

THE EARTHQUAKE POTENTIAL OF THE PAJARITO FAULT SYSTEM, NEW MEXICO

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Abstract—Geologic mapping, topographic profiling, drilling, and trenching studies were conducted to investigate the earthquake potential of the Pajarito fault system (PFS) as part of a seismic hazard investigation for Los Alamos National Laboratory. This complex, north-striking system of normal faults bounds the Jemez Mountains and forms the active western margin of the Española Basin in the Rio Grande rift, New Mexico. The PFS is geomorphically well expressed in early Pleistocene volcanic rocks that erupted from the nearby Valles caldera, but latest Pleistocene and Holocene fault scarps are generally absent, largely because of the sparsity of late Quaternary alluvium along the faults. The main 41-km-long Pajarito fault forms a prominent east-facing escarpment as high as 180 m, offsetting the 1.2 Ma Tshirege member of the Bandelier Tuff down to the east. Topographic profiles on the Pajarito fault suggest average and maximum net vertical tectonic displacements (NVTD) of 81 m and 154 m, yielding average and maximum NVTD rates of 0.07 and 0.13 mm/yr, respectively, for the past 1.2 Ma. The shorter Rendija Canyon and Guaje Mountain faults (9 to 14 km) lie within 5 km to the east of the Pajarito fault and dip steeply to the west. The maximum NVTD estimated for the Rendija Canyon fault of 36 m yields a maximum NVTD rate of 0.03 mm/yr, whereas the average NVTD of 22 m yields an average NVTD rate of 0.02 mm/yr for the past 1.2 Ma. The maximum NVTD estimated for the Guaje Mountain fault of 27 m yields a maximum NVTD rate of 0.03 mm/yr, and an average NVTD of 15 m over the past 1.2 Ma yields an average rate of 0.01 mm/yr. Shorter-term (past 0.3 Ma) vertical separation rates for the Guaje Mountain fault, estimated from offsets of fluvial terraces, range from 0.01 to 0.03 mm/yr. Paleoseismic evidence from nine excavation sites on the PFS suggests complex rupture behavior, including variations in rupture patterns through time and independent rupture behavior of closely-spaced faults. Trenches at the base of the Pajarito fault escarpment exposed indirect stratigraphic and structural evidence for as many as five surface-faulting events, with the youngest event probably having occurred shortly before deposition of the El Cajete pumice, 50 to 60 ka. However, this record is ambiguous and incomplete because the main scarp-forming fault was probably not exposed. Geomorphic, stratigraphic and structural evidence for two or three events on the Guaje Mountain fault since 150 to 300 ka suggests average recurrence intervals between 47 and 300 ka. Stratigraphic and structural evidence for three (possibly four) events on the Rendija Canyon fault since more than 140 ka suggests a preferred recurrence interval of 33 to 66 ka, although if four events did occur, average recurrence intervals would range from 16 to 33 ka. Available data suggest independent rupture behavior between the Rendija Canyon and Guaje Mountain faults. However, it is unknown whether these faults are newly forming rift-bounding structures that rupture independent of the Pajarito fault, or are antithetic faults that rupture dependently with the Pajarito fault.

INTRODUCTION

As part of a deterministic and probabilistic seismic hazard evaluation for Los Alamos National Laboratory (LANL) (Wong et al., this volume), we investigated the earthquake potential of the Pajarito fault system (PFS) (Fig. 1). Since the early 1960s, several investigations of the structure, stratigraphy and potential seismic hazard of the PFS have been conducted (Griggs, 1964; Kelley, 1979; Boden, 1980; Golombek, 1983; Gardner and Goff, 1984; Gardner and House, 1987; Wachs et al., 1988; Gardner et al., 1990). However, until recently little was known about the paleoseismic (prehistoric earthquake) activity on this complex system of faults. As defined here, the Pajarito, Rendija Canyon and Guaje Mountain faults comprise the PFS (Fig. 2). This 41-km-long, north-striking, discontinuous fault system marks the active western boundary of the Española Basin portion (Fig. 1) of the Rio Grande rift. Because the PFS is the most significant earthquake source near LANL and the town of Los Alamos (Wong et al., this volume), the Quaternary behavior of the PFS is important to evaluating seismic hazards in the region. In addition, the behavior of the PFS is significant to understanding the evolution of the northern Rio Grande rift in New Mexico.

Source parameters needed to characterize the earthquake potential of a fault for a seismic hazard evaluation include fault geometry, activity or seismogenic capability, rupture scenarios or segmentation, and maximum magnitude. For a probabilistic evaluation, slip rates and/or recurrence intervals are also needed to characterize rates of earthquake occurrence. To better determine these parameters for the PFS and understand its Quaternary behavior, our investigation included aerial photograph interpretation, aerial and ground reconnaissance, detailed surficial mapping of specific sites, topographic profiling of fault scarps, fluvial terraces, and fault escarpments, drilling, excavation of soil pits and trenches at six different sites (Fig. 3), and analyzing radiocarbon and luminescence samples to estimate ages for deposits significant to the faulting history. We highlight selected aspects of our studies and synthesize results for the entire PFS here. Wong et al. (unpubl. report to LANL, 1995) discussed all our studies in more detail and Kelson et al. (this volume) discusses our studies on the Rendija Canyon fault.

GEOMORPHIC EXPRESSION AND SURFICIAL INVESTIGATIONS

The length, orientation, and sense of slip of the PFS are significant to the hazard evaluation because these parameters are used in determining the maximum magnitudes, locations, and nature of potential surface-rupturing earthquakes. Geomorphic expression of the PFS varies considerably along strike but typically the PFS is well expressed in early Pleistocene volcanic rocks, despite the general lack of fault scarps in late Quaternary deposits. The main 41-km-long Pajarito fault (Figs. 1, 2) is an east-dipping, down-to-the-east normal fault that forms a prominent east-facing escarpment along the western edge of the Pajarito Plateau. The Rendija Canyon fault is 9 to 14 km long, lies 3 km east of the Pajarito fault, dips steeply to the west and shows dominantly normal slip down to the west (Figs. 2, 3). The Guaje Mountain fault is 9 to 12 km long, lies 1 to 2 km east of the Rendija Canyon fault, and is similar in its orientation and sense of slip (Figs. 2, 3). The 8-km-long Sawyer Canyon fault lies 1 to 2 km east of the Guaje Mountain fault but it dips to the east, away from the other faults of the PFS (Fig. 3). The Sawyer Canyon fault shows dominantly normal slip, offsetting early Pleistocene volcanic rocks down to the east (Carter and Winter, 1995; Carter and Gardner, 1995). We did not conduct detailed studies of this short, more distant fault strand and we do not discuss it further here. Little is known about the paleoseismicity of the Sawyer Canyon fault, and additional studies are needed to assess if it ruptures with the PFS during large earthquakes.

Pajarito fault

The Pajarito fault is the longest fault with the largest cumulative displacement in the PFS. Along its central portion, the Pajarito fault is characterized by a complex range-front escarpment as high as 180 m in the Bandelier Tuff, a rhyolitic ash-flow tuff that erupted from the Valles caldera 1.2 Ma (Izett and Obradovich, 1994). The lateral extent of the Pajarito fault has been defined differently by previous studies. Although Aldrich and Dethier (1990) showed that the Pajarito (normal-slip) and Embudo (strike-slip) faults intersect near Clara Peak, Gardner and House (1987) considered the Pajarito and Embudo faults (Fig. 1) to be continuous struc-

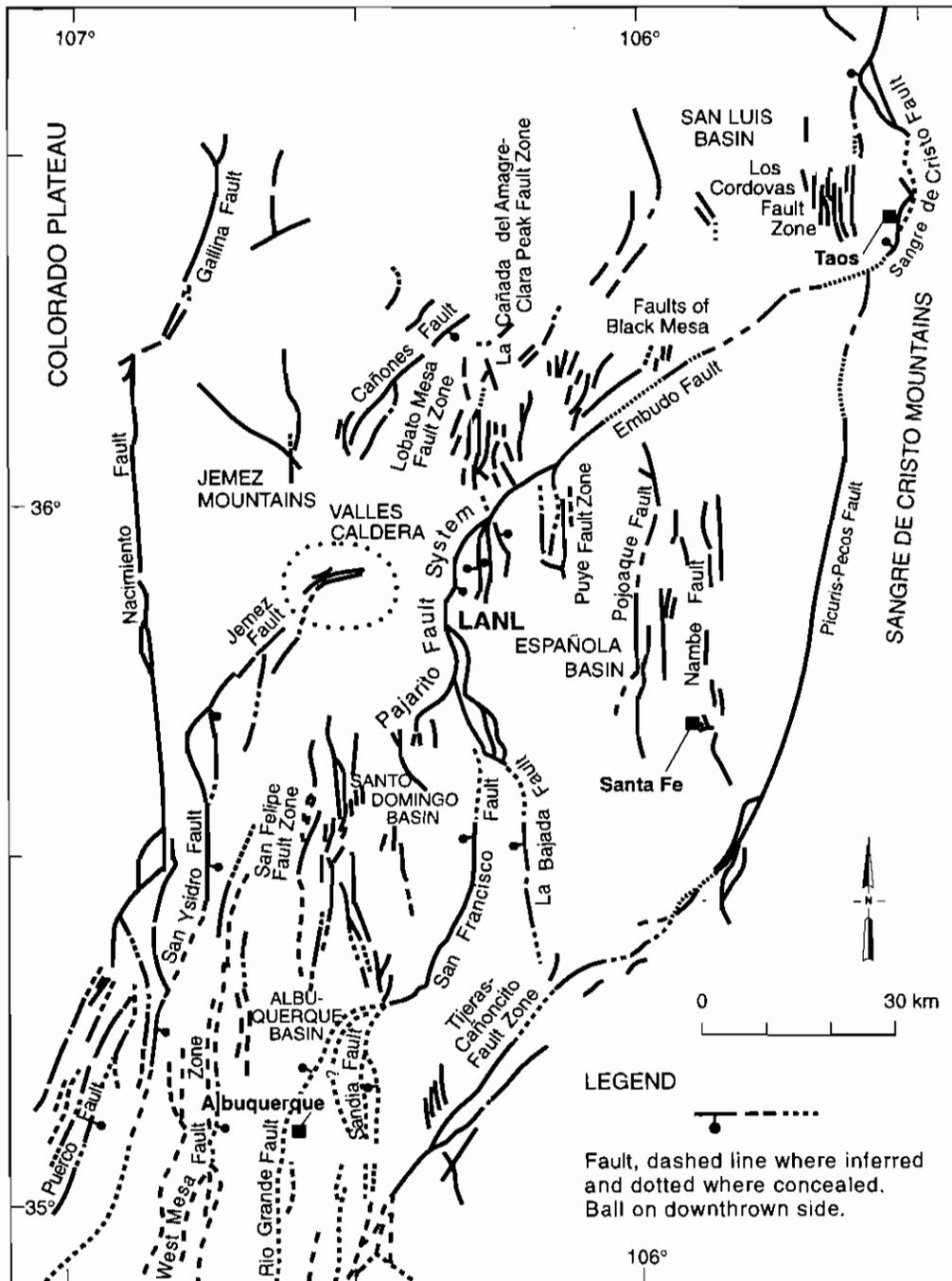


FIGURE 1. Selected faults in the Rio Grande rift region of northern New Mexico. LANL: Los Alamos National Laboratory.

tures. Based on analysis of aerial photography, aerial reconnaissance, and review of geologic mapping, we interpret the Pajarito fault to extend as far as Clara Peak, with faulting northeast of Clara Peak occurring on the Embudo fault. There is no direct evidence of any late Quaternary faulting northeast of Clara Peak (Wong et al., unpubl. report to LANL, 1995). In addition, slip northeast of Clara Peak appears to be predominately strike slip with minimal down-to-the-southeast vertical slip, which contrasts with the down-to-the-east geomorphic expression of the Pajarito fault. Similarly, we interpret the southern end of the Pajarito fault to coincide with a complex intersection of faults where the sense of slip changes. Near Cochiti Lake, the down-to-the-east Pajarito fault intersects the down-to-the-west La Bajada and San Francisco faults (Fig. 1). Several northwest-trending lineaments in this complex intersection are probably a result of transfer of strain from the Pajarito fault to the La Bajada and San Francisco faults (Wong et al., unpubl. report to LANL, 1995).

The Pajarito fault shows significant normal slip, but the amount and direction of lateral slip are not well constrained (Carter and Gardner, 1995). Golombek (1983) reported slickenside data that suggest predominantly dip-slip motion along the central part of the Pajarito fault. Stratigraphic separations and slickensides along secondary faults exposed in trenches excavated on the central portion of the Pajarito fault also indicate dominantly normal slip, but a few secondary faults show a lateral component of slip (Wong et al., unpubl. report to LANL, 1995). Gardner and House (1987) reported a northward change in sense of slip from dip slip to oblique to lateral slip along the fault toward its intersection with the Embudo fault. Salyards et al. (1994) interpreted paleomagnetic data as evidence of left-lateral slip along the Pajarito fault. However, Baldrige et al. (1990) noted that oblique slickensides plunge both to the north and to the south, offering different senses of lateral offset. In addition, kinematic characteristics along the fault north of Los Alamos Canyon may be

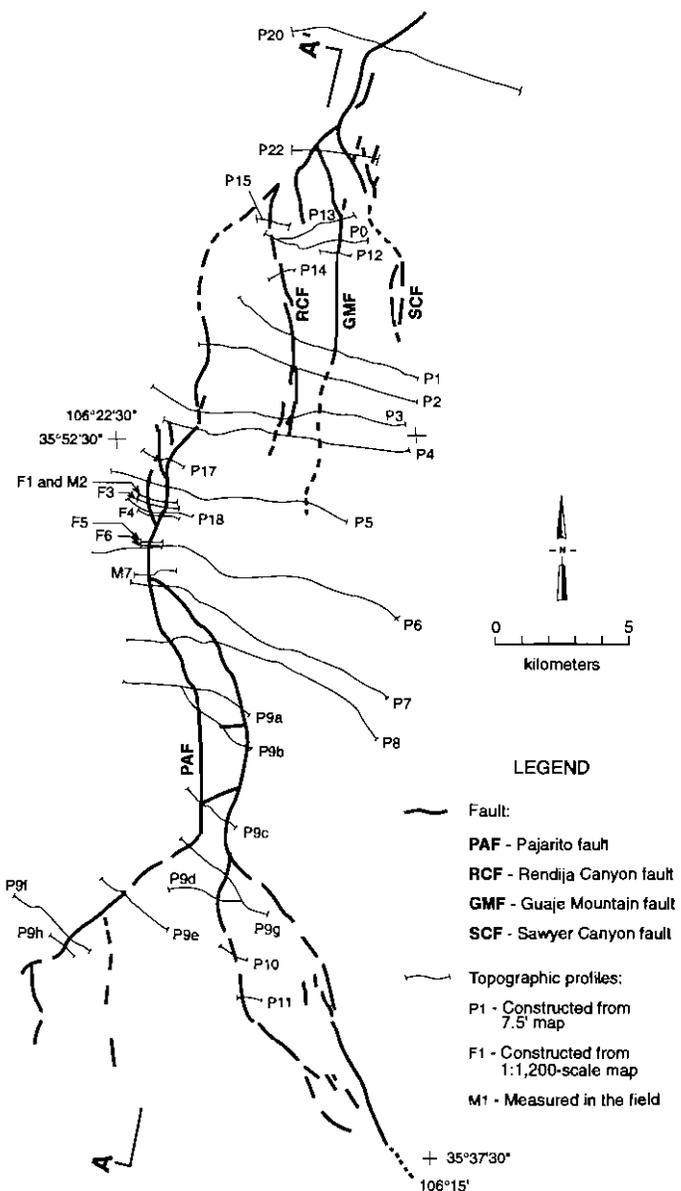


FIGURE 2. Map of the Pajarito fault system showing locations of topographic profiles. A-A' marks the line of transect for displacement curves in Figure 5.

different from those along the central part of the fault, based on (1) a substantial change in fault strike north of Los Alamos Canyon; (2) the presence of several fault splays and cross structures north of Los Alamos Canyon (Golombek, 1983; Gardner and House, 1987); (3) the change in geomorphic expression from prominent fault escarpments south of Los Alamos Canyon to an apparently more subdued monoclin flexure north of the canyon; and (4) the possible connection with the Embudo fault (Aldrich, 1986; Aldrich and Dethier, 1990).

The Pajarito fault differs from other major faults bounding the Rio Grande rift to the north and south in that it does not lie at the base of a Precambrian-cored range block, many of which were originally uplifted during Laramide deformation. Perhaps the absence of a major range block along the footwall of the Pajarito fault is related to thin crust and high heat flow associated with the Jemez volcanic province (Goff et al., 1989), or to a possibly shorter displacement history that spans about 16 Ma (Gardner and Goff, 1984), rather than about 15 to 30 Ma, as along the Sangre de Cristo fault in northern New Mexico and southern Colorado (Kelley and Duncan, 1984; Menges, 1990a,b; Lindsey et al., 1983). Regardless, the development of the Pajarito fault primarily in early Pleistocene volcanic rocks rather than in unconsolidated or semiconsolidated

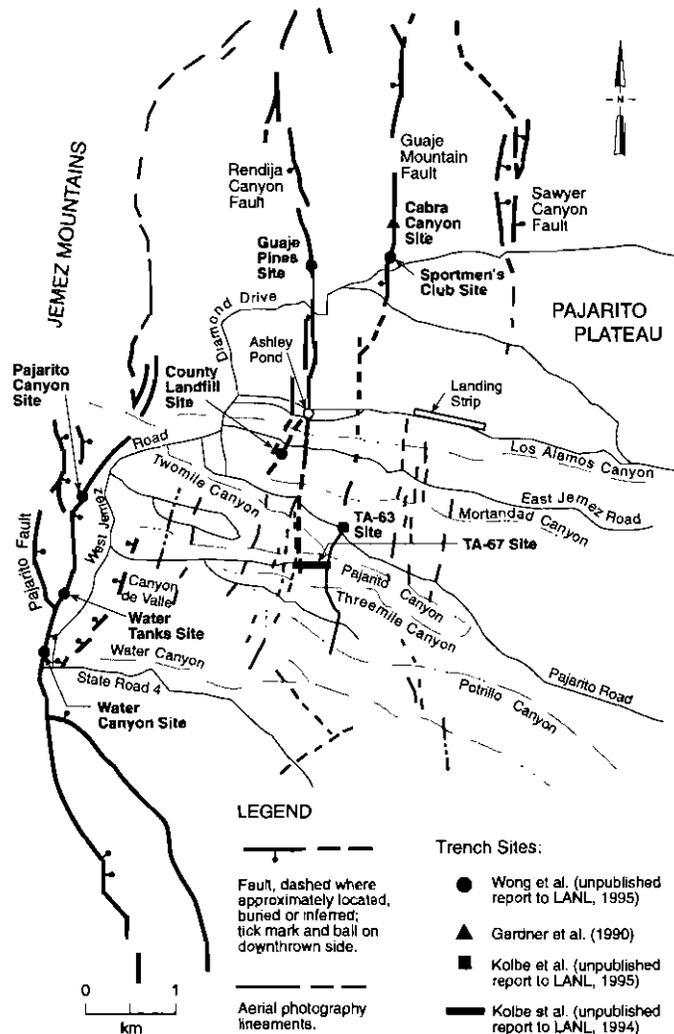


FIGURE 3. Location map of trench sites on the Pajarito fault system.

sediments at the surface, has influenced the geomorphic expression of the fault. Along much of its length, the Pajarito fault is characterized by multiple bedrock escarpments forming a complex range-front that is morphologically similar to many other late Quaternary range-bounding normal faults in the Rio Grande rift (e.g., Sangre de Cristo fault), and elsewhere in the Basin and Range province, with steep, faceted spurs forming linear mountain fronts. However, the Pajarito fault is noticeably different in two respects. First, the total structural and topographic relief are much less, only a couple hundred meters compared to thousands of meters that is typical of many range-bounding faults in the Rio Grande rift and Basin and Range province (e.g., Wallace, 1978; Menges, 1990a,b). Second, the Pajarito fault apparently does not have prominent single- or multiple-event fault scarps developed in late Quaternary alluvium at the base of a range front as do most late Quaternary faults in the Rio Grande rift (Machette, 1986; McCalpin, 1982; Menges, 1990a,b). Boden (1980) identified a short fault scarp in older alluvium at the southern end of the fault. However, we observed no evidence of prominent fault scarps in alluvium along the central section of the fault, which probably is a result of sparse well-preserved late Pleistocene to Holocene alluvial deposits and the occurrence of faults at the bedrock-alluvium contact or west of the alluvium on the bedrock slope. The general lack of fault scarps in alluvium along the Pajarito fault escarpment makes it difficult to constrain the age and size of recent surface-faulting earthquakes.

Rendija Canyon fault

Stratigraphic and geomorphic evidence suggest that the Rendija Canyon fault extends from a possible intersection with the Pajarito fault on

the north to probably Pajarito Mesa on the south (TA-67 site on Fig. 3). Fault plane measurements made during detailed bedrock mapping along the Rendija Canyon fault show dips ranging from 75°W to 90° with dominantly dip-slip slickensides (Carter and Gardner, 1995). The fault changes from a single strand north of Diamond Drive to two primary strands and numerous secondary strands through the town of Los Alamos, and then a zone of distributed deformation south of Los Alamos Canyon (Wong et al., unpubl. report to LANL, 1995; Kelson et al., this volume). Aside from lineaments, there is little geomorphic expression of the fault south of Mortandad Canyon. It is unclear whether the Rendija Canyon fault intersects the Pajarito fault at depth north of Los Alamos Canyon or the Pajarito fault dies out and more recent slip is accommodated along the Rendija Canyon and Guaje Mountain faults. Nevertheless, we interpret the northern termination of the Rendija Canyon fault to lie at a possible intersection with the Pajarito fault.

The southern extent of the Rendija Canyon fault remains uncertain. Gardner and House (1987) believed it extends south of Los Alamos Canyon beneath the Bandelier Tuff. Vaniman and Wohletz (unpubl. report to LANL, 1990) inferred that the fault extends to Cañon del Valle based on the presence of a broad zone of abundant, open fractures in the Bandelier Tuff. Trenches along Pajarito Mesa at TA-67 exposed several minor faults that are roughly coincident with a lineament that extends south of Mortandad Canyon (Fig. 3). These faults offset alluvium overlying the Bandelier Tuff, but do not offset air-fall and associated deposits of the El Cajete pumice (Kolbe et al., unpubl. report to LANL, 1994). The pumice has recently been reinterpreted to have erupted from the Valles caldera roughly 50 to 60 ka (Reneau et al., 1996). If the small faults at TA-67 are part of the Rendija Canyon fault, they apparently did not rupture during the most recent surface rupture on the Rendija Canyon fault, which was identified at the Guaje Pines site and is much younger than 50 ka (Kelson et al., this volume). Therefore, the most recent surface rupture on the Rendija Canyon fault apparently did not extend as far south as TA-67 (Kolbe et al., unpubl. report to LANL, 1994).

Guaje Mountain fault

The Guaje Mountain fault is structurally and geomorphically similar to the Rendija Canyon fault. Measurements of bedrock faults indicate dips ranging from 75°W to 90° and dominantly dip-slip movement on the Guaje Mountain fault (Carter and Gardner, 1995). Gardner and House (1987) mapped the 5-km-long central part of the Guaje Mountain fault as a single continuous strand, whereas the fault location south of this central section is approximate because of a lack of prominent geomorphic expression. Carter and Gardner (1995) refined the mapping of the central section and included two additional strands to the north.

The northern termination of the fault occurs at its intersection with the Pajarito fault (Fig. 2) just south of the border between Los Alamos and Sandoval counties. This intersection is characterized by complex deformation in the area between the down-to-the-east Pajarito fault and the down-to-the-west Guaje Mountain fault. Although there is little or no geomorphic expression of the fault across mesas underlain by the Bandelier Tuff to the south of Los Alamos Canyon, aerial photograph lineaments in Pajarito and Threemile Canyons suggest that near-surface faulting may extend farther south. Based on fracture density within the upper Bandelier Tuff and geomorphic features, Vaniman and Wohletz (unpubl. report to LANL, 1990) interpreted that the fault extends to Threemile Canyon. However, trench investigations across their projected traces of the Guaje Mountain fault at TA-63 and TA-67 (Kolbe et al., unpubl. reports to LANL, 1994, 1995) revealed no evidence for near-surface faulting of the Bandelier Tuff or thin overlying sediments.

Topographic profiles

The Pajarito Plateau is underlain by the Tshirege Member of the Bandelier Tuff, which forms a dissected, gently east-sloping surface on the eastern flank of the Jemez Mountains. This deposit provides an extensive and relatively well-preserved stratigraphic and geomorphic 1.2-Ma datum from which to estimate the amount of long term vertical displacements along faults that traverse the plateau. To this end, 34 topographic profiles were constructed where the Pajarito, Rendija Canyon and Guaje Mountain faults transverse several mesas underlain by the

Bandelier Tuff (Fig. 2). To construct profiles we used (1) 1:24,000-scale topographic maps with 40 ft contour intervals; (2) 1:1200-scale topographic maps with 2 ft contour intervals that were generated by the Facility for Information Management, Analysis and Display (FIMAD) at LANL; and (3) an abney level, a 50-m tape measure, and a 5-m telescoping stadia rod to measure profiles in the field.

Before discussing our results, we first note a few caveats about using the profile data. To adequately account for backtilting and graben formation in quantifying vertical displacements on all the topographic profiles, we estimated net vertical tectonic displacements (NVTD) of surfaces. Surfaces on the upthrown and downthrown side of the scarp or escarpment were projected from outside the zone of deformation to the fault, and NVTD was measured as the vertical component of displacement between the projected surfaces measured at the fault (after Swan et al., 1980, see Fig. 4). Profile locations were chosen to cross entire deformation zones, which are as wide as 2 km, and include range-front escarpments as well as fault scarps, of the Pajarito, Rendija Canyon and Guaje Mountain faults. Projections of surfaces over these large distances result in large error estimates for some of the profiles (Fig. 5). We also assume that the present topographic surface closely represents the uppermost surface of the 1.2 Ma Tshirege Member. Finally, we note that if there was a significant hiatus in faulting activity after deposition of the tuff, then shorter-term displacement rates could be much higher than these long-term estimates.

There is substantial variation along strike in the post-1.2 Ma NVTD estimated along each of the faults (Fig. 5). Along the Pajarito fault, down-to-the-east NVTD is generally more than 40 m along each of two or more individual fault strands, and cumulative NVTD across all traces along a given profile is as high as 154 ± 5 m (Fig. 5). The amount of NVTD is highest in the central part of the fault and decreases rapidly north of Los Alamos Canyon where the fault is primarily expressed as an apparent monoclinical flexure. To estimate an average displacement, we used the NVTD data to plot a displacement curve that generally envelopes the data (Fig. 5). The area under this curve yields an average post-1.2 Ma NVTD of 81 m along the Pajarito fault. The Rendija Canyon fault exhibits as much as 36 ± 10 m of down-to-the-west NVTD along its central part, although NVTD decreases to zero within about 6 km to the north and south (Fig. 5). We estimate an average post-1.2 Ma NVTD of about 22 m for the Rendija Canyon fault. The Guaje Mountain fault shows as much as 27 ± 4 m of down-to-the-west NVTD at its northern end (Fig. 5), where it intersects the Pajarito fault. Estimates of NVTD on the Guaje Mountain fault progressively decreases southward to zero in the vicinity of Los Alamos. We estimate an average post-1.2 Ma NVTD of 15 m on the Guaje Mountain fault.

PALEOSEISMIC INVESTIGATIONS

Although no historic surface-faulting earthquakes have occurred on the PFS, the large displacements of the Bandelier Tuff indicate repeated surface-faulting events have occurred along each major strand of the PFS since deposition of the tuff 1.2 Ma. To locate faults and identify prehistoric surface-faulting earthquakes, nine excavation sites have been investigated on the PFS (Fig. 3). This section briefly summarizes results from five of these sites. Detailed trench logs, stratigraphic, structural and soil descriptions, and details on radiocarbon and luminescence analyses for these sites are included in Wong et al. (unpubl. report to LANL, 1995). Kelson et al. (this volume) discuss the Guaje Pines site. Gardner et al. (1990) and Gardner and Reneau (this volume) discuss the Cabra Canyon site. Kolbe et al. (unpubl. reports to LANL, 1994, 1995) reported on the TA-67 and TA-63 sites.

Trench site selection posed a particular challenge due to the general lack of fault scarps on late Pleistocene and Holocene deposits, particularly on the Pajarito fault. Trenching the entire Pajarito fault escarpment posed significant logistical and interpretive problems. Geologic evidence for surface faulting would likely be more difficult to identify and not as well preserved on the face of the bedrock escarpment as at the base. Therefore, four trenches were excavated at the base of the escarpment at three different sites along the Pajarito fault (Fig. 3). Although indirect evidence for surface-faulting events was exposed, none of the trenches exposed unambiguous, primary scarp-forming faults. Therefore, the

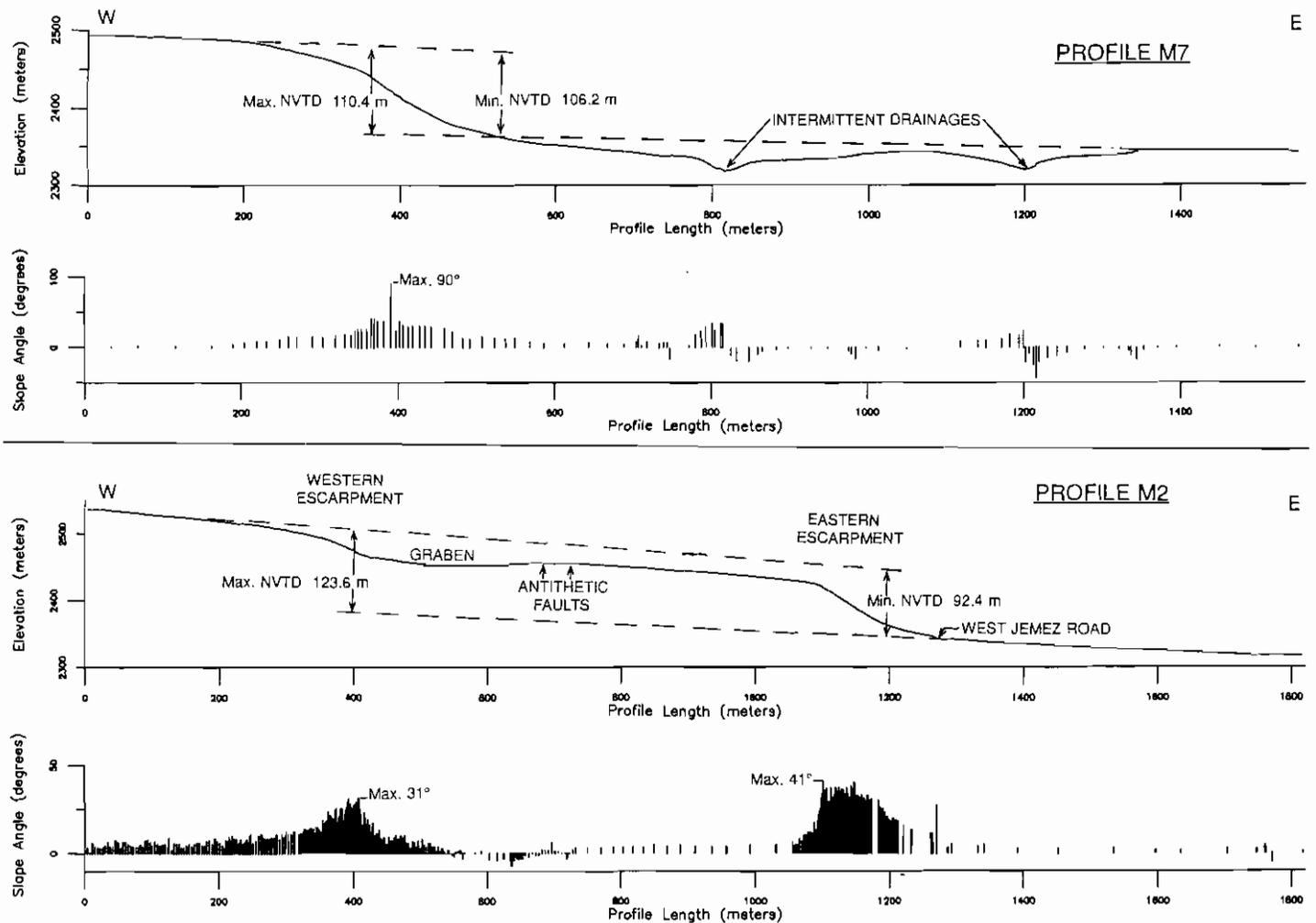


FIGURE 4. Slope angle plots and topographic profiles M2 and M7 across the Pajarito fault. There is no vertical exaggeration on profiles.

paleoseismic record presented here is incomplete and somewhat ambiguous. Interpreting fault history from the Pajarito fault trenches illustrates the problems inherent in paleoseismic investigations of shallow bedrock faults, where identifying individual surface-faulting events is hampered by a poorly preserved or ambiguous stratigraphic record. Regardless, results from the trenches still provide information on the late Quaternary behavior of the Pajarito fault and the Quaternary stratigraphic framework of the Pajarito Plateau.

Water Canyon site

At the Water Canyon site (Fig. 3), one trench and three soil pits were excavated at the base of the main 120-m-high Pajarito fault escarpment. Here a flight of inset fluvial terraces are partially preserved and do not appear faulted. Excavations revealed no evidence for faulting or deformation in alluvium that was deposited after the El Cajete pumice (50 to 60 ka) and probably before 9 to 10 ka (Wong et al., unpubl. report to LANL, 1995). Although evidence for no Holocene faulting was present in the trench, this does not preclude the possibility of Holocene displacement at this site on strands of the Pajarito fault located east or west of the trench.

Water Tanks site

At the Water Tanks site (Fig. 3), two trenches were excavated at the base of the main 110-m-high Pajarito fault escarpment. Here colluvial deposits that contain El Cajete pumice overlie the Tshirege Member of the Banderier Tuff. Although the primary scarp-forming fault was not evident in exposures, secondary faults, fissure fills, and possible fault-scarp colluvium that buries soil horizons provide evidence for the occurrence of at least

three surface-faulting events (Events P-W, P-X, and P-Z on Fig. 6) (Wong et al., unpubl. report to LANL, 1995). Apparent warping and possible fissure fills provide speculative evidence for two additional events (Events P-V? and P-Y? on Fig. 6). Secondary faults that formed during the youngest event (Event P-Z) do not offset deposits of El Cajete pumice but do offset underlying colluvial units with luminescence ages of about 57 to 61 ka for the upper unit, and 56 to 63 ka for the lower unit (Reneau et al., 1996). Although two radiocarbon samples from the upper colluvial unit provide a much younger age (circa 19 to 22 ka), this is inconsistent with stratigraphic relations, suggesting that radiocarbon samples were intrusive or contaminated (Wong et al., unpubl. report to LANL, 1995). An infinite radiocarbon age of > 47,500 yr B.P. for the lower colluvial unit is consistent with the luminescence ages for this unit. If event P-Y? occurred, it was after deposition of this lower colluvial unit.

Pajarito Canyon site

At the Pajarito Canyon site (Fig. 3), the Pajarito fault consists of two escarpments that reach a total height of roughly 180 m. One trench was excavated south of the drainage at the base of the 80-m-high easternmost escarpment. Similar to the Water Tanks trenches, the Pajarito Canyon trench exposed indirect evidence for as many as five surface-faulting events but the primary scarp-forming fault was not exposed (Wong et al., unpubl. report to LANL, 1995). Secondary faults, possible fault-scarp colluvium, and intense shear deformation at the west end of the trench provide evidence for the youngest event exposed in the trench. Secondary faults and stratigraphic relations provide suggestive evidence for the other events, including apparent formation of a graben during the third oldest event exposed in the trench. A luminescence age of 137 ± 22 ka for

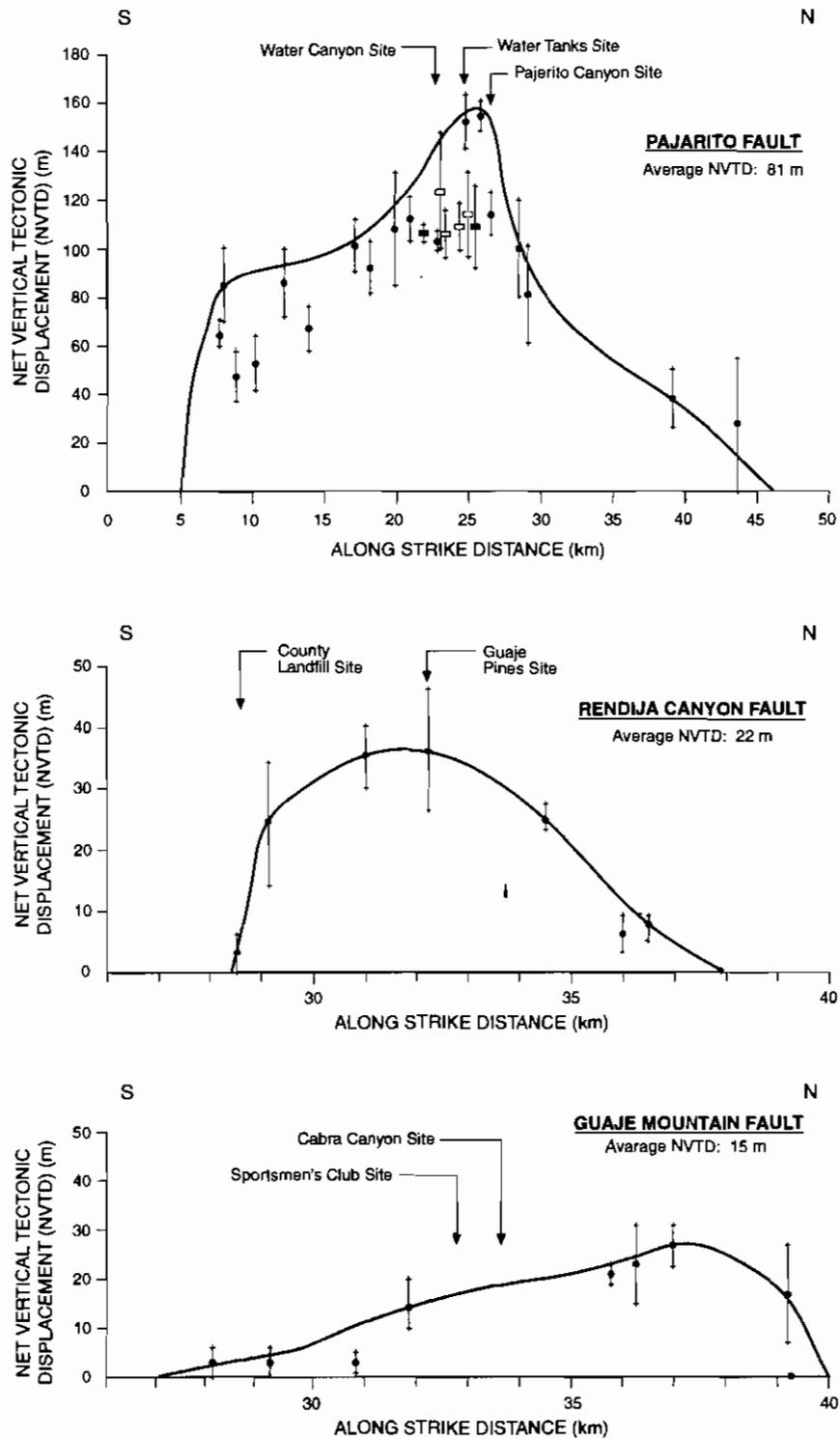


FIGURE 5. Displacement curves for the Pajarito fault system showing estimated net vertical tectonic displacements (NVTD) of the top of the Bandelier Tuff. Solid circles show data from profiles constructed from 7.5' topographic quadrangles; solid rectangles show data from profiles measured in the field; open rectangles show data from profiles constructed from 1:1200-scale topographic maps.

graben fill deposits provides a minimum-limiting age for this event (Wong et al., unpubl. report to LANL, 1995).

County landfill site

The County Landfill site is on one of three prominent strands of the Rendija Canyon fault that cross South Mesa, south of Los Alamos Canyon (Fig. 3). A large pre-existing pit at the site revealed pumice-rich fluvial deposits overlying the Tshirege Member of the Bandelier Tuff. Vertical

separation of the 1.2 Ma tuff is 4 m down to the west, but evidence for a significant component of lateral slip suggests that net slip could be as much as 10 to 60 m (Wong et al., unpubl. report to LANL, 1995). Based on stratigraphic and structural relations, at least three surface-faulting events have occurred since deposition of the tuff. However, this is a minimum as the stratigraphic record is incomplete due to erosion and cultural modification of the site (Wong et al., unpubl. report to LANL, 1995). There are no absolute age constraints on these post-1.2 Ma paleoearthquakes.

SURFACE-FAULTING EVENTS

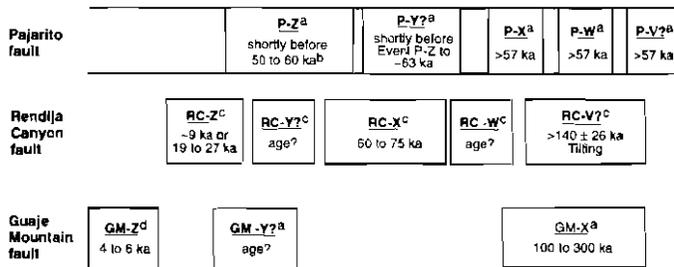


FIGURE 6. Summary diagram of known and suspected surface-faulting events on the Pajarito fault system. All events shown occurred after deposition of the Banderier Tuff, 1.2 Ma. Events with equivocal evidence are queried. Age constraints for events on the Pajarito fault are based solely on data from the Water Tanks site. Shading indicates incomplete record due to the main scarp-forming fault not being completely exposed. Sources: Wong et al., unpubl. report prepared for LANL (1995); Reneau et al. (1996); Kelson et al. (this volume); Gardner et al. (1990) and Gardner and Reneau (this volume).

Sportsmen's Club site

The Sportsmen's Club site is on the north side of Rendija Canyon along the Guaje Mountain fault (Fig. 3). Four trenches and four soil pits were excavated in late Holocene fluvial and alluvial-fan deposits that overlie epiclastic deposits of the Cerro Toledo Rhyolite. No offsets or deformation were observed in either the alluvium or bedrock. Field evidence suggests that the Guaje Mountain fault lies just west of the trenches, in a zone of faulting in Cerro Toledo deposits exposed in a gully to the northwest (Wong et al., unpubl. report to LANL, 1995).

Farther upstream and downstream of the trench site, several late Pleistocene and Holocene terraces are preserved on the upthrown and downthrown side of the fault (Wong et al., unpubl. report to LANL, 1995; McDonald et al., this volume). Topographic profiles of these terraces along Rendija Canyon reveal larger displacements of older surfaces, suggesting that at least two or possibly three events have occurred on the Guaje Mountain fault within the past 150 to 300 ka. The highest terrace (Qt1), estimated to be 150 to 300 ka, is displaced down to the west with 2.5 to 4 m of vertical separation. A younger terrace (Qt2), estimated to be 100 to 200 ka is displaced down to the west with 1.8 to 2.5 m of vertical separation. There is no evidence of displacement on the youngest late Holocene surfaces (Qt7 and Qt8).

SUMMARY OF EARTHQUAKE CHARACTERISTICS AND UNCERTAINTIES

Timing of events, recurrence intervals, and rupture behavior

Determining the timing of individual surface-faulting events along each of the principal faults of the PFS is critical to understanding both rupture behavior and earthquake recurrence. Results from this and previous trenching studies along the Rendija Canyon and Guaje Mountain faults have made considerable progress toward deciphering the timing of recent events on these two faults (Kelson et al., this volume; Gardner and Reneau, this volume; Kolbe et al., unpubl. reports to LANL, 1994, 1995). However, paleoseismic information is too limited to adequately characterize rupture behavior or earthquake recurrence along the Pajarito fault. We synthesize results for the entire PFS here and discuss what implications can be made given the uncertainties in the geologic record.

Figure 6 summarizes present understanding of the timing of the individual surface-faulting events identified along the PFS. Although indirect evidence for as many as five events on the Pajarito fault was identified at both the Pajarito Canyon and Water Tanks sites, the constraints on timing of events at the Pajarito Canyon site is inadequate to definitively correlate events between the two sites. Therefore, timing constraints for events on the Pajarito fault (Fig. 6) are based on information from only the Water Tanks site. Based on the available data, recurrence intervals cannot be reasonably constrained for the Pajarito fault. Kelson et al. (this volume) estimate a recurrence interval between Events RC-Z and RC-X on the Rendija Canyon fault ranging from 33

to 66 ka, assuming that event RC-Y? did not occur. If event RC-Y? did occur, the average recurrence intervals become 16.5 to 33 ka. Estimates of average recurrence intervals for the time between events GM-Z and GM-X on the Guaje Mountain fault range from 47 to nearly 300 ka based on data from Rendija Canyon terraces. This large range in estimates results from uncertainties as to whether or not event GM-Y? occurred, and uncertainties in the timing of event GM-X, which occurred after terrace Qt1 formed about 150 to 300 ka, but before terrace Qt2 formed about 100 to 200 ka.

The incomplete paleoseismic record of the Pajarito fault and the large age uncertainties for events on the other two faults precludes definitively determining whether the Rendija Canyon and Guaje Mountain faults have ruptured simultaneously with the Pajarito fault, as would be expected if these smaller structures behaved dependently on the larger main fault. For example, event P-Z may or may not have occurred simultaneously with events RC-Y?, RC-X, or GM-Y? (Fig. 6). Interestingly, the available data does suggest that the most recent event on the Rendija Canyon fault did not occur simultaneously with the most recent event on the Guaje Mountain fault. Thus, although the close proximity and kinematic similarity of these two faults might suggest a structural link and dependent behavior between the faults, the paleoseismic record suggests independent rupture behavior. However, it is unclear whether this independent behavior has persisted through time because age constraints on older events are so broad. This caveat is particularly relevant because suggestive evidence on the Rendija Canyon fault for along-strike variations in rupture patterns through time (Kolbe et al., unpubl. report to LANL, 1994) would imply that rupture histories could be quite complex for the PFS. It is possible that the faults of the PFS exhibit both dependent and independent rupture behavior, changing through time as this relatively young fault system continues to evolve.

Developing an appropriate structural model for the PFS is important to better understanding expected rupture patterns. Kinematic relations and long-term displacement patterns (Fig. 5) suggest two different structural models for the PFS: (1) the main Pajarito fault intersects and truncates the smaller antithetic Rendija Canyon and Guaje Mountain faults at depth; or (2) the Rendija Canyon and Guaje Mountain faults are not truncated by the Pajarito fault but have more recently been the active structures in accommodating rift extension north of Los Alamos Canyon (Wong et al., unpubl. report to LANL, 1995). In the latter model, slip on the main Pajarito fault dies out north of Los Alamos Canyon, and is transferred to the Rendija Canyon and Guaje Mountain faults. Carter and Gardner (1995) speculated that faulting within the Española basin is advancing toward the basin center. The limited paleoseismic record appears to support this hypothesis and favor the latter structural model for the PFS, but additional paleoseismic data are needed to adequately test this hypothesis.

To incorporate all uncertainties in dependent versus independent behavior, variations in rupture patterns through time, and different structural models, we included 22 different rupture scenarios for the PFS in the seismic hazard evaluation (see Wong et al., unpubl. report to LANL, 1995 for more details). This complexity in the input was used to explicitly address and weight each type of uncertainty. Fault lengths for the different rupture scenarios vary from 12 to 41 km. Using empirical relations of Wells and Coppersmith (1994) to estimate maximum magnitudes for ruptures of these lengths yields moment magnitudes ranging from 6.3 ± 0.3 to 7.0 ± 0.3 .

Slip rates

Because slip rates can often vary over time along a fault, we differentiate here between long-term rates, for the past 1.2 Ma, and short-term rates, for the past 0.30 Ma. Long-term slip rates can be calculated for the primary strands of the PFS from the topographic profile data. The average NVTD of 81 m on the Pajarito fault yields an average NVTD rate of 0.07 mm/yr, whereas the maximum NVTD of 154 m yields a maximum rate of 0.13 mm/yr for the past 1.2 Ma. Thus, the maximum rate is almost twice the average rate. The average NVTD of 22 m on the Rendija Canyon fault yields an average NVTD rate of 0.02 mm/yr, whereas the maximum NVTD of 36 m yields a maximum rate of 0.03 mm/yr for the past 1.2 Ma. Finally, the average NVTD of 15 m on the Guaje Mountain

fault yields an average NVTD rate of 0.01 mm/yr, whereas the maximum NVTD of 27 m yields a maximum rate of 0.02 mm/yr.

These data highlight the importance of along-strike variations of fault displacements in estimating average slip rates for seismic hazard evaluations. Typically, data are collected at sites where the fault is most prominent and best expressed geomorphically, and displacements are probably closer to a maximum than representative of an average. Thus, use of slip rate data in seismic hazard evaluations without consideration of along-strike variations can result in overestimating the hazard. Unfortunately, the number of data points collected along a fault from offset datums of the same age typically is small, usually precluding calculation of a meaningful average rate. In this regard, the long-term slip rate data along the PFS is better constrained than many faults in extensional environments that have only a few data points. Regardless, in characterizing fault slip rates for seismic hazard evaluations, it is important to at least consider how well the data for a few sites may actually represent the average slip rate over the entire fault.

Short-term slip rate data are more limited on the PFS. Unfortunately, ages of late Quaternary deposits and their displacements are not constrained well enough to reliably estimate slip rates for more recent seismic cycles on the Pajarito or Rendija Canyon faults. Short-term rates for the Guaje Mountain fault can be estimated based on offsets of terraces in Rendija Canyon, which yield short-term rates for the past 0.30 Ma. Notably, these rates are similar to long-term rates for the past 1.2 Ma. Vertical separations of about 2.5 to 4 m on the Qt1 terrace yield estimated vertical separation rates of 0.01 to 0.03 mm/yr for the past 0.15 to 0.30 Ma. Vertical separations of about 1.8 to 2.5 m on the Qt2 terrace also yield vertical separation rates of 0.01 to 0.03 mm/yr for the past 0.1 to 0.2 Ma.

Although available short-term slip rates are comparable to long-term rates, data are inadequate to quantify possible short-term variations of slip rates on the PFS. In an attempt to address uncertainties due to the lack of short-term slip rate data on the PFS, McCalpin (1995) compiled slip rate data for other faults in the Rio Grande rift for comparison. He found that higher slip rates are generally associated with shorter-term intervals, usually due to observations of a couple of earthquakes closely spaced in time (i.e., temporal clustering of events). Somewhat surprisingly, this variability results in an order of magnitude difference between the mean slip rate and the 95% cumulative frequency value for the data set of Rio Grande rift faults (McCalpin, 1995). Such large variations and resulting uncertainties in slip rates are important because incorporating them in the seismic hazard evaluation significantly increased the hazard contribution of the PFS to nearby sites (Wong et al., this volume; unpubl. report to LANL, 1995). More data are needed to test whether this large variability in slip rates over a region might be applicable to individual faults in the rift. Regardless, evidence for temporal clustering of earthquakes has been found for individual faults and over regions (e.g., Wallace, 1984; Machette et al., 1991; Olig et al., in press) in the western U.S. Therefore, in the absence of adequate short-term data for a particular fault, possible temporal variations in slip rates should be addressed by incorporating uncertainties and McCalpin's (1995) analysis suggests that these uncertainties can be much larger than expected.

In conclusion, additional paleoseismic and structural studies are needed to reduce uncertainties in rates of earthquake occurrence for the PFS, and to simplify the modeling of expected rupture scenarios. Significant outstanding issues include: (1) do the Pajarito, Rendija Canyon and Guaje Mountain faults rupture dependently or independently of each other?; (2) what is the relation of the Sawyer Canyon and Puye faults to the PFS?; (3) how much have rupture patterns varied through time?; and (4) have slip rates varied significantly through time, and in particular, have short-term rates been much higher than long-term rates, as observed elsewhere in the Rio Grande rift? Although these issues are specific to seismic hazards on the Pajarito Plateau, they correspond to more general issues relevant to normal fault systems elsewhere. For example, understanding how earthquake behavior may vary in time and space on closely aligned faults in an extending region is important to evaluating seismic hazards throughout the Rio Grande rift, at Yucca Mountain, Nevada (Wong et al., 1995), and along parts of the Wasatch Front, Utah (e.g., Youngs et al., 1987). More generally, a better under-

standing of how and why rates of surface-faulting activity may vary significantly through time is important to evaluating seismic hazards throughout most of the western U.S.

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