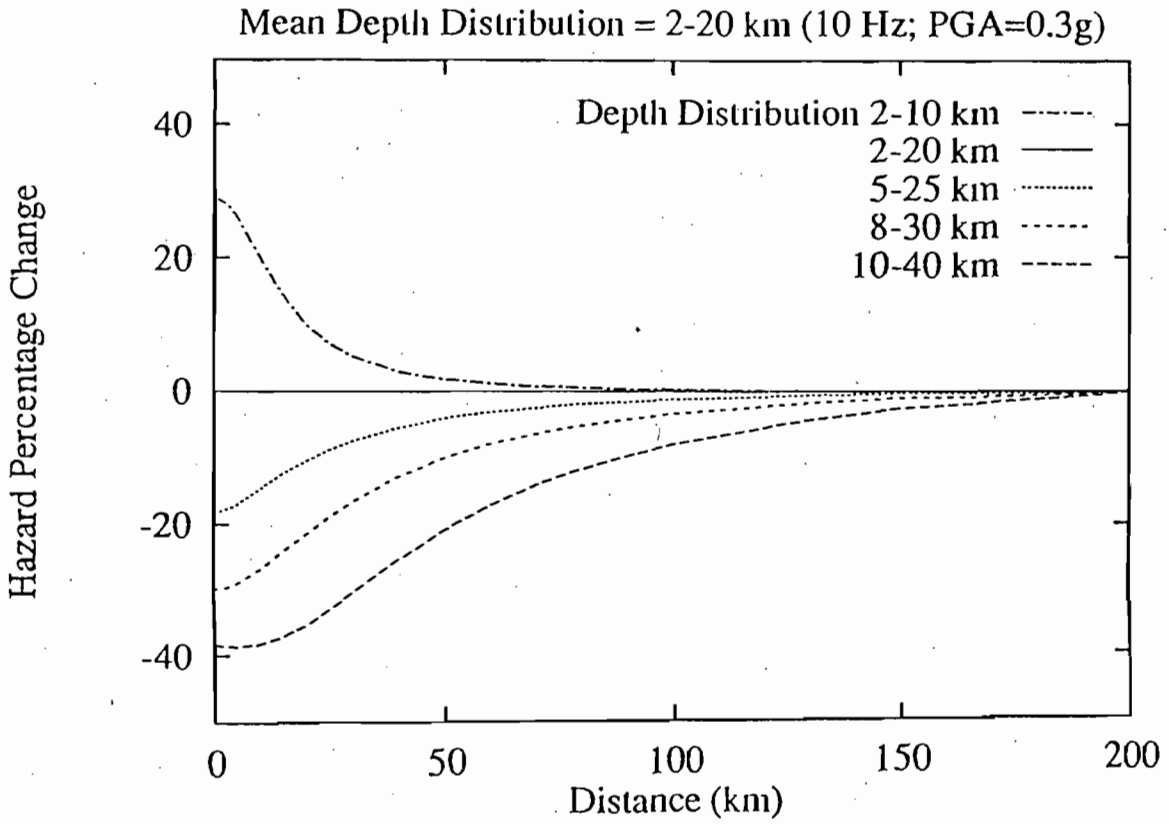
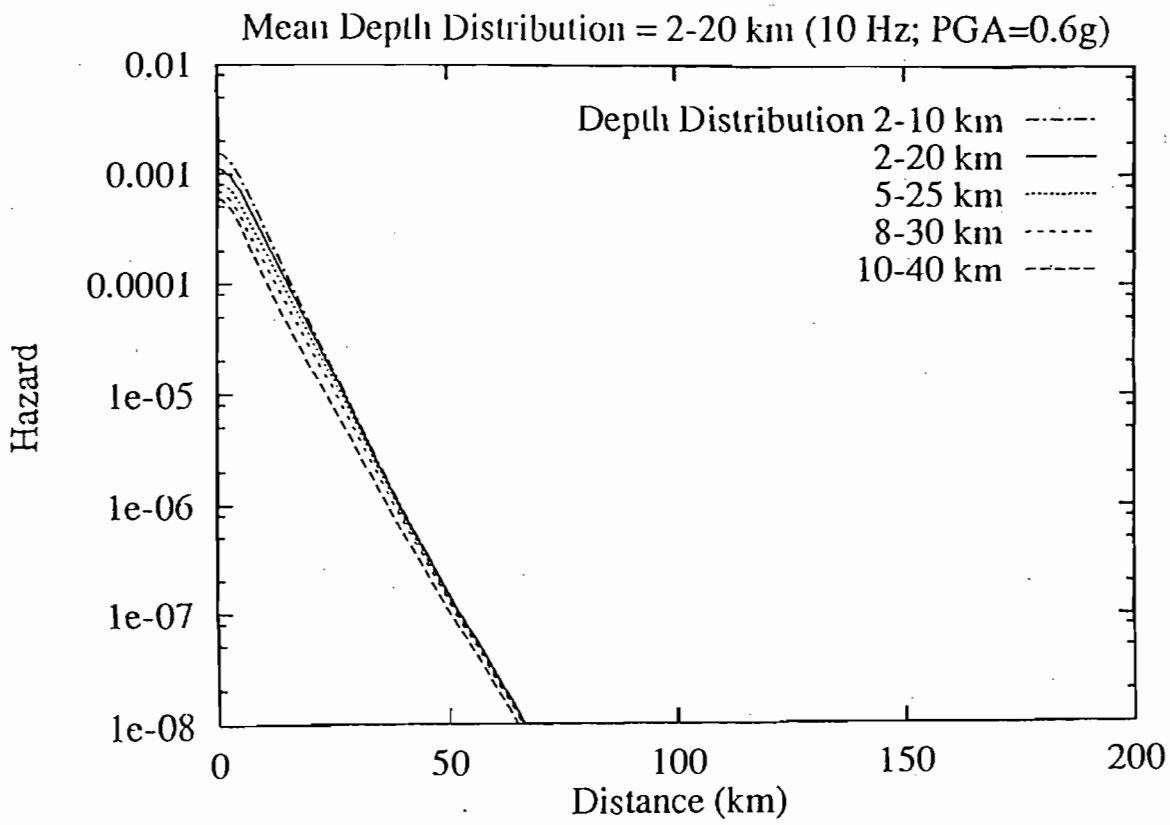


Figure G-29a. Sensitivity of 10 Hz hazard to depth distribution for PGA = 0.3g, Group C sites.



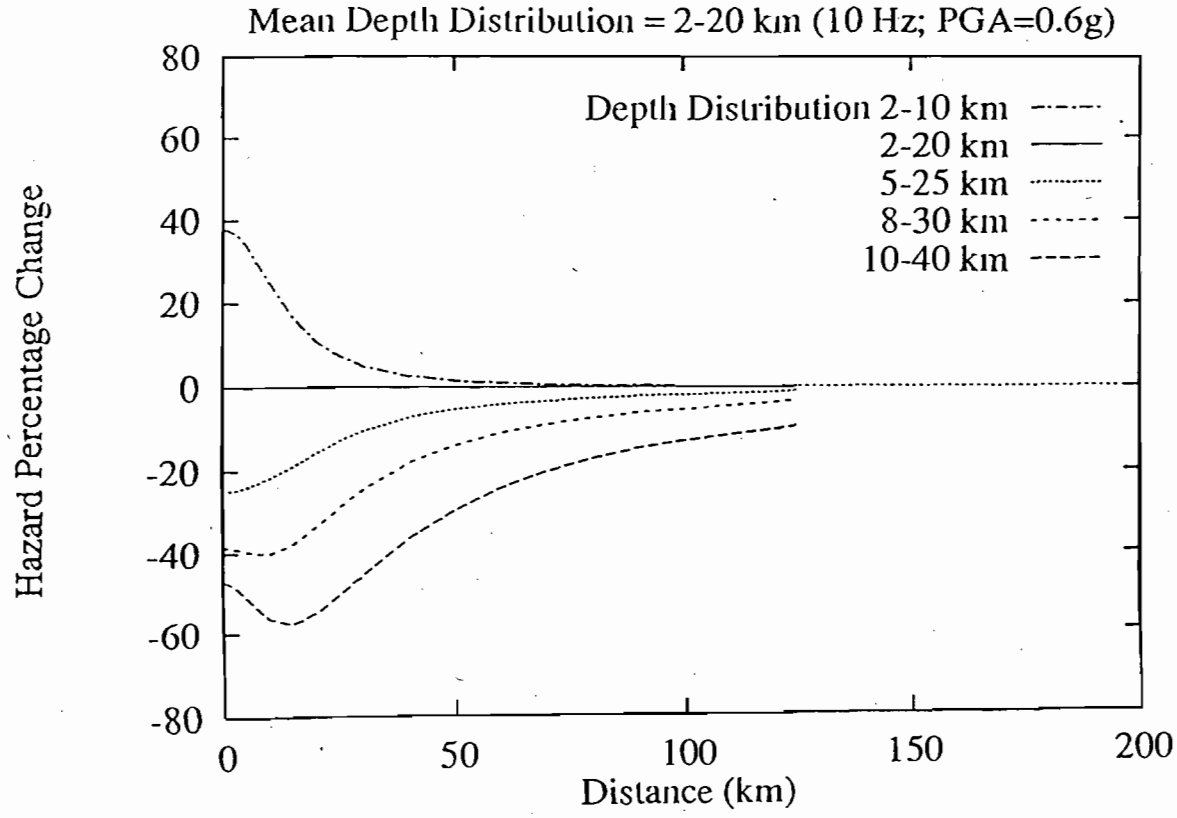
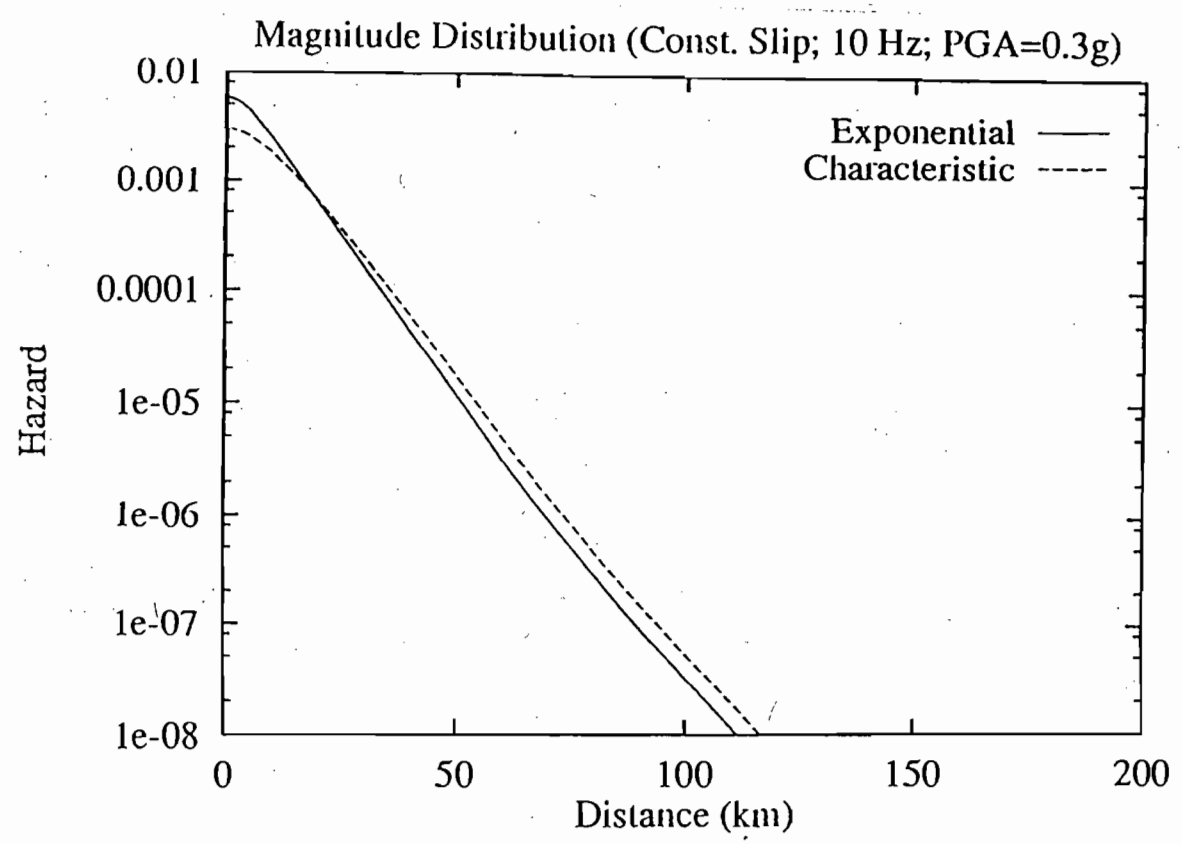


Figure G-29b. Sensitivity of 10 Hz hazard to depth distribution for PGA = 0.6g, Group C sites.



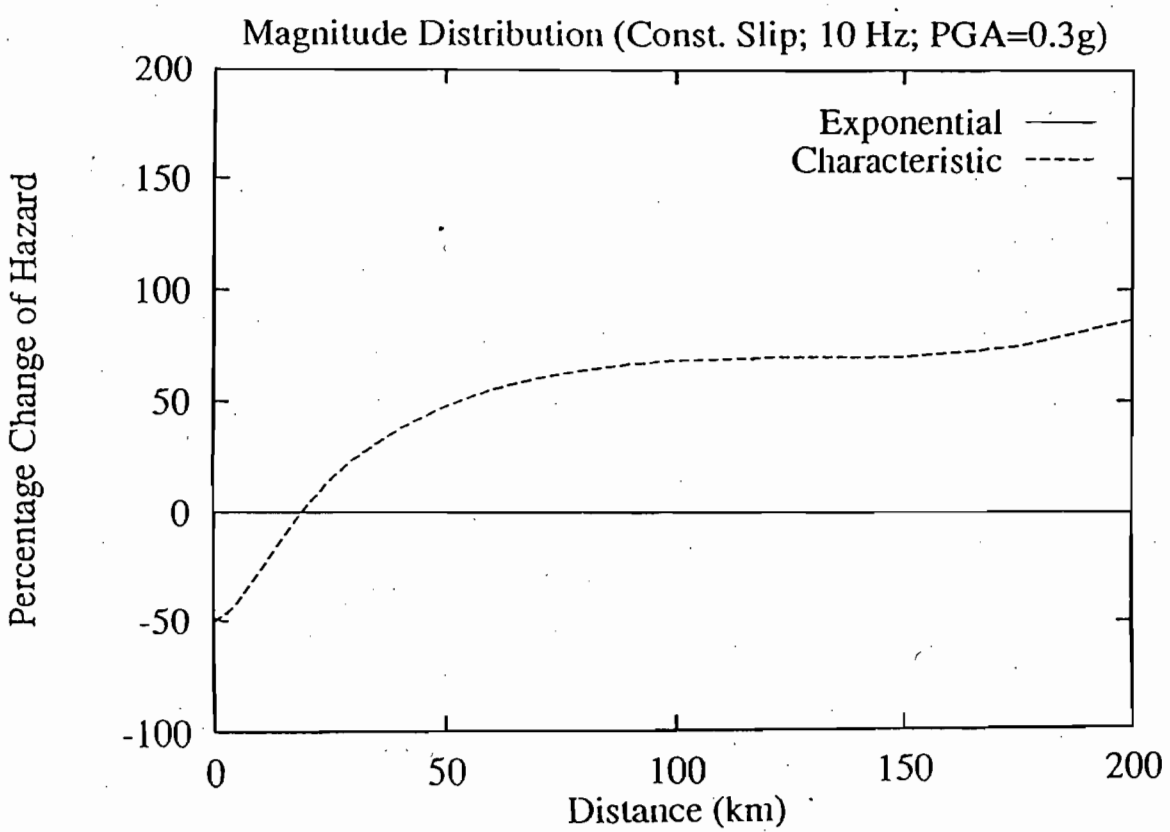
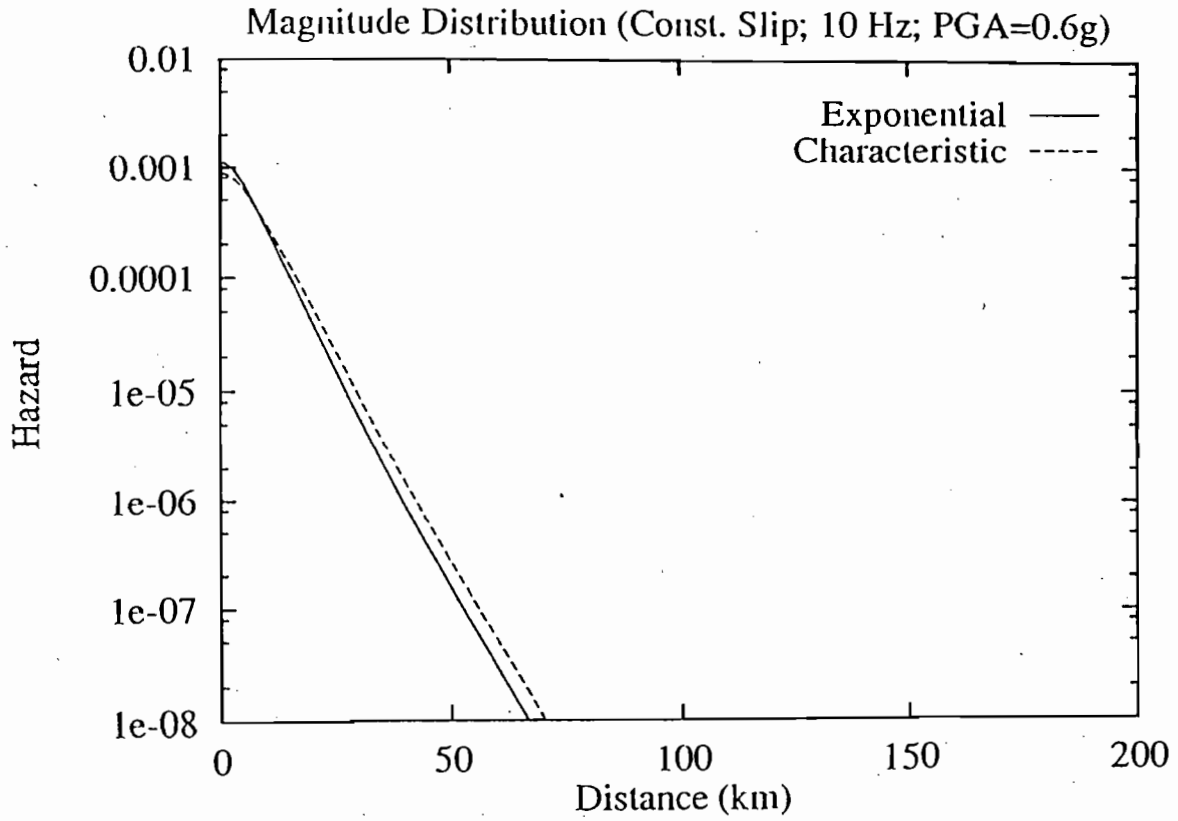


Figure G-30a. Sensitivity of 10 Hz hazard to magnitude distribution (with constant slip assumption), PGA = 0.3g, Group C sites.



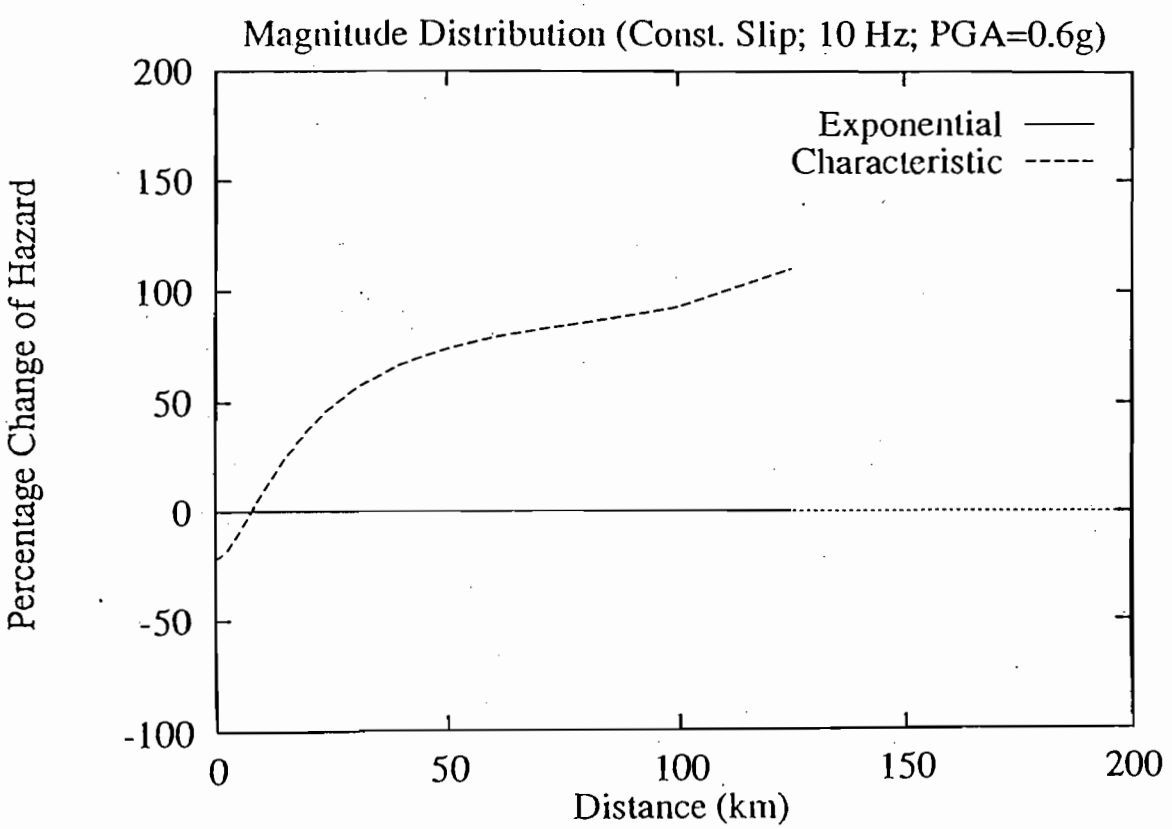
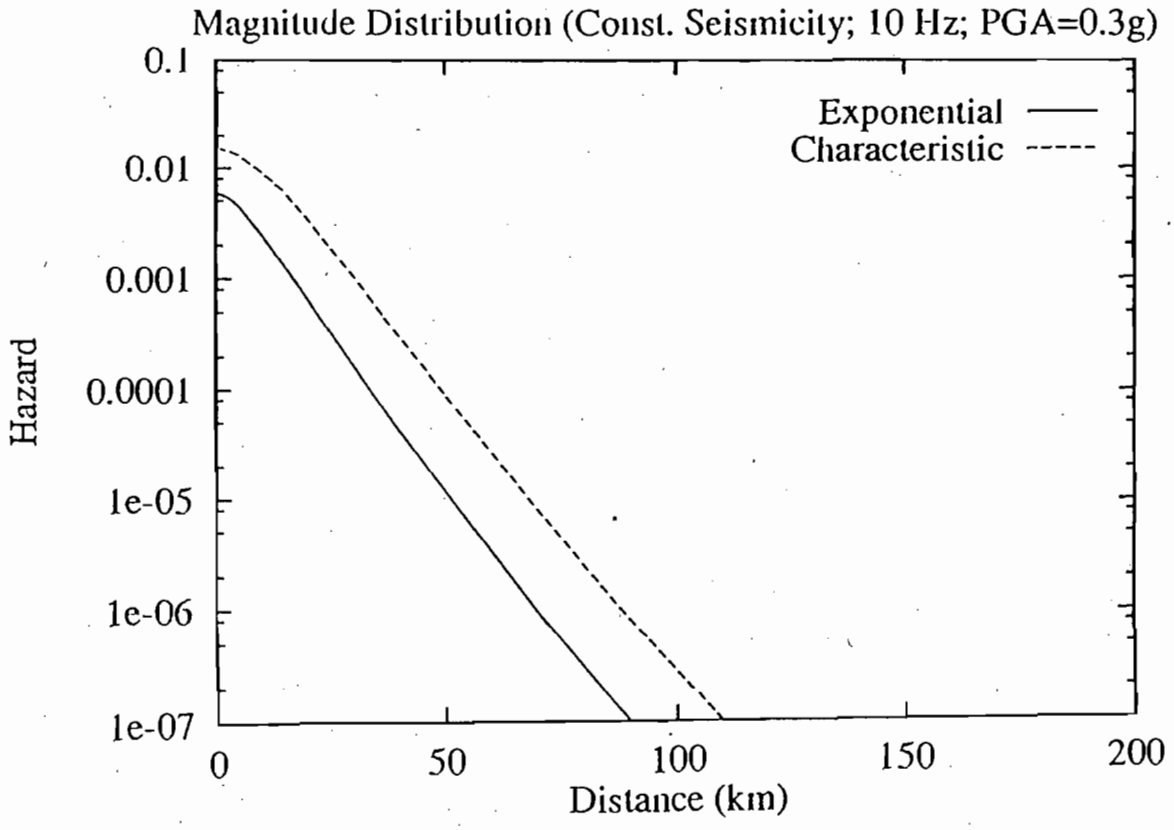


Figure G-30b. Sensitivity of 10 Hz hazard to magnitude distribution (with constant slip assumption), PGA = 0.6g, Group C sites.



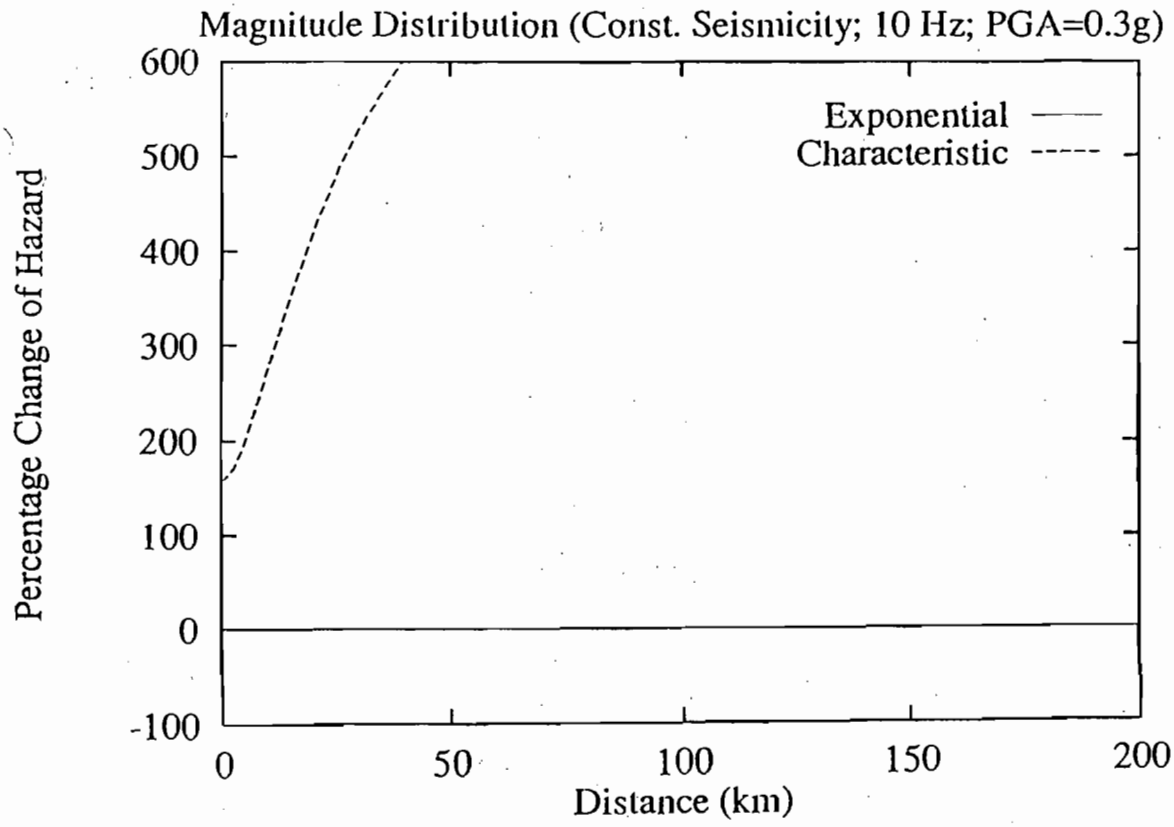
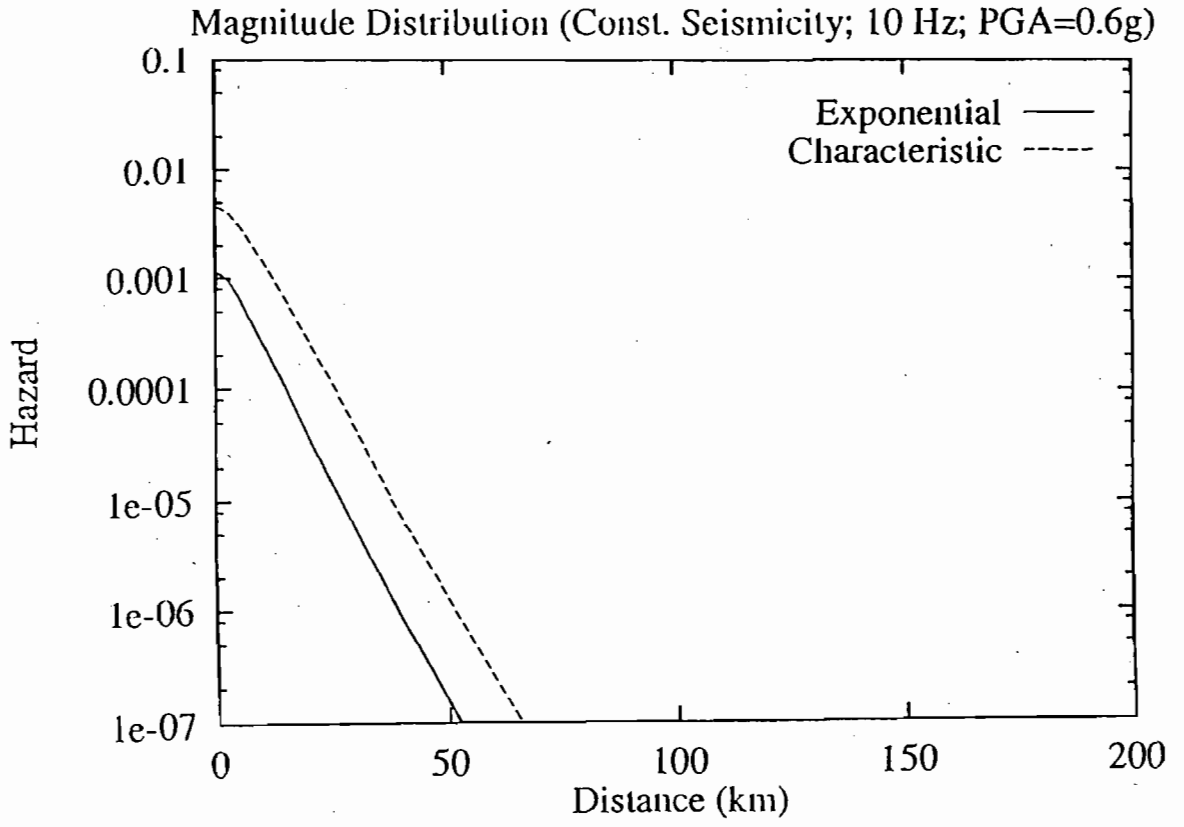


Figure G-31a. Sensitivity of 10 Hz hazard to magnitude distribution (with constant seismicity assumption), PGA = 0.3g, Group C sites.



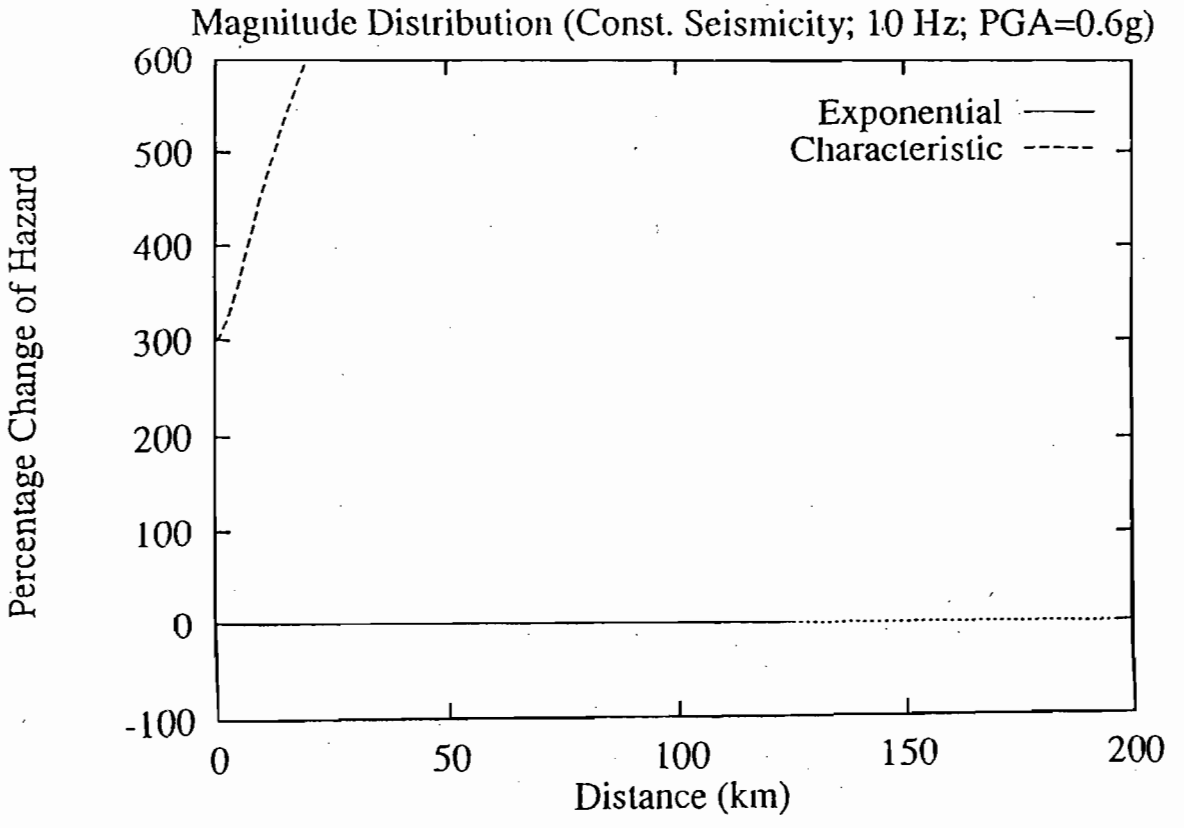
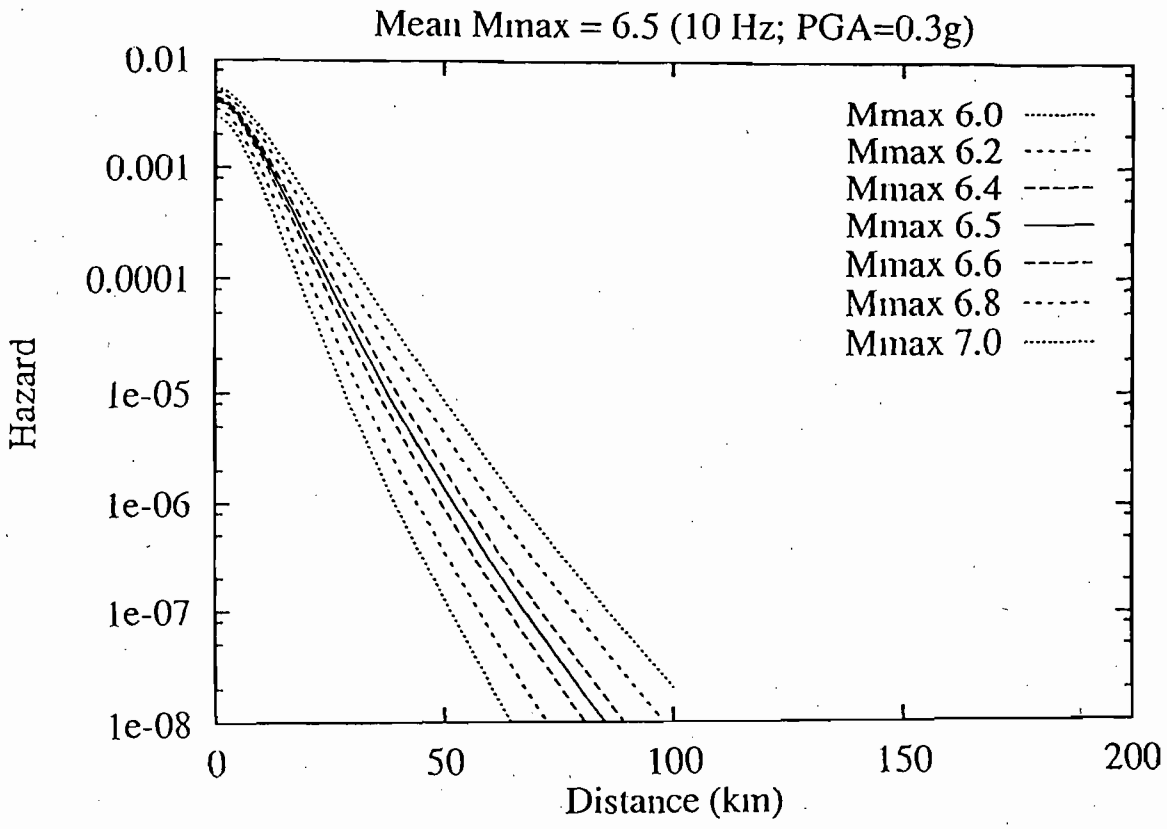


Figure G-31b. Sensitivity of 10 Hz hazard to magnitude distribution, (with constant seismicity assumption), PGA = 0.6g, Group C sites.



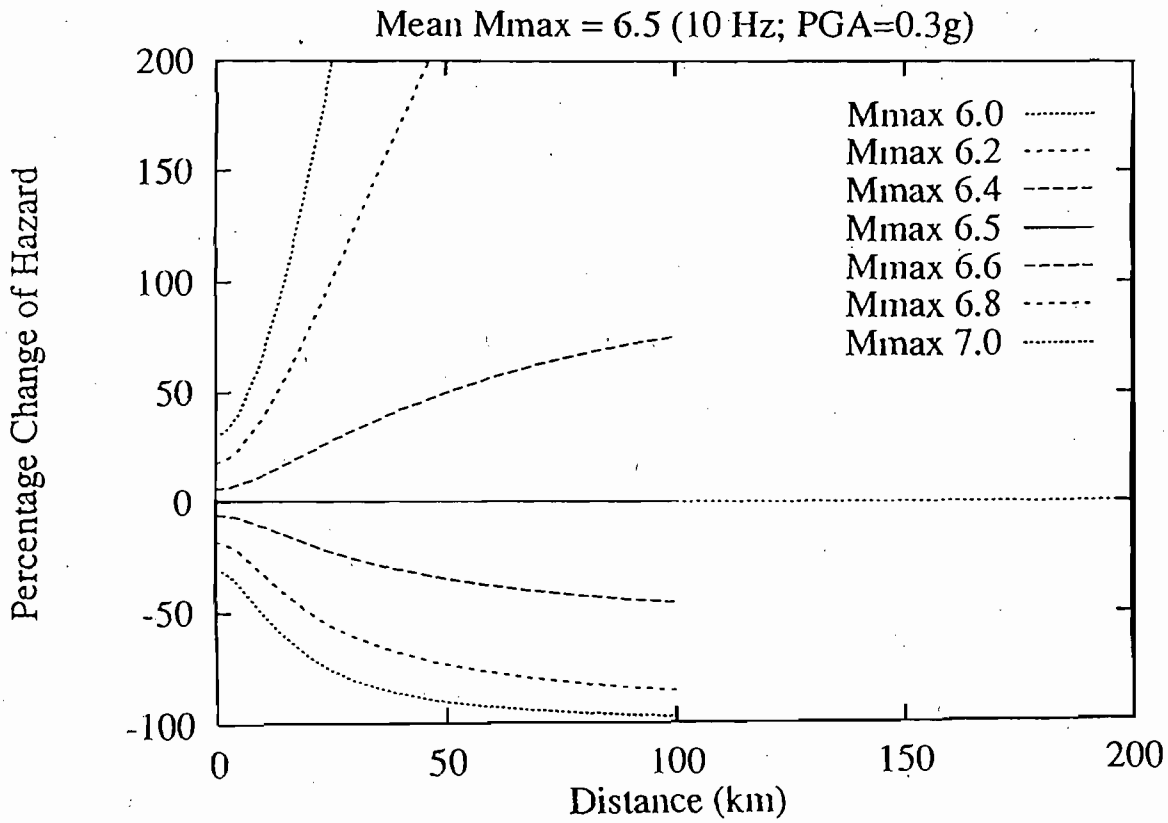
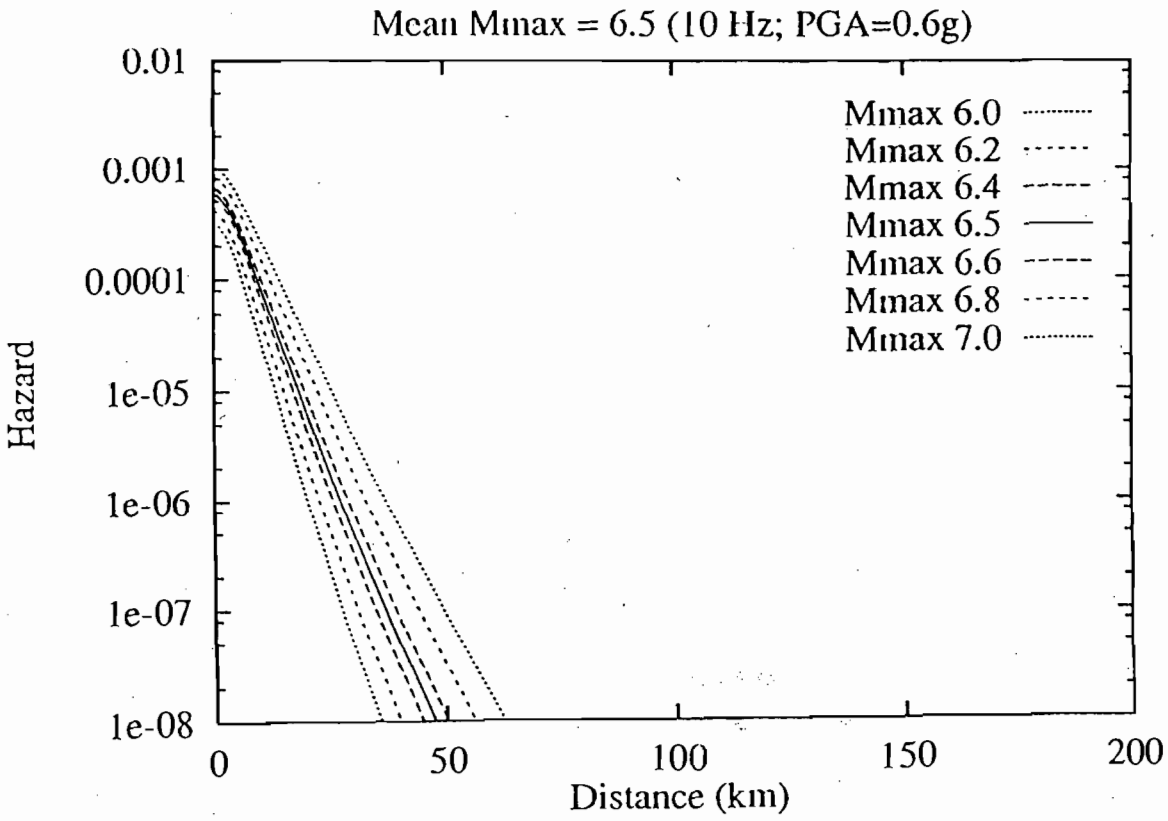


Figure G-32a. Sensitivity of 10 Hz hazard to m_{max} = 6.0, PGA = 0.3g, Group C sites.



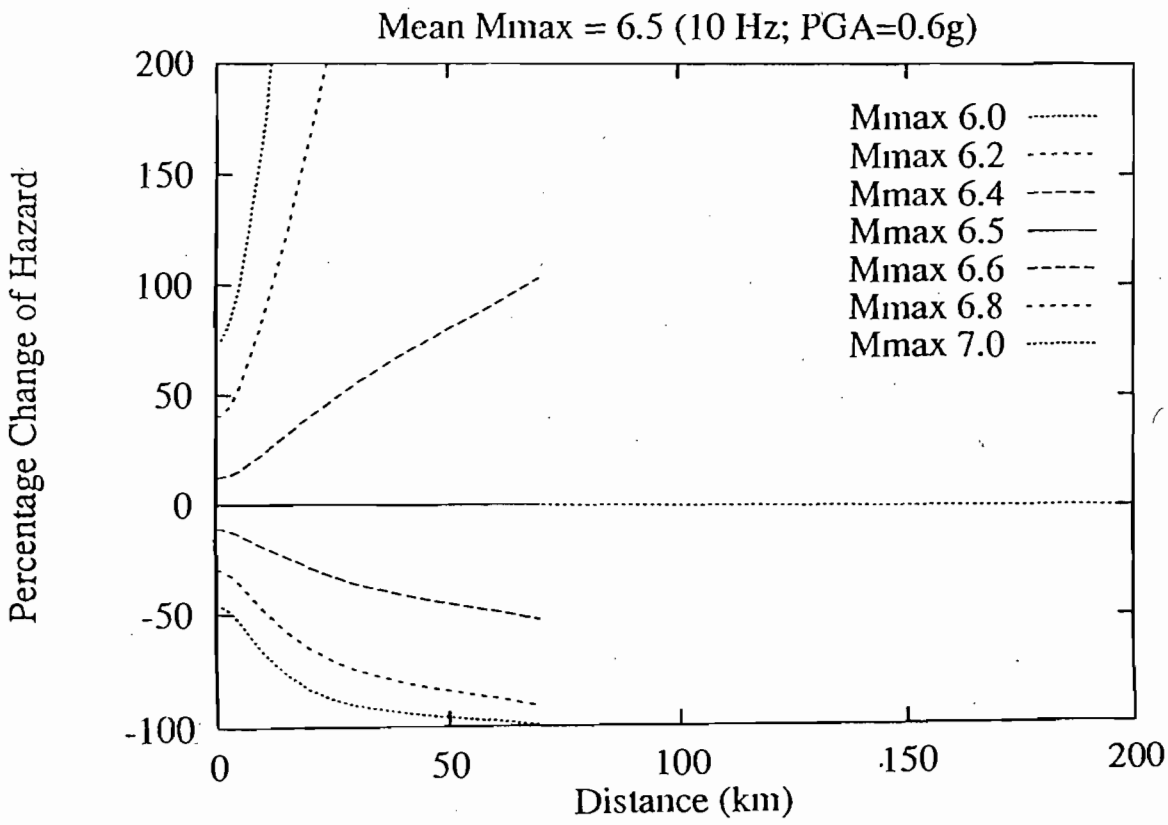
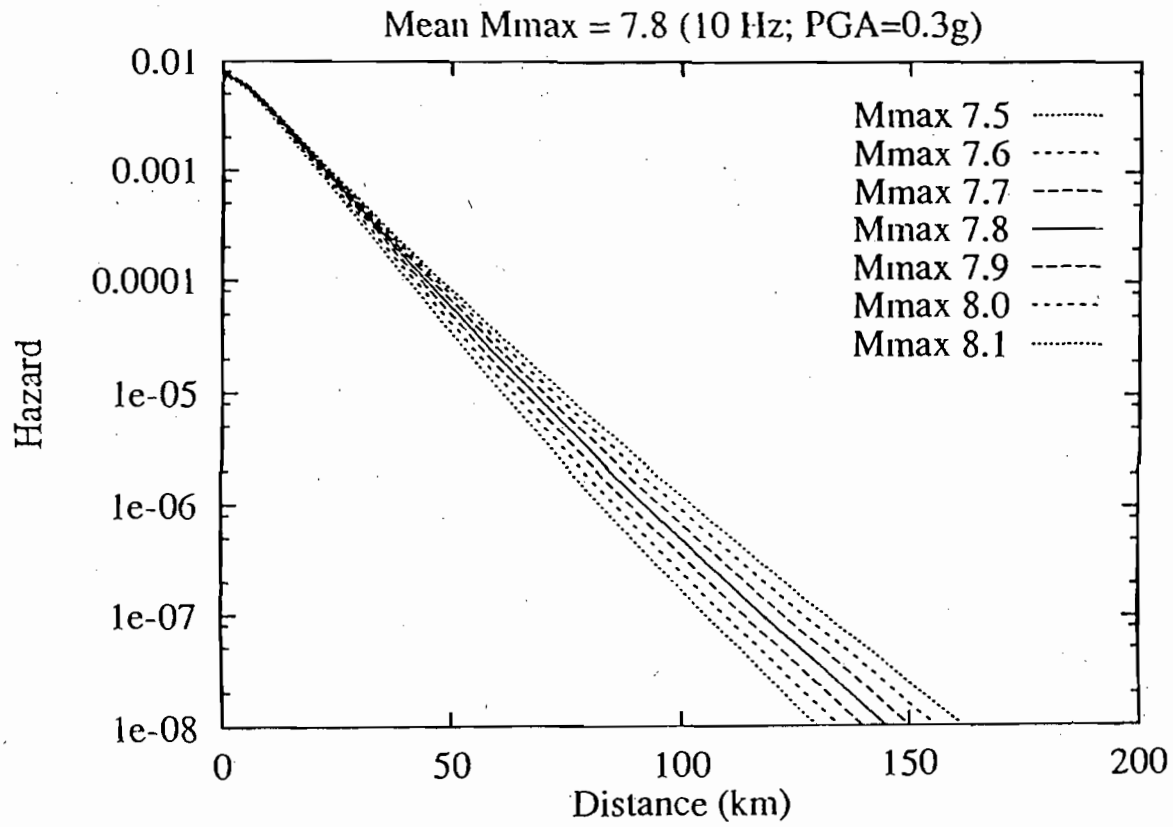


Figure G-32b. Sensitivity of 10 Hz hazard to m_{max} = 6.0, PGA = 0.6g, Group C sites.



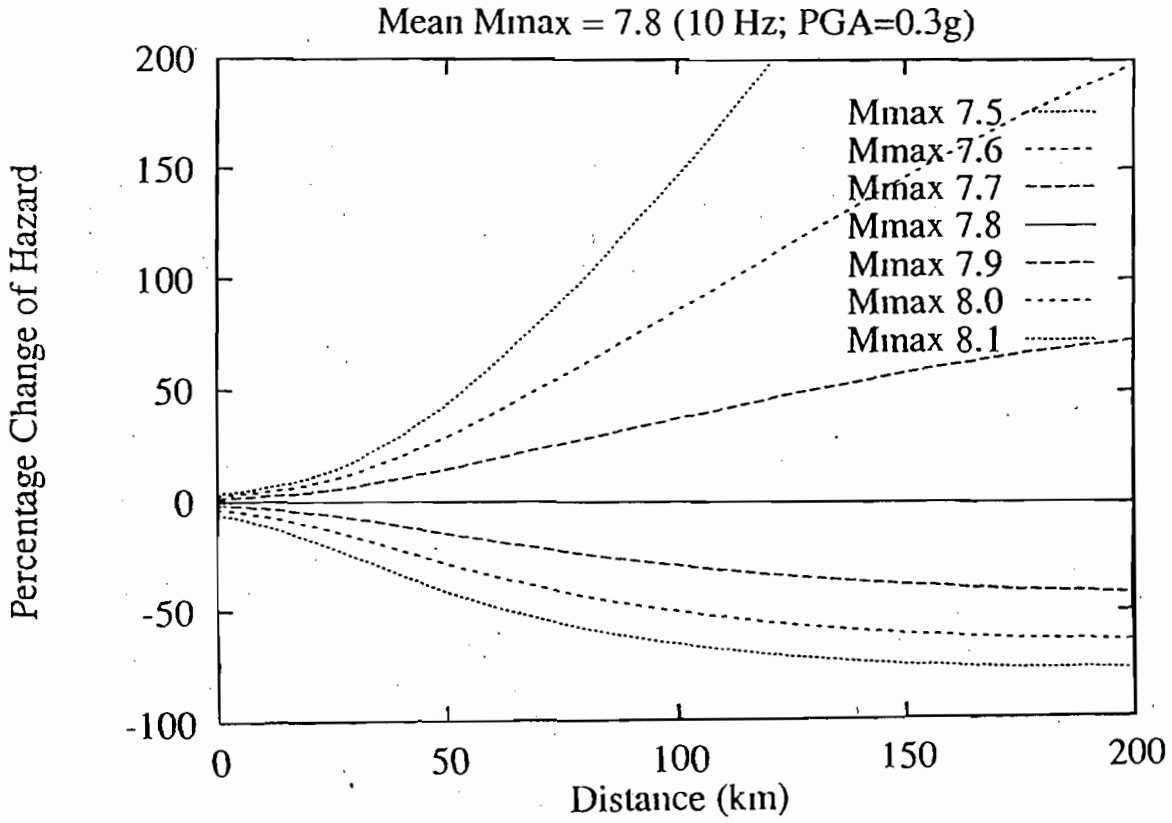
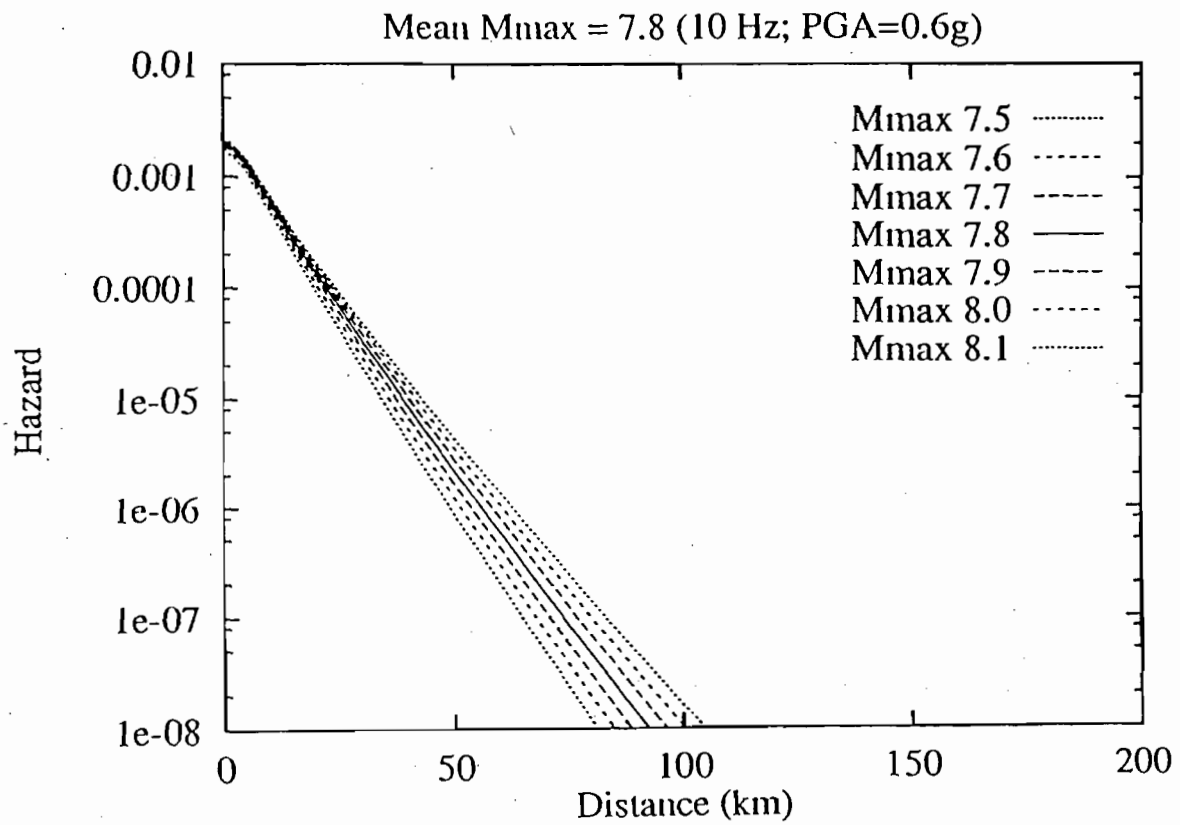


Figure G-33a. Sensitivity of 10 Hz hazard to m_{max} = 7.5, PGA = 0.3g, Group C sites.



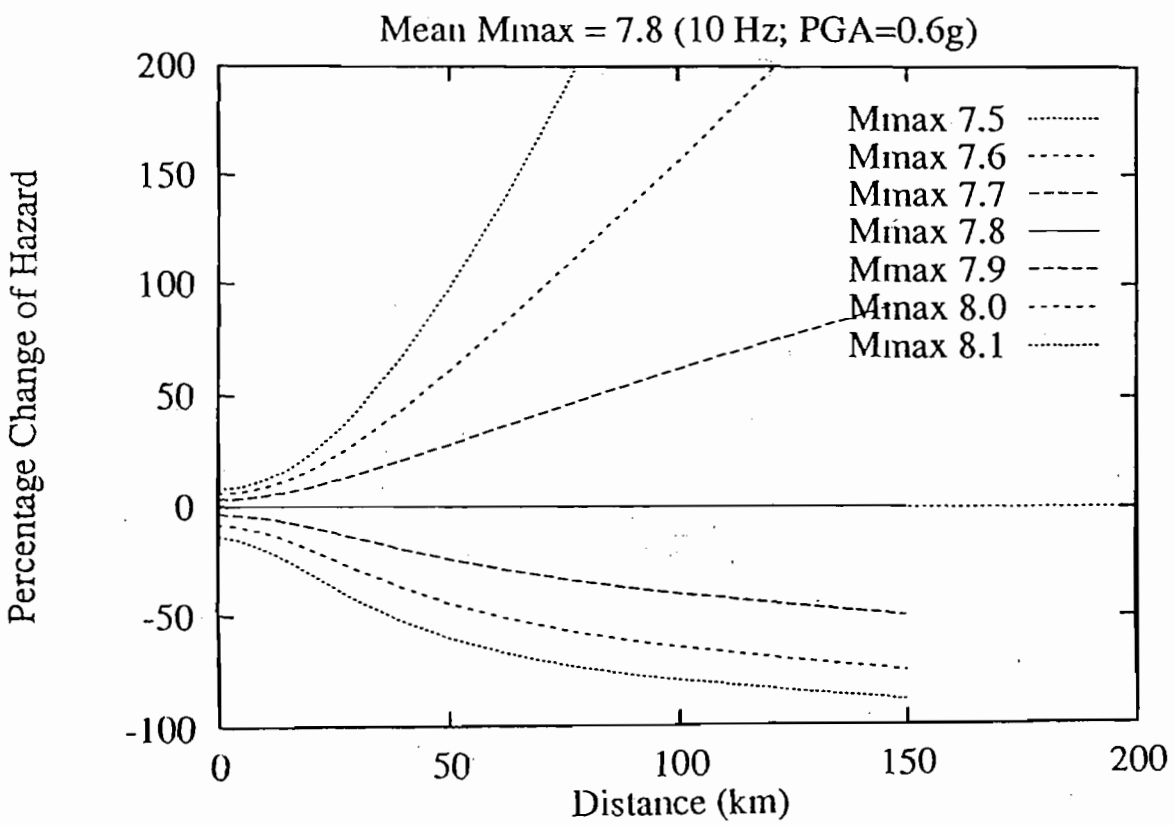
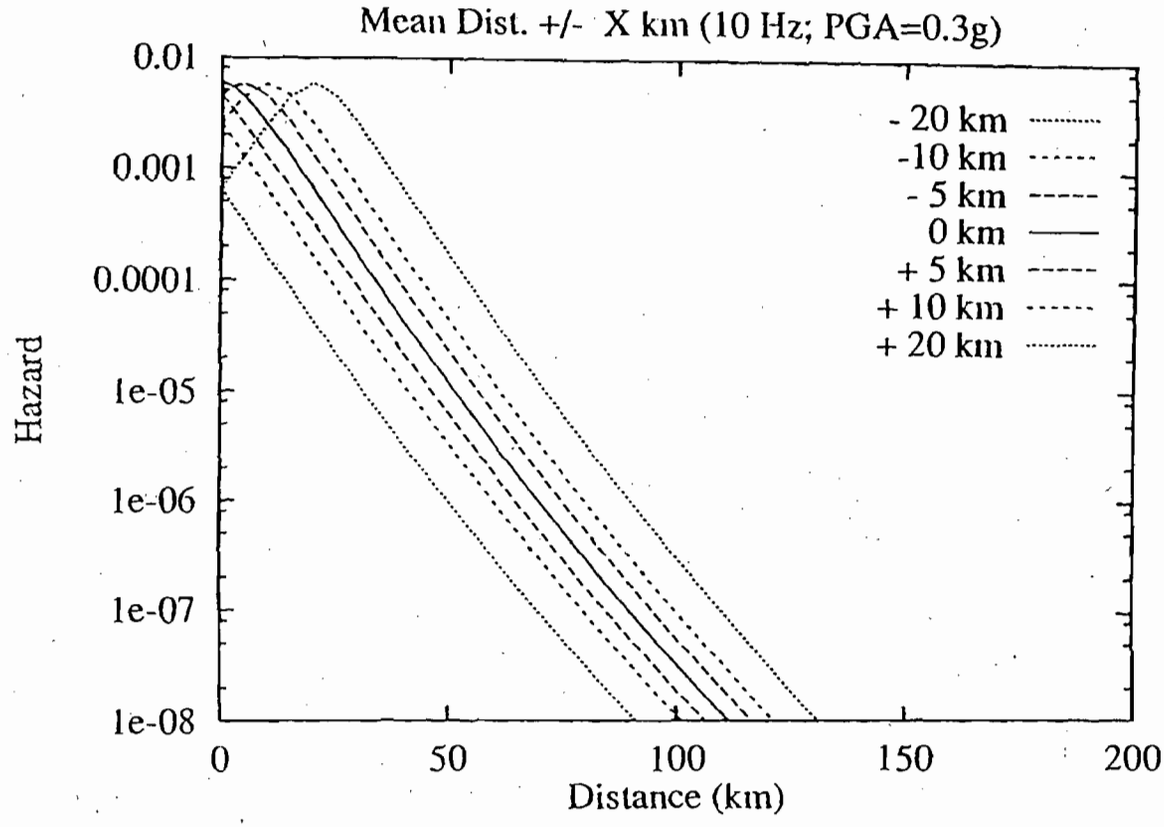


Figure G-33b. Sensitivity of 10 Hz hazard to m_{max} = 7.5, PGA = 0.6g, Group C sites.



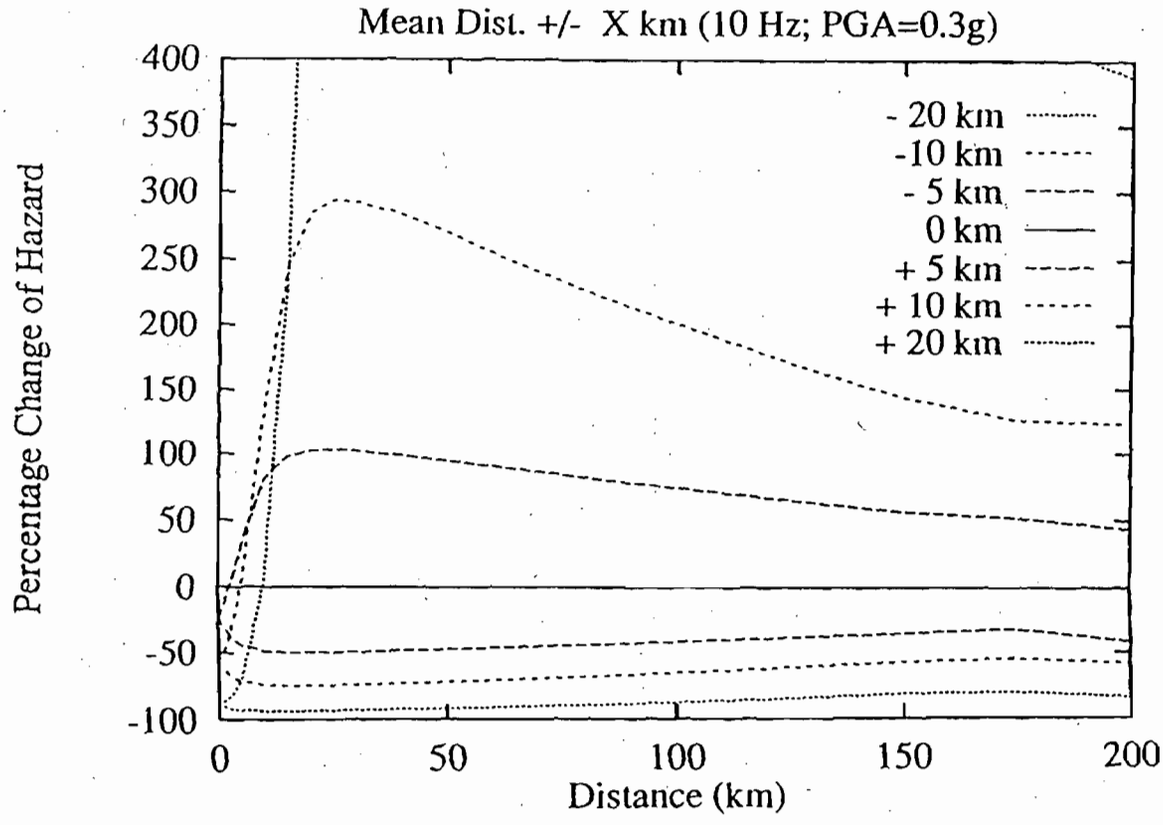
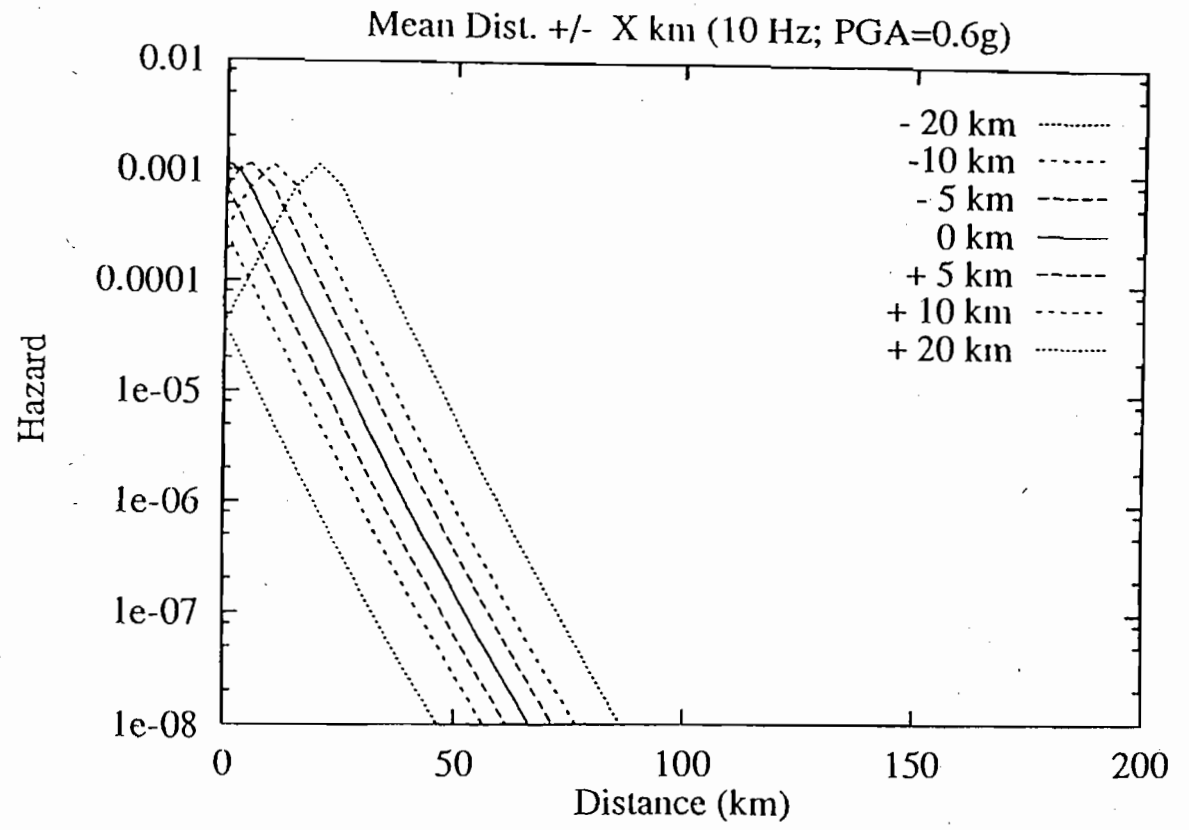


Figure G-34a. Sensitivity of 10 Hz hazard to distance from fault, PGA = 0.3g, Group C sites.



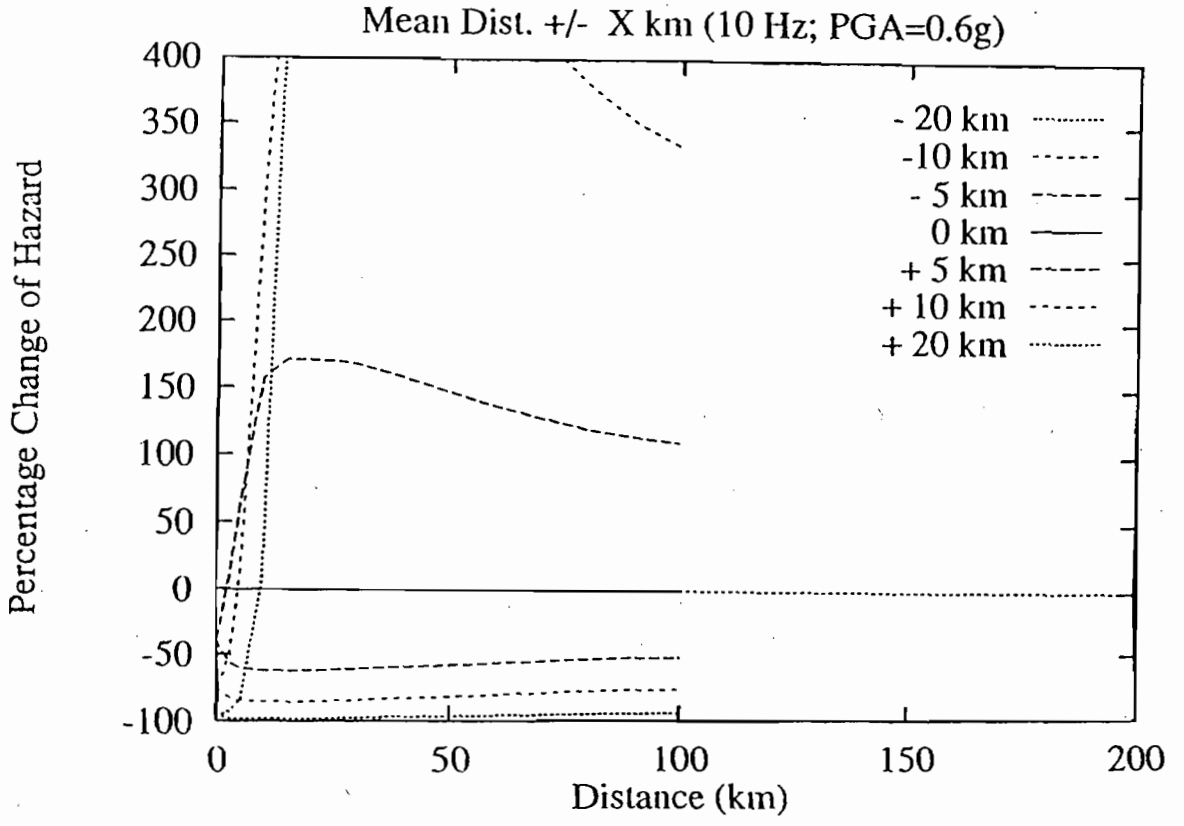
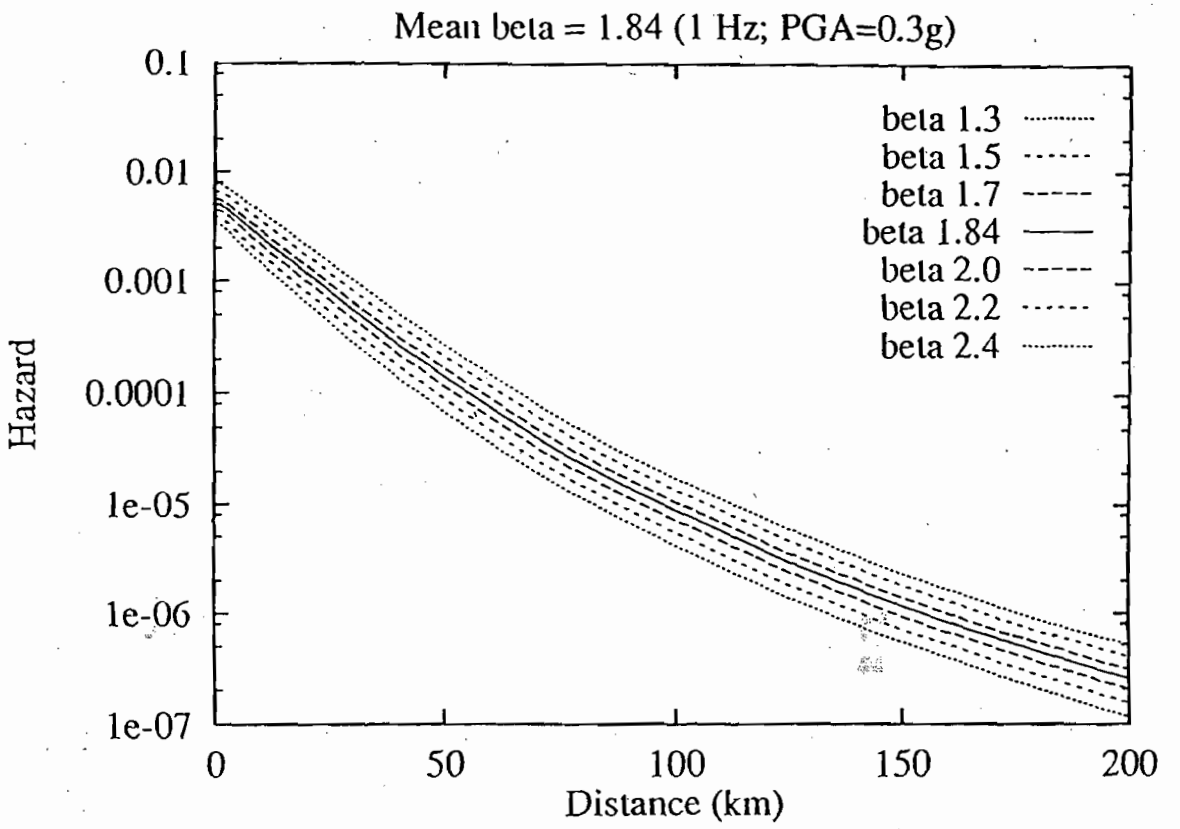


Figure G-34b. Sensitivity of 10 Hz hazard to distance from fault, PGA = 0.6g, Group C sites.



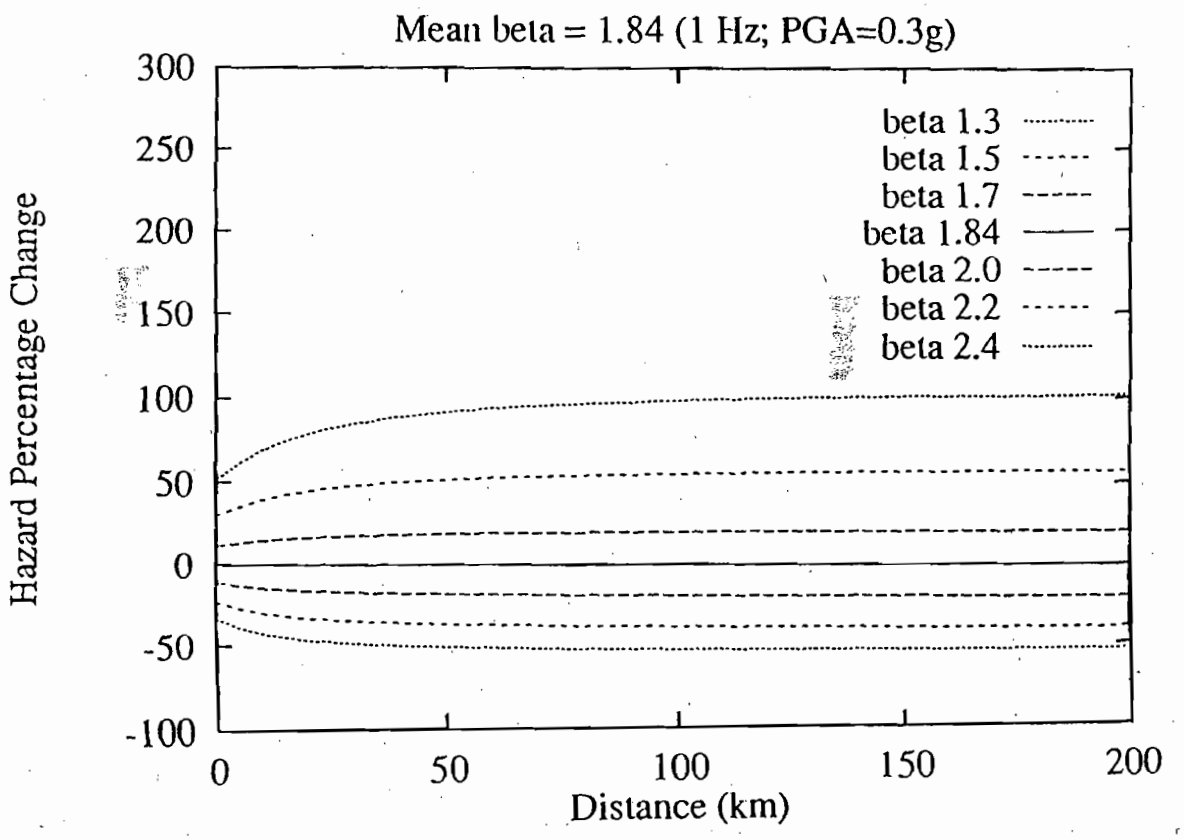
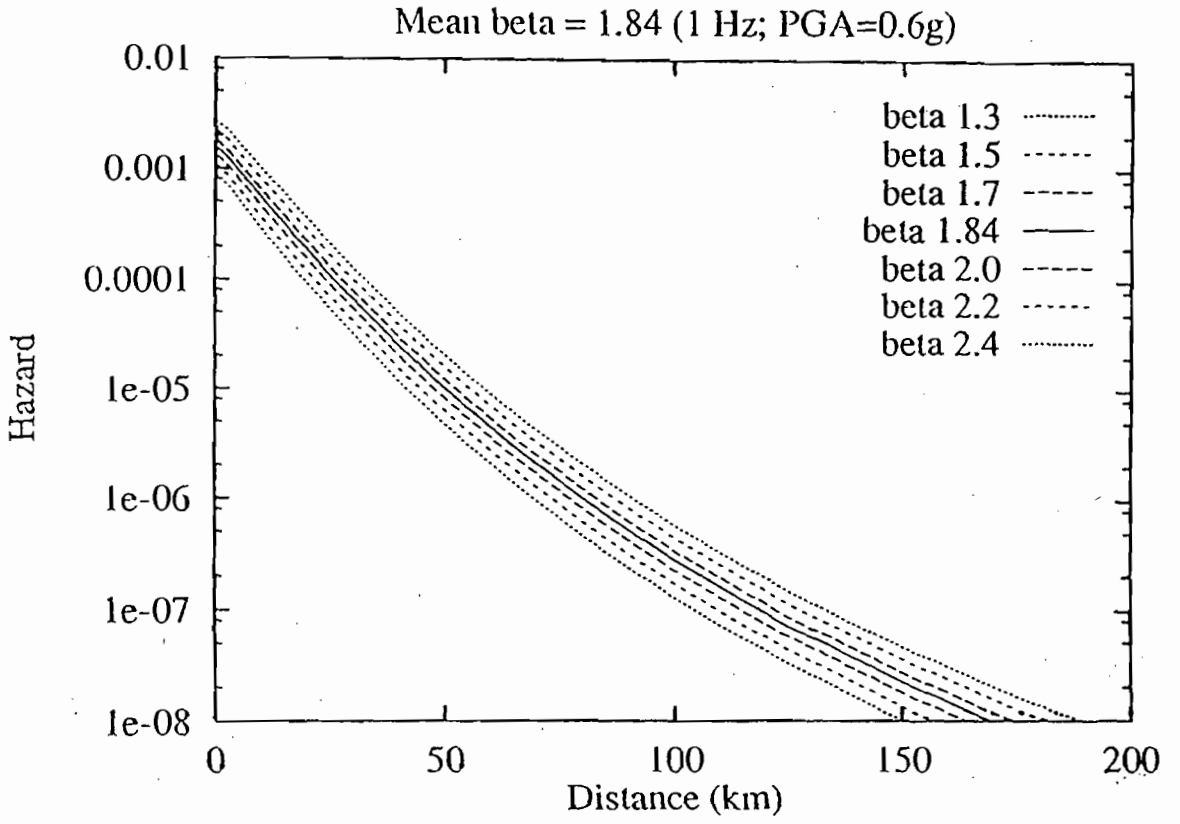


Figure G-35a. Sensitivity of 1 Hz hazard to beta for PGA = 0.3g, Group C sites.



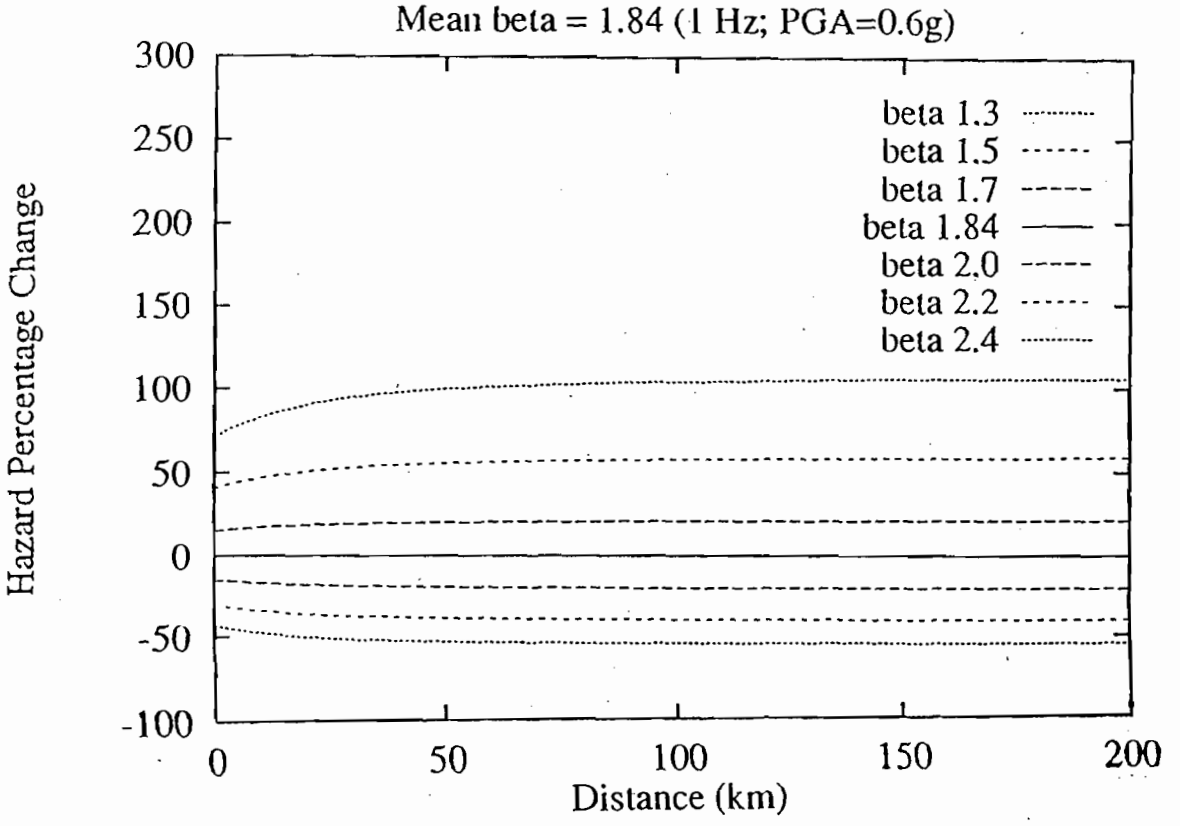
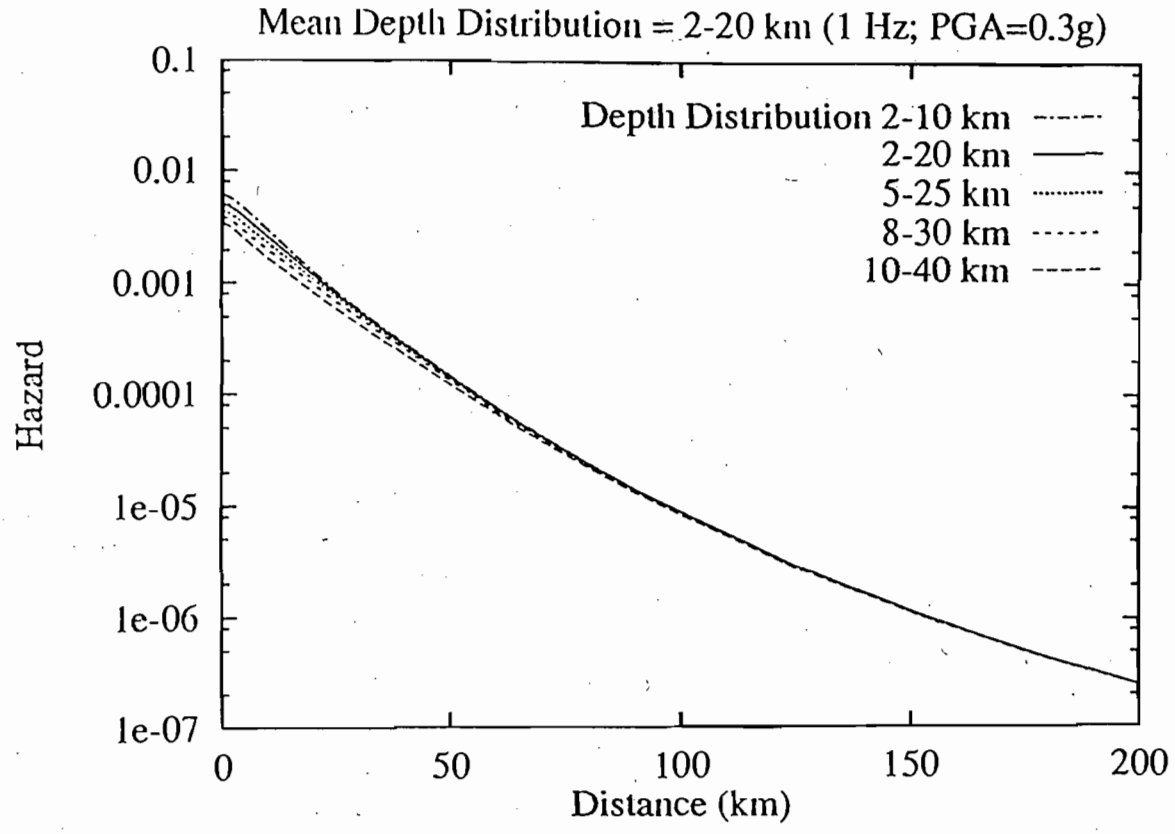


Figure G-35b. Sensitivity of 1 Hz hazard to beta for PGA = 0.6g, Group C sites.



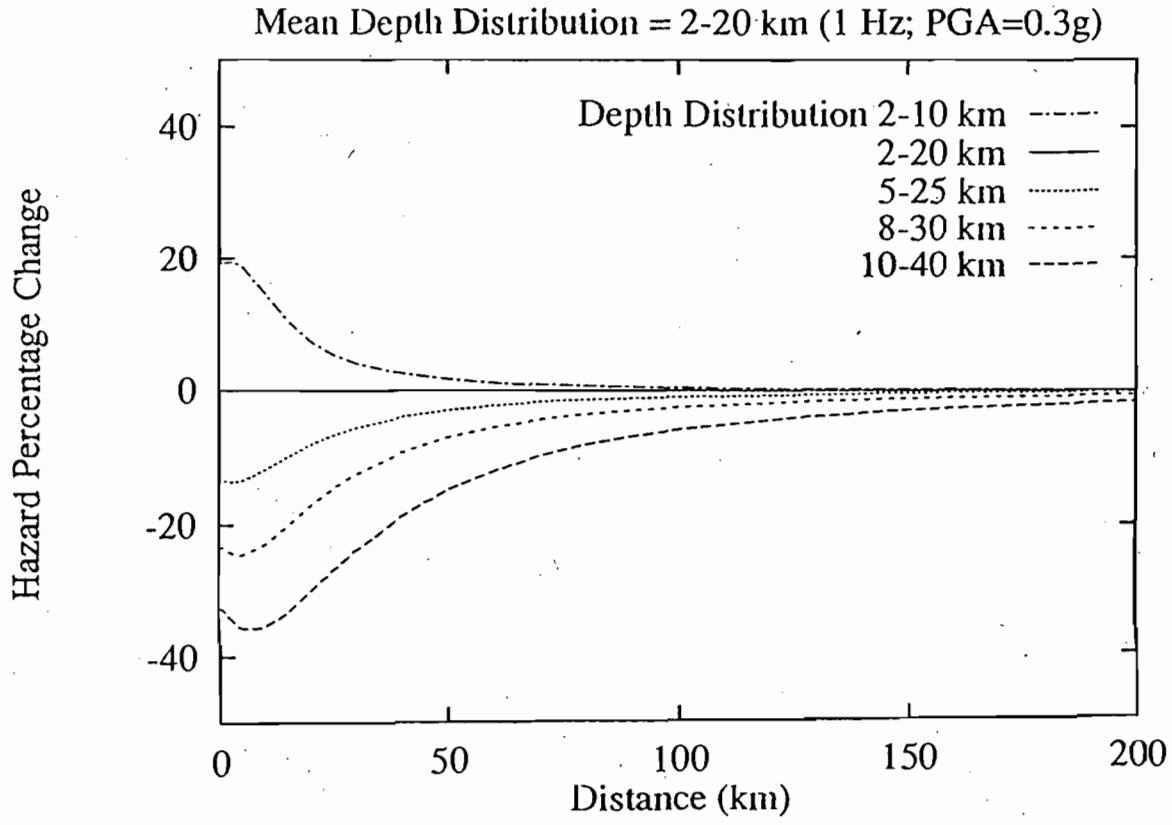
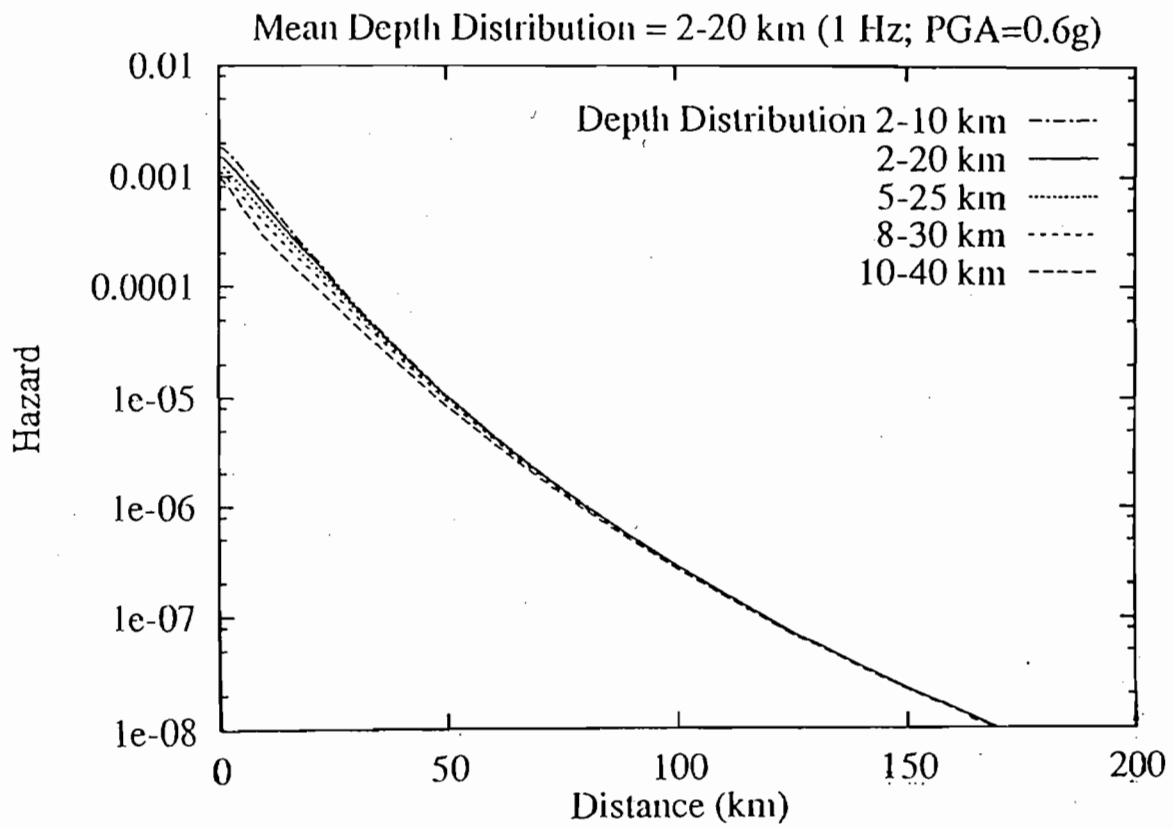


Figure G-36a. Sensitivity of 1 Hz hazard to depth distribution for PGA = 0.3g, Group C sites.



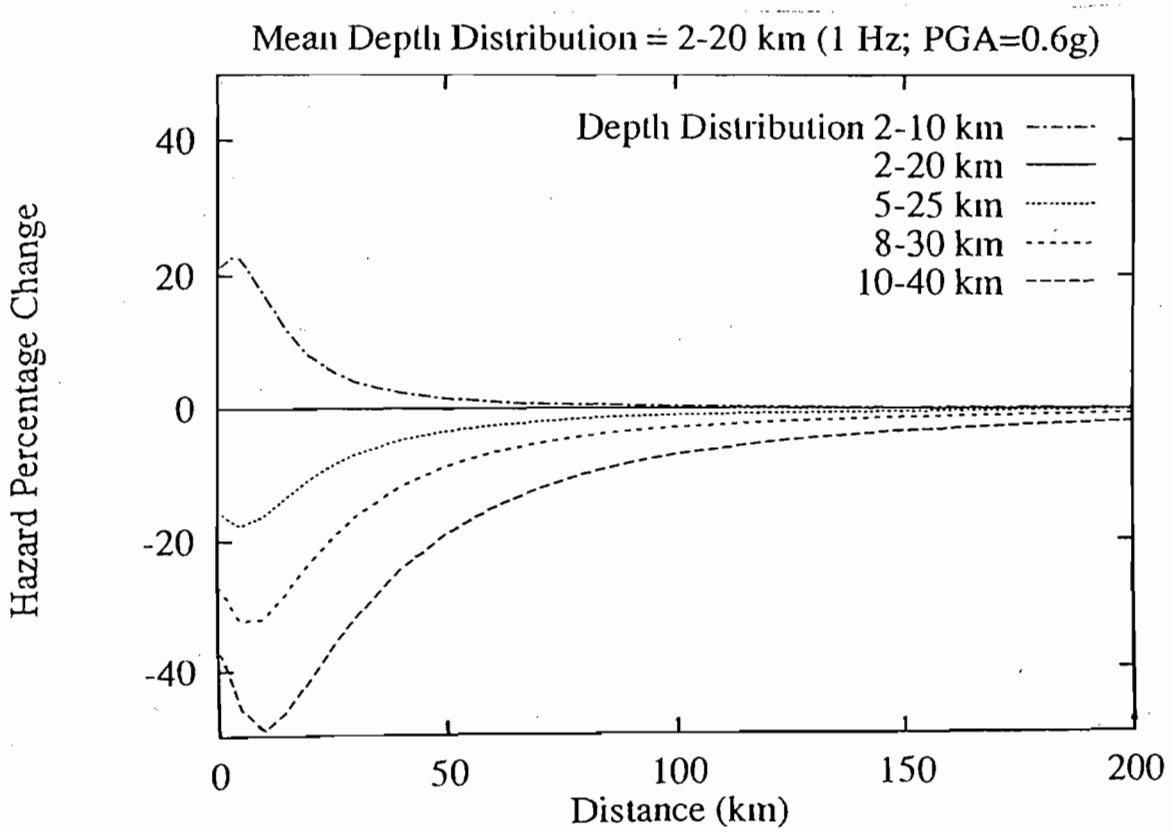
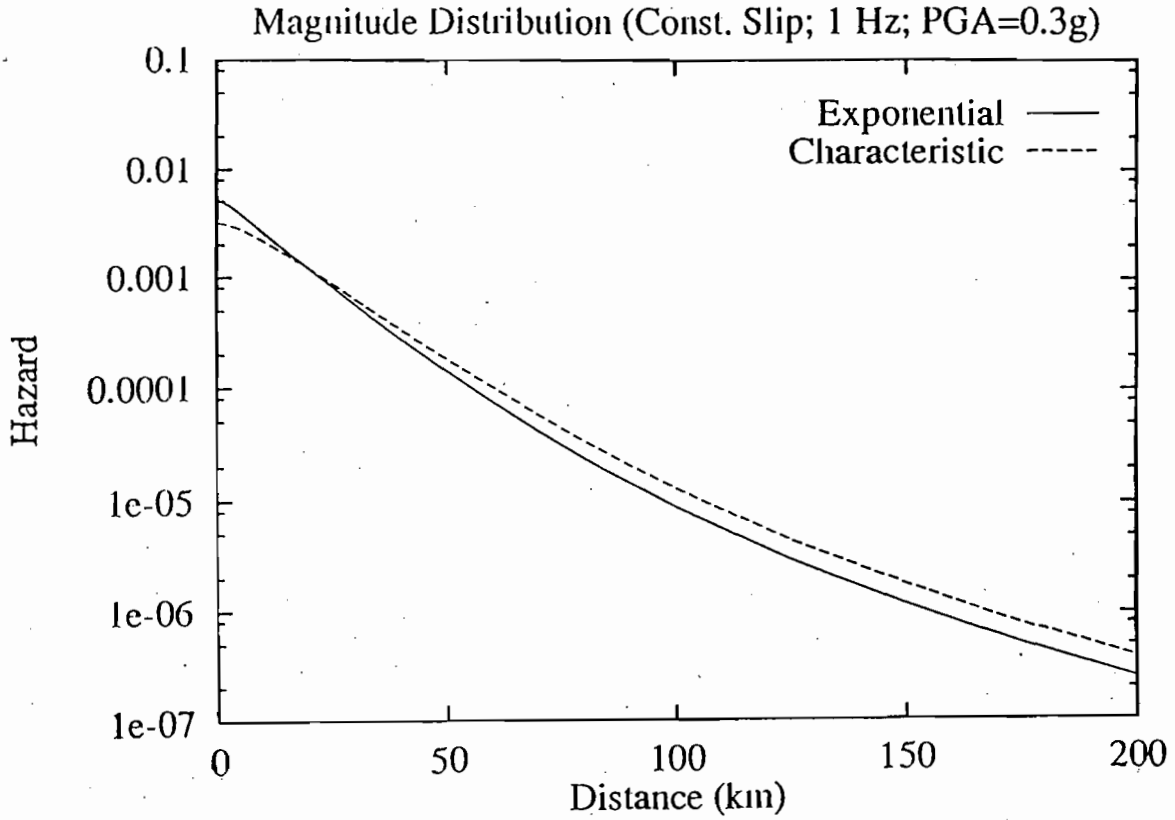


Figure G-36b. Sensitivity of 1 Hz hazard to depth distribution for PGA = 0.6g, Group C sites.



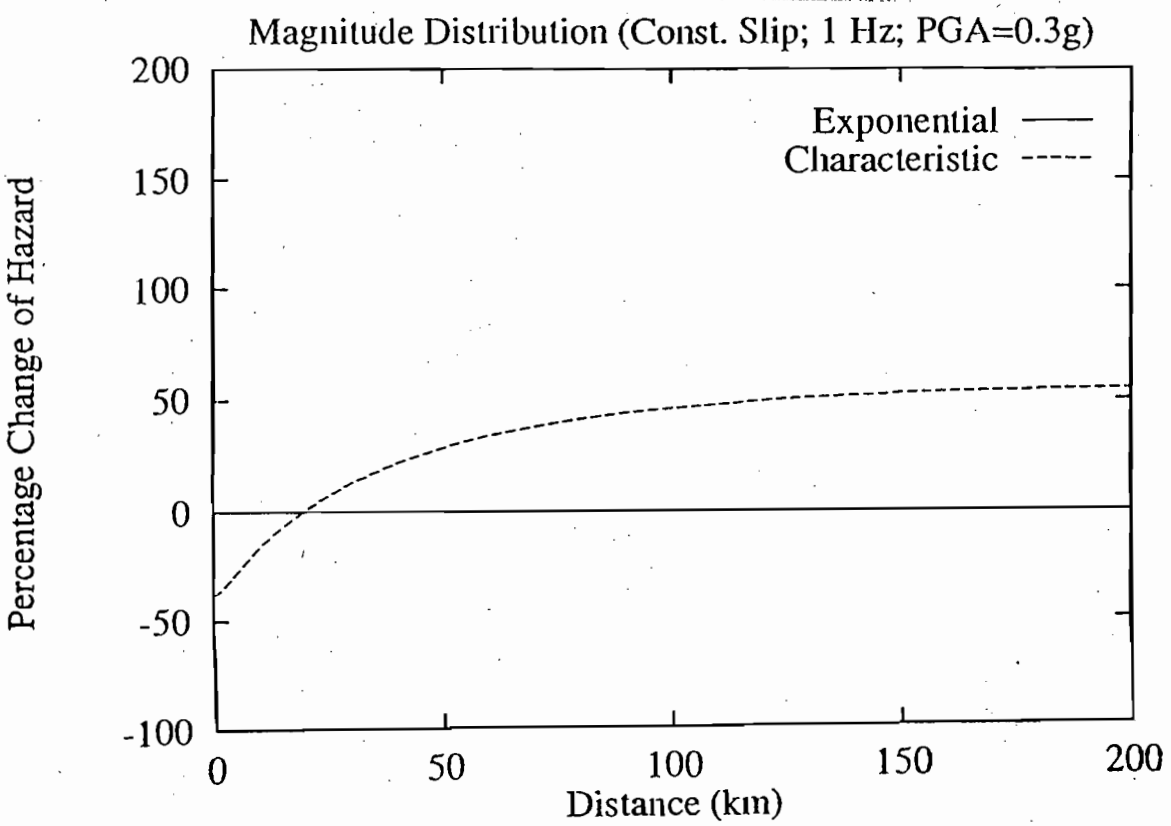
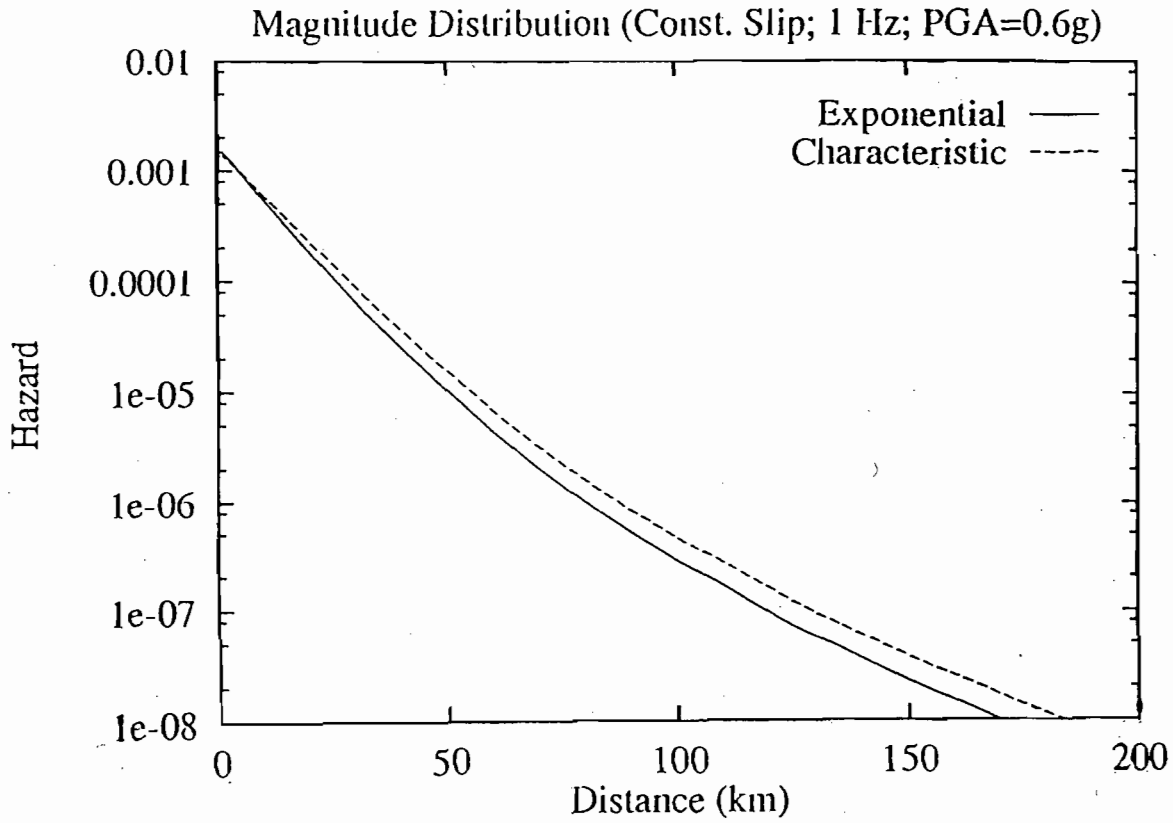


Figure G-37a. Sensitivity of 1 Hz hazard to magnitude distribution (with constant slip assumption), PGA = 0.3g, Group C sites.



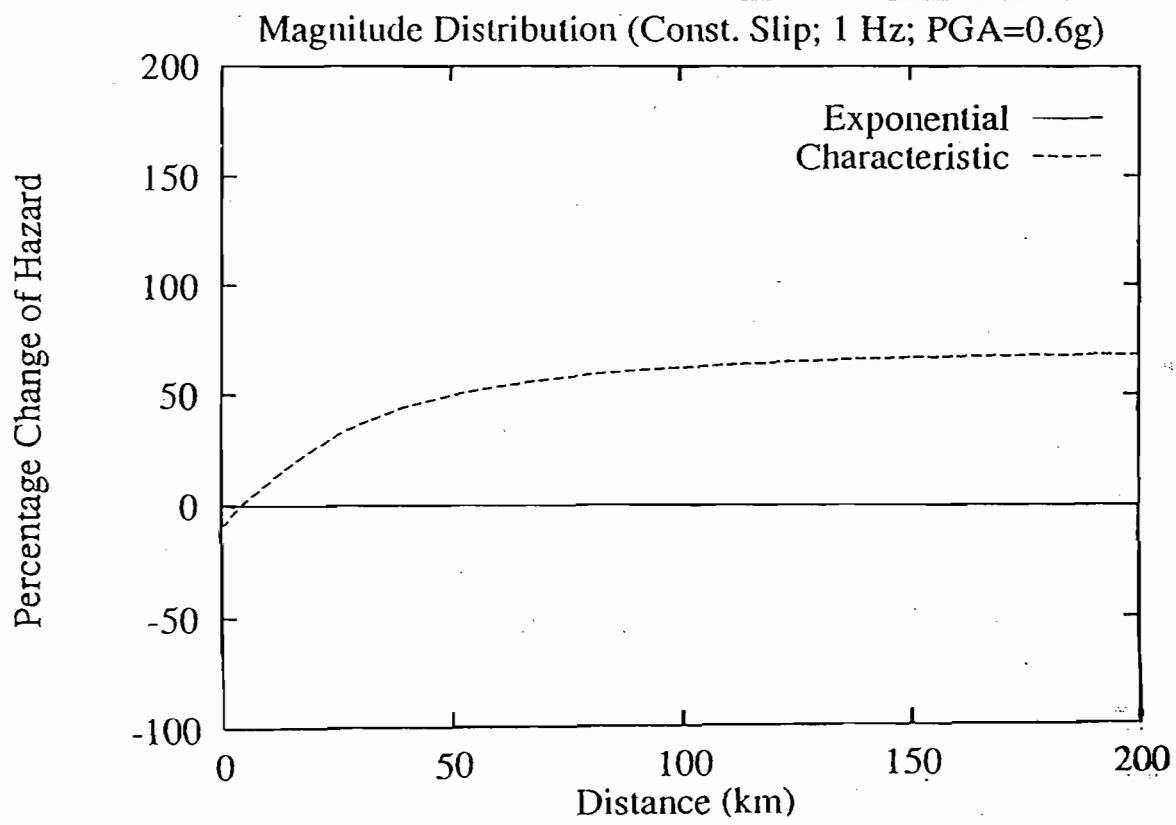
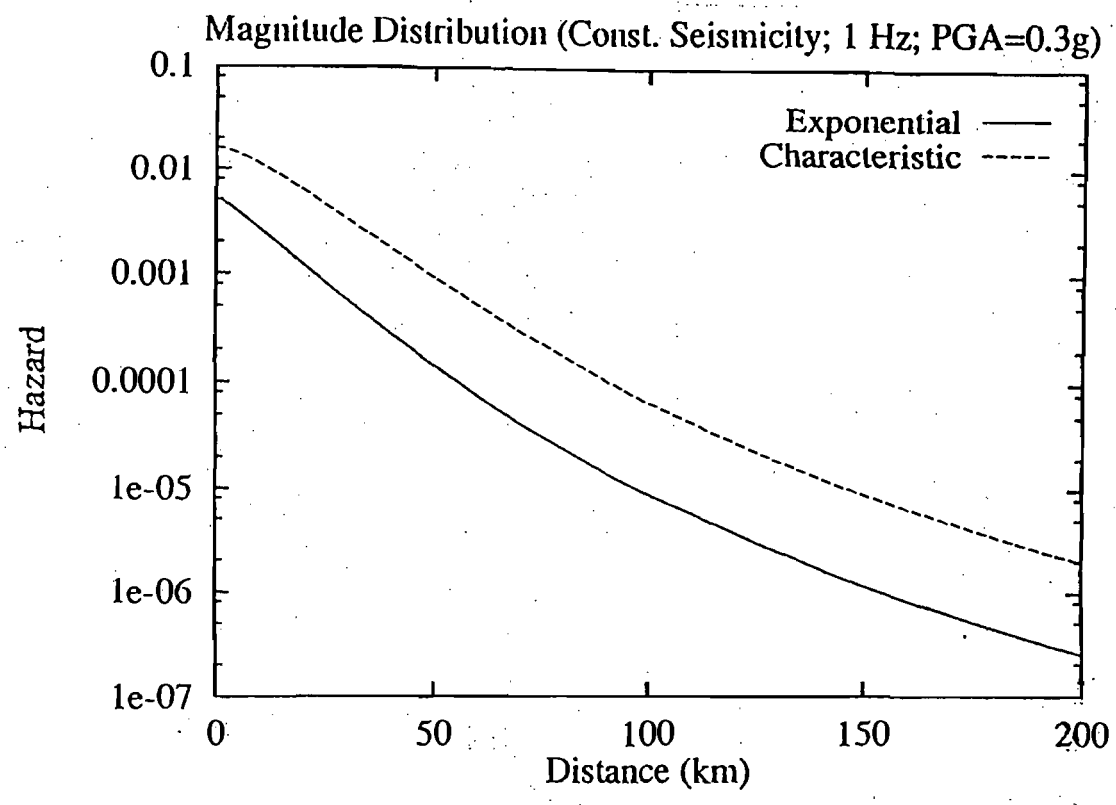


Figure G-37b. Sensitivity of 1 Hz hazard to magnitude distribution (with constant slip assumption), PGA = 0.6g, Group C sites.



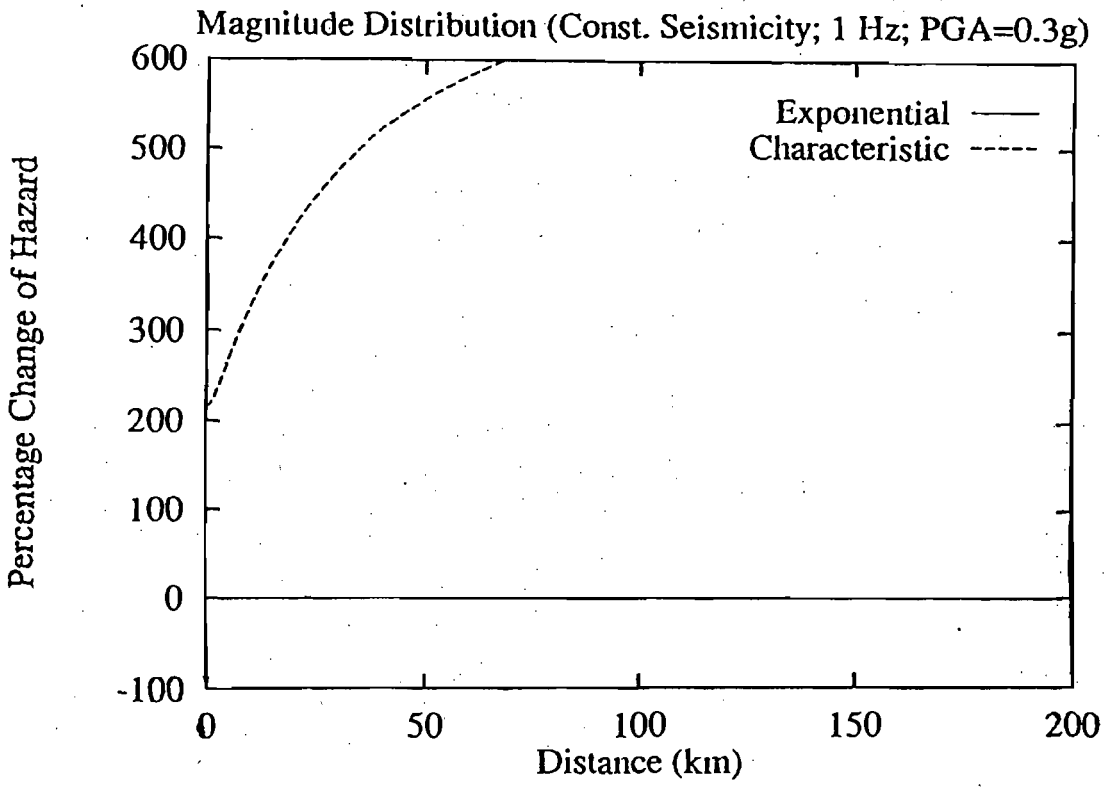
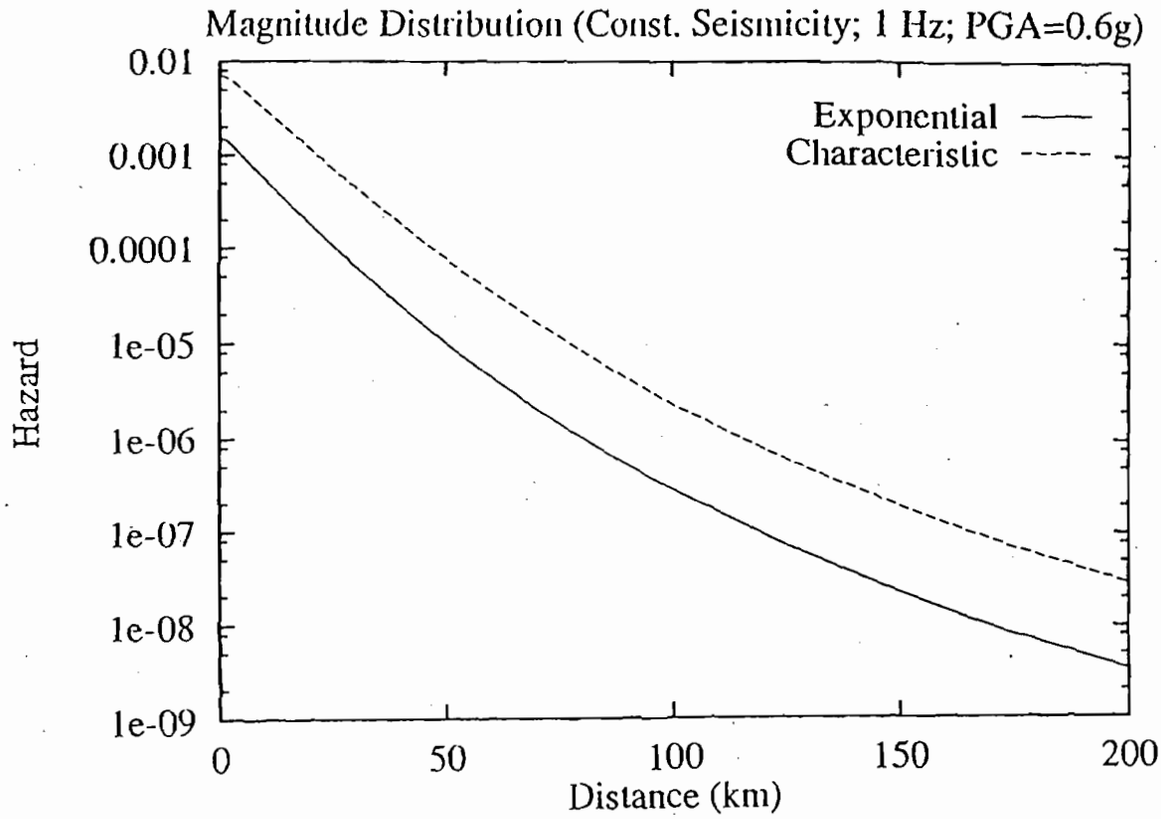


Figure G-38a. Sensitivity of 1 Hz hazard to magnitude distribution (with constant seismicity assumption), PGA = 0.3g, Group C sites.



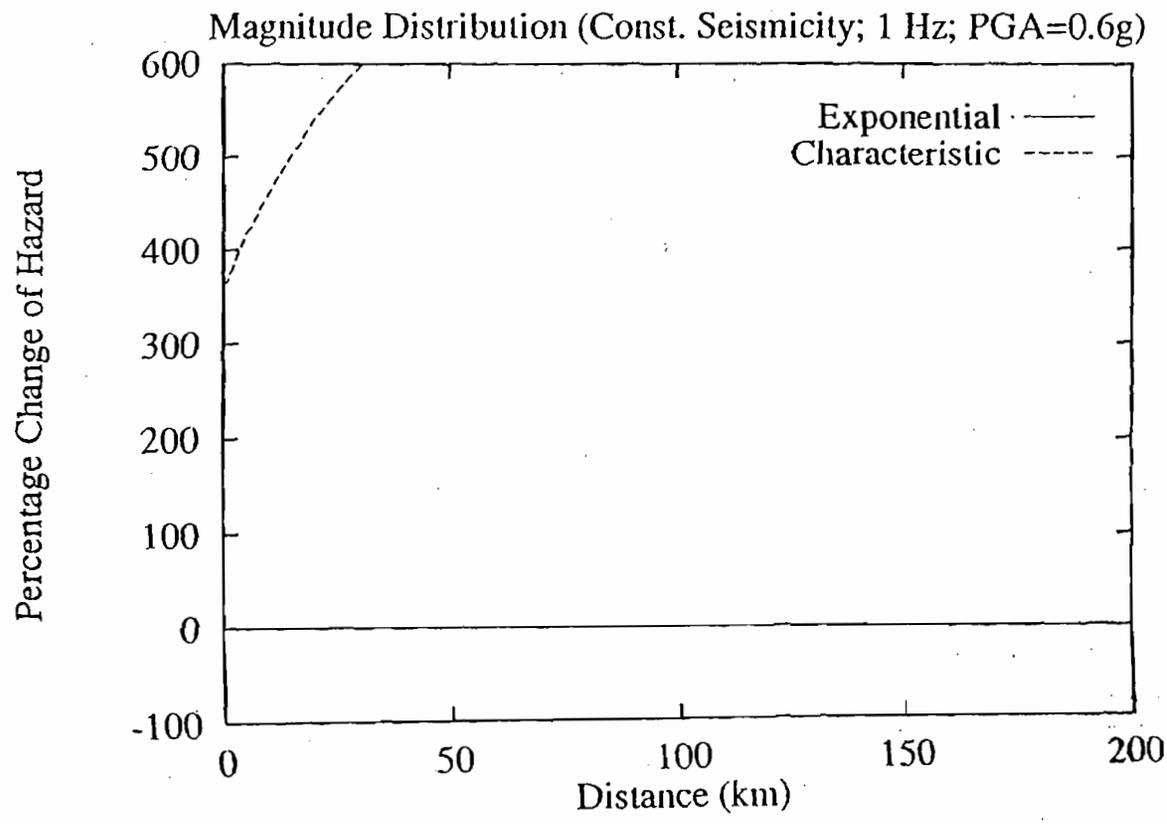
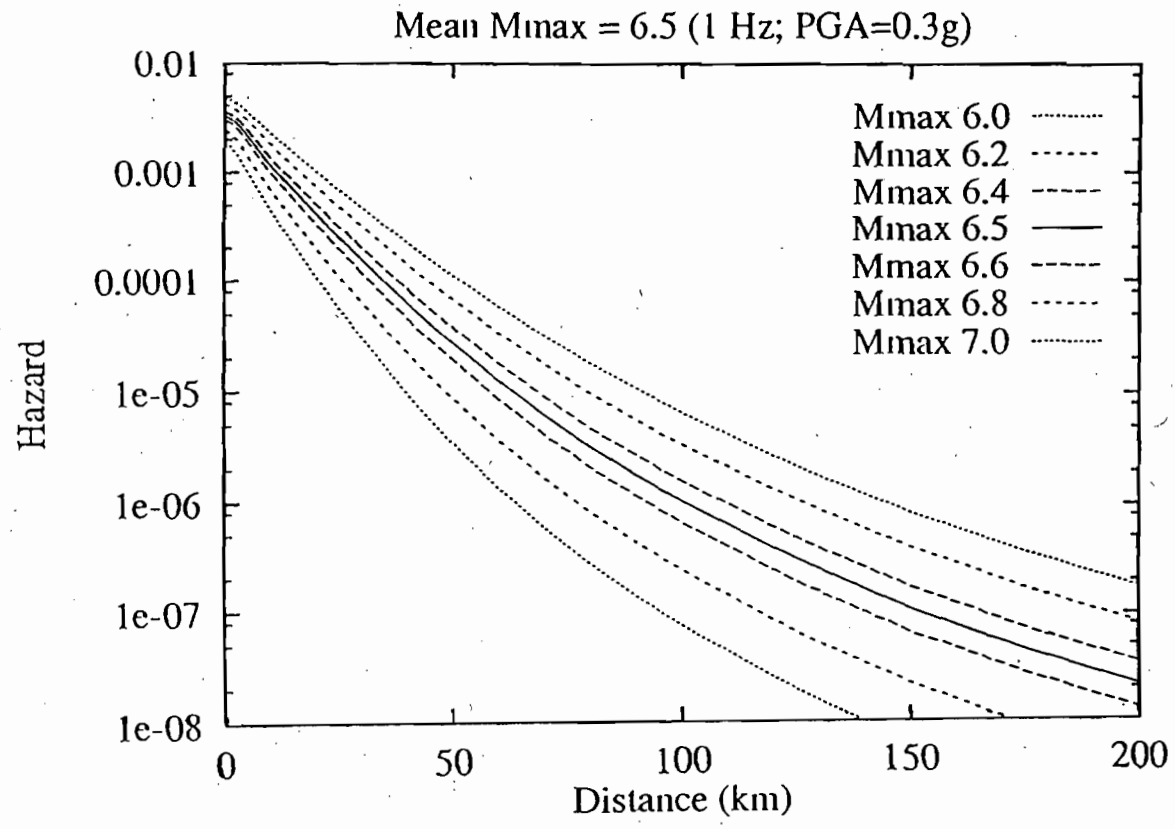


Figure G-38b. Sensitivity of 1 Hz hazard to magnitude distribution (with constant seismicity assumption), PGA = 0.6g, Group C sites.



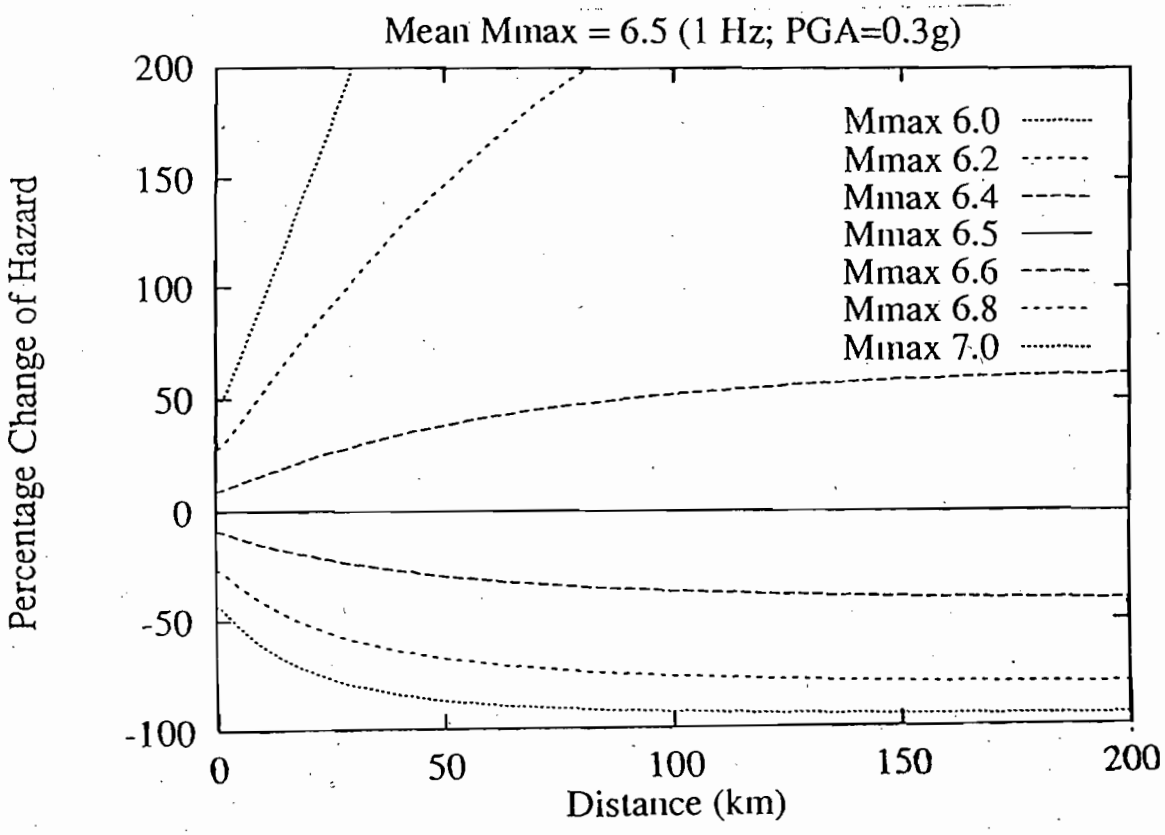
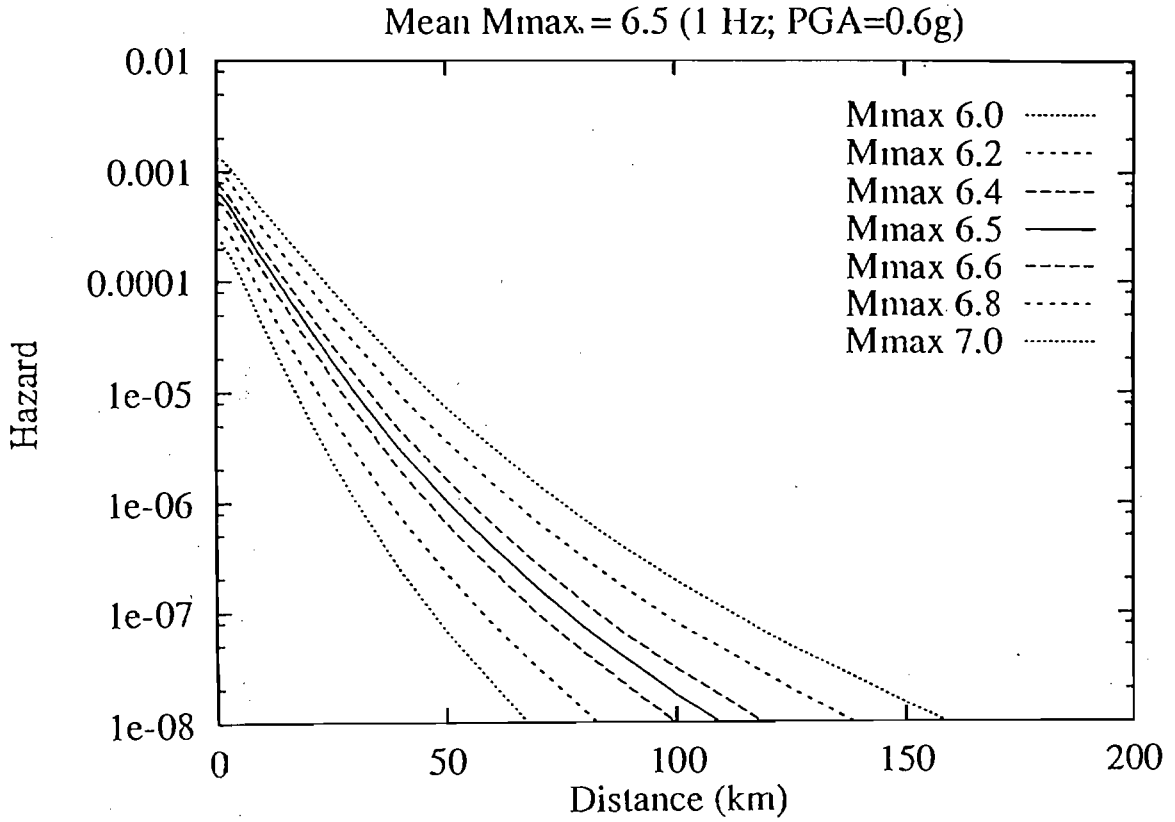


Figure G-39a. Sensitivity of 1 Hz hazard to m_{max} = 6.0, PGA = 0.3g, Group C sites.



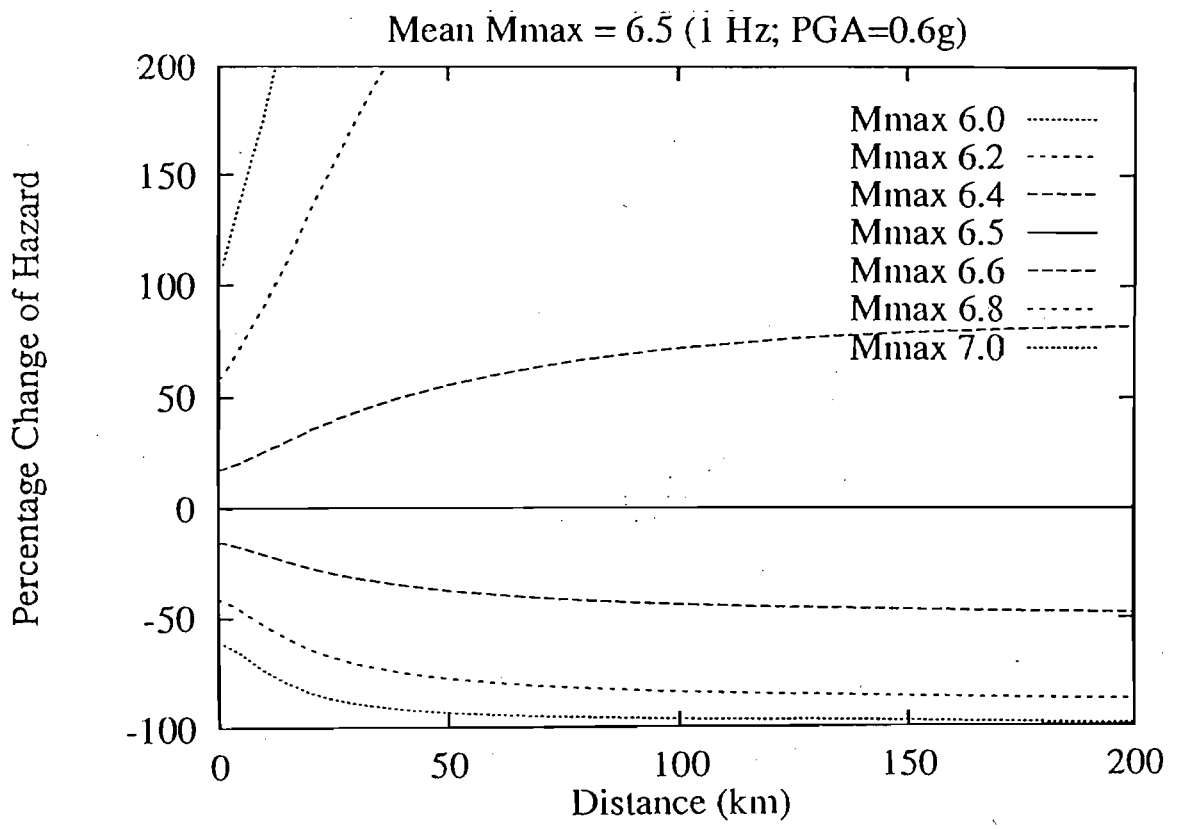
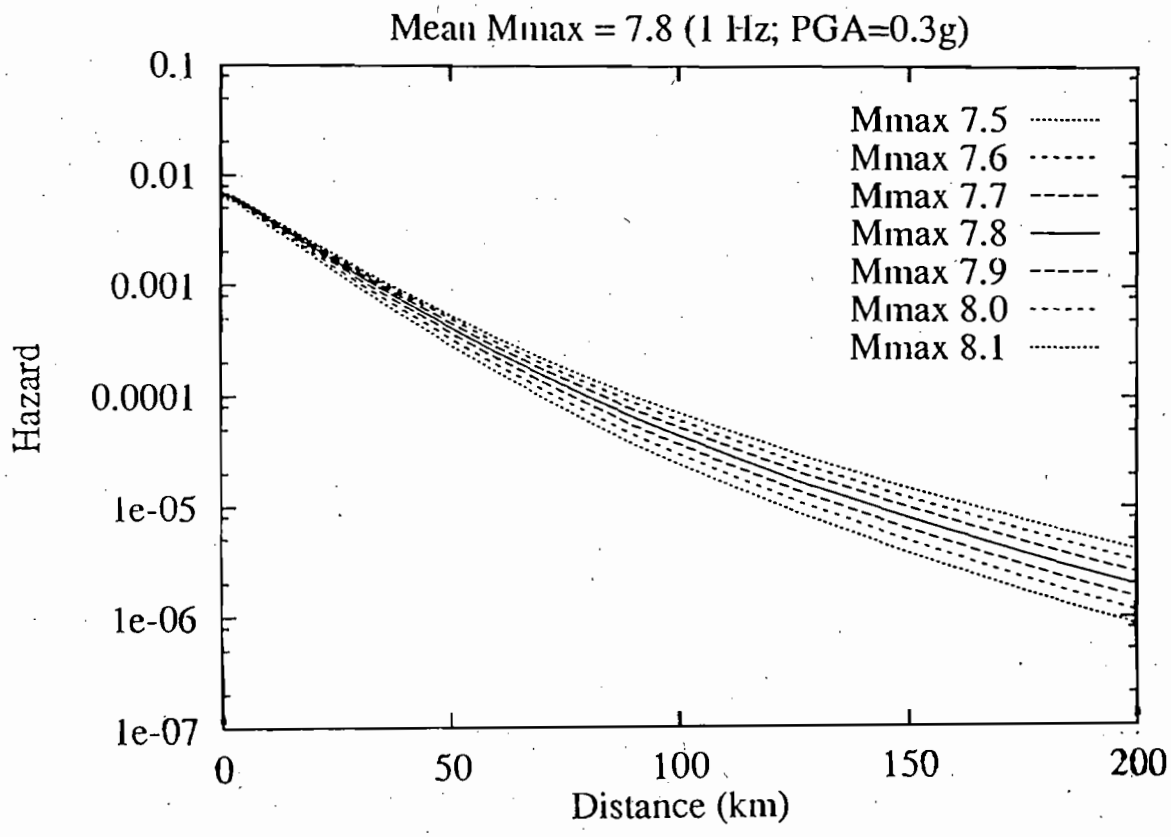


Figure G-39b. Sensitivity of 1 Hz hazard to m_{max} = 6.0, PGA = 0.6g, Group C sites.



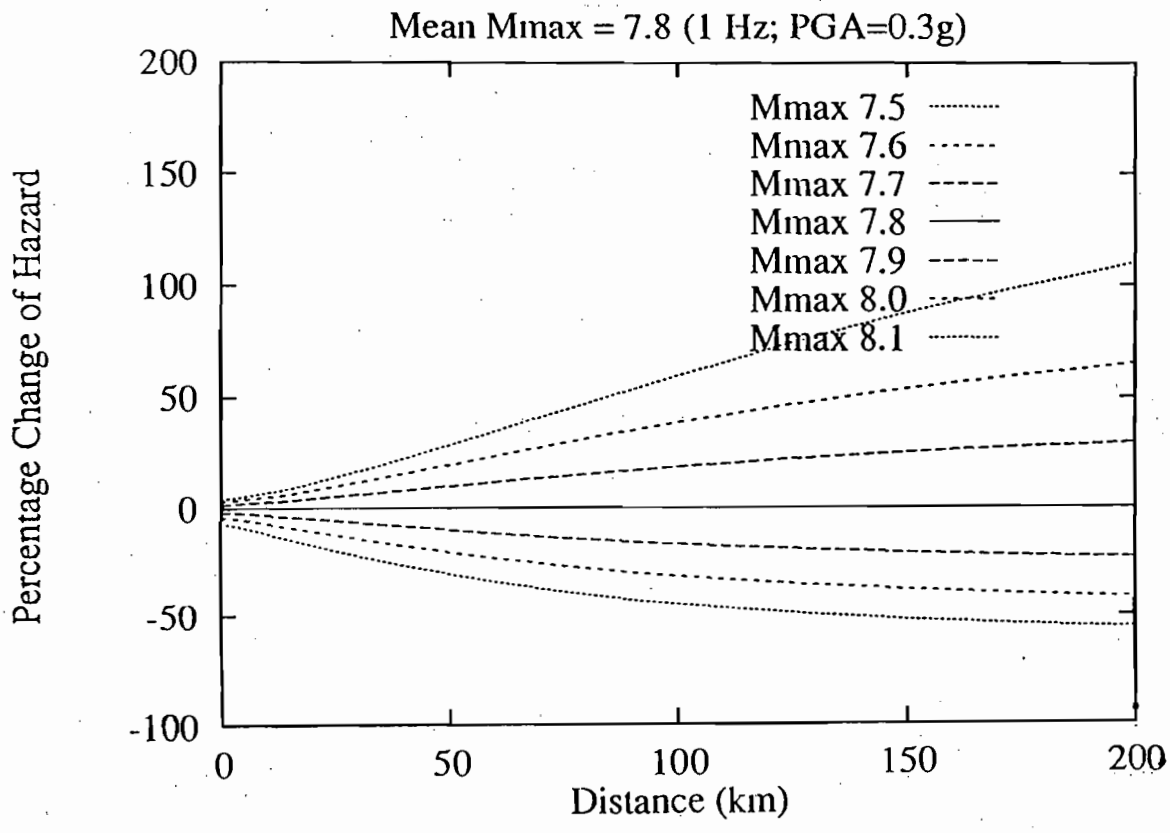
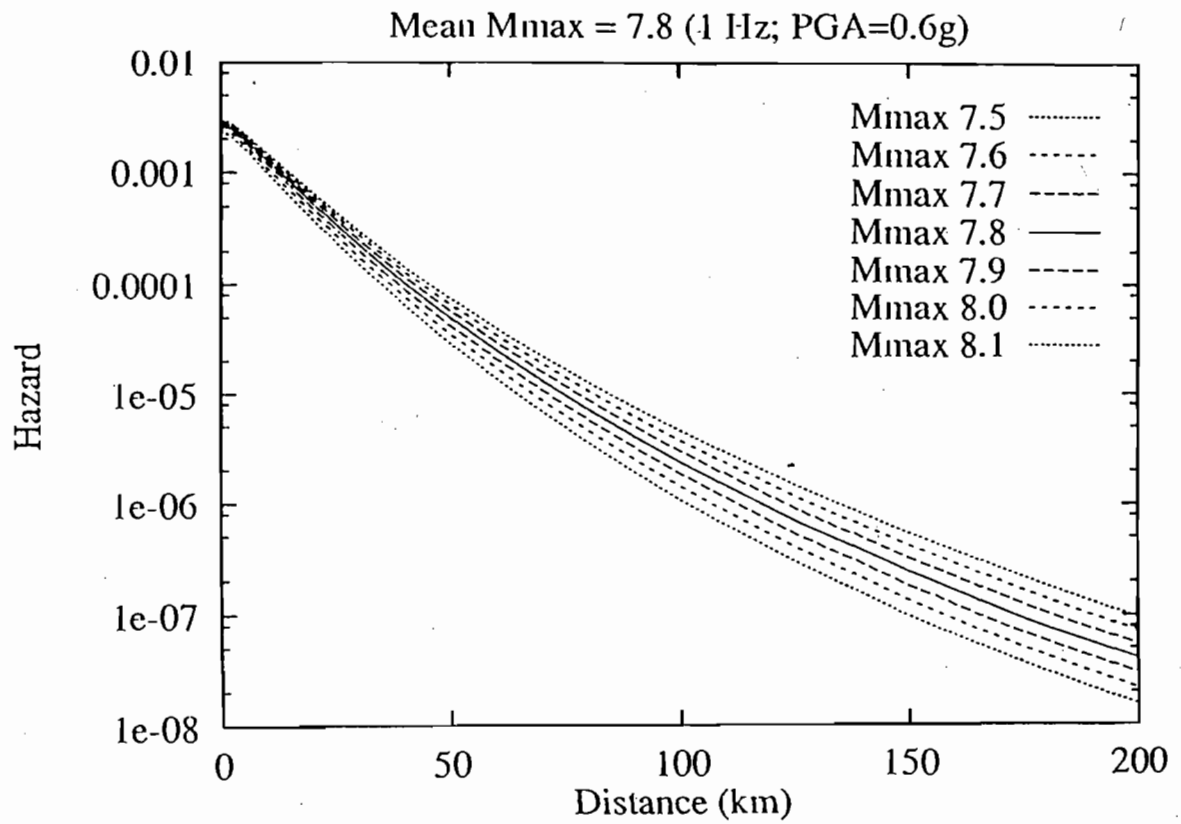


Figure G-40a. Sensitivity of 1 Hz hazard to m_{max} = 7.5, PGA = 0.3g, Group C sites.



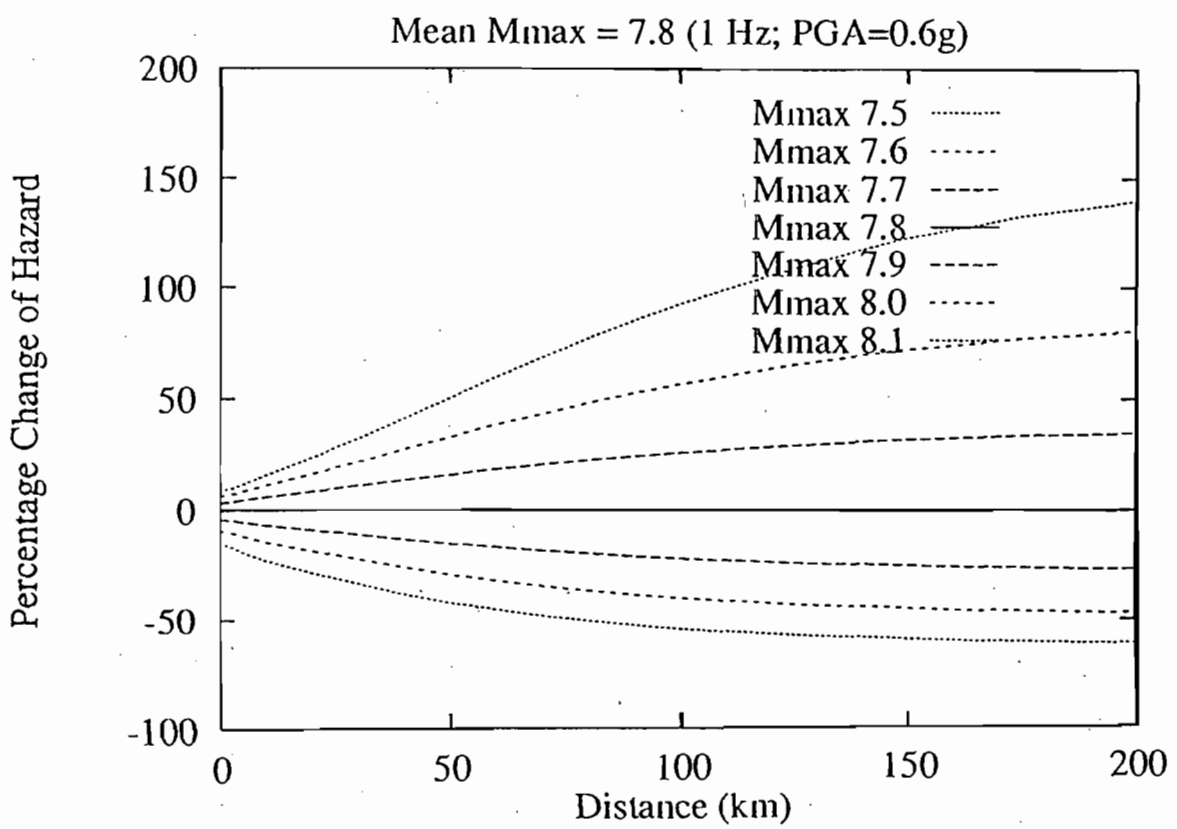
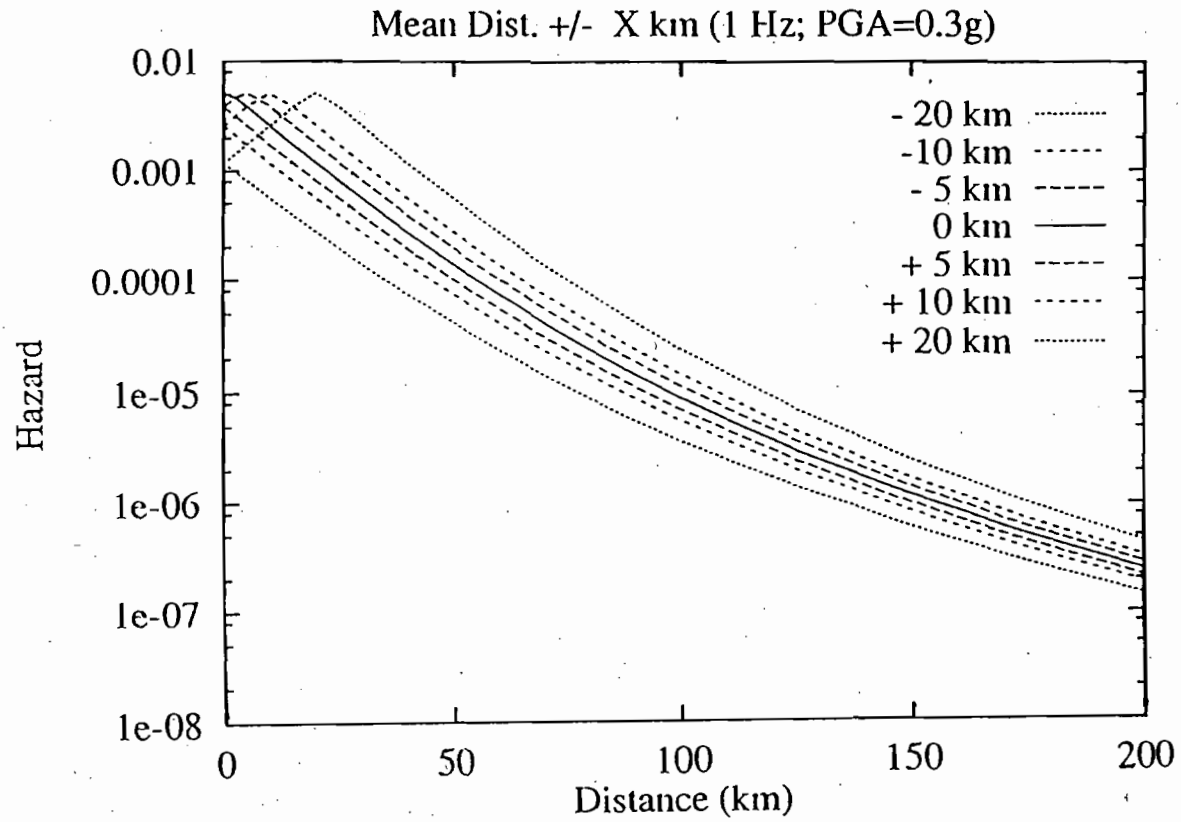


Figure G-40b. Sensitivity of 1 Hz hazard to m_{max} = 7.5, PGA = 0.6g, Group C sites.



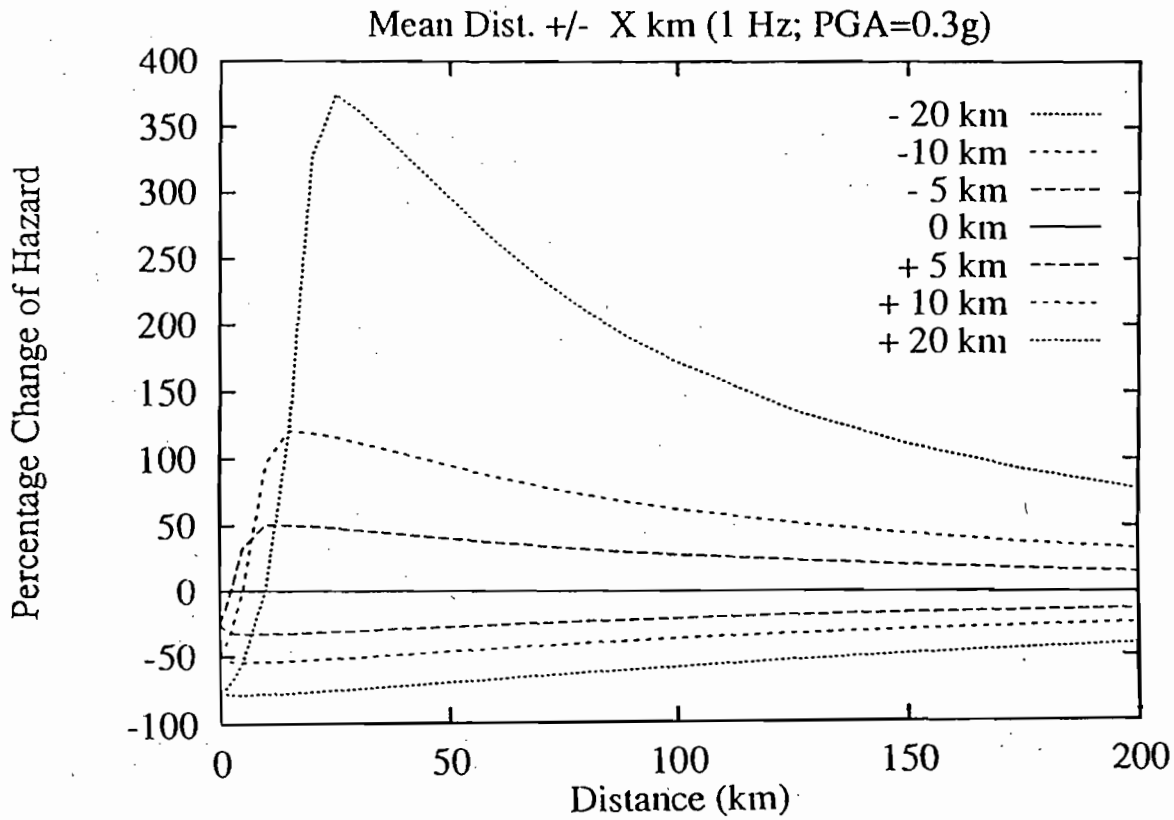
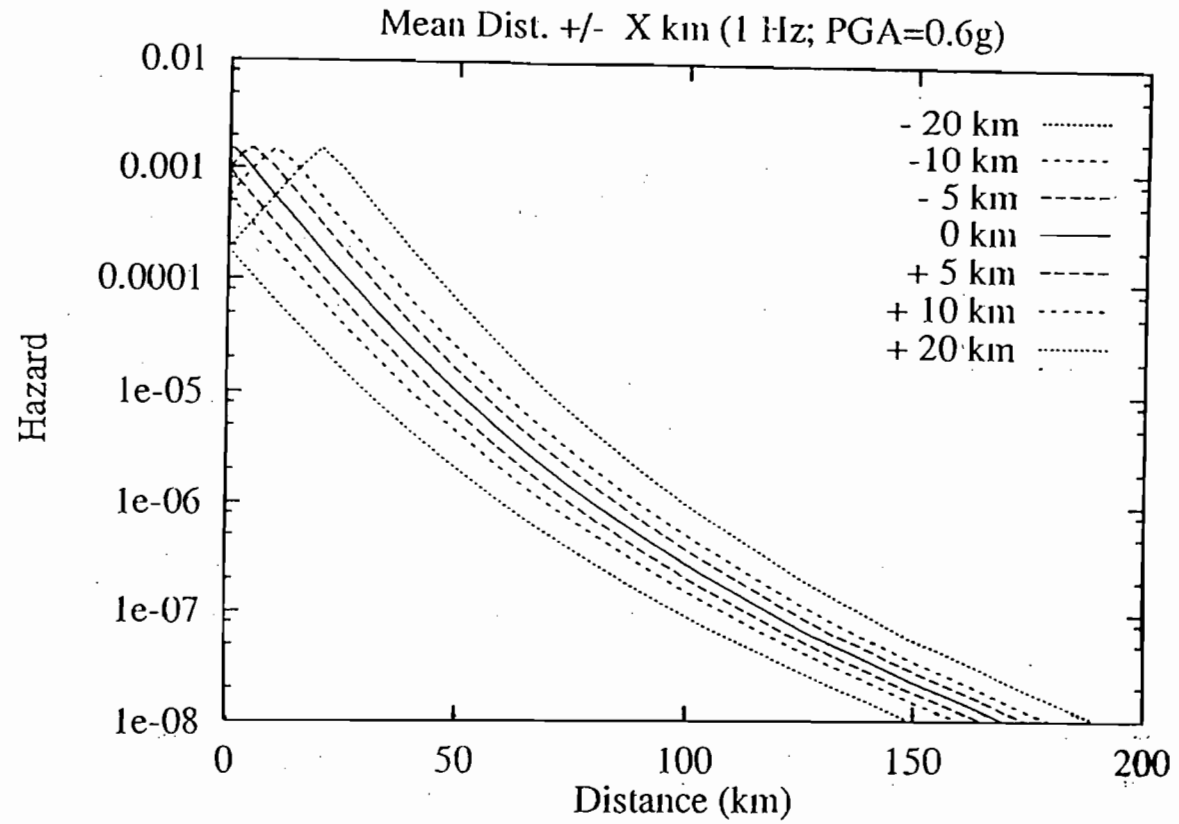


Figure G-41a. Sensitivity of 1 Hz hazard to distance from fault, PGA = 0.3g, Group C sites.



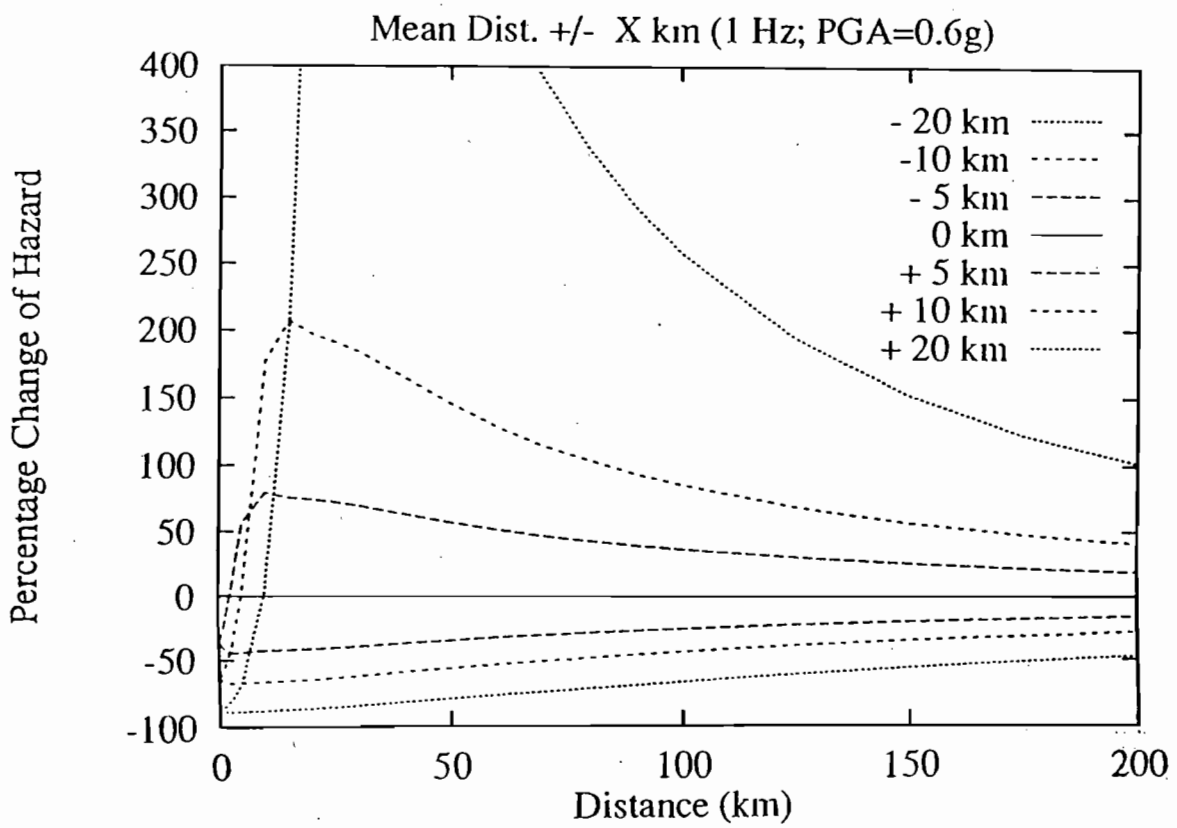


Figure G-41b. Sensitivity of 1 Hz hazard to distance from fault, PGA = 0.6g, Group C sites.

APPENDIX H

SEISMIC SOURCE CHARACTERIZATION WORKSHOP
JUNE 13-14, 1994
BOULDER, COLORADO

Purpose of the Workshop

SSHAC sponsored a two-day workshop with the following primary purpose: to gain first-hand information on what methods were successful and unsuccessful in eliciting seismic source characterization (SSC) information, from the perspectives of those SSC experts who were elicited. In addition, the experts were asked to give their personal reactions and recommendations to the approaches being contemplated by the SSHAC for eliciting SSC information (e.g., the role of the technical facilitator/integrator). Six experts with considerable experience in providing SSC information, primarily for eastern U.S. (EUS) sites but with some WUS experience as well, were selected for attendance at the workshop. Also in attendance were members of SSHAC's SSC Subcommittee and contractors for SSHAC (Apostolakis, Budnitz, Cluff, Cornell, McGuire, Bernreuter, Savy, and Mensing) and representatives of the sponsors (Bieniawski, Stepp, Schneider, and Zurflueh).

Although several workshops on the *technical (or substantive) issues* related to SSC have been conducted, this SSC workshop was the first time that specific focus has been given to *elicitation (or normative) issues* in the SSC domain. As such, the focus of the workshop was unique to the participants and, based on feedback from the experts, provided an incentive to examine methodology issues that they had not considered previously. For example, all of the experts have participated in technical workshops and, as active participants, have provided their scientific interpretations of the mechanisms for earthquakes in the EUS. In the SSC workshop they had an opportunity to discuss the value of such technical workshops and interactions in exchanging information prior to formal SSC elicitations. Further, they were asked to consider the scope of such interactions (i.e., should elicitations be conducted in a workshop setting), the focus and number of such interactions (e.g., identifying data needs, outlining alternative approaches, etc.), and the pros and cons of encouraging expert interaction prior to and

following elicitations. Several topics were considered in the SSC workshop, such as the criteria and methods that should be used to select the experts, that many of the experts had not considered at all in the past.

The primary focus was on SSC assessments for the EUS, reflecting the make-up of the workshop participants. Further, the discussion centered around methodologies most appropriate for large, regional seismic hazard assessments, with lesser emphasis on site-specific studies or more modest studies.

Prior to the workshop, each expert was asked (via telephone) a series of questions about his experience and opinions regarding methodologies for eliciting SSC information. Based on these interviews, several key issues were identified for which there appeared to be either strong opinions or significant differences of opinion. These key issues provided the basis for the agenda for the meeting. The findings related to each of these issues is summarized below.

Use of Expert Teams vs. Individuals

The issue is the relative pros and cons of eliciting the judgments of experts as individuals or as multi-disciplinary teams. The experts were able to identify several advantages and disadvantages to either approach. For example:

<u>Team Approach: Pros</u>

- Can use multiple disciplines to deal with the range of technical SSC issues
- Provides for more interaction and sharing of knowledge among experts
- Ensures a higher energy level; less time commitment for individual members of the team
- Allows for individual lack of expertise in some areas

- Provides for challenge of ideas and lessens variance due to misunderstandings of evidence and misunderstandings of the issues

Team Approach: Cons

- Team may be subject to dominance by a single (outspoken) individual
- Can be expensive because it involves several people
- May lead to a more `homogenized' product (i.e., less total uncertainty) if there is a requirement for team consensus
- Result may be less defendable because there is no individual ownership

Individual Approach: Pros

- Less expensive and more straightforward
- Individual ownership/responsibility of the result (assuming waive anonymity)
- Not subject to the problems of group consensus and thereby may capture a wider diversity of interpretation

Individual Approach: Cons

- Most individuals are limited in their expertise and may run out of endurance
- Must ensure that all individuals have data available
- Must be coupled with workshops or other interactions to provide for exchange and challenge of ideas

The general conclusion in light of these pros and cons seems to be that either approach is acceptable. All of the experts emphasized that SSC is multidisciplinary and requires the infusion of a wide range of technical expertise. By their nature, teams can span the needed range of expertise, but have some disadvantages as noted above. The individual approach can work provided that there is a concerted effort to provide each expert with the means of spanning the range of disciplines himself. It was suggested by some experts that future hazard studies should attempt to capture the advantages of both approaches by, for example, allowing the experts to work as small teams during the project (e.g., identifying data needs, forming interpretations, etc.) and then eliciting each individual separately. Another alternative might be to have a team of technical experts that serves as a resource to each individual expert to provide data, discuss interpretations, etc.

Interactions Among Experts

This issue is the amount and frequency of interactions among SSC experts in forums such as workshops or smaller working meetings. All of the experts strongly endorsed having multiple interactions during the SSC process: early on to identify data needs, during the process to discuss data interpretations and models, and following the elicitations to discuss the interpretations prior to hazard calculations. The workshops and meetings serve several purposes such as educating the experts on the available data and tectonic interpretations, deciding on what are the important technical issues and which issues are addressable, identifying methods and procedures for evaluating SSC characteristics, and reviewing and challenging alternative interpretations. Many of the experts felt that a workshop *following* the elicitations would provide a valuable opportunity to review each expert's interpretations and uncertainties, and would provide a final opportunity for the expert to make changes prior to the hazard calculations. Another valuable purpose of workshops is to train the experts in the methods that would be used to elicit their judgments and subjective probabilities. It was also noted that workshops can provide an opportunity for observers (e.g., regulatory representatives or sponsors) to witness and understand the process.

Each expert cited experience with both beneficial and worthless workshops and provided the following advice:

- Provide for plenty of time to plan and set the agenda for the workshop

- Assign responsibilities to participants well in advance of the meeting and ensure that participants are prepared and aware of their position within the overall agenda

- Strike a balance between tight control of the progress of the meeting and allowing for a free exchange of ideas by all participants

- Provide written material to participants in advance of the meeting.

It was suggested that, because it is often difficult to schedule workshops such that active participation in ensured, perhaps an SSC "camp" at a remote location lasting several days would be an effective way to promote mutual education (both seismotectonic and probability training) and exchange of ideas.

Most experts felt that a workshop setting was not appropriate for conducting elicitations, but could be an opportunity to provide a demonstration of elicitation procedures through some example assessments using a "model team".

Role of the Technical Facilitator/Integrator (TFI) Team

The issue is the "strength" of the TFI relative to the experts, ranging from a strong role (TFI runs the project, integrates the results, and takes responsibility for the results) to a weak role (TFI organizes logistics, combines expert assessments, but the experts take responsibility for the results). Because the TFI issue is complex and multi-faceted (e.g., management of the project, aggregation, ownership for the product, etc.), the responses from the experts were varied. Here we consider the role of the TFI in organizing and leading the project and in conducting the expert elicitations. The role of the TFI relative to integration or aggregation is considered separately below.

The TFI should be a team of 2-3 individuals knowledgeable in SSC as well as elicitation issues. It was generally agreed that the TFI team should have a strong technical background and standing in the SSC community. This would provide for the proper focus in group interactions and in the elicitations. At workshops and other meetings, the

TFI should be proactive and keep the discussions on track, but should not impose its own technical interpretations on the group. The TFI should attempt to draw out all participants' views to ensure that a balanced spectrum of technical interpretations is discussed. Another important responsibility of the TFI is to focus the free discussion of technical issues toward those issues of greatest significance to the hazard results. These issues may not be intuitively obvious to many of the experts at a workshop. For example, considerable discussion could ensue regarding recent paleoseismic evidence for the occurrence of large-magnitude earthquakes at a location at a large distance from a site of interest. The TFI should remind the experts that the importance of the new findings would revolve around their possible implications to the characteristics of seismic sources closer to the site.

The experts felt that the role of the TFI in the elicitations was crucial. (In the discussion, it was assumed that the elicitations would occur as individual interviews, perhaps followed by additional work by the expert to complete the assessment). In this format it was felt that the SSC expert within the TFI team should take the lead in asking the questions and documenting the responses. The normative expert on the TFI team should also be present in the elicitation to help with the quantification of uncertainty using subjective probabilities.

Elicitation Approaches

The issue is the means by which experts are elicited and their judgments documented. Issues discussed relate to the basic format to the elicitations, the nature of the information elicited (e.g., specify parameters or methods for calculating parameters), and the pitfalls to avoid in making the elicitations.

The elicitation should be viewed as only one step in a larger process that prepares and educates the expert for the assessment. Basic elements of the SSC elicitation process are the following:

- Identify technical issues and data bases
- Provide all data to experts
- Conduct multiple workshops/meetings for exchange of data, interpretations, probability training, etc.

- Conduct elicitations
- Discuss results, uncertainties, implications, feedback
- Finalize interpretations

In this context, the actual elicitation occurs late in the process, thus taking advantage of the information exchange that has occurred. The preferred approach to eliciting SSC information is through "one-on-one" interviews with each expert and the TFI team present. Written questionnaires, without extensive follow-up and discussion, were not viewed as appropriate. It was suggested that written questionnaires might be provided prior to interviews to help focus the elicitation. Further, the exact questions to be asked could be formulated by the experts and TFI jointly at a workshop, thus limiting the possibilities for misunderstandings. In the elicitations, every effort should be made to avoid bias in the questioning, to probe for the technical basis for the interpretations, and to maintain flexibility such that a variety of approaches could be used by experts to arrive at their interpretations.

Documentation of the elicitations is essential to the credibility of the assessment and should include the expert's assessments of SSC characteristics, the uncertainties associated with the characteristics, and the technical basis for the assessment. Documentation can be accomplished in different ways. The TFI can prepare a written record of the elicitation during the interview and provide it to the expert for his review and approval following the elicitation. The experts can themselves prepare a written summary of their assessment prior to or following the elicitation session. Experience has shown that the former approach, which places the logistical burden on the TFI and the technical burden on the expert, is most effective in maintaining the pace of a seismic hazard analysis.

More specifically, the experts also were asked to give their opinions regarding the manner in which SSC information should be elicited from them and their level of comfort for different techniques. For example, the experts were asked whether they felt more comfortable providing their own *parameter values* or specifying a *methodology* for calculating parameter values (and allowing the TFI to calculate the values). The answers to this question were mixed; some experts prefer to do the calculations themselves, while others feel comfortable selecting methodologies and examining the calculated results. It was noted that their preference could be related to the amount of time and resources provided to the experts to do their own calculations. Another question was asked

regarding a preference for expressing parameter uncertainties as continuous probability distributions or as discrete values with weights. Again, the response was mixed and expressed personal preferences. In cases where continuous distributions are provided, there was strong sentiment to provide very simple representations (e.g., triangular distributions) and not to be forced to quantify the extreme tails of the distribution. It was felt that the present level of knowledge about SSC parameters is not sufficient to provide a reasonable `level of comfort' in expressing these tails.

Number of Experts and Technical Support

The issues here are the optimal number of SSC experts that might be required for a seismic hazard analysis and the level of technical support that should be provided. As discussed below in the context of aggregation, the criteria and process for selecting the experts were considered to be very important as well. In general, the experts felt that the number of experts cannot be rigidly defined but should, in any case, be sufficient to span the full range and diversity of interpretations. This can vary by whether the seismic hazard analysis is being conducted for a large region (whereby the range of geographic expertise may require more experts) versus a site-specific evaluation (whereby few experts may actually exist). A related issue is the amount and quality of data that have been gathered for the SSC assessment (e.g., a site-specific analysis for which there exists a site-specific data base may require fewer experts to interpret the data for SSC purposes).

In addition to the experts whose judgments are elicited, it is also desirable to involve technical specialists as resources. The specialists can make technical presentations at workshops and participate in interactions regarding new data, interpretations, etc. The experts recognized that the involvement of these specialists can be expensive, but they also expressed a comfort level that is reached when scientific researchers summarize their most recent findings to the experts prior to their formulating their SSC interpretations. As an example, a geologist conducting paleoseismic investigations at a particular location in the EUS could summarize his findings at a workshop devoted to methods for assessing earthquake recurrence. Through discussions with the specialist, the SSC experts would be brought up to date with the latest findings and could ask specific questions that relate to the uncertainties and degree of confidence that the researcher places in the results.

Availability of Data Bases

The issue is the degree to which SSC-related data bases should be made available to the experts and, if so, the format of those data. All of the experts concluded that any seismic hazard analysis should strive to make data available to the SSC experts. It is recognized that for more modest studies, it may only be possible to compile existing data (e.g., reprints of published articles). Nevertheless, every effort should be made to get a uniform data base to all of the experts so that differences in SSC interpretations are due to true differences in interpretation and not due to differences in available data. It is also recognized that regional studies may require different data sets (e.g., regional earthquake catalogs) than site-specific studies (e.g., regional seismic network data). In all cases, the project should attempt to provide the data in a format that the experts are most comfortable with. An example was given that reams of computer output listing historical earthquakes is often not a useful way of providing catalog data. Early in the project, preferably at a workshop devoted to data needs, the experts can identify the key data bases that will be needed to address important SSC issues. This is also an opportunity to specify data formats and any data processing that the experts may request to have carried out for them.

Most of the experts agreed that the earth sciences are entering a new era of data and information exchange that can radically improve the problem of dissemination and formatting of multiple SSC-related databases. For example, many data sets such as earthquake catalogs and geophysical data are amenable to compilation on Geographic Information Systems (GIS). Because GIS-type formats allow for variable representations of the data (e.g., map scales can be specified by each user), they can be very useful for the experts. An additional need is the ability to have the data bases in a form that is interactive, such that they can be searched, processed, or otherwise interpreted. Electronic mail systems such as the Internet and data provided on CD-ROM are becoming highly efficient vehicles for transferring large databases at reasonable cost and should be considered for future SSC studies.

Some experts expressed a desire that, because of improved efficiencies in the compilation and transfer of data, *both* unprocessed and, where appropriate, processed data should be provided to the experts. The procedures used in data processing should be explained fully to the experts. Examples given were geophysical data where various types of

frequency filtering may be accomplished, and earthquake catalogs where corrections to earthquake magnitudes may be carried out.

Seismic Source Maps

The issue is the technical basis for defining seismic sources, the usefulness of allowing seismicity parameters to vary within a zone, and the possibility that `consensus' seismic source maps might be developed. It was agreed by all of the experts that the process of identifying the geometry of seismic sources (particularly in the EUS) is highly interpretive and subject to the criteria each expert feels are most appropriate. The experts cited a wide range of data that they use to interpret seismic sources, including: historical seismicity data, paleoseismic data, geophysical anomalies, tectonic maps showing faults and other evidence for deformation, presence of inferred or observed geologic features that serve as stress concentrators such as fault intersections and rifts, geomorphic anomalies, GPS (global positioning system) and geodetic measurements of crustal strain, plate tectonic models, etc.

It was emphasized that a clear definition should be provided (presumably by the expert defining his/her sources) as to what criteria are being used. For many experts, the principal criterion for deciding whether or not a seismic source boundary is required is the assessment of whether there is a change in the maximum earthquake magnitude (Mmax) from one region to another. Inasmuch as changes in, say, the tectonics from one region to another might lead to a change in Mmax, the tectonics can then be used to help define seismic source boundaries. Some experts would use a criterion of significant changes in any of the seismicity parameters (i.e., a, b, or Mmax). In these cases it would be useful to provide to the experts a map of the a and b-values across a region, say for one-degree cells, as a help in defining source boundaries. Most experts felt that the SSC methodology should have the flexibility to allow for variation of a and b-values within a given seismic source, with variable degrees of smoothing of the parameters.

Some recent reviews of probabilistic seismic hazard analysis have criticized the procedure as poorly constrained, citing the wide variation in seismic source geometries in the EUS as symptomatic of the lack of any clear understanding of earthquake processes in this region. A possible mechanism for dealing with the issue might be to develop a single `consensus' map (or a small number of maps) that either represents a single interpretation

that all experts can agree upon or that represents an integration of individual maps developed by experts. This concept was explored at the workshop. The general conclusion was that, at the present time, our understanding of earthquake sources in the EUS is not sufficient to allow for the development of such a map. It was noted that in more active tectonic environments, such as coastal California, single seismic source maps were feasible. But even here uncertainties in the locations of buried or blind faults, and sources having uncertain activity such as the Cascadia subduction zone, would lead to different interpretations.

Likewise, it was concluded that there is no efficient way to "mechanically integrate" alternative seismic source maps to arrive at a single map (noting, of course, that the seismic hazard analysis in fact integrates the maps at the ground motion level). The reason for the different source configurations is, in fact, different scientific interpretations of what controls the spatial distribution of future seismicity. In most cases, the pattern of observed seismicity has a strong influence on the shape of seismic sources. However, tectonic information is also believed to be important and subject to variable interpretations. The method used in the EPRI study whereby individual tectonic features were evaluated for their probability of activity was cited as an effective procedure for encouraging experts to make explicit their consideration of tectonic information. It was concluded that each expert should attempt to document the technical basis for each seismic source and the criteria and data that were used, and that flexibility in the methodology should be maintained such that variations in seismicity parameters within a given seismic source can be allowed.

The experts expressed variable preference for quantifying their uncertainties in seismic source interpretations by either: specifying alternative source boundaries each with an associated weight, or specifying global alternative maps for a region each with an associated weight. Both approaches appear to be effective at quantifying the uncertainties in source geometries for regional seismic hazard studies.

Seismicity Parameter Assessments and Feedback

The issue is the procedure for eliciting seismicity parameters (a,b, Mmax) and the types of feedback and sensitivity analyses that should be provided to the experts to assist in their assessments.

When asked about the methods for assessing earthquake recurrence, the experts noted that the primary data base for the assessment is the historical earthquake record. Because of its importance, the need to process the catalog for recurrence evaluation carefully was discussed, including uniform identification of earthquake magnitudes, catalog completeness, removal of dependent events, etc. It was noted that paleoseismicity data, although only available at a few localities in the EUS, can be extremely important in establishing the recurrence rate of large, damaging earthquakes. Likewise, fault slip rate data, if available, provide a possible constraint. Many of the experts felt that the installation of a wide-scale geodetic network (GPS) system in the U.S. will eventually allow the use of crustal strain data to characterize recurrence rates within the more active portions of the EUS.

In terms of recurrence parameter assessments, the experts expressed different preferences for assessments of a-values and b-values (and their correlation) or assessments of recurrence intervals for particular earthquake magnitudes. It was concluded that both procedures should be made available to the experts and, after application of one approach by the expert, the alternative approach might be applied to provide a `check.' For example, the expert might specify his ranges of a-values and b-values and their correlation for a particular seismic source; the implied mean recurrence intervals for, say, moderate and large-magnitude earthquakes could then be calculated and provided to the expert as a check for consistency. In terms of recurrence parameters, some experts expressed a desire to do the calculations of the parameters themselves from the earthquake catalog; others would rather specify a methodology for calculation and allow the TFI to calculate the parameters, which they would then review. As noted previously, the experts felt that allowing for variations in a-values and b-values within a seismic source was an attractive option. No one felt that it was necessary to allow for variations in Mmax within a seismic source, and some felt that this would violate their basic definition of a seismic source.

Methods for assessing Mmax in the EUS are variable and rely heavily on expert judgment. Cited factors to consider when assessing Mmax for a seismic source include: historical seismicity, paleoseismicity including geomorphic evidence, dimensions of the source or tectonic feature, the 1,000-year earthquake magnitude, the type of tectonic feature or crust (e.g., rifts versus craton), and analogies to similar tectonic environments. An inherent difficulty in the assessment of Mmax is that it is intended in the hazard

analysis to be the maximum *possible* earthquake (i.e., the upper-bound truncation of the recurrence curve) and not an earthquake having a particular recurrence interval. It was noted that extensive research on the EUS maximum magnitude problem will be published by EPRI in the near future and should help in the assessments.

There was discussion of the types of feedback and sensitivity analyses that could be provided to the experts to help in their assessments. Most of these relate to providing a comparison of the assessed or `predicted' recurrence rates for a seismic source with the observed or historical seismicity. Although none of the experts felt that the predicted rates *must* match the observed rates, particularly given the usually inadequate number of observed events, any significant deviations from the observed rates should be fully understood and explained by the expert. Typical feedbacks might include a comparison of the predicted rates (including uncertainties) with the observed rates calculated over different subsets of the total seismicity catalog (e.g., the instrumental period, the historical period, different completeness periods, etc.). One expert suggested that perhaps a `predicted seismicity map' might be constructed for a region based on the assessed recurrence parameters; this map could then be compared with the observed seismicity map. In addition, it could be useful to see how different assumptions about recurrence parameters (say, variations in b-values) might affect the implied recurrence intervals for large-magnitude events in a region. This result might then be compared with paleoseismic recurrence intervals in the same region or with observed strain rates or seismic moment rates. Finally, it was suggested that it would also be helpful to see, for particular sites where seismic hazard is calculated, the degree of sensitivity that the calculated hazard has to variations in recurrence parameters.

Aggregation of SSC Assessments

The issue is the manner in which the individual assessments provided by multiple experts should be combined in order to calculate the seismic hazard. The active discussions covered such issues as applying weights and who does so, dealing with uneven expertise, component-level aggregation, and the role of expert interaction in achieving aggregation. Strong opinions were voiced on this subject and the salient conclusions are summarized below.

By their very nature, individual SSC assessments are difficult to combine. This is because the process begins with seismic source maps, which for the EUS are likely to be different. Then, because all of the subsequent parameters relate to the seismic sources identified initially, there is no easy way to compare or combine the interpretations expert to expert. As discussed above, consideration was given at the workshop to the prospect for developing consensus source maps or mechanically integrating alternative source maps, with the conclusion that such was not possible with some limited exceptions. Exceptions might include active portions of the WUS, very active sources in the EUS (e.g., the configuration of the New Madrid seismic source may be similar among multiple experts), and local site-specific hazard analyses where a very limited number of sources are being considered. Consequently, the potential for component-level aggregation at the seismic source level or recurrence parameters for particular sources is generally not possible. We are therefore left with the need to aggregate the SSC interpretations at the final level of the seismic hazard calculations. What rule, then, should be used to integrate the `entire' SSC assessments for each expert at the hazard level?

Most of the experts expressed the need (or requirement) to combine the SSC assessments using equal weights from expert to expert. Those expressing a desire or allowance for differential weights provided alternative mechanisms for doing so. One possibility is to allow for the experts to give themselves a relative weight that, in particular, might provide for a downweighting in a geographical area or discipline that is outside of the expertise of the expert. Importantly, this would not be a weight relative to the other experts but would be on a rating scale (of, say, 0 to 5) expressing the degree of expertise that the individual possesses in that area or discipline. Another alternative for differential weights might be to allow an independent panel to evaluate the experts on the basis of their `total performance' on the SSC assessment. This evaluation would not be of the experts' reputations or standing in the community, but of their input to the particular project in question. Finally, a provision could be made to allow for the TFI, an independent panel, or perhaps the expert himself/herself to assign zero weight to the assessment in those cases where the expert simply was not able to perform satisfactorily on the project (this could be due to a lack of motivation, unforeseen time constraints that prevented proper preparation, or expertise wholly outside of the realm of SSC).

Although variable degrees of adamancy existed, there was general consensus that the *goal* of the integration process, from the very start of the project, should be to assign equal weights to SSC expert assessments and to be in a strong, defensible position to do

so at the end of the project. Several mechanisms were discussed that would provide for this outcome, including:

- Selection of the experts: explicit selection criteria should be established at the beginning of the project that ensure the proper depth of SSC expertise, reputation in the scientific community, balance of technical views, and representation from alternative groups. Further, the project must be discussed in detail with the expert to ensure familiarity with the types of assessments that will be required for the SSC.

- Motivation and commitment: Each potential expert must be contacted to ensure that he/she is able and willing to make the appropriate commitment of time and effort to carry out the assessment. Potential expert should also be willing to discuss their technical views openly with their peers on the project.

- Dissemination of data: A key part of the SSC assessment should be the identification, compilation, and dissemination of all data bases that the experts will need to make their assessments. The data bases must be made available to all of the experts in uniform fashion. If specialized processing is requested by an individual expert, the results should be made available to the other experts as they desire.

- Education and training: Throughout the project, in the workshops and other meetings, effort should be devoted to reviewing data sets, scientific findings, and SSC-related methodologies and procedures. As appropriate, technical specialists should be invited to discuss their recent findings. In addition, training should be given to the SSC experts in methods for eliciting expert judgment. The goal should be to allow for each expert to supplement his prior training and to fill gaps in knowledge.

- Expert interactions: The interactions of experts in workshops, small working meetings, and in informal settings should be encouraged. The technical exchange of ideas and hypotheses, and the challenge of these ideas by peers, is a natural process familiar to scientists. The goal is not to suppress unorthodox ideas but to ferret out misunderstandings, gaps in

knowledge, reliance on outdated data, etc. This process will result in a `behavioral' aggregation of SSC interpretations.

- Allow to defer: SSC is a multi-disciplinary problem and, despite efforts to educate the experts in fields beyond their own experience, an expert may wish to decline addressing certain aspects of the SSC assessment. Provision should be made to allow him to do so in the elicitation. Gaps would have to be filled using `default' assessments, which must be explained to the expert.

- Post-elicitation interaction: Following the elicitations, the experts should be presented with the assessments made by the other experts, perhaps in a workshop setting. This will allow the experts to review the technical basis for the other assessments, review and discuss their own interpretations with their peers, and to review sensitivity analyses conducted for the assessments. Provision must be made to allow for a final modification of the SSC assessments prior to calculation of the final seismic hazard results.

APPENDIX I

SPATIALLY VARYING SEISMICITY AND ITS EFFECT ON SEISMIC HAZARD

I.1 INTRODUCTION

This Appendix illustrates the treatment of spatially varying seismicity parameters within a seismic source. We use examples from three sites to illustrate the seismicity parameters obtained under various smoothing assumptions, the corresponding epistemic uncertainty in seismicity parameters, and the resulting epistemic uncertainty in the computed seismic hazard. These results support the recommendations provided in Section 4.3.5.

Spatial variability in seismicity is important for large background sources, especially in sources with large contrasts in seismic activity or very low activity rates. We use the EPRI (1986) model of spatially varying seismicity because this model represents the most thorough treatment of this issue, including the calculation of epistemic uncertainty, and because this model was available to this study.

I.2 METHODOLOGY AND ILLUSTRATIVE EXAMPLES

I.2.1 Seismicity Parameters and Smoothing Assumptions

The EPRI methodology for the calculation of spatially varying seismicity parameters estimates separate values of parameters a[1] and b for each 1-degree sub-source contained in the source. The

[1]Parameter a is defined in the EPRI methodology as the decimal logarithm of the rate of earthquakes with $3.3<m_b\leq3.9$ per square degree. This definition (i.e., anchored at the lowest magnitude in the EPRI catalog) is preferable to the standard definition (anchored at magnitude 0), because there is little or no correlation between a and b when these parameters are estimated using maximum likelihood or regression.

resulting seismicity parameters may be viewed as maps of a and b within the source. The a and b values for the sub-sources are estimated using a penalized maximum-likelihood formulation. The likelihood function for all a and b values in the source is the product of the likelihood functions for the individual sub-sources, with each sub-source likelihood function calculated in the standard manner (e.g., Weichert, 1980). The likelihood function for the a and b values of a sub-source depend only on the earthquakes in that sub-source.

Spatial smoothness between adjacent sub-sources is introduced by multiplying the likelihood function by penalty functions of the form:

$$Q_a = \prod_i \exp\left\{ -\frac{W_a}{2} (a_i - \hat{a}_i)^2 \right\} \tag{I-1}$$

$$Q_b = \prod_i \exp\left\{ -\frac{W_b}{2} (b_i - \hat{b}_i)^2 \right\} \tag{I-2}$$

where the subscript i indicates sub-source and the quantities $\hat{a}_i$ and $\hat{b}_i$ indicate the average values of a and b in all sub-sources adjacent to sub-source i. Parameters W_a and W_b are the smoothing parameters for a and b; they control the amount of spatial roughness that is tolerated in the {a,b} maps. The penalty terms may be interpreted as prior distributions on the spatial roughness of a and b, with W_a and W_b being the reciprocals of the prior deviations from adjacent sub-sources. Large values of W_a and W_b indicate a strong belief that seismic activity is uniform throughout the source[2]. Lower values of W_a and W_b indicate a belief that not all portions of the

[2]The assumption of uniform seismicity implies that no portions of the source are more active than others. If this assumption were valid, a seismicity plot from a very long catalog would show a roughly uniform pattern of events. The assumption of uniform seismicity is <u>different</u> from the situation where the expert believes that seismicity may or may not be uniform, but does not have sufficient information to characterize the spatial variability of seismicity at a scale finer than the source's dimensions. The former assumption implies no epistemic uncertainty in the

earth's crust contained in the source are identical in their seismogenic characteristics, that some degree of spatial variation in seismic activity within the source is possible, and that the spatial distribution of historical seismicity provides information about that spatial variability. Multiple alternative values of W_a and W_b (referred to as multiple "smoothing assumptions") may be specified, in order to represent the expert's uncertainty about the proper amount of smoothing for a given source. Statistical tests of the type discussed in Section 4.3.5 aid the expert in the specification of smoothing parameters. Typically, more smoothness is specified for b than for a, because b is believed to be regionally stable.

The estimated {a,b} maps are obtained by finding the maps that maximize the penalized likelihood function. If both W_a and W_b are very large (say, 1000), one obtains the conventional homogeneous solution (i.e., constant a and b within the source). If both W_a and $W_b$are 0, the a and b values for each sub-source depend only on the seismicity within the sub-source and one obtains the same parameters that one would obtain by treating each sub-source as a separate source. Intermediate values of W_a and W_b yield solutions where the value of a and b within a source depend on both the seismicity within those sources and the seismicity in adjacent sources. The spatial roughness in the resulting maps of a and b depends on both the values of the smoothing parameters and the statistical significance of activity contrasts in the catalog.

The first example to be considered here is Bechtel's southern Appalachians background source from the EPRI (1986) study (the same source shown in Section 4.3.5). The geometry of this source and its seismicity are shown in Figure I.1; the three smoothing assumptions specified by the Bechtel team are shown in Table I.1

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within-source spatial distribution of the activity rate, the latter implies epistemic uncertainty. Because we wish to characterize both the epistemic and aleatory uncertainty in the hazard (See Section 2.2), it is important to consider this difference between uniform seismicity and the inability to specify a within-source spatial distribution of the activity rate.

Table I-1. Smoothing Parameters for Bechtel Background Sources

Assumption	Weight	Smoothing on a	W_a	Smoothing on b	W_b
1	1/3	Full	999	Full	999
2	1/3	Low	5	High	100
3	1/3	Low	5	Low	25

Figures I-2 through I-4 show the spatial distributions of the activity rate (m_b>3.3) and b value for the southern Appalachians source, under the three smoothing assumptions. For the last two smoothing assumptions, the ratio between the highest activity rate (near New York City) and the lowest activity rate (central Alabama) is approximately 30. For the last smoothing assumption, the values of b range from 0.8 to 1.1.

I.2.2. Effect of Spatial Variability on Seismic Hazard and its Epistemic uncertainty

The spatial variability of seismicity parameters within a seismic source affects the calculated seismic hazard, particularly for sites located within that source. Under the assumption of homogeneous seismicity (i.e., full smoothing), the hazard from a seismic source is the same for all sites located within that source and sufficiently far from the source boundaries, regardless of the actual distribution of historical seismicity within that source. Under partial or no smoothing, the hazard from a seismic source is not necessarily the same for all sites within that source (although the PSHA calculation in Eq. 2.2 involves some spatial weighting of activity rates). The effect of spatial variability in seismicity is incorporated in the hazard calculations by integrating separately the contributions from each sub-source within a source. These calculations are performed separately for the different smoothing assumptions, in order to quantify the sensitivity of seismic hazard to smoothing assumptions and the resulting epistemic uncertainty in the hazard

due to uncertainty about the proper smoothing assumption.

The assumptions about smoothing also have an effect on the statistical uncertainty in the estimates of the seismicity parameters a and b (another contributor to epistemic uncertainty). If one makes the conventional assumption of homogeneous seismicity (i.e., full smoothing), all the seismicity data within the source are used to estimate only two parameters; namely a and b for the entire source. One potential problem with assuming homogeneous seismicity is that any statistically significant deviations between the data and the homogeneous-seismicity model (i.e., lack of fit), such as the deviations shown in Figure 4.6, are not captured as epistemic uncertainty anywhere in the process. If spatial variability is introduced, and values of a and b are calculated for each sub-source, the number of independent parameters being estimated is greater than two, resulting in higher statistical uncertainty in these parameter estimates. Thus, the smoothing assumptions have an effect on the calculated statistical uncertainty in seismicity parameters[3].

Analytical quantification of statistical uncertainty in the seismicity parameters (for a given smoothing assumptions) and propagation of this uncertainty through the hazard calculation is not practical because of the complex correlation between the seismicity parameters of the sub-sources. We use a powerful, but computationally intensive, way to characterize this statistical uncertainty is by using a technique known as bootstrapping (Efron, 1982). The calculation of statistical uncertainty in the seismicity parameters, and the associated epistemic uncertainty in hazard, is performed in the following steps.

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[3]This paragraph would seem to suggest that one should assume homogeneous seismicity, whether this assumption is justified or not, because it leads to a lower epistemic uncertainty in the calculated hazard. The difficulty is that the conventional treatment of seismic sources in PSHA does not provide for a way to express uncertainty in whether or not a seismic source has truly homogeneous seismicity. The assumption of spatially varying seismicity thus appears to be penalized because it leads to higher uncertainty in the estimated parameters. If the data do not suggest homogeneity in seismicity, and the expert has no other reasons for assuming homogeneity (possible reasons might be based on the geological or geophysical homogeneity of a well-studied source, analogous regions, etc.), the uncertainties that arise when one allows for spatial variability are real and should be considered.

1. Generate artificial earthquake catalogs. Two approaches may be followed: empirical or parametric bootstrapping. In empirical bootstrapping, each artificial catalog is formed by selecting events at random (with replacement) from the historical catalog. In parametric bootstrapping, a map of a and b is first calculated using the actual catalog and penalized maximum likelihood. Then, artificial catalogs are generated from the stochastic recurrence model defined by the calculated {a,b} map, using a Monte Carlo approach. Empirical bootstrapping has the advantage that it does not rely on parametric assumptions (e.g., stationary Poisson occurrences), but has the disadvantage that no artificial events will ever occur in a sub-source with no historical events.

2. Calculate one map of a and b within the source for each artificial catalog, using the maximum penalized likelihood procedure described earlier.

3. Calculate seismic hazard for each {a,b} map obtained in step 2.

4. Calculate summary statistics to display the effect of statistical uncertainty on the estimated seismicity parameters and on the hazard.

These calculations were performed for the southern Appalachians background source. Fifty artificial catalogs were generated using parametric bootstrapping, for the three smoothing assumptions in Table I-1. Figures I-5 through I-7 show the standard deviations in a and b obtained for the three smoothing assumptions. Because the activity rate (m_b>3) is proportional to 10^a, the coefficient of variation of the rate is approximately equal to the standard deviation of a times ln(10)=2.3. Comparing Figures I-5 to I-6 and I-7, we see that statistical uncertainty in a is much higher under low smoothing than under full smoothing, especially for the sub-sources with very low activity rates. Comparing Figures I-6 and I-7, we see similar results for statistical uncertainty in b.

Seismic hazard calculations were performed for two sites located in this background source (step 2 above). For the sake of computational efficiency, only the hazard contributed by this

background source is considered. The first site considered is Washington, D.C. (38.9°N, 77.04 °W), which is located in an area of low seismicity, but is not far from areas of higher activity (particularly the Central Virginia seismic zone). Figure I-8a through c show the calculated hazard under the three alternative smoothing assumptions given in Table I-1. The spread between the fractile curves represent the effect of statistical uncertainty in a and b[4]. Figure I-8d shows the sensitivity of the median hazard to the various smoothing assumptions; this sensitivity introduces epistemic uncertainty because the team was uncertain about the proper smoothing assumption. Figure I-8e shows the total epistemic uncertainty in the hazard due to seismicity parameters (including both statistical uncertainty in a and b and epistemic uncertainty in the smoothing parameters). This figure may be compared to Figure I-8f, which shows the total epistemic uncertainty in the hazard[5] (due to epistemic uncertainty in seismicity parameters, maximum magnitude, and attenuation equations). This comparison shows that, in this case at least, epistemic uncertainty in seismicity parameters is a small contributor to the total epistemic uncertainty in hazard for this site. Even if an expert had specified low smoothing on a and b as the only smoothing assumption, the contribution of epistemic uncertainty in seismicity parameters to the total epistemic uncertainty in hazard would be small.

Washington, D.C., is located near a sub-source corner. Thus, four sub-sources contribute significantly to the hazard. Calculations were also performed for a nearby hypothetical site in the middle of the same sub-source (38.5°N, 77.5 °W) to investigate the sensitivity of the above results to location within a sub-source. Differences between the two locations were small.

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[4]The uncertainties due to maximum magnitude and attenuation equations were removed from the hazard results by averaging all hazard curves obtained using the same smoothing assumption and artificial catalog, but with different maximum magnitudes and attenuation equations. The scatter that remains (among average hazard curves) represents uncertainty due to smoothing assumptions and/or seismicity parameters. This averaging procedure preserves the mean hazard curve, but distorts the median.

[5]These calculations used the maximum-magnitude distribution specified by Bechtel for this source (5.7[0.1], 6.0[0.4], 6.3[0.4], 6.6[0.1]) and the ground-motion epistemic uncertainty in the EPRI(1993) ground-motion model.

The second site considered is located in central Alabama (32.5°N, 86.5 °W), in an area of very low seismicity (only two events in the host sub-source and adjacent sub-sources) near the SW corner of the same background source. Results are presented in Figure I-9a through f. Unlike the Washington, D.C. case, the epistemic uncertainty due to seismicity parameters is a large contributor to epistemic uncertainty in the hazard.

The third site considered is located in central Minnesota (44.5°N, 89.5 °W), in a low-seismicity portion of Bechtel's Northern Great Plains background source (Figure I-10). Hazard results are shown in Figures I-11a through f[6]. Comparison of Figures I-11e and f shows that epistemic uncertainty in seismicity parameters is a moderate contributor to the total epistemic uncertainty in hazard for this site. Rough calculations suggest that ignoring epistemic uncertainty in seismicity parameters (both statistical uncertainty and epistemic uncertainty in smoothing parameters) would result in approximately a moderate reduction in the epistemic uncertainty in hazard (in the form of a 25% reduction in the distance between the median and 85-percentile hazard curves in Figure I-11f).

I.3 DISCUSSION AND SUMMARY OF RESULTS

The results shown here illustrate one approach for the treatment of spatially varying seismicity within a seismic source, and the implications of that treatment on seismic hazard and its epistemic uncertainty. These results support the recommendations in Section 4.3.5. A number of additional insights can be drawn from these results. These insights are useful for deciding how to treat seismicity in a large background source.

Results indicate that the smoothing assumptions may have a significant effect on the hazard from

[6]These calculations used the maximum-magnitude distribution specified by Bechtel for this source (5.4[0.1], 5.7[0.4], 6.0[0.4], 6.6[0.1]) and the ground-motion epistemic uncertainty in the EPRI(1993) ground-motion model.

large background sources that contain the site and have non-uniform spatial patterns of seismicity. These effects are most important when the site is located on a large patch of very low or no seismicity (e.g., the Alabama and Minnesota sites).

If the assumption of homogeneous seismicity is relaxed, allowing for some spatial variation of seismicity parameters within the source, the statistical uncertainty in the seismicity parameters is increased. This increase is moderate if high smoothing on b is specified, but becomes large if low smoothing on b is specified. The latter effect is generally ameliorated in practice by the tendency to specify more smoothing for b than for a (or by giving a low weight to the assumption of low smoothing on b, as done in the examples considered here), because it is believed that b is more spatially uniform. On the other hand, b may not be stable at the scale of individual faults within the seismic source, if those faults have characteristic magnitudes (as postulated by Schwartz and Coppersmith, 1984, and Wesnousky, 1995, among others).

For the three sites and smoothing assumptions considered here, the sensitivity of the hazard to smoothing assumptions provides an indication of the epistemic uncertainty in hazard due to statistical uncertainty in seismicity parameters. Moreover, the epistemic uncertainty due to smoothing assumptions is roughly half the total epistemic uncertainty due to seismicity (i.e., the epistemic uncertainty due to both smoothing assumptions and statistical uncertainty in parameters).

The three examples considered here did not include a site in a high-seismicity portion of the background source (e.g., New York city). One can anticipate, however, that the effect of smoothing assumptions will be comparable to that at the lower-seismicity sites, but the effect of statistical uncertainty will be lower.

All calculations shown here considered PGA. Calculations for 1-Hz spectral velocity were also performed at one of the sites. Results indicate that the epistemic uncertainty in hazard due to seismicity parameters is slightly smaller for 1 Hz than for PGA. This suggests that the reduction in epistemic uncertainty associated with more spatial averaging (due to the slower attenuation of

1-Hz energy with distance) compensates for the increase associated with more sensitivity to larger magnitudes (whose recurrence rates are more uncertain).

The hazard results presented here relate to one background source. At many sites, sources other than the background source make significant contributions to seismic hazard. Thus, epistemic uncertainty in the seismicity parameters for a background source may not be an important contributor to the total epistemic uncertainty in the hazard at a site, even if it is an important contributor when only the background source is considered. On the other hand, there are sites (like the Minnesota site and many other sites in the upper Midwest) where the background source is the dominant contributor to hazard for PGA and for other high-frequency measures of ground motion. The recommendations in Section 4.3.5 provide conservative guidance regarding the need to consider spatial variability for a background source depending on that source's contribution to the total hazard. Additionally, one may apply the procedure in Tables G-2 through G-4 (see Appendix G) to decide whether to consider spatial variability for a background source.

These insights are based on calculations for one expert team and a limited number of sites, but are believed to be typical. Also, the calculated epistemic uncertainties are based on certain modeling assumptions (particularly the assumption of Poisson, independent, exponential [PIE] earthquake occurrences). The uncertainties would be higher, for example, if earthquake occurrences followed an on-off process (e.g., Bender, 1984; Coppersmith, 1988).

I.4 ALTERNATIVE MODELS

An alternative approach for the treatment of spatially varying seismicity has been developed by the USGS for national seismic-hazard mapping (Frankel, 1995; Frankel et al., 1995). This approach simply assigns to each sub-source an activity rate computed as a weighted average of rates in that sub-source and nearby sub-sources, using a weighting function (or kernel) with a correlation distance of 50 km. An important difference between the USGS approach and the EPRI approach used here is that the USGS approach introduces smoothness without regard for

the statistical significance of seismicity contrasts. The following example clarifies this distinction. Suppose there is a group of nearby sub-sources 1, 2, 3, 4, ... m, with earthquake counts n_1, n_2, n_3, n_4, ... n_m , where the n_i's are of the order of 0 to 5. Suppose that the USGS smoothing procedure assigns to these sources the smoothed activity rates s_1, s_2, s_3, s_4, ... s_m. Consider another group of sub-sources with earthquake counts $10n_1$, $10n_2$, $10n_3$, $10n_4$, ... $10n_m$. The USGS smoothing procedure would apply the same smoothing weights to both sets of earthquake counts and would assign the smoothed activity rates $10s_1$, $10s_2$, $10s_3$,$10s_4$, ... $10s_m$ to the second set of sources. The EPRI procedure (with partial smoothing) would, on the other hand, perform more smoothing on the first set of sub-sources because seismicity contrasts in the first set of sub-sources have less statistical significance than contrasts in the second set of sub-sources. In terms of the penalized likelihood formulation, the sub-source likelihood functions for the second set are more peaked (because more data are available) and the optimal solution is therefore influenced more by the sub-source likelihood functions and less by the (smoothing) penalty functions.

Another important difference in the way the EPRI and USGS approaches to spatial variability have been used relates to the treatment of seismic source zones and source boundaries. The EPRI approach has been used mainly to characterize seismicity <u>within</u> a seismic source zone. In contrast, the USGS approach has been applied over the entire central and eastern U.S., without considering any seismic source zones. This fundamental methodological difference about the validity of seismic source zones is not, however, inherent to the smoothing approaches. The penalized-likelihood-based EPRI model of spatial variability can be applied without source boundaries (treating the whole CEUS as one large source), and the kernel-based USGS smoothing approach can be used within a seismic source (after straightforward correction for edge effects).

The EPRI approach presented above considers spatial variations in seismicity over distances of 50 to 100 km. A model that considers variations in seismicity over a smaller spatial scale has been proposed by Wu and Cornell (1993). In this model, the activity rate within a background source is itself presumed to be a stochastic point process (i.e., the spatial distribution of activity rate within a background source is made up of scattered spikes reflecting active features). Future

earthquakes will only occur where past earthquakes have occurred and in other, still undetected, discrete locations. According to this model, if the seismicity catalog were infinitely long and all earthquake locations were sufficiently accurate, one would observe all events clustering into a relatively small number of active points on the background source, without ever filling up the entire source. This model constitutes an interesting limiting case, corresponding to zero spatial correlation in seismicity. The physical and empirical validity of models of this type, and their implications on the calculated hazard and its epistemic uncertainty, should be explored further. These issues may be important at sites where the seismic hazard is controlled by background sources.

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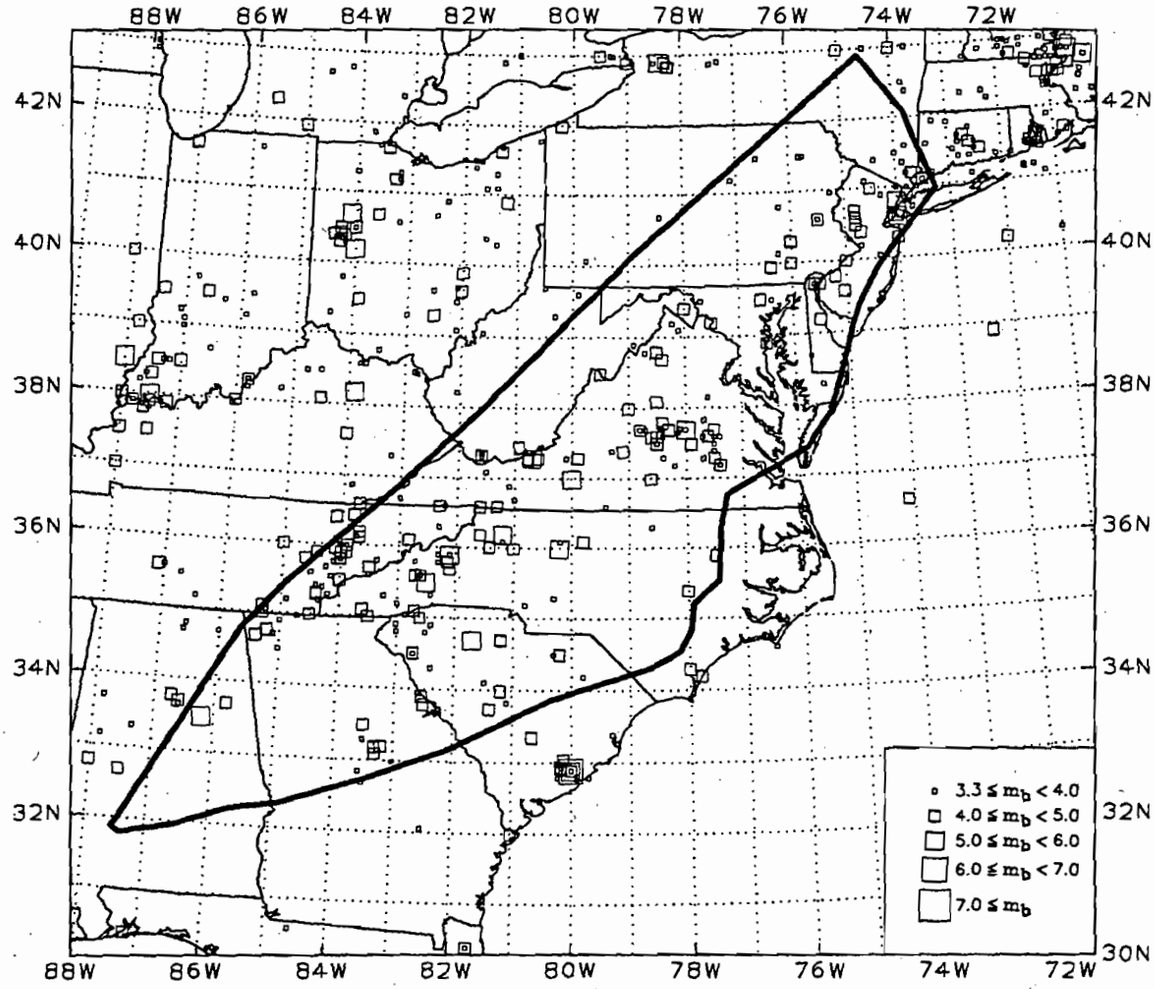


Figure I-1. Map showing the Bechtel background source for the southern Appalachians and the historical seismicity in the EPRI catalog.

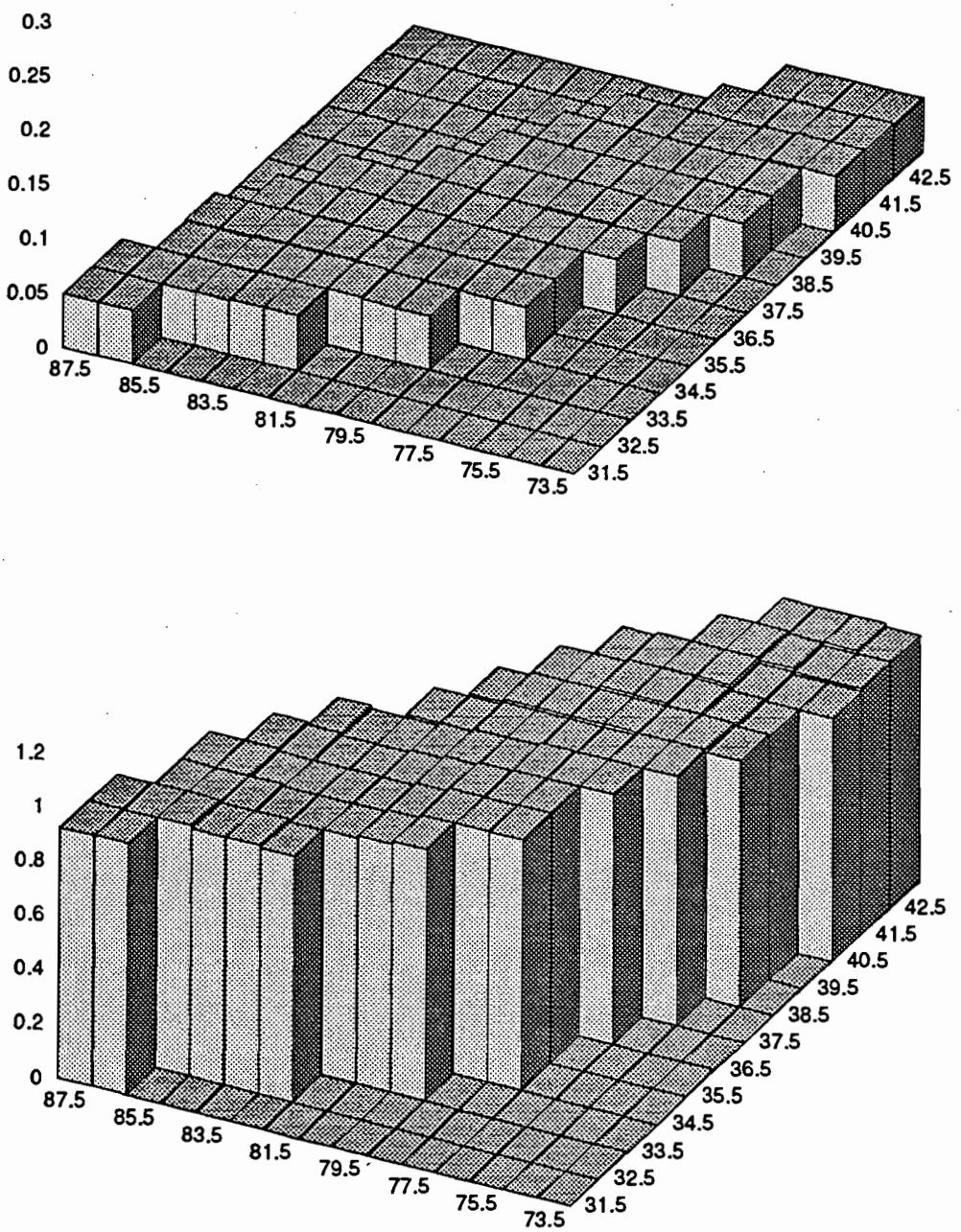
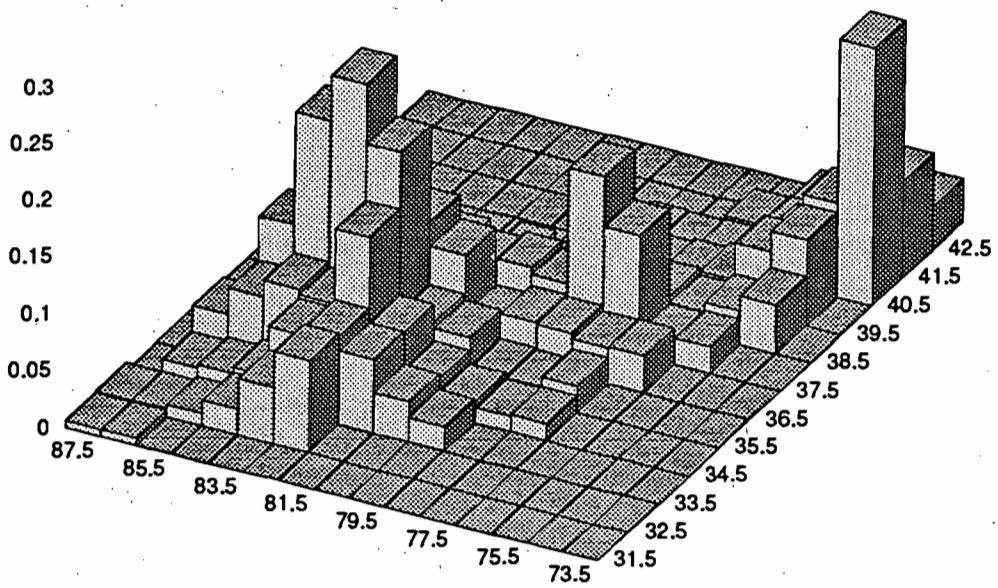


Figure I-2. Spatial distributions of rate (m_b>3.3) per unit area (events/yr/deg^2; top) and *b* value (bottom) for the background source in Figure I-1. First smoothing assumption.



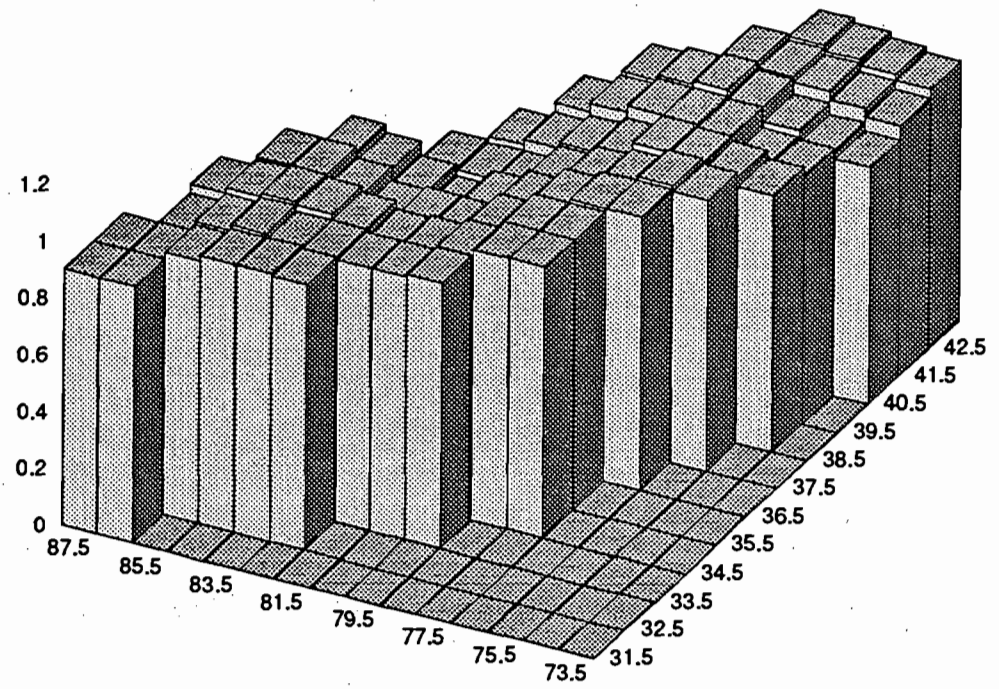
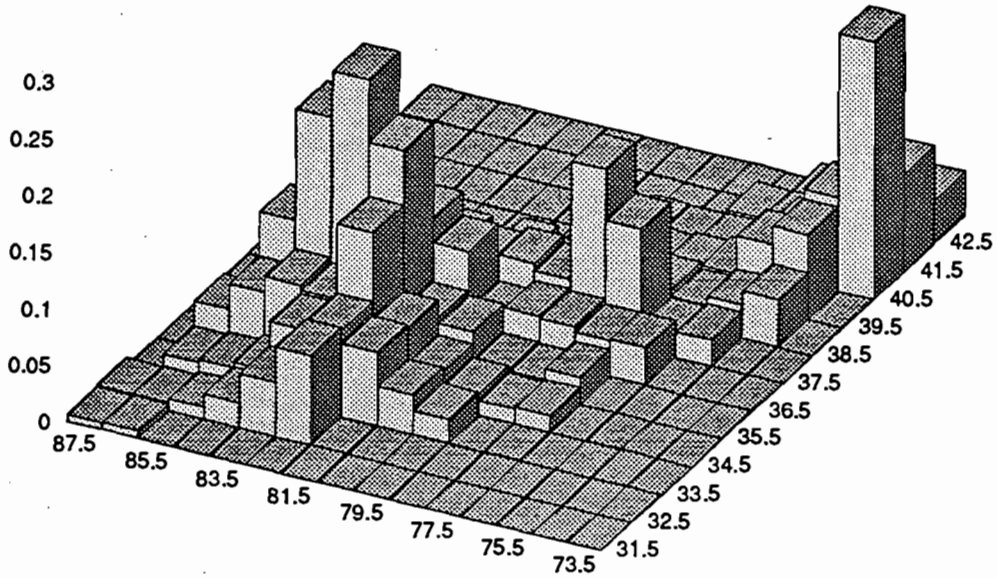


Figure I-3. Spatial distributions of rate (m_b>3.3) per unit area (events/yr/deg^2; top) and *b* value (bottom) for the background source in Figure I-1. Second smoothing assumption.



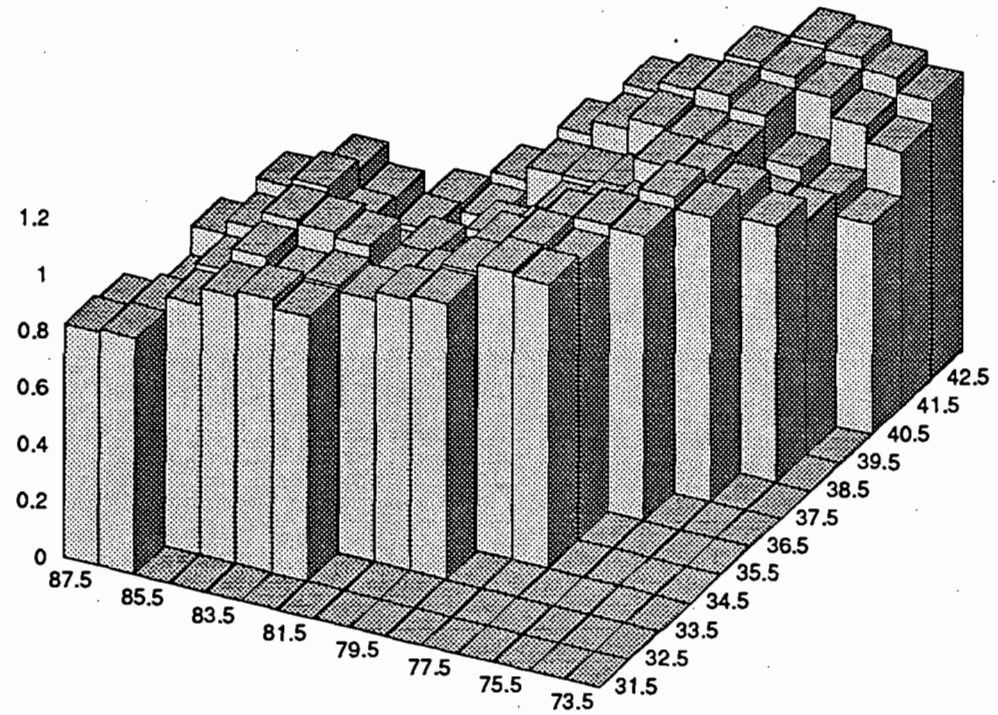
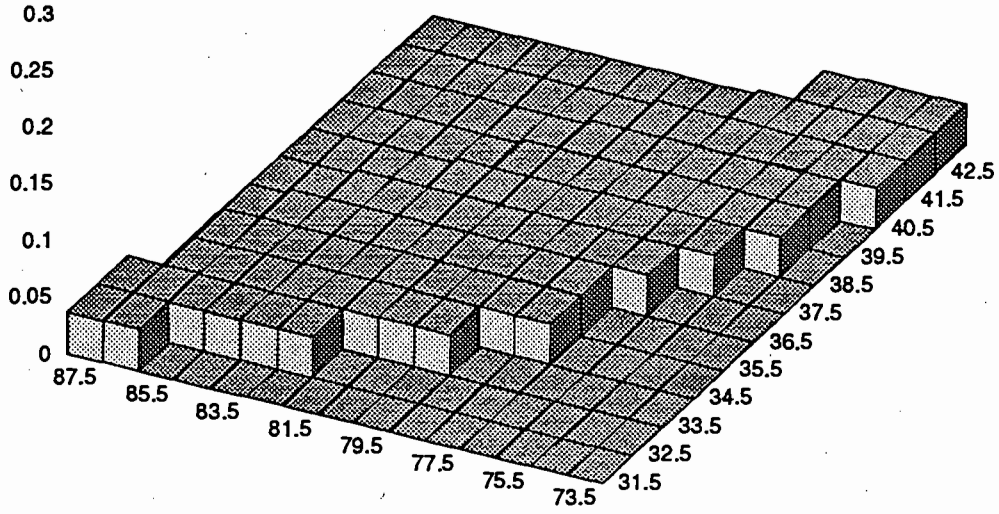


Figure I-4. Spatial distributions of rate (m_b>3.3) per unit area (events/yr/deg^2; top) and *b* value (bottom) for the background source in Figure I-1. Third smoothing assumption.



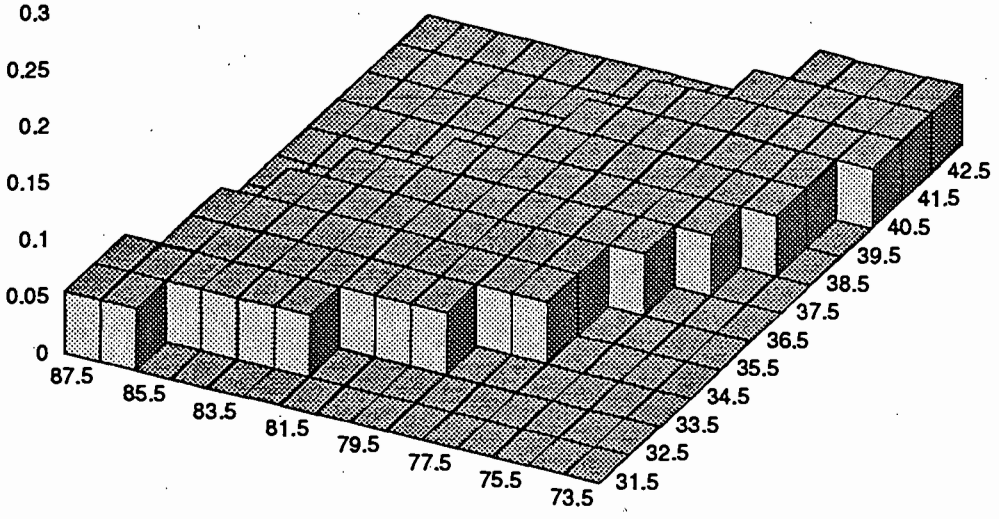
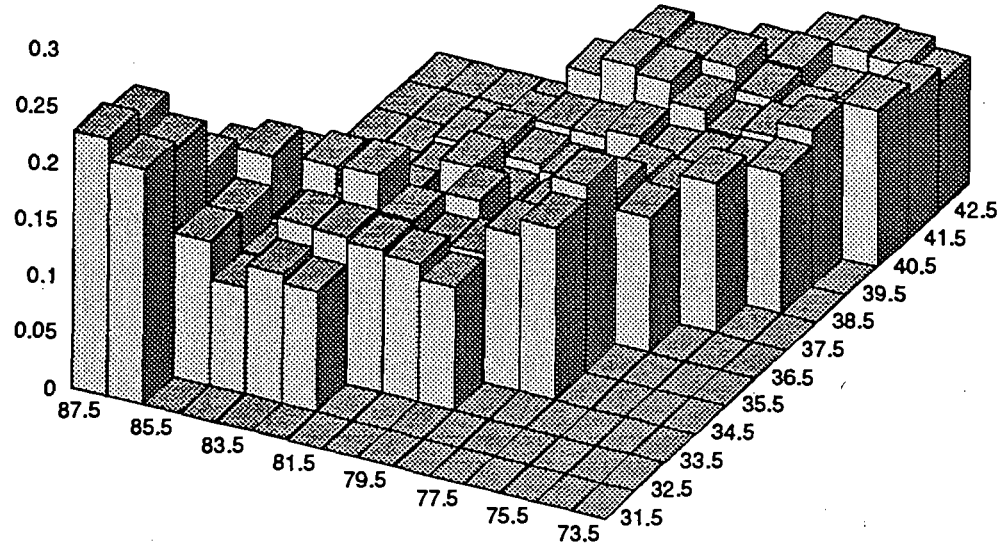


Figure I-5. Spatial distributions of the standard deviations of the *a* (top) and *b* (bottom) values for the background source in Figure I-1. First smoothing assumption.



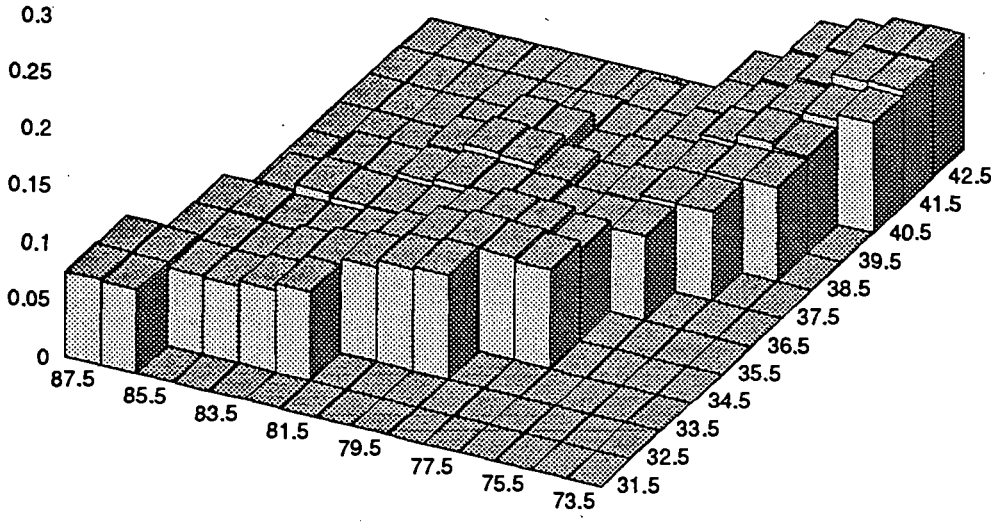
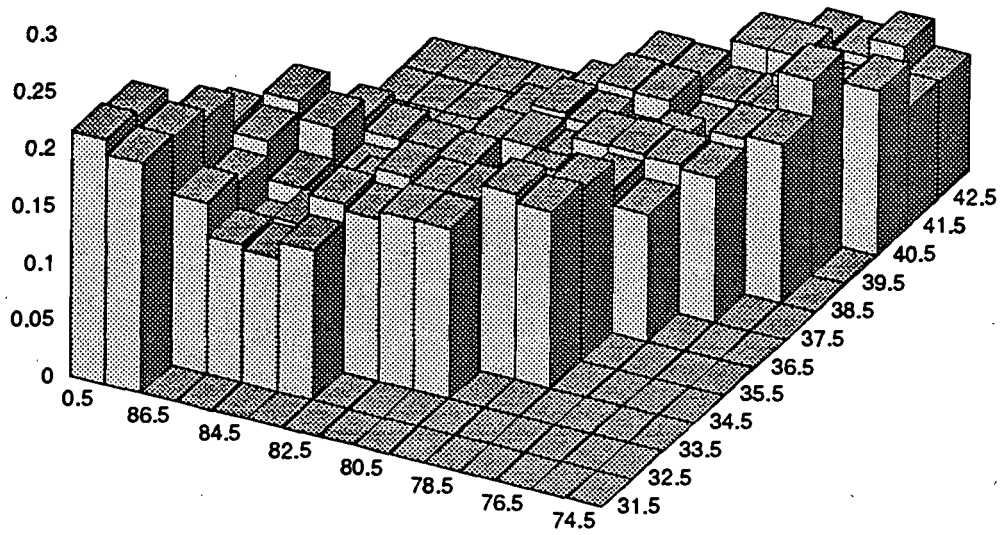


Figure I-6. Spatial distributions of the standard deviations of the *a* (top) and *b* (bottom) values for the background source in Figure I-1. Second smoothing assumption.



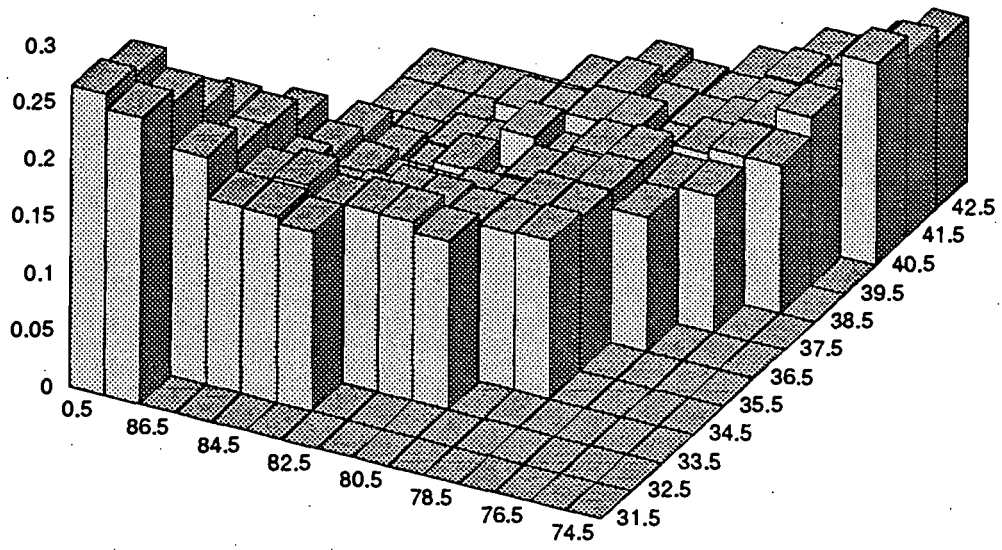


Figure I-7. Spatial distributions of the standard deviations of the *a* (top) and *b* (bottom) values for the background source in Figure I-1. Third smoothing assumption.

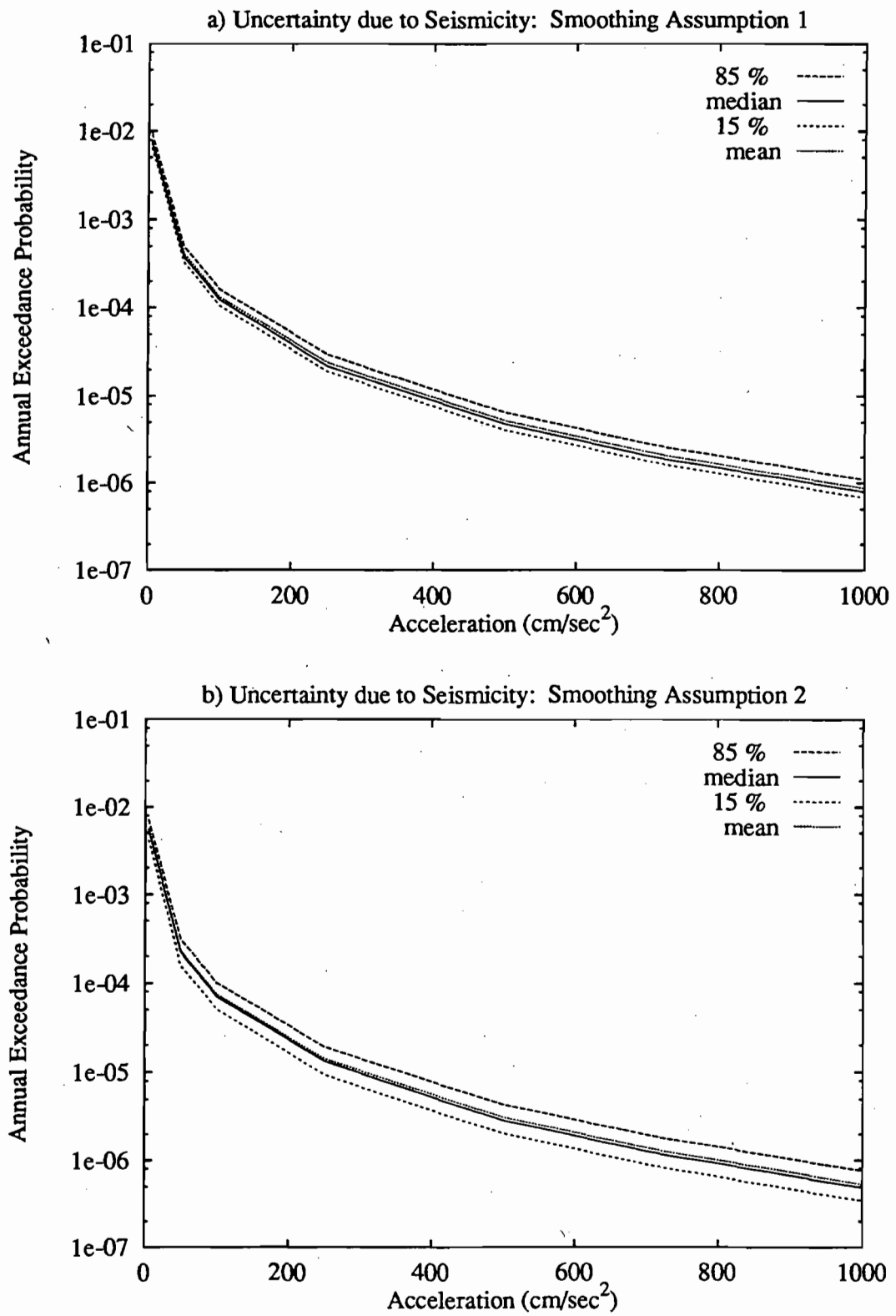
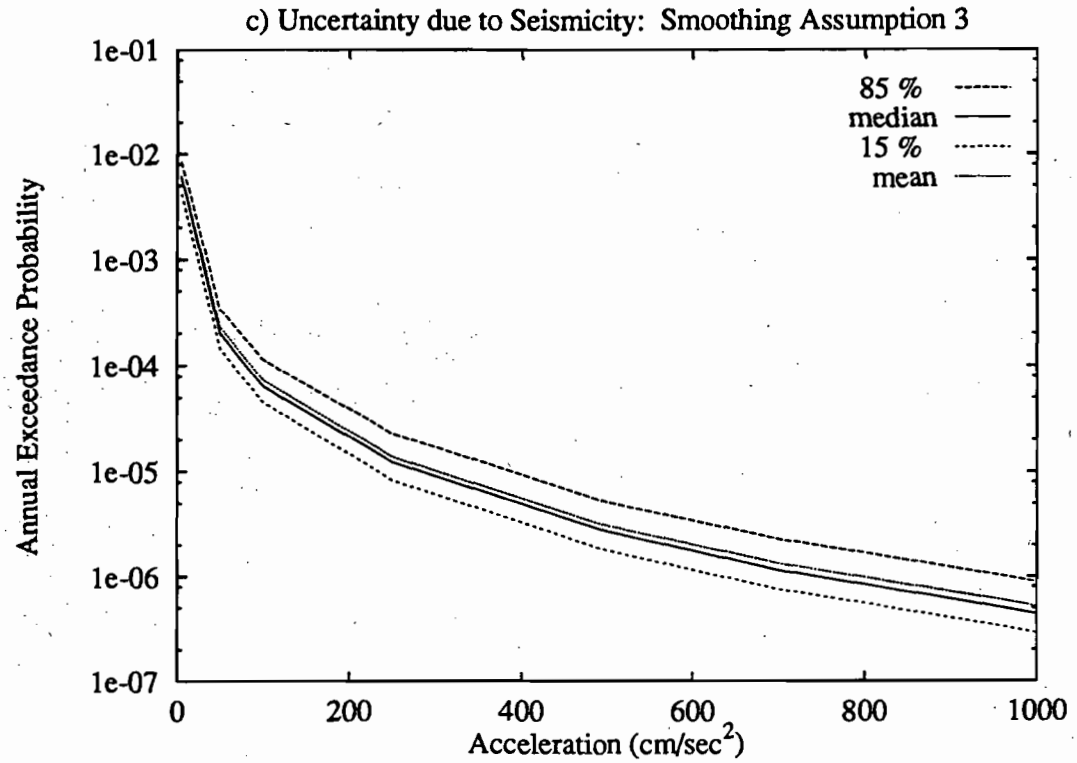


Figure I-8. Seismic hazard results for Washington, D.C. site. (a) Hazard under smoothing assumption 1. (b) Hazard under smoothing assumption 2. Fractiles indicate effect of statistical uncertainty in seismicity parameters.



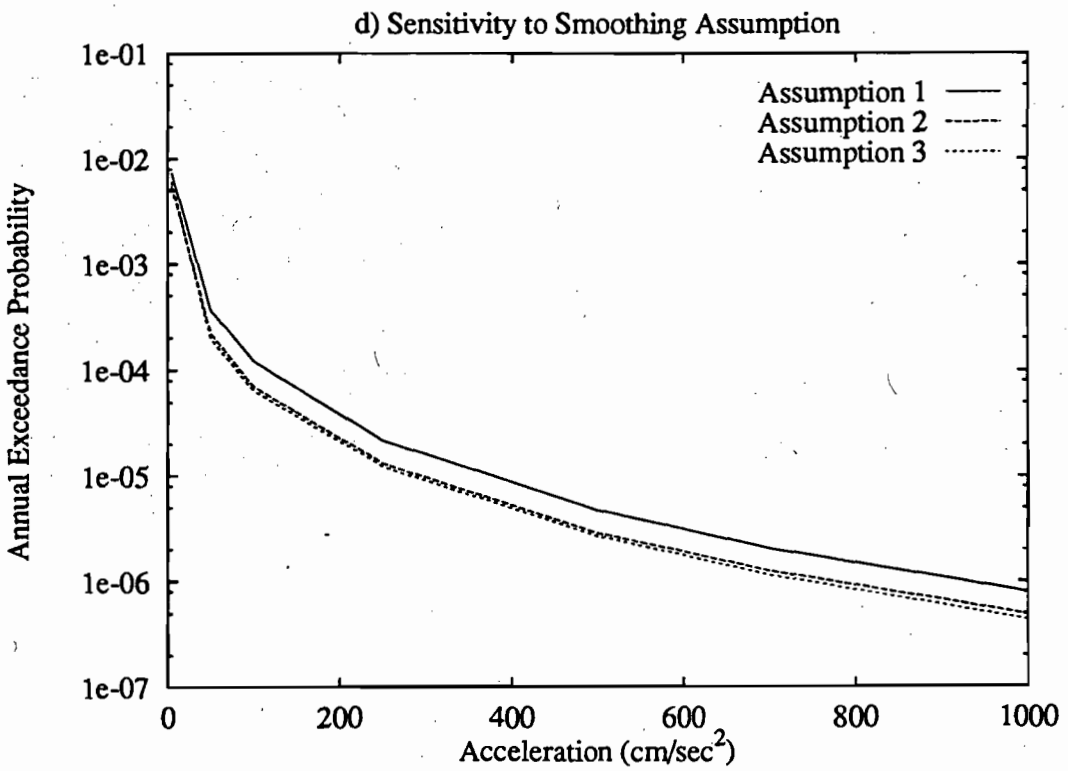
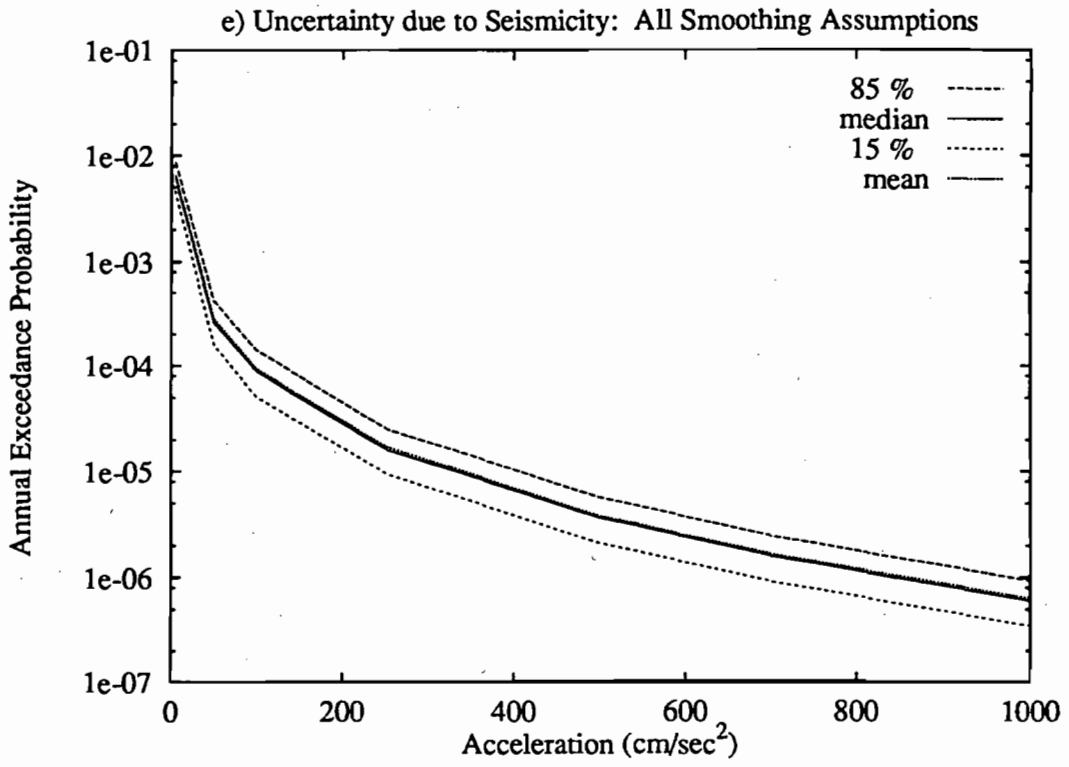


Figure I-8 (continued). Seismic hazard results for Washington, D.C. site. (c) Hazard undersmoothing assumption 3. (d) Sensitivity of the hazard to smoothing assumptions.



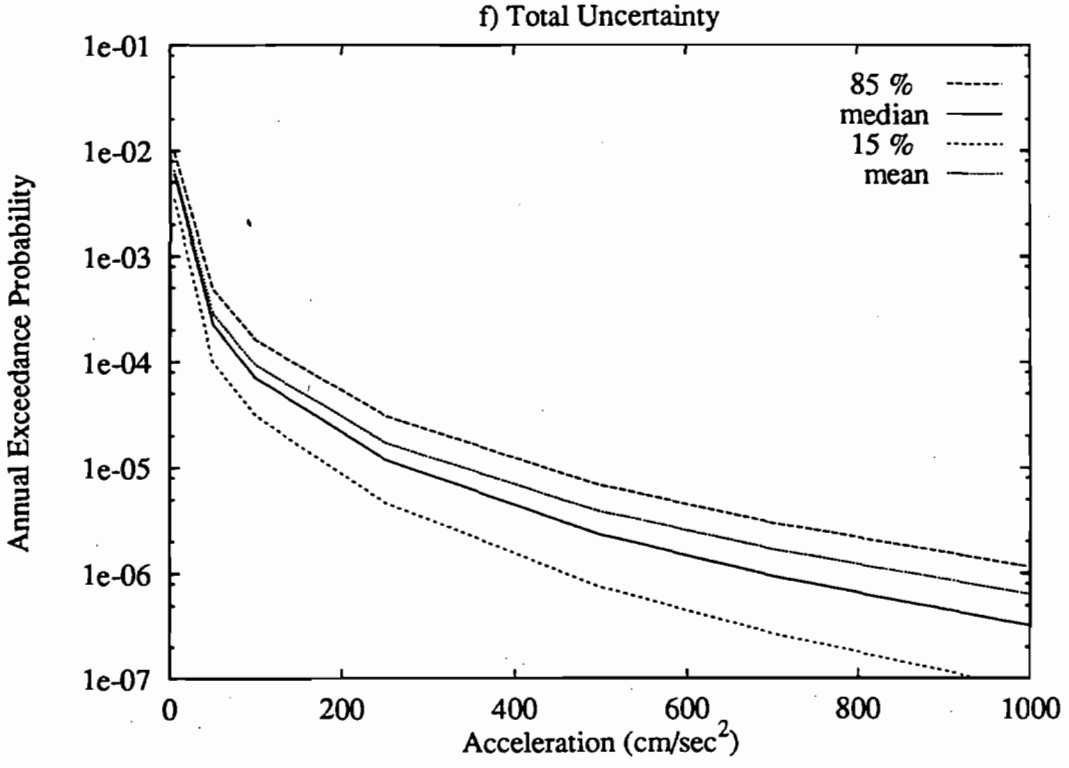


Figure I-8 (continued). Seismic hazard results for Washington, D.C. site. (e) Uncertainty due to smoothing options and statistical uncertainty in seismicity parameters. (f) Total uncertainty in hazard.

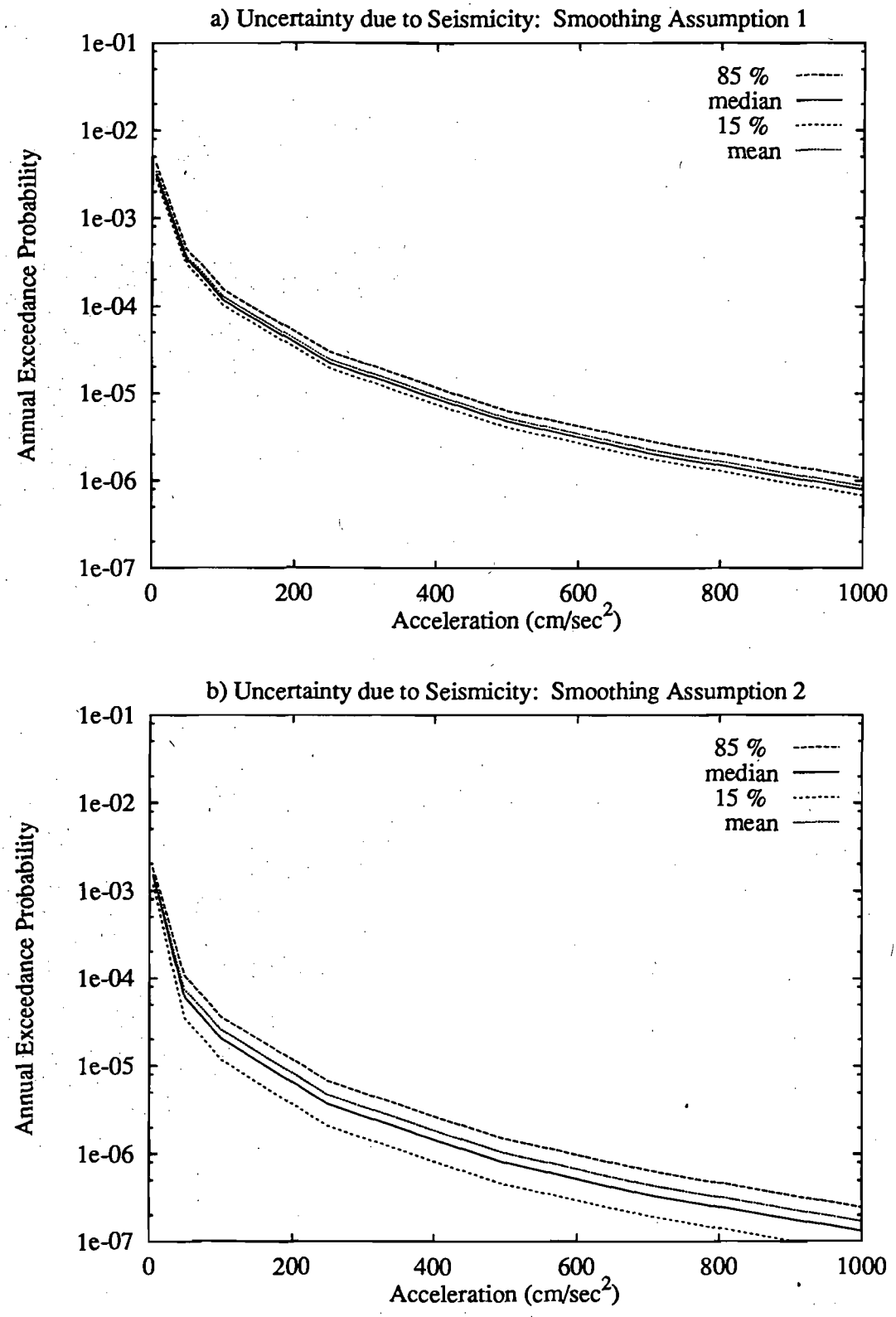
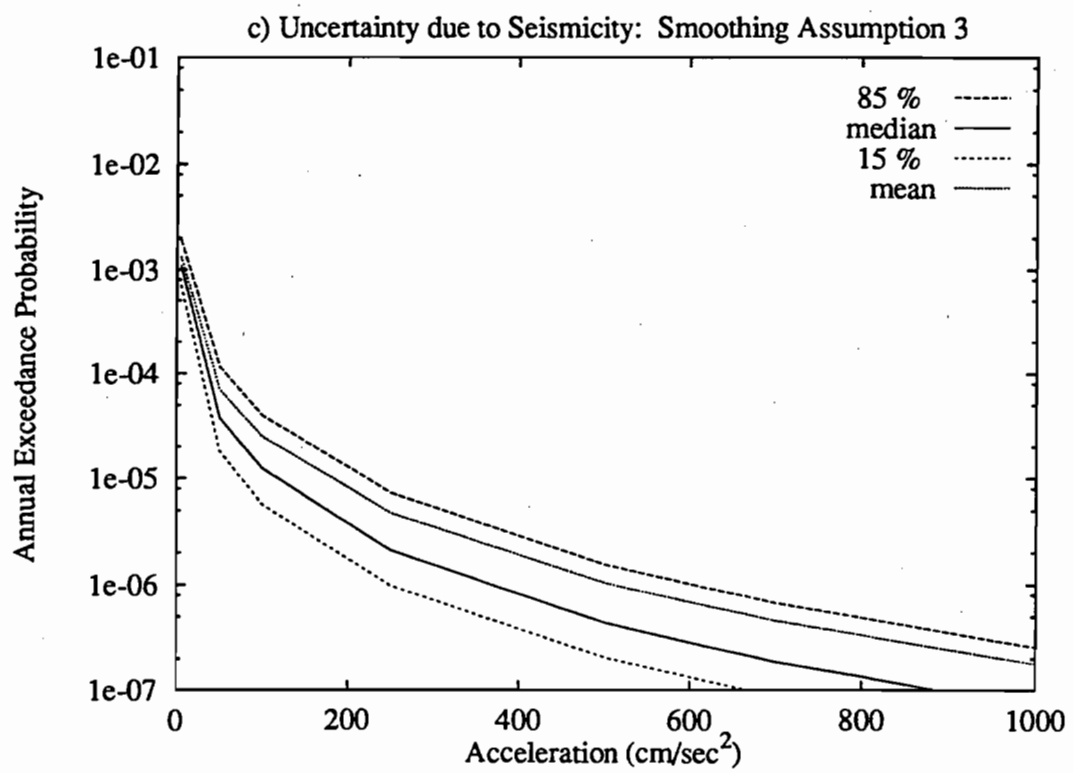


Figure I-9. Seismic hazard results for central Alabama site. (a) Hazard under smoothing assumption 1. (b) Hazard under smoothing assumption 2. Fractiles indicate effect of statistical uncertainty in seismicity parameters.



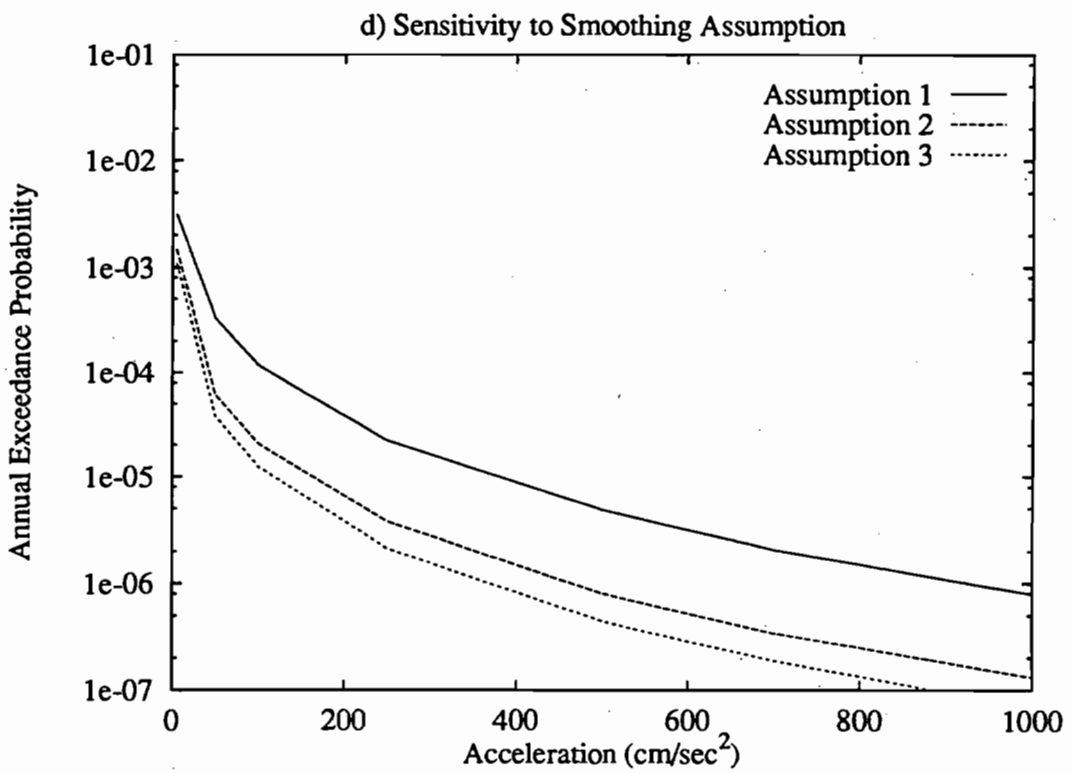
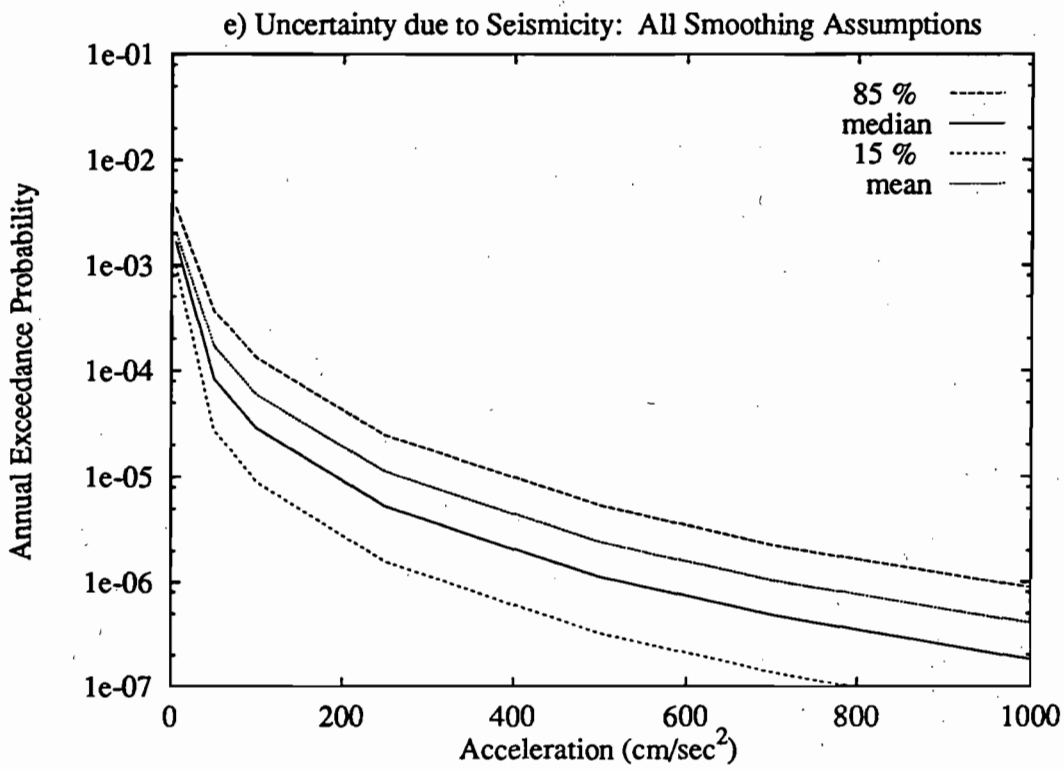


Figure I-9 (continued). Seismic hazard results for central Alabama site. (c) Hazard undersmoothing assumption 3. (d) Sensitivity of the hazard to smoothing assumptions.



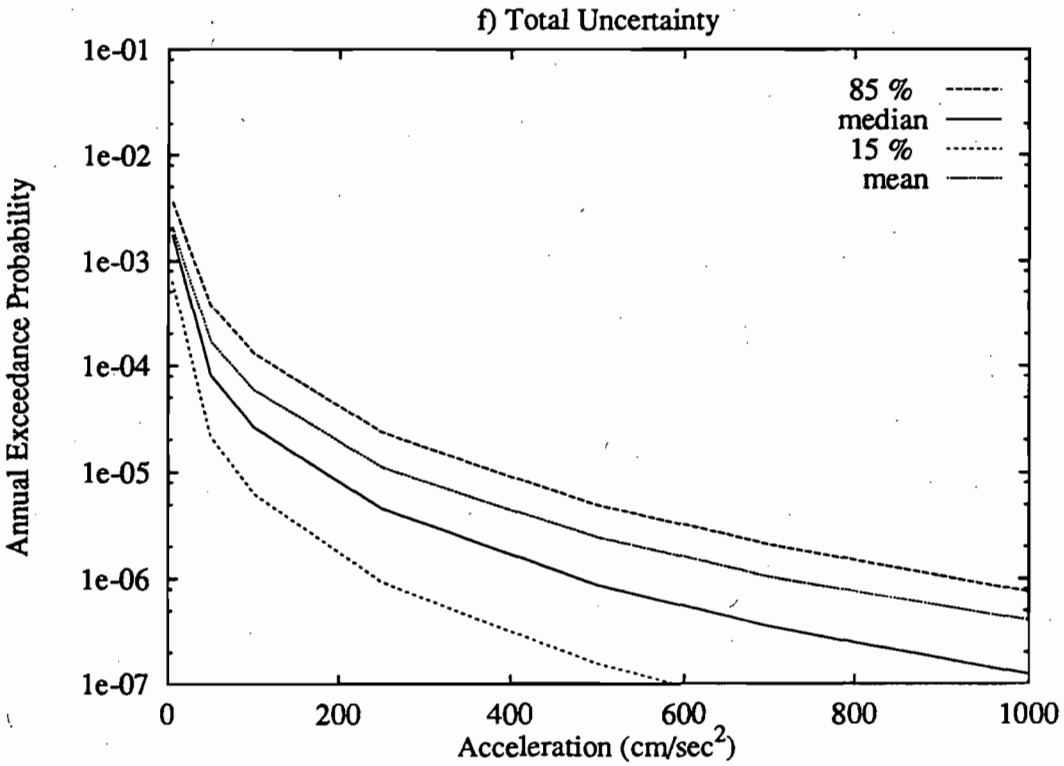


Figure I-9 (continued). Seismic hazard results for central Alabama site. (e) Uncertainty due to smoothing options and statistical uncertainty in seismicity parameters. (f) Total uncertainty in hazard.

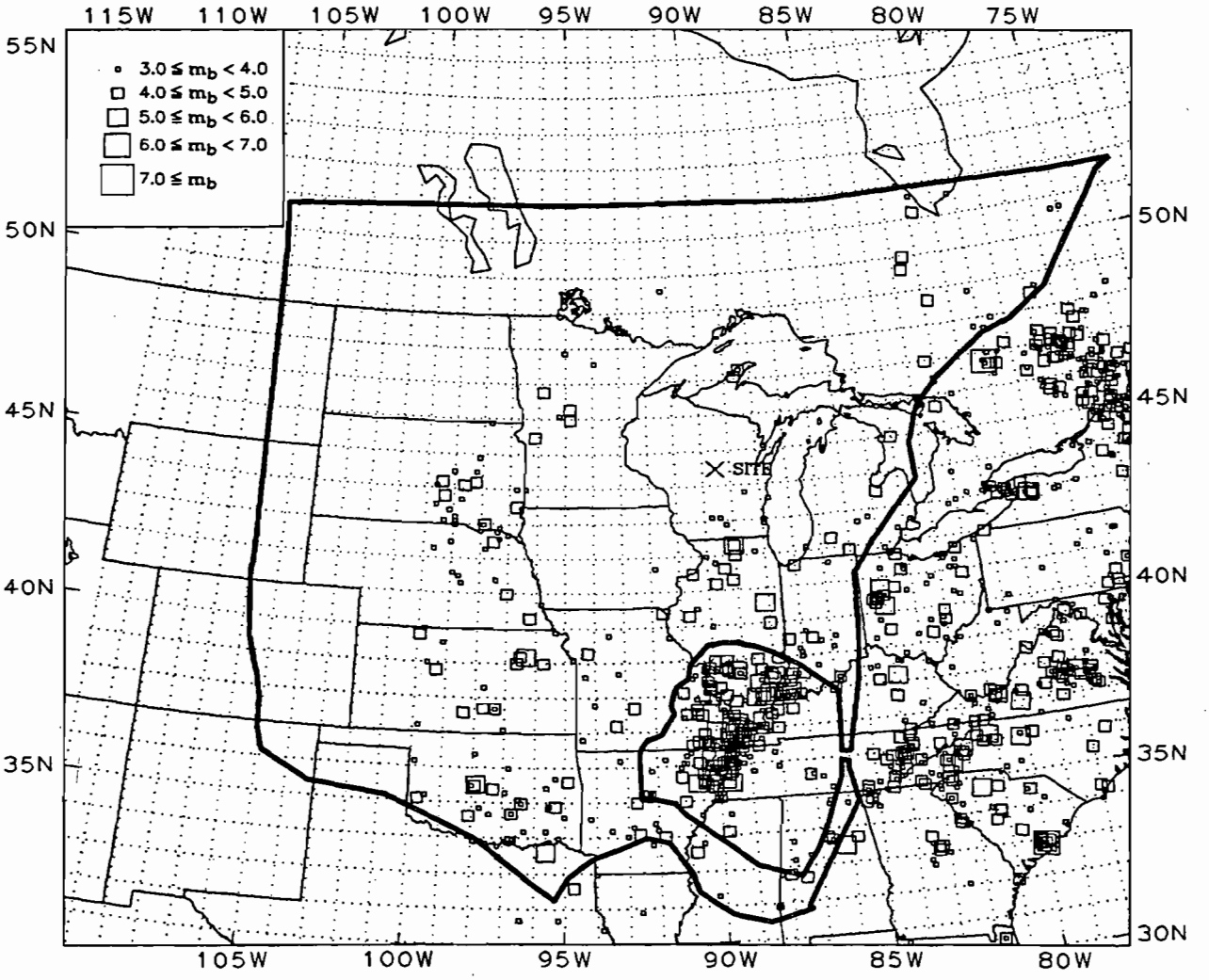


Figure I-10. Map showing the Bechtel background source for the central Minnesota site and the historical seismicity in the EPRI catalog.

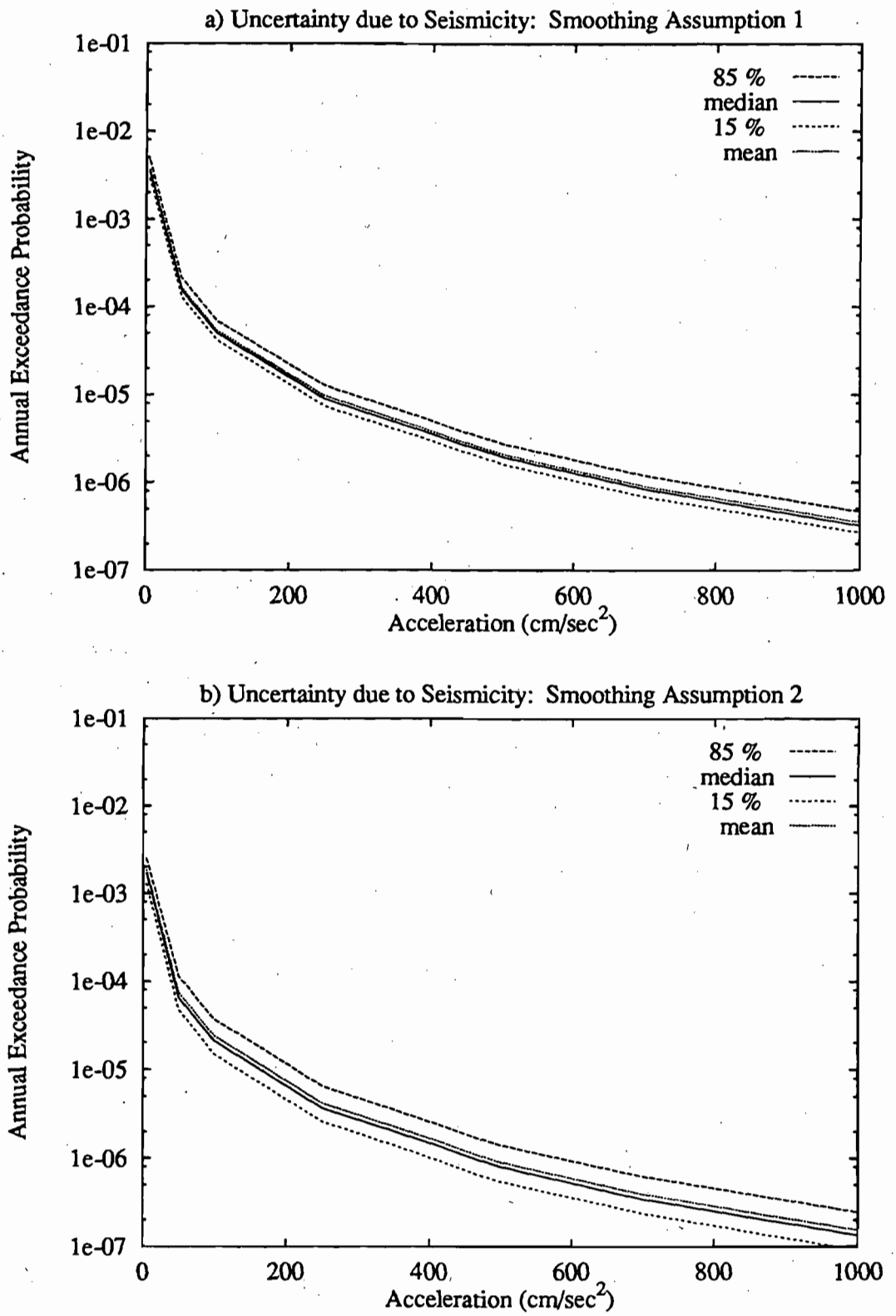
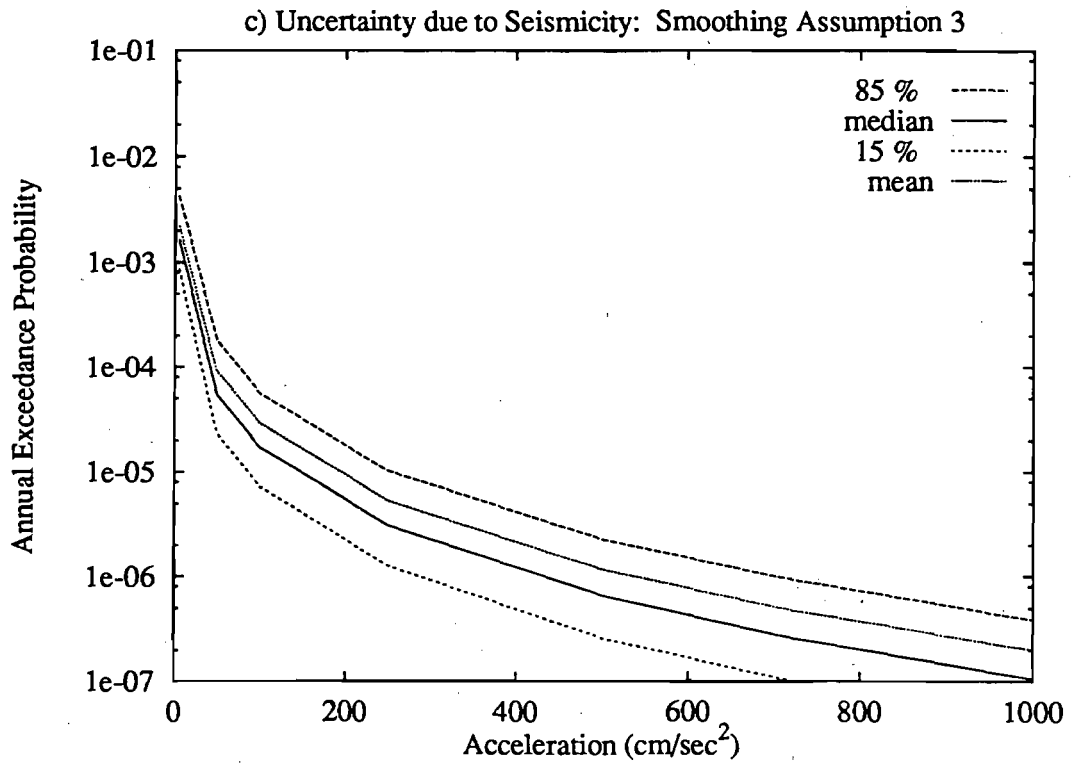


Figure I-11. Seismic hazard results for central Minnesota site. (a) Hazard under smoothing assumption 1. (b) Hazard under smoothing assumption 2. Fractiles indicate effect of statistical uncertainty in seismicity parameters.



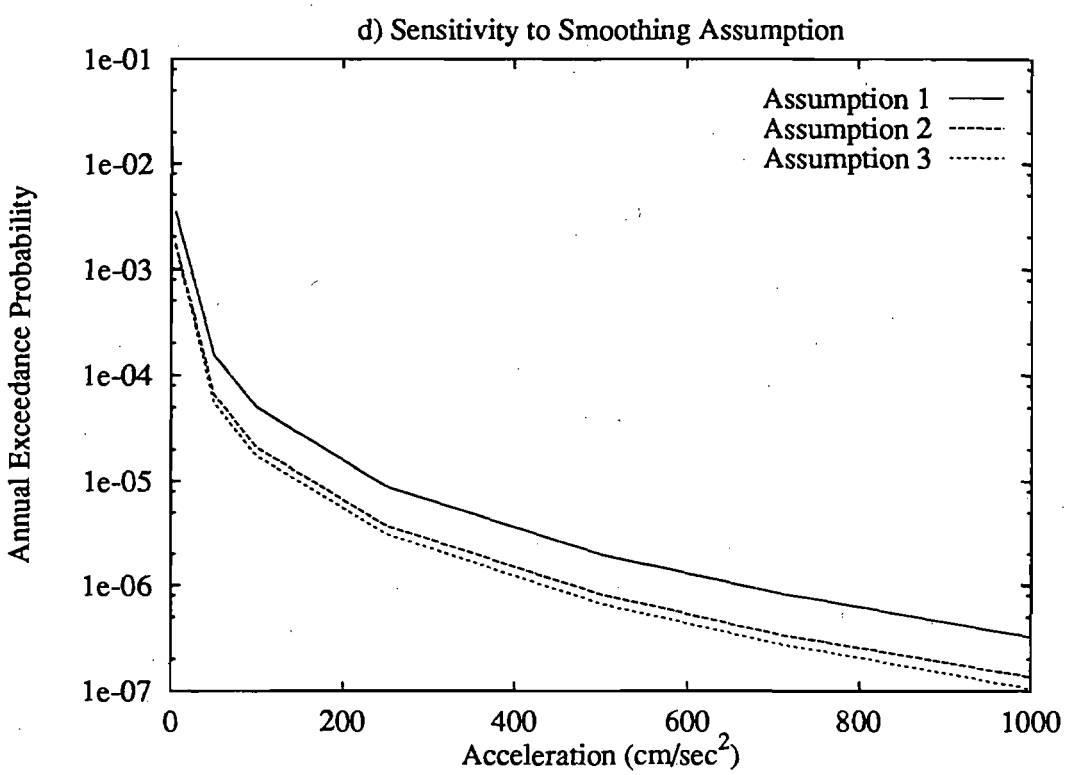
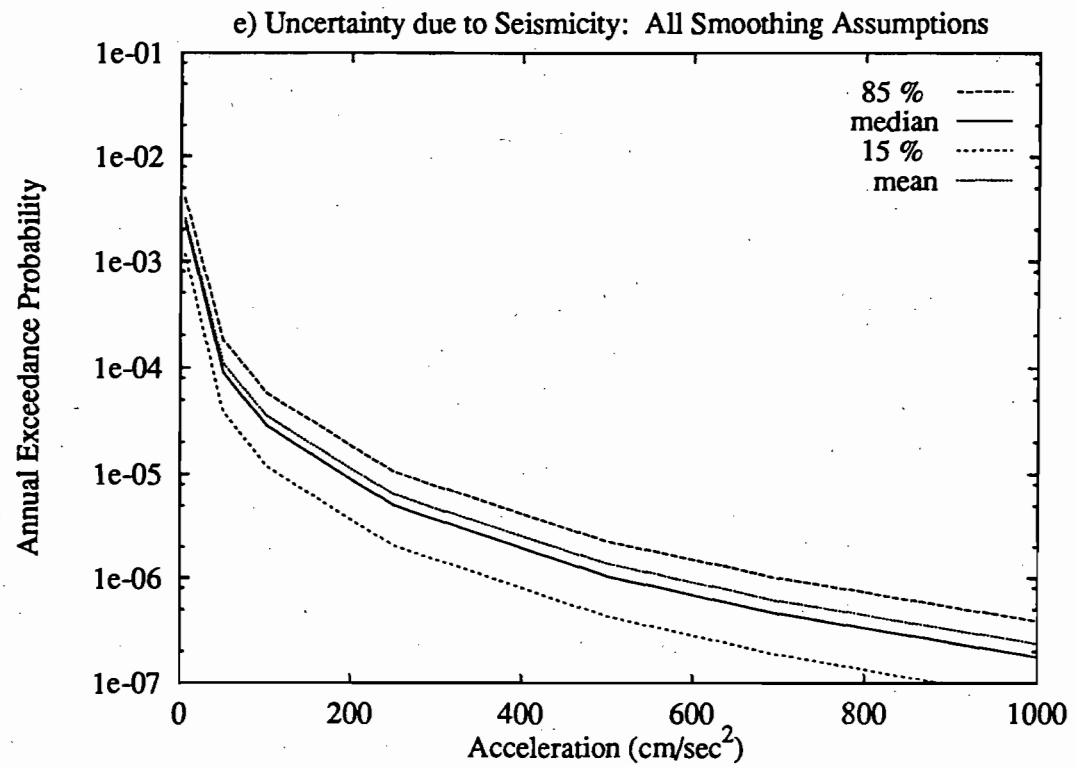


Figure I-11 (continued). Seismic hazard results for central Minnesota site. (c) Hazard undersmoothing assumption 3. (d) Sensitivity of the hazard to smoothing assumptions.



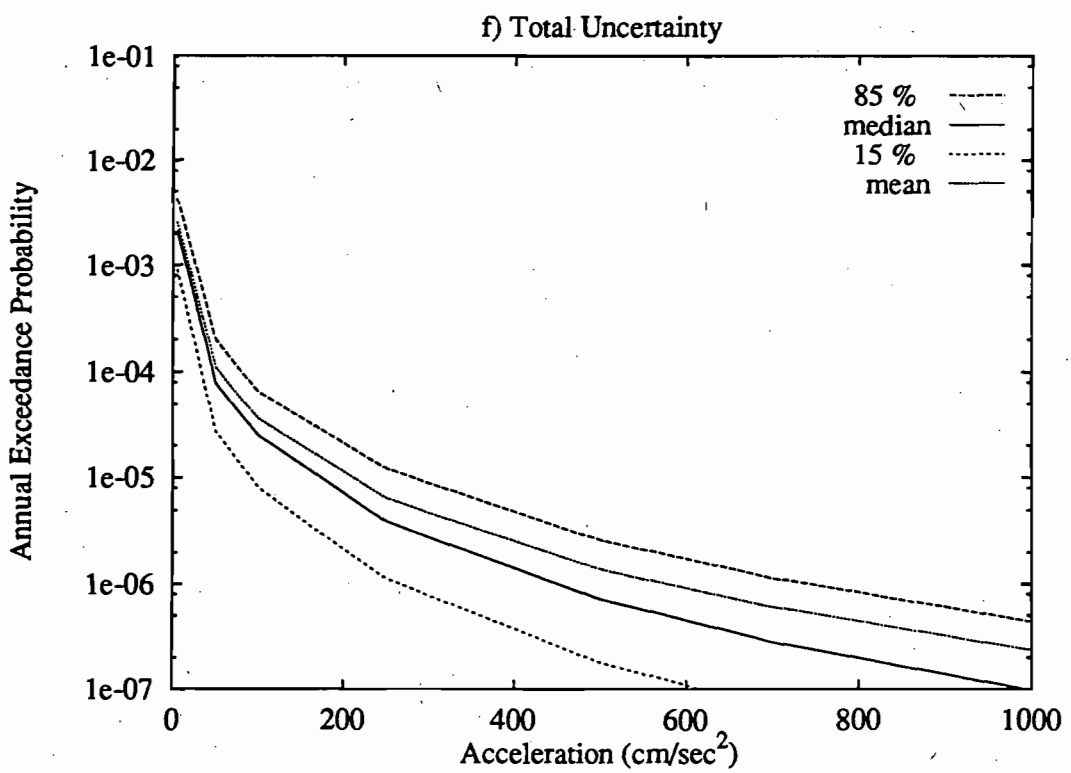


Figure I-11 (continued). Seismic hazard results for central Minnesota site. (e) Uncertainty due to smoothing options and statistical uncertainty in seismicity parameters. (f) Total uncertainty in hazard.

APPENDIX J

GUIDANCE ON TFI PRINCIPLES AND PROCEDURES

This appendix contains guidance to supplement Chapter 3 in four areas. Section 1 describes a more detailed perspective on historical approaches to the multiple expert problem, Section 2 provides additional facilitation guidance and Section 3 provides additional integration guidance. Section 4 presents details of the two stage elicitation process and Section 5 a simplified model of the TFI process. Some of the discussion in this section has been sprinkled throughout Chapter 3 of the main body of the report, but much of the appendix contains new details for the practicing TFI and TI. The partial redundancy in this appendix is recognized; it is necessary to make the report a more useful reference document for various types of users.

Section 1. Guidance on Historical Approaches to the Expert-Use Problem

This section provides additional detail on the literature on expert-use schemes. One of the principal reasons for introducing the TFI concept lies with the step that deals with the aggregation of the elicited information. To place the TFI approach in perspective, it is useful to review existing aggregation approaches.

Historical Aggregation Schemes

Historically, two basic types of aggregation processes have been used:

- Mathematical Schemes, in which expert inputs are combined using a mathematical formula, and

- Behavioral Schemes, in which aggregation is accomplished through consensus or some type of qualitative argument.

A great variety of mathematical schemes have been proposed and reviewed in the literature, e.g., in (Cooke, 1991; Genest and Zidek, 1986; Clemen, 1989; and Lindley,

1988). They include linear and logarithmic opinion pools, weights on the parameter values of underlying probability distributions, and Bayesian models.

Most behavioral schemes are centered around some type of consensus process in which the group through either structured or unstructured interaction is given the task of reaching a consensus. A number of such schemes have been discussed in the literature, e.g., in (Meyer and Booker, 1991). They include Delphi methods (Linstone and Turoff, 1975) and expert "information" (rather than "opinion") focused group interaction (Kaplan, 1992).

In seismic hazard analysis, both mathematical and behavioral schemes have been used. The analysts typically decide at which level aggregation will take place (e.g., at the ground-motion level or at the overall seismic-hazard level) and they employ mathematical combination formulas either explicitly (e.g., equal or unequal weights on expert probability distributions) or implicitly (e.g., throwing out outliers, implying zero weights, or Monte Carlo sampling implying equal weights).

Mathematical aggregation has several advantages. The logic is transparent and completely checkable. Combination formulas can isolate and separate specific assessments of dependence, expertise, and overlap, so that sensitivity studies are straightforward. Unfortunately, given the current state of the art, there are several substantial disadvantages to mathematical aggregation, at least if applied in a cookbook fashion. Mathematical models are not advanced enough to include all the factors that are important. A survey of the literature on this subject reveals that each model makes assumptions that may be only partially relevant to the problem at hand; worse, important considerations, such as the degree of interdependence of the expert inputs, are either not handled at all by most models or are addressed in a very limited way. This view is consistent with Winkler's statement (Statistical Science, 1986): "My own feeling is that different combining rules are suitable for different situations, and any search for a single, all-purpose, "objective" combining procedure is futile." Similarly, Kaplan (1992) states: "Needless to say, the expert opinion "problem", so called, is never going to be 'solved' by any single mechanical or cookbook-type procedure. The expert information approach should be viewed as one more tool in the toolbox. A skillful user will create the right mix to fit each situation and his or her own style."

Consensus processes are designed to encourage a group to reach consensus. The major advantage of this scheme is that, if the information exchange is full and unbiased, and if the result truly reflects each expert's state of information, then the consensus result is credible and non-controversial. Unfortunately, there are several problems with such methods. The overriding concern is whether the result is a true consensus that accurately reflects the diversity of education, experience and reasoning within a group, or whether it is more the result of negotiation. The result may also depend strongly on personalities, with the more forceful experts overwhelming the less forceful ones. There is also the risk of suppressing uncertainty; it is easy for a group to fall into the trap of suppressing discussion of differences and focusing on points of agreement, because it is a more comfortable process.

Should consensus be an objective? Recall the discussion in Chapter 3 of the four types of consensus. In theory, where there are unsettled technical issues, consensus of type 1 or 2 ("technical consensus"} should rarely occur. In practice, technical consensus is better viewed as a convenient result, not as an objective. Moreover, to get a high-quality and non-controversial representation of the state of information of an expert community, it is important to include a wide range of expert opinion, which tends to inhibit technical consensus but does not necessarily inhibit consensus of types 3 and 4. SSHAC believes that is very important, whatever process is used, not to force unwarranted consensus of any kind that appears to be agreement but that does not reflect the state of information of any reasonable individual or group.

Section 2. Guidance on Facilitation

This section lists a number of useful facilitation tips and traps designed to help the TFI accomplish the thorough interaction required by the SSHAC process. It is must reading for would-be TFIs.

Emphasis on Interaction

The TFI must conduct structured, facilitated discussions in which the focus is on underlying models and hypotheses, rather than on individual experts. Viewing the individuals as experts who provide evaluations of data and models for the TFI is an attractive alternative compared to the view of experts as advocates of their own models or assessments.

Basic elements of the TFI elicitation process were developed and tested in the two SSHAC ground motion workshops (documented in Appendices A and B). The workshops generated much useful information exchange and provided information directly useful for the TFI. Feedback from the experts who participated in those two workshops suggests that the process is viewed as a very useful one from the point of view of the experts themselves. In the course of isolating sources of disagreement, many common points of agreement were established and a number of points of unintended disagreement were revealed. The workshop seemed to generate a great deal of clarity and new understanding on matters ranging from data to models to methodology to philosophy.

Types of disagreements

The "disagreement onion" in Figure J-1 (adapted from (Bonduelle, 1987)), illustrates the different types of disagreement that may occur among a group of experts. Experts may disagree about underlying scientific hypotheses and principles; these would be reflected in different model structures. Even for the same model structure, different experts have very different interpretations of the relevance and implications of different available data sets; this is termed data disagreement. Also, two experts who agree on the basic model structure and on the appropriate data may still disagree about the correct value of model parameters. Finally, even with agreement on models, data and parameter values, we have observed that ground motion experts may disagree substantially about the ranges of uncertainties that affect seismic hazard.

Figure J-1 also illustrates what we observed in the SSHAC workshops, namely that much disagreement at each level may be unintended due to incomplete communication among experts, and sometimes just due to simple misunderstandings (as discussed in Chapter 3, similar conclusions were reached by the organizers of the Ispra Benchmark Exercises). The TFI Team must be chosen carefully to be capable of understanding, exposing and analyzing each of the various sources of disagreement.

In addressing the potential types of expert disagreement, the elicitation and group interaction processes must be designed carefully to:

- Identify sources and kinds of disagreement;
- Eliminate unintended disagreement; and
- Promote full understanding among the experts and the TFI of all substantive disagreements.

In order to achieve these goals, the process is highly interactive and necessarily time consuming.

Thus, it is clear that the TFI must act as a scientist, as an information elicitor and as a facilitator for group interactions. The substantive expert in the TFI team is essential in clarifying and facilitating scientific interchange and in summarizing points of agreement and disagreement. It is preferable to have the TFI substantive expert lead most of the technical discussions, with the TFI normative expert taking a supporting role in the face-to-face group discussions. The substantive expert has the credibility and ability to play devil's advocate, to help the group focus on what affects PSHA and to play back key scientific points to the group.

Interactive Process

Chapters 4 and 5 provide step-by-step guidance for the TFI facilitation process for seismic source characterization and ground motion, respectively. Here, to illustrate the highly interactive nature of the facilitation process, Figure J-2 provides a road map of the ground motion elicitation process used in the SSHAC workshops. Note that in most stages there are group interactions and each group interaction is preceded and succeeded by TFI interaction with individual experts (these individual interactions range from informal interchanges to formal elicitations).

In the ground motion application, the group interactions are naturally organized into two group workshops (illustrated by the dotted line boxes in the figure) but the number of workshops is not as important as ensuring that every type of interaction occurs.

Asking the experts to wear different "hats" in which they view themselves at different times in the interaction as (i) proponents or defenders of a particular position, (ii) as expert

evaluators of the range of different positions and as (iii) integrators who are representing the overall expert community can be very effective.

Focus on Logic before Numbers

The focus in initial interactions should be on the logic of different basic approaches, rather than on different "flavors" of the same basic approach. There should be much more dialogue at the level of structure than at the level of numbers. Over-focusing on numbers can get the group quickly fixated on too fine a level of detail; however, as the interaction evolves, numbers become increasingly useful to the extent that they show how different modeling approaches work over ranges of applications and how well they fit data.

SSHAC believes that it is important to have a large and diverse group of experts who can act as multiple evaluators to make sure that all credible points of view are represented, including all fundamental interpretations and modeling approaches. The set of experts as a group should have a comprehensive understanding of existing data and its limitations and should be capable of representing the overall expert community as a whole.

In initial group interactions, the agenda should be organized around a discussion of modeling approaches. The TFI should isolate and then focus on areas of strong agreement and disagreement. The purpose is not to achieve consensus on technical points (although that is a good outcome if it is a true consensus) but rather a detailed understanding of the rationale for underlying differences. The discussion should illuminate and eliminate any unintended disagreements. Typically, the experts will want to reconsider their estimates after the group discussion. This can be done informally (say over-night) at the workshop, but then needs to be done more carefully immediately after the workshop. Similarly, the TFI may need a round of individual interactions after the group meeting to make sure that the basis for the expert estimates is fully understood.

Active Listening

SSHAC believes that it is extremely important for the TFI to summarize points of agreement and disagreement. This is accomplished by playing back a clear summary of the conversation frequently during the meeting. A useful facilitation model is the concept of "active listening", in which a person's reasoning is not fully understood unless each listener can explain the point back to the person who made it. A useful facilitation device is for the TFI to ask experts who are having difficulty communicating to try to state each other's positions clearly. Sometimes, this is not possible, in which case the TFI needs to assist.

Experts are far more comfortable with a process in which they are not only allowed, but encouraged, to provide a full accounting of their expertise, including the data and models they rely on and details of their interpretations. Until the TFI can state each expert's position in a form agreeable to that expert, complete communication has not been achieved.

All group meetings in which experts interact require careful facilitation. It is critical for the TFI to set the right tone for the meeting. In doing so, two elements are critical:

- The purpose is not to choose the best model or answer. The experts should be made to understand that the TFI concept is founded on the premise that there is no one correct model or answer, and that the meeting will not be focused on trying to identify a single "winner" or "loser." It is very important psychologically to have the participants feel that they are not there to win or lose, but to get the important scientific and application issues out on the table for everyone to understand.

- The purpose is not to achieve technical consensus. Technical consensus may occur as a serendipitous outcome, but it is important to state explicitly that the meeting will not be a failure if consensus is not achieved. It is also important psychologically for the participants not to feel that they are contributing to a failed meeting, if everyone does not agree. Rather, it should be communicated that all the experts are credible experienced evaluators or they would not be there in the first place, and that disagreement is not only expected, but perfectly acceptable.

SSHAC strongly suggests that the TFI meet with at least several of the experts individually in preparation for group meetings. This greatly aids the TFI in anticipating potential confusions and problems, in understanding the subsequent discussion at the group level, and in helping pre-structure discussion topics and define key agenda items.

Time must be allocated for enough iteration so that the TFI can come to a full understanding of the basis for the model estimates. Roughly a month should be allocated afterwards for individual interactions among the TFI and the proponents and experts, and for final model and expert estimates.

Data

A key lesson in the SSHAC workshops was that it is crucial to dig into the details of data issues in order to understand the model results and expert positions. The goal is to see if consensus can be reached on what data should be used against which to check expert and model estimates. If, as is likely, no consensus is reached, then a clear understanding of the reasons for differences must be reached. For example, in the ground motion arena, issues that may work against a consensus include differing ideas on whether to include recordings from abutments of dams and basements of tall buildings, whether or not to include aftershock data, whether to include data that may have been affected by local geologic conditions, whether to include data collected at distances beyond the distance to the first operational non-triggered instrument, whether to include data from other geographic regions, and so on.

Resource Experts

Another essential attribute of the TFI concept is a person or small group called "resource experts." Resource experts are needed for processing expert information, technical note-taking at group meetings, providing detailed instructions to experts, disseminating results of model or PSHA runs and expert assessments, handling logistics, etc. At least one resource expert must be a substantive expert in his or her own right, who is knowledgeable on the subject matter and familiar with the data and models.

The heavy focus on intensive interaction in the TFI process implies the need for ongoing technical and administrative interaction with a large group of people. Thus, the choice of

resource experts can make or break the process. It is also essential that the resource experts report directly to the TFI because the team must respond quickly to expert logistical and technical needs in order for the process to work.

Expert Buy-in

An important psychological aspect of the TFI process is that in Stage II it puts the experts in the role of integrators in which they are expected to integrate the diverse interpretations of the whole technical community. One way of viewing the process is that the experts are essentially being asked to provide the TFI with their best advice on how to integrate. Evidence from the SSHAC workshops indicates that experts are highly willing to use information from different points of view and are quite willing to learn and change their opinions, so long as they do not feel that they are being attacked personally or feel pressured to do so.

Another lesson learned from previous elicitation exercises in the seismic hazard arena, and from a large number of discussions with seismicity and ground motion experts as the SSHAC project unfolded, is that experts are very suspicious about any process that appears to be a "black box". A common concern is that mechanical schemes that are applied without much expert interaction, even equal weighting schemes, tend to look and feel to the participant like they are "reductionist". Experts are unhappy and wary if they feel as if they have been asked to summarize their entire body of professional expertise in the form of a few numbers which have unclear impacts on the final answer.

An important aspect of the TFI process is that the panel experts, as independent evaluators, must provide input to the TFI as to how they would evaluate all models, data and information. Then, as integrators, they must provide input as to how to represent the overall informed expert community. It is important that the experts understand these high-responsibility roles; if the experts feel involved, they will tend to be constructive, and rather than resisting the process, will assist it.

Another important element of the group interaction is for the experts to write down explicitly their judgment about the relative forecasting abilities of the various models and how much overlap or similarity there is between different classes of models. Verbal interaction provides a great deal of information on the rationale for why different experts place different weights on different models, but it is important to quantify these judgments

both to ensure that the TFI understands the various positions and to make sure that the experts themselves are thinking consistently about the issues. Such information can be processed by the simple expert aggregation formulas described below. The survey for the second SSHAC ground motion workshop provides a starting point for such a quantification (the survey and its results are discussed in Appendix B).

When the TFI is comfortable that the bases for each model's and expert's inputs are completely understood, the TFI team should develop composite estimates and distributions. In the seismic-source-characterization arena, this may only be possible at the final-hazard-curve stage, because different expert maps preclude further disaggregation. The TFI should carefully document the rationale for the TFI estimate and present it to the experts. If resources and time are available, it is best to do this in face-to-face meetings (individually or group); if not, written feedback from the experts can be adequate.

After interacting with the experts, the TFI forms a final position/representation and then obtains feedback from each expert on whether the TFI's representation is a "fair" picture of the expert community as a whole. An effective interaction process should result in most, if not all, experts agreeing that the TFI position is a reasonable composite representation. However, each expert should be given the opportunity to document his or her own specific position as an independent evaluator. The TFI is responsible for presenting all individual positions in the project report and for defending the ultimate representation.

Expert Aggregation Checklist

The TFI must carefully consider each expert aggregation issue discussed in Section 3 below. It is especially important to evaluate the relative forecasting power of the key models and approaches, as well as the degree of dependence or correlation among the approaches (discussed below). It is also useful to apply the simplified aggregation models, described below, but these should be viewed as providing guidelines only. The value of applying these simple models, especially for TFI members who are less familiar with probability elicitation principles, is to see how each basic issue can affect the final aggregated probability distribution.

Section 3. Guidance on Integration: Issues and Models

As stated earlier, SSHAC expects that the TFI will aggregate the expert input behaviorally using mathematical models in a supporting role to gain insights into the implications of various plausible assumptions. Before addressing different models for aggregating expert judgments, we need to consider the various forms that such judgments may take in PSHA studies:

- *The experts may provide point estimates or probability distributions for a scalar quantity.* An example is an epistemic distribution on the maximum earthquake magnitude for a seismic source.

- *The experts may provide probability distributions for correlated parameters.* An example is the a and b pairs in seismicity assessment.

- *The experts may use different models to estimate a scalar.* An example is the estimation of the median value of the ground motion parameter for a specified magnitude, distance and spectral frequency.

- *The experts may provide alternative seismic source maps and their relative weights.*

- *Finally, in the TFI context, the experts may provide evaluations (possibly including weights) for a range of models and proponent positions.*

Many variations in these cases can be visualized. For example, the experts may not provide a full distribution function for a scalar, but only a point estimate with or without a statement on how confident they are in that estimate (e.g., a standard deviation or a 5-95 probability range).

These distinctions are critical to understanding which aggregation concepts or tools are applicable. For example, most of the mathematical combination formulas in the literature apply to the problem of aggregating several experts' probability distributions on a single scalar variable. However, for seismic source maps, it would be meaningless to compare one expert's "a" value defined over one source zone with another expert's "a" value defined over a differently configured source zone.

The issues below are intentionally discussed in a general context. They can be applied at different levels in the TFI process. For example, the section on equal weights is probably most useful for the TFI in attempting to create conditions for equally weighting the experts-as-integrators' (Stage II) composite representations. In contrast, the material on dependence and unequal weights is probably more useful for individual panelists acting as evaluators (Stage I), or to the TFI in educating the panelists, who will almost certainly want to weight different models and scientific hypotheses unequally (the surveys for the two Ground Motion workshops were based on the expert-use concepts described below).

The remainder of this section provides background and guidance to the TFI or TI regarding a set of important aggregation issues that are commonly encountered in practice. The issues are not intended to be a comprehensive list of all issues involved in expert aggregation. Rather, it is a minimal checklist of fundamental issues that should be addressed.

For each aggregation issue, we include a description of a simplified mathematical aggregation model that addresses it. The model is included only to provide insights; the final result should always be the result of a behavioral process (which, of course, may be a TFI decision to use a specific mathematical scheme). There is no "right" model; thus, SSHAC recommends that the TFI examine the results of application of two or more models for each issue to develop insights as to how that issue affects the aggregation process.

Important Caveat

The issue discussions are intentionally oriented towards the classical context of aggregating experts-as-proponents, not the TFI context of aggregating experts-as-integrators. The distinction is critical, but to save needless repetition, since the set of issues special to the TFI context are dealt with extensively in main report, they will be mentioned here only occasionally.

In the experts-as-proponents context, it is important to note that, in concept, the issues apply equally well to either expert interpretations or models and/or their parameter values. At a conceptual level, models or experts may be viewed as entities that provide forecasts

(deterministic or probabilistic) that are, in essence, noisy observations of the real world. For simplicity, much of the text below addresses multiple-expert issues, but the very same issues underlie the use of multiple models.

Different Degrees of Expertise

Simply put, all experts are not created equal. Common sense says that different experts will have different degrees of information, experience, competence and forecasting ability, particularly when considering a specific site or geographical region. For example, two equally capable experts may have very different degrees of expertise about a particular region of the United States if one of the experts has specialized in that region and the other has not. Any meaningful attempt to represent the composite state of information of a community of experts must deal explicitly with potential differences in expertise, either by behaviorally creating conditions under which equal weighting is appropriate or in some manner unequally weighting the different expert assessments. Equal weighting schemes are dealt with separately below; here we discuss the case in which equal weighting is not appropriate.

Consider the simple case in which two proponent experts provide point estimates of some uncertain scalar quantity. Suppose, hypothetically, that the experts have been observed making similar estimates or forecasts over a long period of time (e.g., Dow-Jones levels one week in the future) and we were able to observe the difference between the actual outcome and the forecast in each case. One simple measure of expertise in this case is the standard deviation of the forecasting error. Consider the example shown in Figure J-3 in which two experts provide the point forecasts labeled E1 and E2, each with a different observed forecasting error distribution. On the right we contrast the answers that would be attained by equal weights versus weighting based on expertise. The simple model described below will show one possible way to aggregate based on expertise; however, the main point here is that common sense demands that the most reasonable aggregate forecast be shaded more towards Expert 2's forecast than Expert 1's.

In PSHA practice, of course, such empirical error distributions are rarely, if ever, available. Ground motion and seismological models change over time, and data sometimes are extremely scarce. Thus, the analysis above must be based on judgmental error distributions rather than empirical ones, but the same basic logic applies.

Outliers

An important special case of unequal expertise is experts who provide opinions that are "outliers," that is, estimates or judgments that are extreme relative to the other interpretations. Outlier opinions may be viewed as just a special case of the weighting problem in the sense that throwing out an outlier opinion has the same mathematical effect as attaching a negligible weight to that opinion. However, treatment of outlier opinions can affect the success of an integration process.

If the issue is dealt with directly, outlier interpretations can be dealt with explicitly by forming judgments about their value conditional on the logic and empirical support that is supplied. For example, if an proponent supplies an outlier estimate, and supplies a credible rationale and provides explicit supporting data and interpretations, then that estimate ought to be given significant weight. However, if the proponent cannot technically support an outlier position, then the position should be given less, if any, weight. Recall from Section 3.3.3 that in the case of a outlier panelist acting as an integrator (Stage II), the outlier issue has a special twist, i.e., whether the expert's representation is an unbiased estimate of the composite distribution of the overall expert community. In this case, as discussed earlier, the panelist may be violating the conditions for retention on the panel.

The alternative to addressing the outlier issue directly is very unattractive. Suppose that for some reason (political expediency, simplicity, etc.) an outlier proponent expert whose position leads to especially high seismic hazard is given equal weight with the other proponents. The problem here is that the outlier estimate, being by definition extreme, can greatly affect the final aggregate result. This is especially dangerous in the seismic hazard arena in which small probabilities abound: for example, if three experts assess the probability of an event to be 0.1% and one outlier expert assesses the probability to be 10%, the equal-weighted aggregate estimate is close to 2.5%, twenty-five times more than the three similar assessments!

Fortunately, there are rigorous methods for dealing explicitly with differing levels of expertise, especially among panel members; moreover, it is often possible to do this without insulting the experts or creating heated debate. One approach is to facilitate enough structured panel interaction so that experts wind up with roughly the same degree

of expertise regarding the specific issue of interest. A very useful approach, which was followed in the SSHAC ground-motion workshops (Appendices A and B) is to go one stage deeper and determine the scientific hypotheses and models on which experts base their judgments and then conduct a dialogue so that aggregation can be considered at the level of models. This is good practice in general and it avoids the stigma of assigning differential weights to different individuals. (Note that in seismic source characterization, the problem is more difficult because different expert maps make direct comparisons impossible. This makes it even more critical to focus on intensive expert interaction at the level of more basic hypotheses and models.)

A Simple Mathematical Aggregation Model for Independent Experts

This subsection will describe the well known Bayesian Normal model for independent experts who provide a point of a scalar quantity. This model and others presented here are based on variants of the multivariate Normal model developed by Winkler (Winkler, 1981) and the Conditional Likelihood model developed by Clemen and Winkler (Clemen and Winkler, 1992). Later, we will discuss the implications of experts providing full probability distributions. A model specially tailored to the TFI process in which expert judgments are viewed as samples of the overall expert community is also treated separately below.

This independent-experts model and the following simplified aggregation models are presented, not as mechanical methods for calculating the final composite distribution, but rather as sensitivity analysis tools for the TFI to use to develop insights for a given application into the relative importance of the different basic aggregation issues. The TFI should perform extensive sensitivity analyses by exercising a set of alternative aggregation models over a wide range of assumptions. Examples of expert-aggregation sensitivity analyses are found in [Chhibber, et. al., 1994].

The Bayesian model treats an expert's estimate as a noisy observation of the real world and the aggregation formula is derived as a simple linear-weighting formula where the weights are equal to the precision (the reciprocal of the variance) of the experts' forecasting error distributions. The variance is judgmentally assigned by an informed evaluator (TI or TFI).

For convenience, consider the case of three independent experts (the formulas are easily generalizable) who provide estimates of some uncertain quantity, μ:

$\mu_1 = \mu + \varepsilon_1$	Expert 1's estimate
$\mu_2 = \mu + \varepsilon_2$	Expert 2's estimate
$\mu_3 = \mu + \varepsilon_3$	Expert 3's estimate

Here, the ε_i's denote forecasting errors equal to the difference between the estimates and the true value; for this simple model the forecasting errors are assumed to be independently normally distributed with zero mean and variance σ_i^2. The result of a Bayesian analysis is that the TFI's aggregated distribution is Normal as well, with mean,

$$\mu_* = \lambda_1\mu_1 + \lambda_2\mu_2 + \lambda_3\mu_3$$

and variance,

$$\sigma_*^2 = 1/(h_1 + h_2 + h_3)$$

where h_i is equal to the precision (reciprocal of the variance) of the forecast error of Expert i,

Forecast precision: $h_i = 1/\sigma_i^2$

The result assumes a "non-informative" prior distribution, i.e., that the TFI does not introduce any of his own prior judgment into the estimates. The weights (λ_i's), which sum to unity, are computed as the relative precisions in each forecast:

Weight for Expert i: $\lambda_i = h_i/(h_1 + h_2 + h_3)$

Note that the weights have a specific meaning: they reflect each Expert's judged (by the TFI) precision as a forecaster. They are not *ad hoc* probabilities of "correctness," but well defined judgments. In this simplest model, the TFI must form one judgment per weight. If, as in many applications, the experts provided an entire distribution (in the Normal context, a mean and variance), the TFI could interpret the width (e.g., standard deviation) of the distribution as an indication of the expert's confidence in his or her own forecasting

ability. The TFI could, of course, adjust this number based on an assessment of whether the expert was a biased estimator of his own forecasting precision.

The three tables below provide numerical examples of how the model works. The first table assumes that two experts provide mean estimates of 60 for some uncertain quantity, while a third expert estimates the quantity at 120. The experts are judged *a priori* to be equally accurate -- each expert's forecasting accuracy, measured here by the standard deviation of his forecast error, is assumed to be equal to 30.

Independent Experts: Case 1 -- Equal Forecasting Accuracies

	Expert 1	Expert 2	Expert 3	Aggregated
Estimate (mean)	60	60	120	80
Accuracy (std. dev.)	30	30	30	17
Calculated Weights	0.33	0.33	0.33	1.00

Note that the aggregated estimate is equal to the weighted average of the three expert estimates and that equal accuracies results in equal weights. The next table shows an example in which Expert 3 is judged to be more accurate than Experts 1 and 2:

Independent Experts: Case 2 -- Unequal Forecasting Accuracy

	Expert 1	Expert 2	Expert 3	Aggregated
Estimate (mean)	60	60	120	92
Accuracy (std. dev.)	30	30	20	15
Calculated Weights	0.24	0.24	0.52	1.00

For comparison, here is an example in which Expert 3's accuracy is even higher relative to the other two experts:

Independent Experts: Case 3 -- Larger Difference in Forecasting Accuracy

	Expert 1	Expert 2	Expert 3	Aggregated
Estimate (mean)	60	60	120	109
Accuracy (std. dev.)	30	30	10	9
Calculated Weights	0.09	0.09	0.82	1.00

The tables show that the weights are *not* simply proportional to the experts' judged accuracies. Although the independent-expert model is simplified, it illustrates the danger of having experts assign weights without instruction. It is preferable to have the TFI and/or the experts to first form explicit judgments about forecasting accuracy, and then use these judgments to determine the appropriate weights.

One consequence of the independent-additive error model is that as the number of experts goes up, the posterior standard deviation of the estimate goes to zero. If the experts were truly independent estimators of a single parameter, this would not be counter-intuitive, but it is difficult to think of real multiple-expert cases in which this would-be satisfactory result: simply adding experts to a panel typically does not ensure elimination of all uncertainty. The non-independent-expert model presented in the next section provides a partial resolution of this issue. Later, we will introduce a model in which the posterior standard deviation does not go to zero as the number of experts is increased, but rather converges (in the simplest case) to the average variance of the expert distributions.

Further, it is clear that the aggregated standard deviation is <u>independent</u> of the diversity of the experts' point estimates (the μ_i's). Whether these values are equal or widely separated, the aggregate accuracy or precision is calculated to be the same. This conclusion, which also seems contrary to the natural reaction to such observations, created the motivation for the TFI model presented at the end of this appendix.

Non-Independent Experts

The issue of non-independence among experts is critically important because it significantly affects both the aggregated estimate and the amount of uncertainty that one associates with the estimate. It has been the single most difficult practical issue in applications (Morris, 1977; Winkler, 1981; Chhibber and Apostolakis, 1994), which have traditionally placed experts in a proponent role.

The discussion below has two very different purposes: First, to provide the underlying analytical basis for the TFI process, which aims at achieving strong, but roughly equal, interdependence among panel members. Second, to provide a discussion of issues that must be dealt with in aggregating judgments of *proponent* experts who have not been exposed to a carefully structured TFI-like interactive process. To avoid repetition, and for clarity, the discussion below assumes that the experts are proponents (*not* evaluators or integrators); we assume that the interested reader will see the relevance to the design of the TFI process.

Explicitly dealing with dependence among proponent experts is in many ways the toughest expert integration issue of all. Stated simply, the degree of overlap in expert data bases and/or models and reasoning processes can significantly affect the ability to integrate the knowledge of a group of experts. Here is a simple example: two expert weather forecasters use different methods and data to come up with two forecasts of rain of 20% and 80%. If the experts are equally credible, you might conclude that you should average the two estimates to obtain a "best estimate" of 50%. Suppose then that a third forecaster says 80%. How does this affect your state of information? Common sense says that it matters a great deal whether the third forecaster provided an independent forecast or simply used the same data and reasoning as the other 80% expert.

The generally accepted decision analysis definition of expert dependence (Morris, 1974) is based on a conditional probability statement: two experts E1 and E2 are considered to be dependent when the probability distribution on E2's estimate (before he or she provides it), *given the true value of the variable of interest*, depends also on E1's estimate. In other words, E2's estimate is correlated, not only with the true value, but also with E1's estimate.

Researchers on expert use have proposed a large number of models of expert dependence consistent with the general definition, ranging from very simple to extremely sophisticated (one of the simplest models is described below). However, while the details of the models vary, they all strongly support the assertion that understanding the degree of dependence among the group of experts is essential to determining how to integrate their judgments. Yet, dependence is often ignored in many expert combination formulas, probably because it is difficult to think about, much less quantify.

Non-independence results from at least four sources: overlapping data, overlapping methodology, direct observation, and exchange of viewpoints. These relationships between expert judgments (or models) that result in non-independence are illustrated in Figure J-4.

Overlapping data result from the fact that in most situations most experts have access to the same basic information and are basing their opinions on roughly the same body of data. Overlapping methodology exists, if experts in the field have similar academic and professional training or read the same literature. In this case, even if experts observe different data, they may be expected to employ many of the same modeling methods or modes of thinking. The peer review process in the scientific community also causes dependence among experts. The direct observation of other expert opinions, the presentation of public reports to the scientific community, and the open discussion of viewpoints and hypotheses will add to the overlap among expert judgments.

It is important to distinguish between two cases: 1.) two experts who, acting as informed evaluators, happen to choose the same model, estimate or data set, and 2.) two experts, one of whom simply "parrots" the other's estimate without independent thinking. In the first case, the experts performed independent evaluations, and are not (necessarily) probabilistically dependent in the sense defined above, since *a priori* they were not constrained to use the same model. In the second case, the two experts are clearly completely dependent, since *a priori*, knowing the first expert's estimate also specifies the second expert's estimate, regardless of the true state of the world. Robin McGuire provides an example of five experts, four of whom believe that F=MA, and one of whom believes that $F=M^2A^2$. Can the last expert make the case that his method deserves 0.5 weight because the first four experts are dependent (they employ many of the same modes of thinking, etc.)? The answer is "no" because the four experts independently arrived at

their common choice of modeling methods. Ultimately, the presumption of dependence or independence among experts must be a judgment call that the TFI must make and defend.

In the case that a subset of experts happen to choose the same model, the credibility of that model becomes especially important. Instead of assessing the degree of dependence among the expert estimates, [Bonano and Apostolakis, 1991], and [Chhibber, Apostolakis, and Okrent, 1994] propose that the model itself be considered as the "expert," with the estimates of the experts being treated as independent evaluations of the credibility of that model. A decision to use this type of approach will have to be made by the TFI based on the evidence that is available regarding the source of dependence of the expert estimates. It also demonstrates, once again, that no mechanistic mathematical aggregation schemes can be chosen *a priori* and that the TFI must evaluate the totality of the available evidence.

A simple example of the potentially large impact of dependence is shown in Figure J-5. Consider three experts who, for the sake of argument we shall assume are believed to have equal expertise, so that other than issues of dependence, equal weighting would be appropriate. Suppose E1 provides a probability of 0.1 for an event and E2 and E3 say that the probability is 0.9. If the experts were completely independent, then a simple average would imply an aggregated probability of 0.63. However, suppose that the latter two experts are completely dependent (e.g., imagine that the three experts are weather forecasters, and that expert 3 simply listens to expert 2's weather forecast and adopts it as his own). Then, clearly, expert 3 is redundant and the best estimate would be a simple average of expert 1 and expert 2's probabilities, or 0.5. The redundancy of additional experts when there is strong dependence is discussed more generally in [Clemen and Winkler, 1985].

In simple terms, failing to take into account dependence or correlation among experts results in double counting. In the seismic hazard field in which seismologists and ground motion experts are generally intimately aware of others' models and databases, there is likely to be a large amount of non-independence among proponents, so that this issue is not merely theoretical. For example, in the second SSHAC ground motion workshop, seven ground motion experts were asked to judge the amount of correlation among estimates that they provided and the correlation was significant (see Appendix B).

A Simple Mathematical Dependent - Expert Model

Here we present one of the simplest expert-aggregation models that explicitly addresses the issue of dependence among the experts -- the Normal-linear-dependence model. The basic result is that the impact on the composite distribution of an additional expert is a function of how correlated that expert is with other experts. Basic references include [(Clemen, 1987); (Winkler, 1981); (Clemen and Winkler, 1992); (Morris, 1977); and (Apostolakis and Mosleh, 1986)].

Once again, the model treats an expert's estimate as a noisy observation of the real world; in this model, however, the errors inherent in the experts' estimates are probabilistically interdependent in a simple linear way, as follows

$\mu_1 = \mu + \varepsilon_1$

$\mu_2 = \beta_2 \mu + \alpha_{21} \mu_1 + \varepsilon_2$ where $\beta_2 = 1 - \alpha_{21}$

$\mu_3 = \beta_3 \mu + \alpha_{31} \mu_1 + \alpha_{32} \mu_2 + \varepsilon_3$ where $\beta_3 = 1 - \alpha_{31} - \alpha_{32}$

Once again, the epsilons denote forecasting error, normally distributed with zero mean and variance σ_i^2. However, now, the forecasting error is conditional on knowledge of, not only the true value μ, but also on knowledge of the preceding experts' estimates. The α_{ij}'s and the σ_i^2's capture the degree of dependence or "overlap" with each of the preceding experts, and the β_i's may be thought of as the degree of independence or non-overlap with the preceding experts. For example, setting α_{21} equal to 0.5 would indicate that the TFI believes that Expert 2's estimate is equally dependent on the true value and on Expert 1's estimate -- alternatively, Expert 2 has a 50% overlap with Expert 1. Setting α_{21} equal to 1.0 would indicate the belief that Expert 2 simply repeats (without independent thinking) Expert 1.

The result (not derived here) of the Normal-linear dependence model is that the TFI's aggregated distribution is also Normal with mean:

Aggregated mean: $\mu_* = \lambda_1\mu_1 + \lambda_2\mu_2 + \lambda_3\mu_3$

and precision/variance:

Aggregated precision: $h_* = h_1 + \beta_2^2 h_2 + \beta_3^2 h_3$

Aggregated variance: $\sigma_*^2 = 1/h_*$

where, as in the independent case, the weights sum to unity (a *result*, not an assumption). But, now the weights depend on the specific assessments of dependence (the α_{ij}'s) as well as the assessed precision of the forecasts (the h_i's):

$\lambda_1 = (h_1 - \beta_2\alpha_{31}h_2 - \beta_3\alpha_{31}h_3)/h_*$
$\lambda_2 = (\beta_2 h_2 - \beta_3\alpha_{32}h_3)/h_*$
$\lambda_3 = (\beta_3 h_3)/h_*$

The above model was developed by Clemen and Winkler (1992). We propose a simple variant in order to simplify the assessment task. A difficulty with using the model directly is that the forecast error distribution for each expert is, by definition, conditional on knowledge of the predecessor expert estimates. Unfortunately, the variance or precision of these conditional densities do not reflect particularly intuitive quantities. Logically, by the rules of probability, the conditional variance must be less than the unconditional variance; however, it is unlikely for someone to have relevant experience on which to base this judgment (it depends, not only on an expert's individual forecasting ability, but also on his interdependence with the specific experts in the group). A more natural quantity to think about would seem to be the unconditional variance, which is a measure of each expert's individual forecasting accuracy, independent of the other experts. Assessment of the unconditional variance could be related to relevant experience gained by comparing past expert forecasts and actual outcomes. It turns out that the conditional variances can be calculated from assessments of the unconditional variances and the α_{ij}'s. Thus, in the remainder of this appendix, including the examples below, the assessments are assumed to be judgments of *unconditional* forecasting accuracy (which are translated to conditional variances for use in the above formulas -- we omit the details for brevity).

The example below is identical to "Independent Experts: Case 1," except that Expert 2 is assumed to be 50% dependent on Expert 1 ($\alpha_{21} = 0.5$, $\alpha_{31} = \alpha_{32} = 0.0$):

Dependent Experts: Case 1 -- Experts 1 and 2 Dependent

	Expert 1	Expert 2	Expert 3	Aggregated
Estimate (mean)	60	60	120	86
Accuracy (std. dev.)	30	30	30	20
Dependence on Expert 1		0.5	0.0	
Dependence on Expert 2			0.0	
Dependence on true value	1.0	0.5	1.0	
Calculated Weights	0.29	0.24	0.52	1.00

In comparison with the independent-expert case, the effect of dependence between Experts 1 and 2 is to shade the result more towards Expert 3, reflecting the model's implicit elimination of "double counting" the redundant information shared by Experts 1 and 2. Next, we consider the effect of increased dependence between the first two experts.

Dependent Experts: Case 2 -- Increased Dependence Between Experts 1 and 2

	Expert 1	Expert 2	Expert 3	Aggregated
Estimate (mean)	60	60	120	89
Accuracy (std. dev.)	30	30	30	21
Dependence on Expert 1		0.90	0.0	
Dependence on Expert 2			0.0	
Dependence on true value	1.0	0.10	1.0	
Calculated Weights	0.26	0.26	0.49	1.00

Increasing the dependence between Experts 1 and 2 results in an aggregated estimate even closer to that of Expert 3. Dependence of 0.9 is close to complete informational overlap; in fact, the aggregated estimate of 89 is close to the estimate of 90 that would be obtained by ignoring the one of the two dependent experts. Thus, the dependent-expert model effectively avoids double counting two overlapping information sources. Note also the effect on aggregate accuracy.

The next example illustrates a case in which all three experts are correlated, with Expert 3 having a 25% and 50% interdependence with the first two experts.

Dependent Experts: Case 3 -- Dependence Among All Three Experts

	Expert 1	Expert 2	Expert 3	Aggregated
Estimate (mean)	60	60	120	74
Accuracy (std. dev.)	30	30	30	23
Dependence on Expert 1		0.25	0.25	
Dependence on Expert 2			0.5	
Dependence on true value	1.0	0.75	0.25	
Calculated Weights	0.41	0.35	0.24	1.00

Notice that, not only is Expert 3 downweighted due to the dependence, but that the aggregated variance is increased relative to the cases with less expert interdependence. In general, as experts are added to a group, we would expect them, after a point, to have less and less independent knowledge (lower α_{ij}'s). In the limit, as the dependence on the true value goes to zero, the incremental reduction in the final variance diminishes to zero. Thus, explicitly modeling expert dependence offers a partial solution to the problem of artificially low variances. However, it does not address the intuitive observation that if n experts agree on an estimate and on a range (i.e., they concur on the forecast and on the forecast uncertainty), the aggregated estimate ought to have the same range. Moreover, the aggregated accuracy is insensitive to the diversity among estimates. We will return to this issue in the final section.

In summary, even with dependence, the aggregated estimate is always a weighted average of the individual-expert estimates. Just as in the independent-expert case, the weights have specific underlying interpretations. They depend on two types of parameters: 1.) a parameter that reflects each expert's judged precision as an individual forecaster, and 2.) parameters that reflect each expert's degree of knowledge overlap with the other experts.

An alternate, and equivalent, formulation of this model is in terms of multivariate normal distributions. In the simple case of two experts, the likelihood function in Bayes' theorem

is the bivariate normal distribution with three parameters, i.e., σ_2 (the standard deviation for expert 1, which is the same as that for ε_1 of the preceding model: σ_2, the standard deviation for expert 2, which is the same as that for ε_2; and ρ, which is the correlation coefficient. It is easy to show that α_{21}, the measure of dependence in the preceding model, is equal to $(\rho\sigma_2)/\sigma_1$. The expressions for the posterior variance and precision are just as before, with the appropriate change in β_2. The weights are now:

$$\lambda_1 = (h_1/h_*)\ \{(1 - \rho\sigma_1/\sigma_2)/(1 - \rho^2)\}$$
$$\lambda_2 = (h_2/h_*)\ \{(1 - \rho\sigma_2/\sigma_1)/(1 - \rho^2)\}.$$

Once again, we see that equal weights require that the precisions of the two experts be equal (i.e., σ_1 and σ_2 must be equal). For more than two experts, these results can be generalized using matrices.

A criticism of these simple models is the requirement of assessing the numerical values of the parameters. Some guidance is available, e.g., the correlation coefficient can be assessed using expressions for the concordance probability given in the literature [Gokhale and Press, 1982]. In fact, given the large uncertainties in risk assessments, [Chhibber and Apostolakis, 1993] utilize concordance probabilities to show that high accuracy in assessing ρ is not required. For the TFI, high accuracy is not critical, because the TFI team is using these models only to conduct sensitivity analyses and, thus, to gain insights into the impact of various sets of assumptions (the preceding tables are examples of such analyses; for further examples, see[Chhibber, Apostolakis, and Okrent, 1994]).

Equal Weights

The issue of whether to aggregate expert judgments or model results using equal weights is really just a special case of the unequal weights implied by explicitly taking into account differing degrees of expertise. However, because the practice of equally weighting expert judgments has been so prevalent in past seismic hazard and other public policy studies, it deserves special attention.

The attraction of equal weights is that it avoids at least two extremely difficult issues:

- No one is forced to make what can be a very politically charged judgment (who is the best expert?)

- No one is forced to make what can be very difficult assessments (if not equal weights, what?)

The equal weights approach is simple to apply. Basically, it involves taking a simple average of expert estimates, probabilities or probability distributions. But, the simplicity can be deceptive. Figure J-6 illustrates that there are at least three types of averages that may be taken. The second two, equally weighting fractiles of distributions and equally weighting moments or other statistics (e.g., means and variances) of distributions are two common mistakes that should be avoided. As indicated in the figure, they both can grossly underestimate the appropriate amount of uncertainty in the aggregate distribution. If equal weights are to be applied, they should be applied to distributions. But the figure shows one immediate problem which we will discuss in detail below, namely that the resulting shape of the aggregate distribution may be an artifact of the equal weighting scheme and may have no intuitive or physical basis.

It is worth repeating that a desirable outcome of the TFI facilitation process with its emphasis on shared information and heavy interaction is the situation under which equal weights are appropriate. However, it is essential to understand and detect the presence of such a condition.

In the traditional context of weighting proponent experts or models, there are two fundamental issues to address in considering equal weights (a third issue particular to the TFI process, whether the expert-as-integrator evaluations are representative of the overall expert community was discussed in Chapter 3). As discussed in the dependence section above, if proponent experts are correlated, then applying equal weights implicitly double counts the data and models they have used. However, this is not a problem if all the correlations are roughly equal in magnitude (see mathematical model below). Second, application of equal weights assumes that there are no substantive differences in the relative expertise among the different experts -- they may have differences in specialized knowledge for the application at hand, but they should be equally credible as scientists.

Assigning equal weights to proponent positions is not a benign assumption, especially if one position is an outlier. Equal weights on probabilities or probability distributions is not

equivalent to equal weights on the underlying scientific hypotheses (which is generally unrealistic in itself!). Actually, equal weights can be quite biased towards the composition of the set of experts being evaluated. If two experts out of ten form estimates based on similar scientific hypotheses (ways of thinking, modeling approaches, etc.) and eight experts condition on another hypothesis, then equal weights is essentially giving 20% weight to the first hypothesis and 80% weight to the second hypotheses. In other words, the answer would depend on the specific composition of the group. Thus, deciding a priori on an equal-weighting-type scheme makes the decision as to whom to weight especially important (indeed, absolutely critical if there is not intensive expert interaction).

The bottom line with equal weight methods is that they are legitimate if they are the result of a more sophisticated analysis, but they should never be assumed without close scrutiny. If after detailed analysis and interaction, it is believed that a set of experts is roughly equally credible and roughly equally interdependent, then equal weights may be appropriate. But equal weights should not be preordained.

The above observations indicate why the TFI process is designed to provide an explicit mechanism for ensuring comprehensive and detailed information exchange that moves the panelists towards equal expertise and high, but equal interdependence for the application at hand. Without this information exchange, using equal weights on the positions of an expert panel can introduce systematic errors into the final hazard curve.

A Simple Mathematical Model for Evaluating Equal Weights

This section illustrates how the simple expert-aggregation models described above can be used to estimate, for different degrees of correlation and forecasting uncertainty, how much error results from assuming equal weights. A variant of the dependent-experts model represents the dependence among the experts with a multivariate Normal distribution, parameterized by a mean vector and a covariance matrix (Clemen and Winkler, 1985; Clemen and Winkler, 1992). The covariance matrix can be specified with a vector of variances (individual forecasting accuracies) plus a correlation matrix in which each entry is the correlation between a pair of experts' estimates. For brevity, we state without proof the intuitive notion that equal weights will result *if and only if all the correlations between different pairs of experts are equal and all experts are judged to be equally accurate estimators*. In other words, the degree of interdependence among any

pair of experts must be exactly the same as that between any other pair. The correlations can be calculated from the assessments of accuracy and dependence described in the dependent expert combination models above. Case 1 below illustrates one example of equal weights resulting from equal assessed accuracies and equal assessed correlations. The top table lays out an example set of assessed inputs; the lower table gives the calculated (equal-correlation) correlation matrix.

Equal Weights: Case 1 -- Equal Correlation Among All Expert Pairs

	Expert 1	Expert 2	Expert 3	Aggregated
Estimate (mean)	60	60	120	80
Accuracy (std. dev.)	30	30	30	24
Dependence on Expert 1		0.5	0.33	
Dependence on Expert 2			0.33	
Dependence on true value	1.0	0.5	0.33	
Calculated Weights	0.33	0.33	0.33	1.00

Equal Weights: Case 1 -- Calculated Matrix of Correlations

	Expert 1	Expert 2	Expert 3
Expert 1	1.0	0.5	0.5
Expert 2	0.5	1.0	0.5
Expert 3	0.5	0.5	1.0

A common mistake is to assume that equal forecasting accuracy is the only necessary condition for equal weights. The table below shows for equal forecast accuracies (standard deviation of 20) how the calculated weights vary as a function of differences in expert correlations. The table was constructed by assuming that Expert 3 is uncorrelated with Experts 1 and 2 and then calculating the weights resulting from varying the correlation (ρ) between Experts 1 and 2.

Equal Weights: Case 2 -- Error Introduced by Assuming Equal Weights When Experts are Not Equally Correlated

	Expert 1	Expert 2	Expert 3	Aggregated
Equal Weights	0.33	0.33	0.33	80
$\rho = 0.25$	0.31	0.31	0.38	83
$\rho = 0.50$	0.29	0.29	0.43	86
$\rho = 0.75$	0.27	0.27	0.47	89
$\rho = 1.00$	0.25	0.25	0.50	90

For example, if equal weights were applied in a case where Experts 1 and 2 were actually 75% correlated, the resulting estimate would be over 10% too low (80 rather than 89). This case is intentionally extreme; in most real applications the error would be much smaller.

Non-Equal Weights

In practice, the weights assigned to expert judgments often appear in one of two forms: the linear opinion pool and the logarithmic opinion pool [Genest and Zidek, 1986; Cooke, 1991]. To make the discussion concrete, let $p_1,\ldots,p_n$ be the set of probabilities that n experts supply for an uncertain event (these are analogous to the point forecasts discussed above), and let $w_1\ldots,w_n$ be the weights that are assigned to these experts by the TFI (their sum is equal to unity). Then, the linear opinion pool (see the simple mathematical model above) gives the aggregated probability P of this event as:

$$P = \sum_{i=1}^{n} w_i p_i$$

while, the logarithmic opinion pool calculates it as:

$$P = [\prod_{i=1}^{n} (p_i)^{w_i}] / \{[\prod_{i=1}^{n} (p_i)^{w_i}] + [\prod_{i=1}^{n} (1-p_i)^{w_i}]\}$$

The NUREG-1150 method [Hora and Iman, 1989] is the arithmetic pool with equal weights, i.e., $w_i = n^{-1}$. It is interesting to note that, in practice, the choice of the

aggregation method is primarily dictated by the numerical values of the p_i's, i.e., when they differ significantly, analysts tend to use the logarithmic pool. Unfortunately, this decision is arbitrary, and its impact on the results can be at least as significant as the choice of the expert weights.

There is no universally accepted approach to the determination of these weights. However, some ideas have been proposed in the literature that may be helpful.

One idea is to ask experts to self-rate themselves or, better yet, to self-weight the set of different basic approaches. Such an exercise is susceptible to the same kinds of biases that may distort probability judgments, although such self-ratings were found useful in early Delphi exercises [Linstone and Turoff, 1975] and were used by LLNL in the 1980's EUS study. A variation that may be more meaningful in PSHA is to ask the experts to quantify their relative forecasting or estimating ability. This means that, for example, they could declare themselves more competent to develop seismic source maps for certain regions of the country, while they would feel less confident in their assessments for other regions. This way, the expert is not judging his or her overall expertise, but, rather, the relative value of his or her judgments. This approach worked well in the SSHAC ground motion workshops.

An extension of the expert-supplied ratings idea is to ask the experts to rate each other's forecasting ability. There are several formal methods for using such information, but they are based on very strong assumptions [De Groot, 1974; Cooke, 1991]. Nevertheless, this type of information may be very useful to the TFI for behavioral aggregation.

An interesting approach to the determination of weights is proposed in what Cooke calls the "classical" model [Cooke, 1991]. The weights are derived by comparing the expert estimates of some unknown (to them) quantities with their actual values which are already known to the decision maker. The assumption is that the performance of the experts with regard to these "seed" or "calibration" variables would be comparable to their performance in answering questions about the unknown quantities of interest. Unfortunately, finding these seed variables for the difficult issues that are encountered in PSHA would be far from straightforward, although, in fairness, it should be stated that such an exercise has not been attempted.

It is worth repeating here that these approaches to weight estimation should be utilized by the TFI only indirectly (although the TFI may need to be more direct for seismic source characterization). The reason is that no method can capture fully the salient characteristics of every problem. In the example discussed in Chapter 3 (Figure 3.3), the TFI was required to form an opinion regarding the applicability of the disputed evidence, and did so as a function of one of the variables, something that any formal weighting scheme would have a very hard time modeling.

Level of Aggregation

A basic issue in seismic hazard analysis is at what level in the analysis to aggregate the multiple expert and model inputs. This is one issue that has a clear answer: aggregation should be performed at the most detailed level possible (for example, aggregate first at the ground motion characterization level and seismic source characterization level separately before the final hazard calculation, rather than aggregate at the hazard calculation level). The primary reason for this is that disaggregation allows focused application of expertise and engenders more debate and interaction on specific points. However, there are some important aggregation issues as well. The remainder of this section raises issues primarily of interest to the normative elicitation expert in the TFI team who needs to consider them in designing both the elicitation and integration process.

Sometimes, such as in the case of seismic maps or ground motion models with different functional forms, it is simply impossible to aggregate at a detailed level because the components are incomparable. One expert's seismic source zone map may be different than another expert's map, so that basic variables, such as activity rates, cannot be compared because they are defined over different regions. However, when experts are supplying judgments about variables that are comparable or that can be manipulated so as to be comparable (e.g., have experts compare their implied activity rate estimates for artificial zones defined by two or three concentric circles around a site), it is beneficial to address and aggregate variables at the component level.

The benefits of disaggregation make it important for the TFI to be active in seeking ways to structure the analysis so that the experts may interact to debate and compare interpretations at as detailed a level as possible. There are at least three basic reasons for aggregating at a detailed level:

- Aggregation at a high level can obscure distinctions that experts make and inhibit useful debate about more fundamental parts of the problem.
- Aggregation at a low level allows different experts to focus their specialized expertise on the parts of the problem they know best and the TFI to spend resources on the issues that are most critical.
- Aggregation at a high level can sometimes filter out important structural information and can produce a result that is logically inconsistent with information at a more detailed level.

Thus, there are both logical and process-related reasons to aggregate at a low level based on the basic principle:

> Basic principle - *The final composite distribution should be consistent with the best composite assessment on each underlying variable.*

This seemingly innocuous principle can lead to serious contradictions if it is not followed. For example, consider two uncertain variables, x and y, that everyone agrees are probabilistically independent: they have no physical relationship whatsoever to each other and there is unanimity in the expert community that the conditional distribution on y given x is equal to the marginal distribution on y. If a higher-level variable z is a function of both x and y, and if individual experts each assess both x and y, then aggregating across experts at the z level can produce a probability distribution on z that contains implicit dependence between x and y ... a relationship that *every* expert agrees is not appropriate. If the expert discussion and aggregation is performed at the x and y level, this problem is automatically avoided. Figure J-7 displays this principle graphically.

Potential issues for the TFI related to this principle are most easily described with a simple example illustrated in Figure J-8. Suppose that two experts assess the probability that a fault is active. Using the type of tectonic framework developed by EPRI, they each assess the probability of 'favorable geometry,' that is, geometry that tends to be associated with earthquakes. They also assess the conditional probability of the fault being active, conditional on whether or not there is favorable geometry (this might be thought of as scientific uncertainty). Notice that the two experts give very different marginal and conditional probabilities (the first two columns of the figure), but in both cases, the

calculated probability that the fault is active is 0.2. For illustrative purposes only, suppose we agree to weight equally the judgments of the two experts. If we equally weight at the result level (i.e., the probability-of-activity level), the aggregate probability is 0.2. However, if we equally weight the three component probability assessments that the experts provide, and then calculate the probability of activity from the component probabilities, the result is a probability of activity of 0.31, which is significantly different! Also note that the composite uncertainty is different.

If the aggregation were performed at the high level, it would appear that the experts completely agreed. But this would be only because important structural information has been filtered out in performing the aggregation. In fact, Expert 2 makes a very significant distinction based on the geometry of the fault, whereas Expert 1 does not.

Aggregating at the component level helps create the highly desirable situation in which the component definitions are identical across experts. Each expert should understand his or her component probabilities in relation to the range of component probabilities. The experts should not have to worry about comparing the composite aggregate result with the aggregate of composite results.

An important practical reason for disaggregation is that without it, the experts may be forced to make assessments that mix in information about factors on which they do not have specialized expertise. One could imagine that Expert 1 as a geologist who is more familiar with the region in question and its geometry, whereas Expert 2 is a geophysicist who is more familiar with the probability of activity conditional on the underlying geometry. Common sense would be to use the geologist's probability to describe the informational uncertainty and the geophysicist's conditional probabilities to describe the scientific uncertainty. The result is shown in the fifth column of the figure, where the resulting calculated probability of activity is 0.65. This illustrates that the analysis at the component level not only provides logical consistency, but also provides a useful focus for specialized expertise. (In fact, the inconsistency discussed above does not even occur if different specialized sets of multiple experts address the two different uncertainties!)

The same observations can be made even in a deterministic analysis in which multiple experts provide different deterministic models of a phenomenon. Here, inconsistencies can arise in dealing with non-linear relationships among multiple factors. Consider, in Table 5.3 below, the estimates of mean ground motion as a function of distance provided

by four experts (playing the role of proponents) in the second SSHAC ground motion workshop (see Figure J-9). For the sake of illustration, two dotted lines were drawn through the Atkinson and Somerville/Saikia estimates (the experts' reasoning was, in fact, not based on simple linear models, but the result is close enough to be useful for illustrative purposes). The dotted lines in the figure indicate that over the regions of distance given, the relationships on a log scale are roughly linear of the form:

$$\log g = a \log d + b,$$

where g is mean spectral acceleration and d is distance to the rupture. The table contrasts what the answer would be if we aggregate at the component level, i.e., aggregate the a values and b values, then estimate the ground motion, contrasted with aggregating at a high level, i.e., averaging the two experts' estimated ground motion. (We note for statisticians that at least two deeper issues are masked by the deterministic nature of this example: first, a and b are not generally considered to be probabilistically independent, and second, in the probabilistic case, it will be true that the mean of the aggregate is equal to the weighted individual means.)

This example is based on equal weights for simplicity, but that is not important to the conclusion. If the TFI believes that the best value of a is -1.12 and the best value of b is 1.32, then the ground motion of 3.7 estimated by high level aggregation is inconsistent with the TFI's state of knowledge about a and b. (Mathematically, this inconsistency stems from the well-known fact that the mean of a non-linear function is not equal to the function evaluated at the mean.)

Again, independent of the mathematics, an important process observation is that it is more fruitful to have the experts focus on the values of a and b than to debate estimates of the overall ground motion. For example, it may be that the experts agree on the slope, but not on the intercept, which would lead the TFI to prompt them to explore this cause of the systematic difference between their two curves.

Implications of Issues

The bottom line concerning these and other expert aggregation issues is that there are no recipes for how to deal with all of them. The good news, however, is that analysis of the issues has resulted in a set of concepts and methods that can provide guidelines for

aggregating expert judgments. The TFI process is designed to ensure that these issues are addressed in the most explicit way possible, and to utilize the various expert elicitation tools that have been developed to address these issues.

Section 4. Guidance on the Two Stage Elicitation Process

Here we describe in more detail the types of assessments required of the experts in the two-stage elicitation process introduced in Section 3.3.4. This section builds on the previous description. At the end of the section we present a simplified mathematical model that provides insights into the two-stage procedure and its implications.

Before presenting the details, note that the first stage is more traditional, and will consume the bulk of time and expense. Much of the time and expense are due to the fact that the Stage I elicitation requires the full range of separate group interactions defined in Section 2's detailed facilitation guidance. The second stage, while novel, should be relatively brief and inexpensive (probably less than one additional day of group interaction), as the experts are building on the knowledge they have already acquired in Stage I.

Recall that the genesis of the two-stage approach is the goal of forming a composite representation of the scientific community.

Stage I Each Panelist as an Independent, Informed Evaluator

For a given variable or model parameter value, this stage requires two traditional (for PSHA) assessments:

a) Each expert gives his best (mean) estimate, based on an evaluation of the full range of models, evidence, data and proponent positions in the community. The assessments are performed only after thorough facilitated interaction (including sharing of all relevant local or site-specific information) as described in Step 6 (Analysis, aggregation, and resolution of disagreements) below.

Result: The average of the mean estimates provides an initial estimate of the panel's composite mean. The variance of the mean estimates provides one component of an initial estimate of the panel's composite variance.

b) Each expert assesses his epistemic uncertainty in the mean estimate. This is also based on thorough interaction; in particular, each expert is exposed to the full range of other panel member estimates (which should generally lead to appropriately wide distributions if there is substantial disagreement).

Result: The mean of the expert-supplied variances provides the other component of an initial estimate of the panel's composite variance.

Note that the TFI need not be limited to assessments of means and variances; indeed, it is often preferable to encode non-parametric distributions without being limited to a set of summary statistics, or even a particular functional form. It is possible to estimate the composite distribution in these cases as well; we address only means and variances here for simplicity of exposition.

If the TFI's goal was to represent the panel's knowledge, the elicitation would stop here (after sufficient interaction, iteration, etc.). However, a second stage is necessary to represent the overall scientific community state of knowledge.

Stage II Panelists as Integrators, Representing the Overall Expert Community

In this stage, the panelists would provide two types of assessments, based partially on what they each observed from other panel members in the first stage:

a) Each expert provides an estimate of what the composite mean of the entire community would be, assuming that the community were provided the same information base and opportunity for interaction that the panel has had.

Result: The difference, if any, between an expert's personal estimate and his population estimate is a measure of his own intended bias relative to the

community. Moreover, the average of the biases is an estimate of the panel's overall bias relative to the overall community.

b) Each expert assesses the composite uncertainty in the community through two assessments: (1.) an estimate of the variance in the distribution of mean estimates throughout the community, and (2) an estimate of the expected variance in the individual experts' distributions.

Result: These assessments provide an indication of whether the panel believes its estimated uncertainty range is representative of the expert community at large.

A pertinent special case is when one expert (i.e., the "incognito" proponent) assumes that the panel of n experts represents the community and the other n-1 experts do not agree -- they see him instead as a singular point (1 out of N, not 1 out of n). In this case, the TFI need not automatically downweight that expert's assessment of the community mean; rather, the TFI should attempt to gather more specific data by asking the apparent proponent to provide names and references of others in the expert community who he believes share his view or position. This provides the TFI and the panel with a more explicit basis for evaluating the expert's assumption.

Chapter 5 on Ground Motion explains how results of the two stage process were used to develop a final TFI position in the context of the two SSHAC Ground Motion workshops.

Section 5. A Mathematical Model For The TFI Process

This section presents a mathematical aggregation model developed in the SSHAC project. This model, called the "TFI model," provides a conceptual framework for elements of the TFI elicitation and expert aggregation processes. It can be used for conducting sensitivity analyses and developing intuition. This model has not been published or externally reviewed. It is presented here solely for the insights it might generate -- the TFI process does not depend upon the model.

This section goes into more mathematical detail than the other sections on aggregation models. Readers uninterested in the mathematics may wish to skip directly to the *Example Results* subsection, which is presented last.

Background

The TFI model was developed in an attempt to extend existing mathematical aggregation models to address some issues in seismic hazard estimation that classical mathematical models ignore or address only partially. The TFI model differs from the simple Bayesian models discussed above in that it results in a wider aggregate distribution that explicitly reflects the observed variation among expert estimates (this component of uncertainty is ignored in the simple Bayesian models). It also provides an underlying conceptual structure for ad hoc methods that involve simple weighted averages of distributions, but, in contrast to these methods, the TFI model explicitly adds the uncertainty introduced by sampling only a small number of experts from the overall expert community. Moreover, the TFI model provides a logical structure for determining when and if equal weights are appropriate. Finally, and perhaps most importantly, the Stage II analysis in which the experts act as integrators is unique to the TFI model.

We use the term "classical models" for convenience to describe formal Bayesian aggregation models, but we do not wish to imply that there is a small set of well-accepted Bayesian models. In fact, skilled modelers invariably mix and match several models from a large set of existing models to address any given problem [Clemen and Winkler, 1992] or

apply ad hoc methods (e.g., equal weights on distributions) that produce results similar to those of the TFI model

Classical formal aggregation models present several issues. First, it is extremely difficult to quantify dependence among experts, especially after dependence-inducing, intensive interaction, although some promising work has recently been published [Clemen and Jouini, 1994]. And, as demonstrated above, misestimating interdependence not only skews the composite mean, but also the composite variance. But, even with a perfect model of dependence, another deeper problem is not addressed by most aggregation models. Consider, for example, the case in which the experts are completely independent (in the formal sense defined above) and in which they have achieved (intentional) consensus on the estimated value of some uncertain quantity. Many Bayesian models would produce a posterior distribution reflecting far less uncertainty than that of any individual expert. A simple example is that if five independent experts agree that the probability of rain is 60%, direct Bayesian updating results in an aggregated probability of over 99%. Allowing for probabilistic dependence reduces this effect, but does not eliminate it. In fact, short of complete dependence among the experts, classical aggregation results in a posterior probability higher than the experts unanimous 60%.

The TFI model avoids this problem. It has the desirable property that if all experts agree on a probability distribution, the aggregated or composite distribution is precisely the consensus distribution.

The TFI model is not entirely inconsistent with ad hoc aggregation practices used in certain previous risk analyses; indeed, it may be viewed as providing conceptual Bayesian underpinnings to certain simple intuitive methods that have been used for years. For example, in NUREG 1150, an aggregated distribution was formed based on an equally-weighted mixture of expert distributions. As we shall see, this ad hoc procedure is consistent with the TFI-model result, but only conditional on a set of important conditions, which include a large and representative panel as well as a formal process for conducting intensive expert interaction and interchange leading to equal problem expertise and interdependence among all experts.

Approach

For clarity, we will address one of the simplest cases, that of estimating a fixed but uncertain (epistemically) scalar quantity of interest, such as the height of the Eiffel Tower or the long term slip rate on a fault. The model may be extended to other more complex cases, such as estimating a set of moments or fractiles of the distribution of ground motion in the Eastern U.S. at a given distance and magnitude, but these cases extend beyond the scope of this appendix.

Our development will proceed in two steps corresponding to elicitation Stages I and II. Recall that in Stage I, the experts assess the uncertain quantity of interest. By viewing the panel of experts as a sample of the overall community of such experts, we shall infer an initial "best" or composite estimate of the community distribution. However, this is not the final composite distribution, but rather a useful intermediate input for both the TFI and the panel in the Stage II assessment. In Stage II, the experts estimate the (unknown) community distribution directly.

For both Stage I and Stage II we will also derive a "predictive distribution" reflecting the updated state of information of a single individual beginning with an "uninformative" prior distribution. As we shall demonstrate, the predictive distribution is a higher-variance version of the best estimate of the community distribution, adjusted to reflect the sampling uncertainty inherent in a limited panel size.

Stage I -- Experts as Evaluators

We begin by addressing Stage I of the elicitation process. Suppose that an individual expert provides a subjective probability distribution on a continuous unknown quantity, x. A non-informed layman would do well to adopt the distribution of the informed expert as his own, so long as the layman believes that the expert has a much stronger capability and training in the appropriate field to make objective, unbiased evaluations of all available information, including data, contending scientific theories and interpretations, models, and hypotheses.

Similarly, suppose hypothetically that a decision maker were able to assemble a large set of experts believed to be objective evaluators, and then to inform them through a process of disseminating information, providing for interaction with proponents of relevant scientific hypotheses, and then promoting and facilitating interaction and debate among the evaluators. Such a decision maker would be well advised to use as his distribution the mixture of the distributions of the individual experts if he believed that the experts (as a consequence of the interaction) in this "perfect community" were effectively equally informed on the issue of interest and equally interdependent (see equal-weights discussion above).

We define this mixture or "community distribution" as the target of our inference. In the discussion below we will assume a mixture calculated with equal weights based on an idealized "perfect community" of unbiased, equally informed experts. We then estimate this hypothetical distribution by sampling "real" experts and putting them through a less-than-perfect process of information exchange and interaction. Finally, at the end of Stage I, we leave open the possibility of the integrators (Stage II experts and the TFI) using unequal weights or even qualitative weighing if appropriate because the sample is "faulty" (e.g., the TFI perceives a bias in an expert, but for some reason doesn't remove him from the panel). In any case, we needn't be too concerned about equal weights in the Stage I model since the Stage I distributions are not the final recommended distributions.

To begin the analysis, let x be the uncertain quantity of interest, and assume that each of N informed experts has an elicited distribution,

f_i (x) = Expert *i*'s distribution

with mean or "best estimate,"

$$E_i(x) = \mu_i$$

and variance,

$$V_i(x) = v_i$$

The community of N experts as a population can be characterized by a frequency histogram of μ_i's , with expected value, or average,

$$E_C(\mu) = \frac{1}{N}\sum_{i=1}^{N} \mu_i$$

and variance,

$$V_C(\mu) = \frac{1}{N}\sum_{i=1}^{N} \left[\mu_i - E_C(\mu)\right]^2$$

Similarly, the population is characterized by a frequency histogram of $v_i's$, with expected value and variance,

$$E_C(v) = \frac{1}{N}\sum_{i=1}^{N} v_i$$

and

$$V_C(v) = \frac{1}{N}\sum_{i=i}^{N} \left[v_i - E_C(v)\right]^2$$

Next, consider the composite community distribution defined by the mixture,

$$f_C(x) = \frac{1}{N}\sum_{i=1}^{N} f_i(x) \qquad \textit{composite community distribution}$$

which is our estimation goal. Probability theory implies that the mean and variance of this composite community distribution are,

$$\begin{aligned} E_C(x) &= \frac{1}{N}\sum_{i=1}^{N} \mu_i \\ &= E_C(\mu) \end{aligned}$$

and

$$\begin{aligned} V_C(x) &= E_C\left(\left[x - E_C(x)\right]^2\right) = \frac{1}{N}\sum_{i=1}^{N} v_i + \frac{1}{N}\sum_{i=1}^{N} \left[\mu_i - E_C(\mu)\right]^2 \\ &= E_C(v) + V_C(\mu) \end{aligned}$$

This simple but significant result indicates that the variance of the composite distribution reflects both the ("typical" or average) individual expert uncertainty, $E_C(v)$, and, in addition, the expert-to-expert diversity, $V_C(\mu)$. These two components of variation are equivalent to Martz's "within-expert" and "between-expert" variations [Martz, 1984], but the TFI model is based on a very different conceptual framework.

The implication of the above results is that a first-order representation of the community, i.e., the mean and variance, $E_C(x)$ and $V_C(x)$, are dependent upon three quantities: 1.) the community's average best estimate, $E_C(\mu)$, 2.) the community's average epistemic variance, $E_C(v)$, and 3.) the variance of best estimates within the community, $V_C(v)$. Unfortunately, these quantities are unknown because the entire expert community is too large to engage in the intensive interaction necessary for the TFI process. Thus, we treat the three quantities as uncertain and as the primary targets of estimation.

Inference about the Community Distribution

Suppose now that we "sample" the expert community by eliciting a subset of n (n<<N) "evaluator" experts. The logical estimate of the community mean is the sample average of the Panel experts' means,

$$\hat{E}_C(x) = \hat{E}_C(\mu) = \frac{1}{n}\sum_{i=1}^{n}\mu_i \equiv E_P(\mu) \qquad \textit{estimate of community mean}$$

where we have adopted the conventions that a "hat" indicates a "best" estimate and a "P" subscript indicates an observable sample quantity from the Panel elicitation. Similarly, we can estimate the average individual variance within the community with the sample average of the Panel variances,

$$\hat{E}_C(v) = \frac{1}{n}\sum_{i=1}^{n}v_i \equiv E_P(v) \qquad \textit{estimate of community average individual variance}$$

Finally, using analogous reasoning, we can estimate the variance of the community estimates as,

$$\hat{V}_C(v) = \frac{1}{n}\sum_{i=1}^{n}\left[v_i - E_P(v)\right]^2 \equiv V_P(v) \quad \textit{est. of community variance in individual variances}$$

and estimate the community expert-to-expert diversity as,

$$\hat{V}_C(\mu) = \frac{1}{n}\sum_{i=1}^{n}\left[\mu_i - E_P(\mu)\right]^2 \equiv V_P(\mu) \qquad \textit{estimate of community diversity}$$

We are now prepared to express the estimate of the composite community variance as the sum of two sample quantities,

$$\begin{aligned}\hat{V}_C(x) &= \hat{E}_C(v) + \hat{V}_C(\mu) \\ &= E_P(v) + V_P(\mu)\end{aligned}$$

and the estimate of the entire community distribution as the mixture of the individual panelists' elicited distributions,

$$\hat{f}_C(x) = \frac{1}{n}\sum_{i=1}^{n} f_i(x) = f_P(x) \qquad \textit{estimate of community distribution}$$

An interesting result is that the magnitude of $\hat{V}_C(v)$ does not influence the final composite distribution.

Sampling Uncertainty

Basic mathematical statistical analysis says that, based on n draws from a large population of N μ_i values, the variance of the estimator $\hat{E}_C(\mu)$ of the community mean is approximately (the approximation gets better as n increases),

$$\text{Variance of mean estimator} = \frac{1}{n}V_C(\mu) \cong \frac{1}{n}\hat{V}_C(\mu) = \frac{1}{n}V_P(\mu)$$

Therefore, an approximate 84% confidence limit on the community's best estimate is,

$$E_P(\mu) \pm \left(V_P(\mu)/n\right)^{1/2}$$

In other words, the larger the sample or panel size, the higher the confidence that the estimate of the community mean is accurate. The same reasoning applies to determining the variance of the estimator of the average individual variance, i.e., the estimator of $E_C(v)$,

Variance of average individual variance estimator $= \frac{1}{n} V_C(v) \cong \frac{1}{n} \hat{V}_C(v) = \frac{1}{n} V_P(v)$

It is more difficult to get an estimate of the variance of estimators of other variances of interest such as $V_C(\mu)$ and $V_C(v)$, or $V_C(x)$, without distributional assumptions, but suffice it to say that they decrease roughly like 1/n.

The implication is that increasing the panel size reduces our uncertainty in estimating the community's composite distribution and its parameters. To develop insight as to how quickly the sampling uncertainty shrinks even for small n, it is possible to develop non-approximate models based on specific named distributions, but this is beyond the scope of this appendix.

Stage I Predictive Distribution

After sampling the n experts it is possible to develop a "predictive" distribution that reflects not only the estimate of the community distribution but also the additional uncertainty caused by the fact that only a subset of the population were elicited. This distribution is sometimes called the "posterior" distribution because it represents the updated probability distribution of an individual who begins with a "diffuse" or "uninformative" prior. Determination of the predictive distribution follows a straightforward but cumbersome Bayesian statistical analysis. Let us for first order simplicity assume that the sampling uncertainty is adequately captured by determining the effects on the mean and variance of the predictive distribution. It is easy to show that the mean of the predictive distribution remains the best estimate or panel average,

$E_I(x|f_i,\ldots,f_n) = \hat{E}_C(x) = E_P(\mu)$ *expected value of Stage I predictive distribution*

where we have adopted the Bayesian notational convention of making the conditioning on the expert distributions explicit. The subscript indicates that this distribution is based only on Stage I information. The variance of the predictive distribution is increased above that of the estimated community distribution by a term that decreases as 1/n (again we omit the details of the derivation for brevity),

$$V_I(x|f_i,\ldots,f_n) \cong \hat{V}_C(x) + \frac{1}{n}V_P(\mu)$$
$$= E_P(v) + V_P(\mu)\left(1+\frac{1}{n}\right) \qquad \textit{Stage I predictive variance}$$

This important result says that the total uncertainty in the variable x after the Stage I elicitation is the sum of three terms: 1.) the average panel (epistemic) variance, 2.) the diversity of the panel's best estimates, plus 3.) a contribution that diminishes as 1/n associated with eliciting opinions from only a subset of n experts.

Most importantly, in contrast to most other Bayesian approaches to expert aggregation, in this approach only a portion of the posterior uncertainty reduces with increasing panel size. More experts help provide better (i.e., more confident) estimates of the average community variance and expert-to-expert diversity, but additional experts cannot be expected to reduce these underlying components of the uncertainty about x in the scientific community.

Stage II -- Experts as Integrators

Traditional processes stop at the end of Stage I, but it is extremely useful to have the experts themselves estimate the community distribution directly. In Stage II, the TFI asks each panelist both whether he believes he, as an individual, is representative of the community as a whole, and whether the overall panel (i.e., both the location and width of the panel's composite distribution) is representative of the community.

Thus, the estimated community distribution and its moments from Stage I are viewed as intermediate information for the TFI and the experts in their integrator roles to use to form their own estimates of the community distribution. They are not constrained to use equal

weights, and, indeed, it is very useful to perform sensitivity analyses that show how the Stage I results change with different weighting schemes.

The basic issue each integrator-expert must consider is how representative the results of the panel interaction would be if it were possible to extend the interaction to the overall community. For example, if an integrator feels that the panel experts after interaction would tend to have higher estimates than the community as a whole, he would estimate the community mean as being higher than the panel mean. Similarly, each integrator can judge whether the panel's range of estimates is likely to be tighter or wider than that of the community. Each integrator observes in the TFI-led interaction, how each panelist influenced others on the panel. As part of the Stage II exercise, each integrator expert must consider whether the same degree of influence would apply to the overall community.

We could ask each expert for detailed information, such as full probability distributions on the mean and variance of the community distribution, but for simplicity here we assume that each expert simply provides a best estimate of the community distribution,

c_i (x) = Expert *i*'s best estimate of community distribution

Expert i's best estimates of the mean and variance of this community distribution are denoted, $E_i(\mu_C)$ and $E_i(v_C)$, respectively, where in terms of our earlier notation,

$$\mu_C = E_C(x)$$

and

$$v_C = V_C(x)$$

Following exactly parallel logic as for Stage I, the Stage II best estimate of the composite distribution is,

$$\hat{\hat{c}}_C(x) = \frac{1}{n}\sum_{i=1}^{n} c_i(x)$$ *Stage II composite distribution*

We use the same notational conventions as in Stage I but with double "hats" indicating Stage II estimates. The mean of the Stage II composite distribution is,

$$\hat{\hat{E}}(x) = \hat{\hat{E}}_C(\mu_C) \equiv \frac{1}{n}\sum_{i=1}^{n} E_i(\mu_C) \equiv E_P(\mu_C) \qquad \textit{Stage II composite mean}$$

and its variance is,

$$\begin{aligned}\hat{\hat{V}}_C(x) &= \frac{1}{n}\sum_{i=1}^{n} E_i(v_C) + \frac{1}{n}\sum_{i=1}^{n}\left[E_i(\mu_C) - E_P(\mu_C)\right]^2 \\ &\equiv E_P(v_C) + V_P(\mu_C) \qquad \textit{Stage II composite variance}\end{aligned}$$

Also, paralleling Stage I, the predictive distribution for Stage II has mean,

$$E_{\mathrm{II}}(x|c_i,\ldots,c_n) = \hat{\hat{E}}_C(x) = E_P(\mu_C) \qquad \textit{mean of Stage II predictive distribution}$$

and variance,

$$\begin{aligned}V_{\mathrm{II}}(x|c_i,\ldots,c_n) &\equiv \hat{\hat{V}}_C(x) + \frac{1}{n}V_P(\mu_C) \\ &= E_P(v) + V_P(\mu_C)\left(1+\frac{1}{n}\right) \qquad \textit{variance of Stage II predictive distribution}\end{aligned}$$

The Stage II predictive distribution is the final distribution. Of course the TFI is not constrained to form it based on equal weights, but equal weights are even more likely to be appropriate for the Stage II distribution than Stage I for the reasons discussed in Chapter 3.

Bayesian Interpretation of the TFI Model

We note to the reader familiar with Bayesian techniques that, while the TFI model may appear to be based on a non-Bayesian way of viewing the problem, it is not inconsistent with Bayesian tenets. The Bayesian approach attempts to characterize the appropriate posterior state of information of a single decision maker. In the public policy context, this

number of individual decision makers at different levels, and a number of participants in the decision-making process, all of whom need to use the results of the expert interaction, and 2.) even if there were one clearly identified decision maker, representing his or her state of information places them uncomfortably in a role like that of a "super-expert." The TFI model leaves any individual the freedom to interpret or modify the results in any way they choose. But, it seems unlikely that any layman integrator would want to choose a different predictive distribution than that based on the estimated hypothetical "perfect-community" distribution, unless he had reason to suspect technical or motivational bias (which is exactly what the TFI expert selection and interaction processes are designed to eliminate). In any case, one can show that the predictive distribution is equivalent to Bayesian updating for an individual with a non-informative prior who believes the experts are exchangeable(as defined by Clemen and Jouini, 1994).

Example Results: Comparison of the TFI and Classical Models

We conclude with some examples that contrast the results of the TFI model with the simple classical models presented earlier in this appendix that do not incorporate the diversity of expert estimates in the final aggregated result. Of course, the experienced decision analyst would never use these models to estimate posterior variances, but would customize models for the application at hand. For example, classical Bayesian models typically provide an intuitive answer for the mean estimate (indeed, often the same answer as the Community model), and they are often used just for mean estimation, not for variance estimation.

For ease of exposition, some simplifying assumptions have been made in the examples. First, we assume for comparison a Stage I analysis only since classical models do not address Stage II. Also, the cases all ignore sampling uncertainty and each case assumes that all experts are independent (if the experts were assumed to be equally interdependent, the TFI model results would be unchanged and the classical model would result in the same composite mean with a higher composite standard deviation).

The classical model used to determine the results below was the simple Normal-additive estimation error model presented earlier in this appendix. The TFI model assumes equal

weights, but the results are generalizable. Each case is described by a table of expert estimates and composite results, followed by a simple graphical display of the results.

CASE 1: Complete Agreement

Consider first the case of complete consensus:

	INPUTS					COMPOSITE	
	Expert 1	**Expert 2**	**Expert 3**	**Expert 4**	**Expert 5**	**Classical Model**	**TFI Model**
Mean	10	10	10	10	10	10	10
Std. Dev.	5	5	5	5	5	2.2	5

Expert Elicited Ranges

```
|-------------|
|-------------|
|-------------|
|-------------|
|-------------|
```

Classical Composite |---|

TFI Composite |-------------|

When all the experts agree on the mean and the standard deviation of an uncertain quantity, the TFI model reflects this consensus. The classical model reflects the consensus mean but estimates significantly less posterior uncertainty than any individual expert. Consider now a case where the experts agree on the spread but disagree on the best estimate:

CASE 2: Variation in Mean Estimates

	INPUTS					COMPOSITE	
	Expert 1	**Expert 2**	**Expert 3**	**Expert 4**	**Expert 5**	**Classical Model**	**TFI Model**
Mean	10	10	30	50	50	30	30
Std. Dev.	5	5	5	5	5	2.2	21

Expert Ranges

```
|-------------|
|-------------|
                |-------------|
                                |-------------|
                                |-------------|
```

Classical Composite

```
                |---|
```

TFI Composite

```
        |-------------------------|
```

The models agree on the posterior estimate but differ by an order of magnitude on the posterior standard deviation. The standard deviation of the TFI model is predominantly driven by the variation among the experts' mean estimates. The classical model is insensitive to this variation. Consider the same case with more elicited uncertainty:

CASE 3: Experts Assess High Uncertainty Range

	INPUTS					COMPOSITE	
	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Classical Model	TFI Model
Mean	10	10	30	50	50	30	30
Std. Dev.	40	40	40	40	40	18	45

Expert Ranges

```
|-------------------------------------|
|-------------------------------------|
              |-------------------------------------|
                                      |-------------------------------------|
                                      |-------------------------------------|
```

Classical Composite |----------|

TFI Composite |----------|

This case shows that both models are sensitive to the experts' assessed standard deviations. Now suppose highly confident experts disagree:

CASE 4: Highly Confident Experts with Substantial Disagreement

	INPUTS					COMPOSITE	
	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Classical Model	TFI Model
Mean	10	10	30	50	50	30	30
Std. Dev.	0.1	0.1	0.1	0.1	0.1	0.05	20

Expert Ranges

```
||
||
      ||
        ||
        ||
```

Classical Composite |

TFI Composite |----------|

If the experts estimates are widely different, even if each expert assigns high confidence to his estimate (hopefully unrealistic after intensive interaction!), the TFI model estimates high uncertainty due to the implied diversity in the expert community, whereas the classical model estimates virtual certainty. Finally, consider the most general case in which the experts disagree about best estimates and ranges.

CASE 5: Diversity in Means and Ranges

	INPUTS					COMPOSITE	
	Expert 1	**Expert 2**	**Expert 3**	**Expert 4**	**Expert 5**	**Classical Model**	**TFI Model**
Mean	10	10	30	50	50	14	30
Std. Dev.	8	5	40	15	25	4	20

Expert Ranges

```
|---------|
      |------|
      |-------------------------------------|
                                            |--------------|
                                     |------------------------|
```

Classical Composite

```
                |--|
```

TFI Composite

```
          |----------------------------|
```

When experts provide disparate mean and uncertainty estimates, the two types of models can differ dramatically.

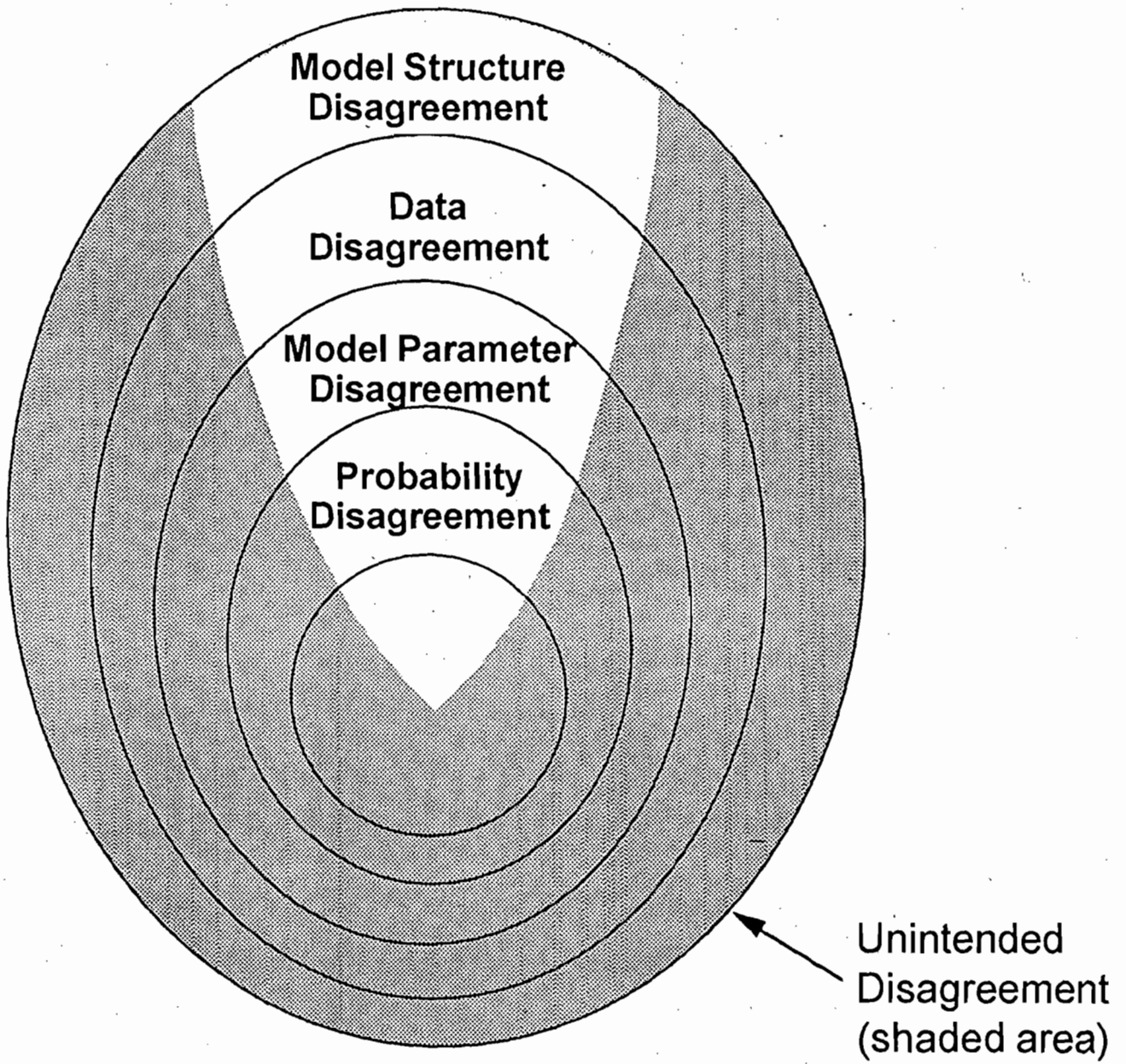


Figure J-1. Peeling the Disagreement Onion

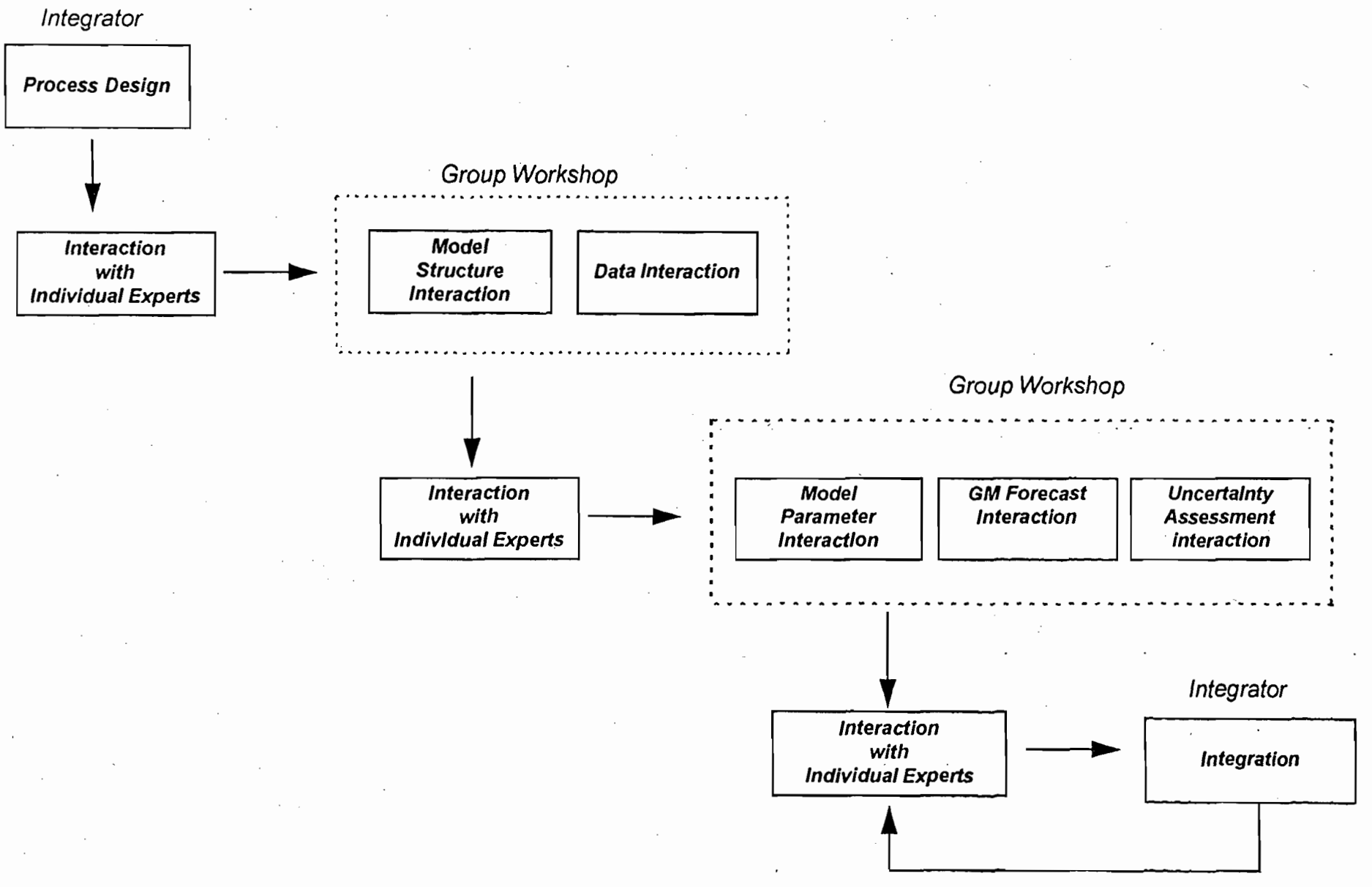


Figure J-2. Roadmap of GM Elicitation Process

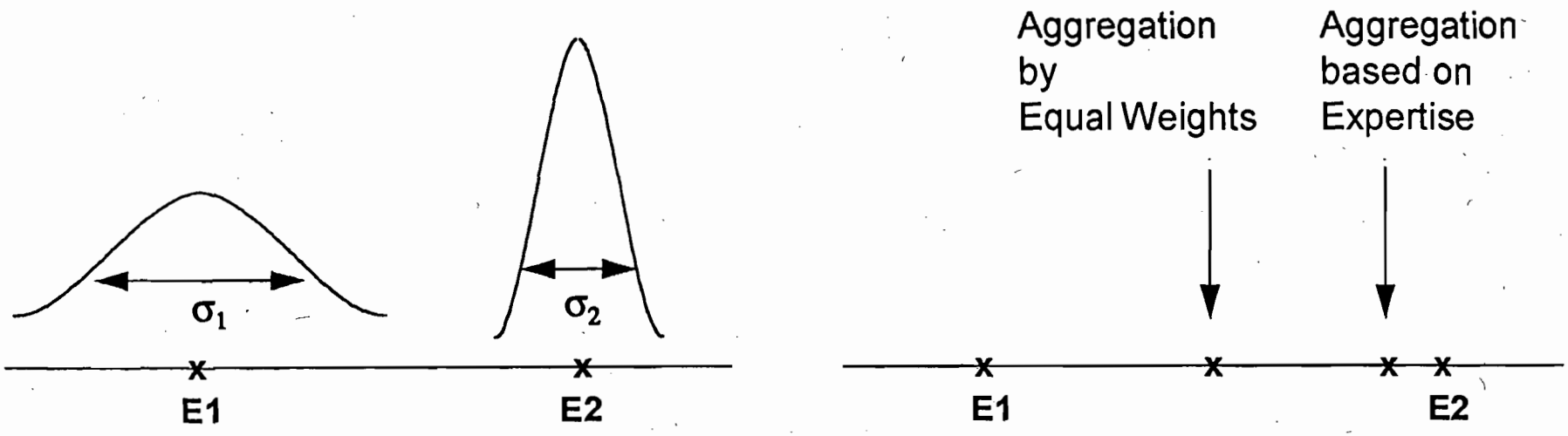


Figure J-3. Expert 2's Forecast Is Less Uncertain Than Expert 1's

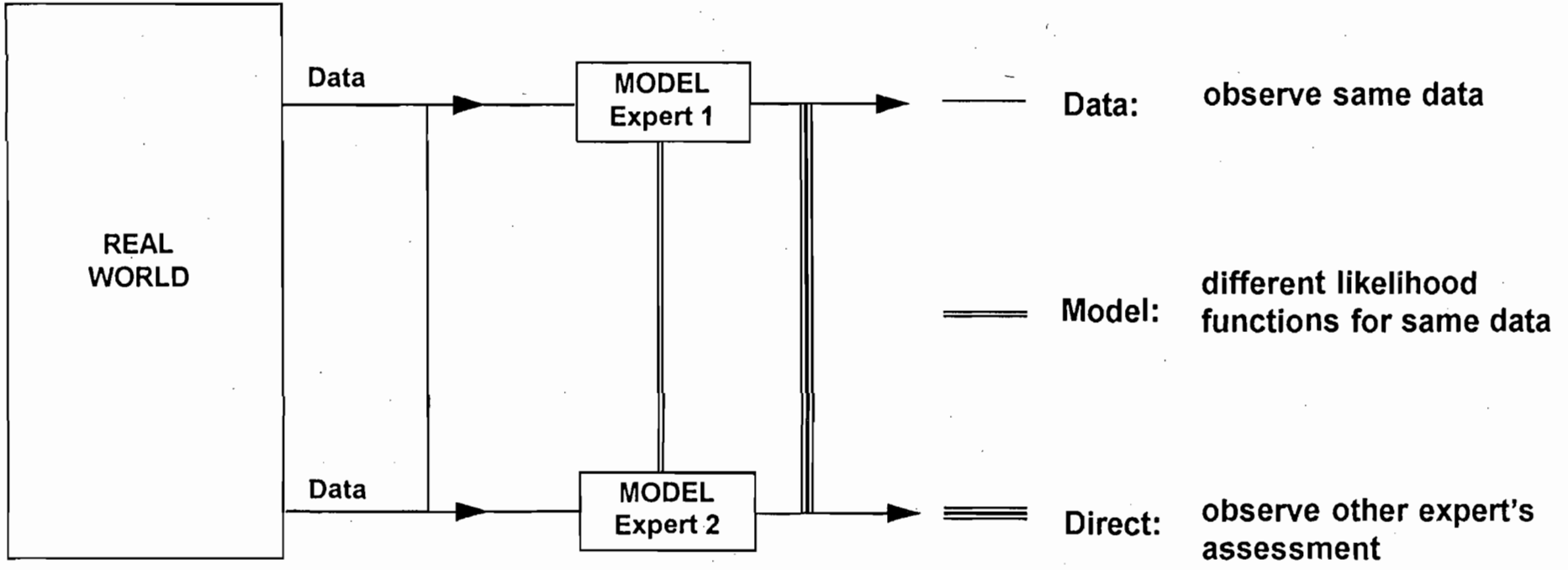


Figure J-4. Nonindependent experts

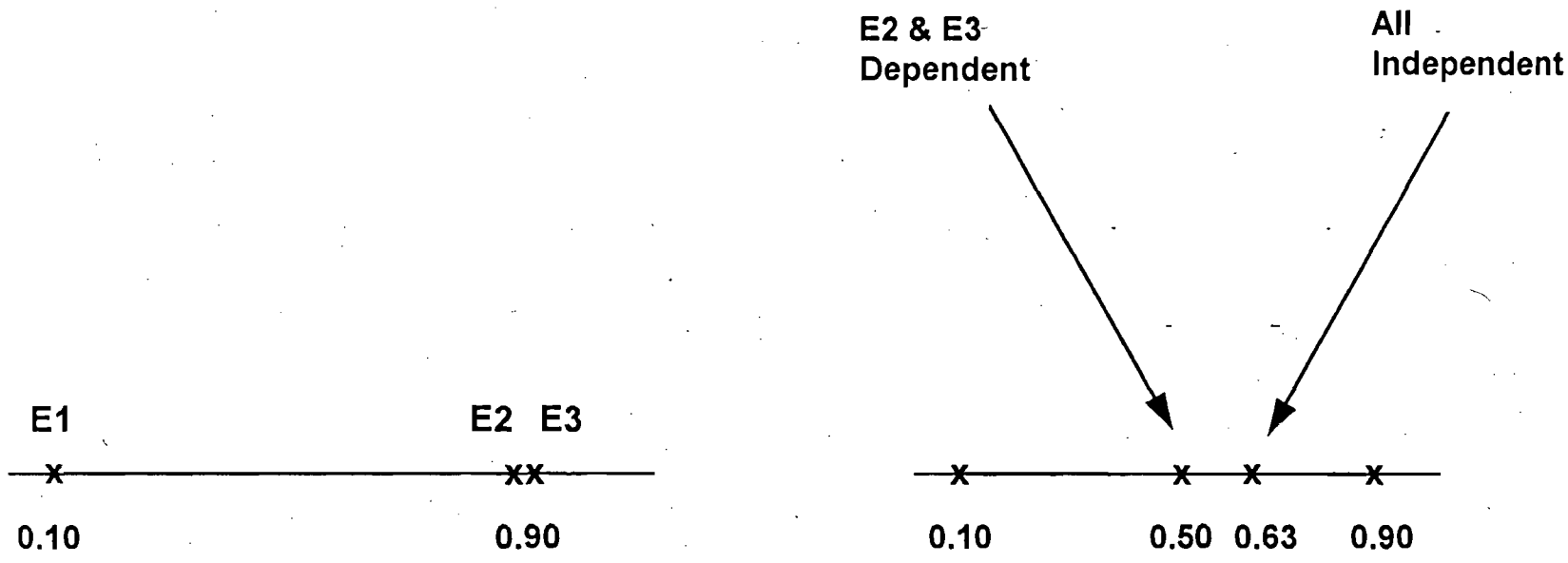


Figure J-5. The Impact of Expert Dependence on Aggregation

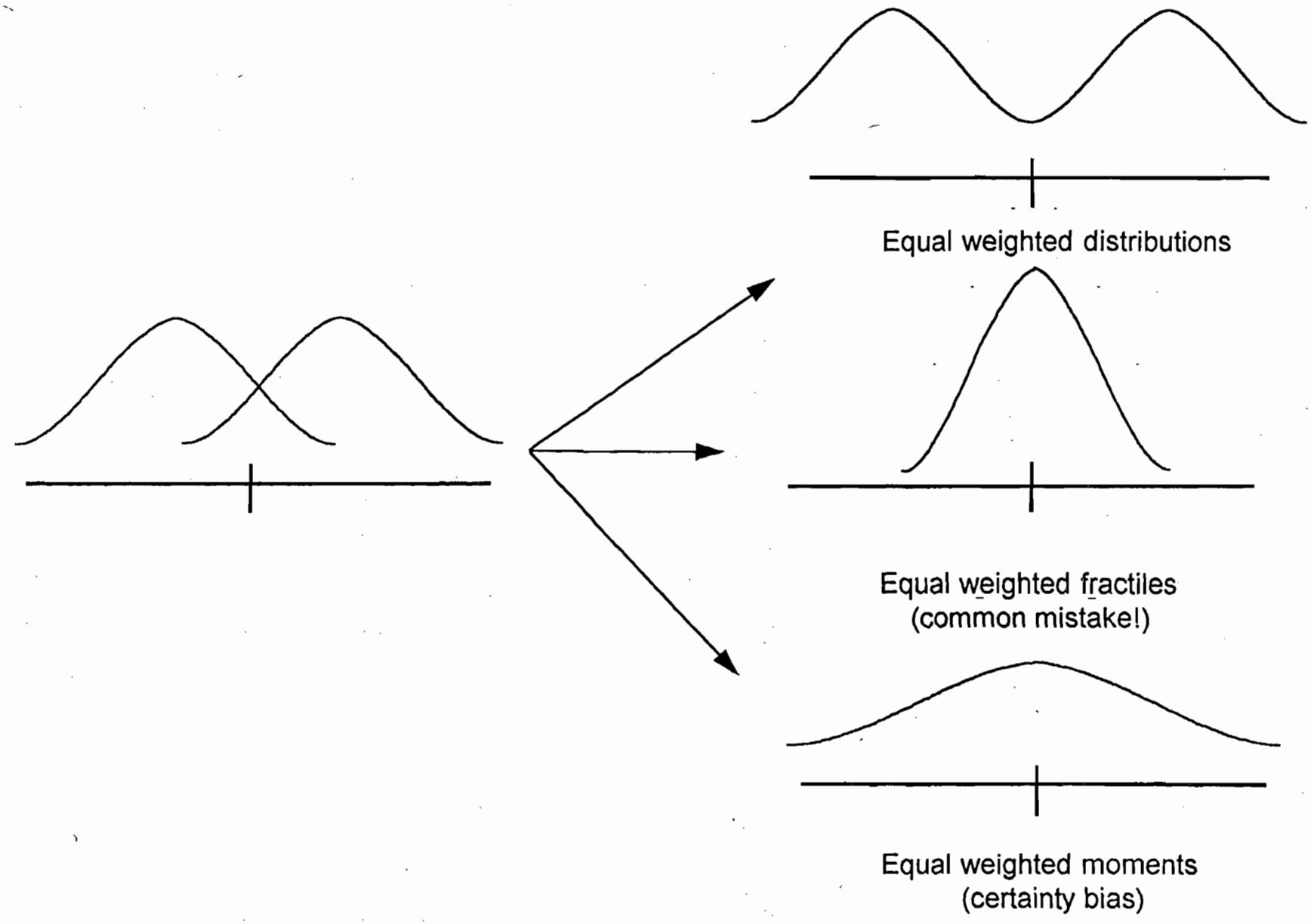


Figure J-6. Averages of What?

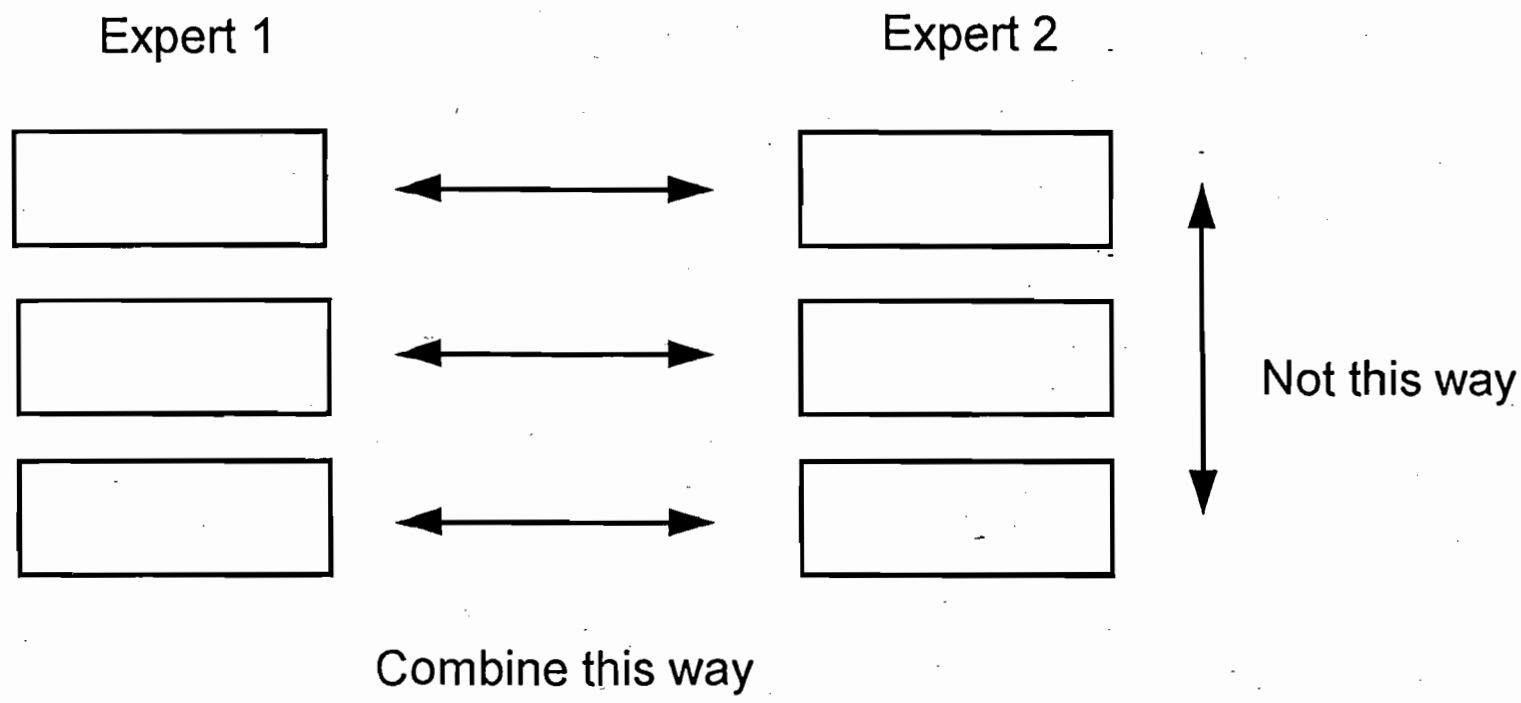


Figure J-7. Basic Issue: Level of Aggregation

		Expert 1	Expert 2	Direct Aggregation	Multi-stage Aggregation	Unequal Weights E1: Geologist E2: Geophysicist
Geological Uncertainty	p(Favorable)	.8	.2	--	.5	.8
Seismic Uncertainty	p(Active/Favorable	.2	.8	--	.5	.8
	p(Active/Unfavorable	.2	.05	--	.125	.05
Calculated	p(Active)	.2	.2	.2	.31	.65

Figure J-8. Example of Two Levels of Aggregation

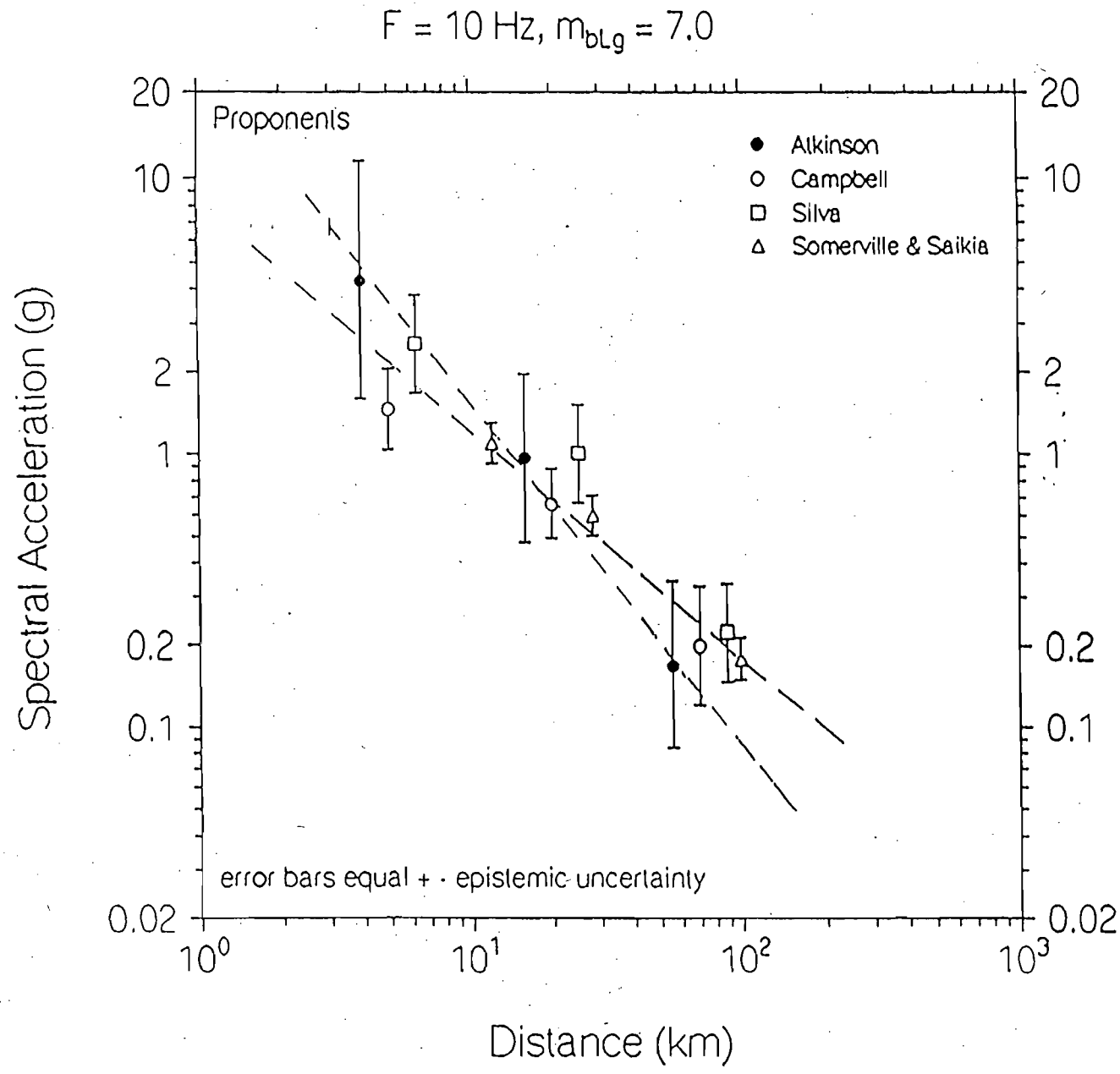


Figure J-9. Ground Motion Estimates from Workshop II

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Senior Seismic Hazard Analysis Committee (SSHAC)
R.J. Budnitz (Chairman), G. Apostolakis, D.M. Boore, L.S. Cluff, K.J. Coppersmith, C.A. Cornell, P.A. Morris

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11. ABSTRACT *(200 words or less)*

Probabilistic Seismic Hazard Analysis (PSHA) is a methodology that estimates the likelihood that various levels of earthquake-caused ground motion will be exceeded at a given location in a given future time period. Due to large uncertainties in all the geosciences data and in their modeling, multiple model interpretations are often possible. This leads to disagreement among experts, which in the past has led to disagreement on the selection of ground motion for design at a given site. The Senior Seismic Hazards Analysis Committee (SSHAC) reviewed past studies, including the Lawrence Livermore National Laboratory and the EPRI landmark PSHA studies of the 1980's and examined ways to improve on the present state-of-the-art. The Committee's most important conclusion is that differences in PSHA results are due to procedural rather than technical differences. Thus, in addition to providing a detailed documentation on state-of-the-art elements of a PSHA, this report provides a series of procedural recommendations. The role of experts is analyzed in detail Two entities are formally defined – the Technical Integrator (TI) and the Technical Facilitator Integrator (FI) – to account for the various levels of complexity in the technical issues and different levels of efforts needed in a given study.

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