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Los Alamos National Laboratory

EES-1, Geology/Geochemistry

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November 14, 1990

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RESULTS OF GEOLOGICAL MAPPING AND FRACTURE STUDIES: TA-55 AREA

(electronic copy of original printed document)

Los Alamos

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memorandum

TO: J. Gardner, EES-1, MS D462

DATE: July 29, 1991

FROM: D. Vaniman, EES-1 6/5/91

MAIL STOP/TELEPHONE: D462/7-1863

SYMBOL: EES-1, Geology/Geochemistry

MEMO NO: EES1-SH91-12

SUBJECT: **REVISIONS TO REPORT EES1-SH90-17**

Recent work by Steven Reneau on comparisons between various stratigraphies used for the upper Bandelier Tuff requires a revision to Table 1, on p. 3 of report EES1-SH90-17. The direct correlations between units 1, 2, and 3 for all workers are not valid, because the nonwelded intervals between zones of welding are inconsistently assigned to either the overlying welded zone (most earlier workers) or the underlying welded zone (Crowe et al., 1978). The inconsistency in assignment of nonwelded intervals is in part a difference in flow-unit versus cooling-unit treatment of stratigraphic subdivisions. In order to allow for either assignment or for further subdivision within the nonwelded intervals, the stratigraphy used for this report is herewith modified to leave the suspect nonwelded units unassigned. The necessary revisions to Table 1, text, and figures/plates are listed below.

Table 1. Approximate Comparison of Stratigraphic Units within the Tshirege Member.

Baltz et al. (1963)	Crowe et al. (1978)	Our units
		unit 4
		nonwelded
	cooling unit 3	
		unit 3
unit 3		
		nonwelded
	cooling unit 2	
unit 2b		unit 2
unit 2a		nonwelded
	cooling unit 1	
unit 1b		unit 1v (vapor phase)*
unit 1a		unit 1g (glassy)

*Note: all numbered units and nonwelded intervals above 1v also contain abundant vapor-phase crystallization.

Los Alamos

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memorandum

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Memo No: EES1-SH90-17

SUBJECT: RESULTS OF GEOLOGICAL MAPPING/FRACTURE STUDIES: TA-55 AREA

ABSTRACT

A geological map of 5.60 square miles (scale = 1:6,000) around the TA-55 area has been completed. This map (Plate 1 in this report) shows that the Rendija Canyon and Guaje Mountain fault zones can be located by geological field observations and fracture studies. The faults lie within a roughly N-S trend about 500 ft west and 1,500 ft east, respectively, of TA-55. Within this zone, the Bandelier Tuff is tectonically deformed. Important structural features include rock fractures, micrograbens caused by downdrop of tuff blocks up to several feet, and "zipper joints" where sets of joints have been incised and along which tuff surfaces have been down dropped several or more feet.

Along with the geological mapping study, detailed structural mapping and measurement of 1,625 fractures along Pajarito and East Jemez roads (Plates 2 and 3) demonstrate notable increases in the abundance of and opening on fractures over areas of the fault projections. The measurements show that fracture linear density increases from background levels averaging 20 fractures/100 ft to about 50 fractures/100 ft over the fault zones. Average fracture openings are about 1.0 cm, and observed vertical displacements along these fractures is a similar amount, making these fractures evidence of fault movement. Cumulative surface deformation calculated over the Rendija Canyon Fault zone along Pajarito Road is about 8.2 ft horizontal and 8.6 ft vertical, dispersed over 900 horizontal feet. Surface deformation on the Guaje Mountain Fault zone along East Jemez Road is calculated to be 5.8 ft horizontal and 6.1 ft vertical, spread out over 1,600 horizontal ft.

We conclude that vertical movement of at least 10 ft has likely occurred in bedrock below the Bandelier Tuff along both of these faults, but that this displacement is accommodated by fractures dispersed over 1,000 horizontal feet across the faults in the tuff.

We recommend that additional fracture measurements be made along blade cuts into the tuff over the fault zones near TA-55. Also our mapping shows a considerable hazard of cliff failure and mass wasting above TA-2, which should be studied further.

Attachment: a/s

Cy: EES-1, MS D462
Seismic Hazards File

In addition to these changes in Table 1, the following revisions must be made to the text:

Page 4:

in line 6, "Unit 4b: weak" should read "nonwelded slope-forming interval between units 4 and 3"

in line 8, "unit 4b" should read "this unit"

in line 16, "Unit 3b: weak" should read "nonwelded slope-forming interval between units 3 and 2."

Page 5:

in line 7, "Unit 2b: moderately weak" should read "nonwelded interval between units 2 and 1"

in line 14, "Unit 1: weak" should read "Unit 1v: vapor-phase altered"

in line 16, "unit 2b" should read "the overlying nonwelded interval"

in line 20: "Unit 1b: moderately weak" should read "Unit 1g: glassy tuff".

Page 10:

in line 12, "unit 2a" should read "unit 2."

In Figures 1, 2, and 3 the stratigraphic units 4b, 3b, and 2b should be referred to simply as "nonwelded"; "Unit 1" should be "Unit 1v"; "Unit 1b" should be "Unit 1g".

A revised version of Plate 1 (the geologic map) has also been prepared and is enclosed with this memo.

DV:jr

Attachment: a/s

Cy: EES-1 File
Seismic Hazards File, MS D462

RESULTS FROM GEOLOGIC MAPPING AND FRACTURE MEASUREMENTS AROUND THE TA-55 AREA

1. Geologic Map

As part of the study of the geology of the TA-55 site, a geologic map has been prepared from a combination of field and aerial photograph studies; all mapping was done at a scale of 1:6,000 (Plate 1). The map is centered on the TA-55 site, and covers approximately four square miles. Within this area, the rocks exposed are all of the Tshirege Member of the Bandelier Tuff (~1.1 m.y. old), with the exceptions of (1) deeper exposures into reworked tuffs and Cerro Toledo fall out tuffs in the central part of Los Alamos Canyon and (2) even deeper exposure, into the Otowi Member of the Bandelier Tuff, in the eastern part of Los Alamos Canyon.

The map generated for this project (Plate 1) is based on a stratigraphy compiled from seven sections that were measured through the Tshirege Member, using a steel tape and (for a few portions) Jacob's staff. Figure 1 is a schematic summary of the stratigraphy in the map area, colored to match the units in Plate 1. Representative detailed stratigraphic columns have been included for Twomile Canyon just south of TA-55 (Figure 2), and for Pajarito Canyon just south of TA-40 (Figure 3). The tightest control of stratigraphic contacts was maintained in Los Alamos, Mortandad, Twomile, and Pajarito canyons, where field work was concentrated.

The stratigraphy used for the map in Plate 1 is based on the physical characteristics of the Tshirege tuff units. The decision to base this map on physical features was made because the Tshirege is relatively homogeneous in chemical and mineralogic character: it is a crystal-rich, high-silica rhyolite tuff in which the mineral and geochemical variations are subtle. Two major subdivisions of rock type were chosen in the physical stratigraphy: (1) resistant tuff units that form cliffs, often with prominent ledge tops, and (2) weak tuff units that are readily incised by erosion, leaving ledges on the resistant units below while undercutting any resistant units above. The principal mechanism of erosion in this area is the undercutting of resistant cliffs via underlying weak tuffs, leading to mass wasting of cliff edges. The instability of cliff margins, with massive failures that occur either in the course of progressive erosion or triggered by seismic events, appears to be a major geologic hazard in the area shown in Plate 1. Areas most at risk are those closest to mesa margins (particularly at southern mesa edges in unit 3, the yellow map unit in Plate 1), and those at the bottoms of canyons within or beneath unit 2 (the blue map unit in Plate 1).

The physical stratigraphy used in this study is generally similar to other stratigraphies of the Bandelier Tuff that are based on cooling units (see, e.g., Crowe et al., 1978, and Baltz et al., 1963). The three units described by Crowe et al. and by Baltz et al. are generally correlative in numbering to units 1 through 3 as used in this report; we have a unit 4 at the top (the sections measured by these two other reports did not include unit 4, which is outside of their map areas). The previous map units and our map units are compared in Table 1.

Table 1. Comparison of Stratigraphic Units within the Tshirege Member*.

Baltz et al. (1963)	Crowe et al. (1979)	Our units
		unit 4 unit 4b
unit 3	unit 3	unit 3 unit 3b
unit 2b unit 2a	unit 2	unit 2 unit 2b
unit 1b unit 1a	unit 1	unit 1 unit 1b

*These different unit designations use the same numbering scheme, but do not necessarily result in the same mappable boundaries. There will be greatest deviation between the units of Crowe et al. and our units, because they used a stratigraphy based primarily on cooling units rather than physical resistance to erosion. In contrast to Baltz et al., we have subdivided unit 3 and we use the letter "b" to indicate the soft and generally basal tuffs that appear with some regularity below many of the cliff-forming welded portions of these units. Unlike Baltz et al., we have not mapped alluvium where the underlying type of tuff can be determined or reasonably inferred.

The similarity between physical stratigraphy and cooling units occurs because cooling units commonly have welded cores that form resistant cliff-forming intervals. This correlation is not perfect, however, because vapor-phase alteration has been superimposed on the cooling units of the Tshirege. This later alteration can affect the resistance of the tuff to erosion, particularly in nonwelded tuffs where slight vapor-phase alteration appears to weaken the macroscopic pumices relative to the groundmass, but thorough vapor-phase alteration tends to make the rock more resistant. Finally, the degree of "case-hardening" of nonwelded and poorly-welded tuffs during weathering varies within and between units for reasons that are still poorly understood. The physical stratigraphic units that result from these combined processes are described below, referenced to their use in Plate 1.

2. Map Units (Physical Stratigraphy; see Plate 1)

(units described from top down)

Unit 4: **resistant** (map color = red; see Fig. 1)

White tuff with relatively uniform grain-size and generally small pumices, thickness ≤100 ft in the map area. This unit contains small pumices and pumice fragments. It is nonwelded to poorly welded, but indurated by vapor-phase alteration. Macroscopic pumices are generally softer than the groundmass, but tend to be smaller (mostly <1 inch) than in most other parts of the Tshirege. This unit is restricted to the western part of the map area. A significant feature of the unit is a continuous, mappable surge interval that occurs near its base. This particular surge interval is typically 1-2 ft thick and pumice-poor; its most significant feature is that it is the only surge that can be traced continuously over distances up to hundreds of feet (where it is exposed). Other surge intervals can be found within unit 4 and 4b, but they are not as continuous.

Unit 4b: **weak** (map color = orange; see Fig. 1)

Nonwelded white tuff with relatively uniform grain-size, thickness 0-20 ft in the map area. This unit is similar to 4, but is less indurated and may have larger pumices. In the northern part of the map area, 4b is absent and the continuous surge interval at the base of unit 4 rests directly on unit 3.

Unit 3: **resistant** (map color = yellow; see Fig. 1)

Brown nonwelded to moderately-welded tuff, thickness 50-100 ft in the map area. Welding is most intense to the west of TA-55, and the upper 20 ft are devitrified and very dense at the western margin of the map area, but even the less-dense nonwelded portions at the eastern margin of the map area are resistant and cliff-forming. Pumices are as hard as the groundmass in welded intervals, and only slightly softer than the groundmass in nonwelded vapor-phase indurated intervals.

Unit 3b: **weak** (map color = green; see Fig. 1)

White nonwelded tuff, thickness 15-80 ft in the map area. Vapor-phase alteration is less intense than in unit 3, and the pumices are extremely soft. Macroscopic pumices are also large (typically >2 inches) and abundant (~20%).

Unit 2: **resistant** (map color = blue; see Fig. 1)

Moderately- to densely-welded brown tuff, salmon-colored in upper few feet of densely-welded zone, 90-150 ft thick in the map area. Densely-welded devitrified rock constitutes the majority of this unit, with pumices and groundmass both being very dense and hard. The top of this unit is the major ledge-forming lithology below the mesa top; these ledges occur on the north walls (and to a lesser extent on the south walls) of all major canyons that cut into unit 2. Platey intervals occur within this unit, and may signify flow boundaries within a compound cooling unit.

Unit 2b: **moderately weak** (not broken out in the map area - included within map color blue; see Fig. 1)

Nonwelded base of unit 2, thickness 10-30 ft in the map area. Macroscopic pumices are abundant (~30%), large (typically > 4 inches), and softer than the groundmass. Vapor-phase alteration is pervasive, but diminished in abundance relative to unit 2. Despite these features, this unit is not as weak as most comparable nonwelded tuff units, apparently because of a common "case-hardening" in many areas where it is exposed. Erosional deepening and canyon widening appears to be more common where stream bottoms occur in the underlying unit 1.

Unit 1: **weak** (map color = violet; see Fig. 1)

White-to-pink nonwelded to slightly-welded tuff, thickness 30 to 80(?) ft in the map area. Macroscopic pumices (~30% of the tuff) are similar in size and abundance to those in unit 2b, but much softer than the groundmass. As in all overlying units, vapor-phase alteration is pervasive. The lowest 1-2 ft at the base of this unit consist of a persistent and mappable pink-colored erosional notch in which the pumices are extremely soft. This notch is described in Fig. 9 of Crowe et al. (1978).

Unit 1b: **moderately weak** (not broken out in the map area - included within map color violet; see Fig 1)

White-to-gray glassy nonwelded tuff, thickness 25 to 80(?) ft in the map area. Macroscopic pumices in this unit are similar to those in unit 1, except that they remain glassy (little or no vapor-phase alteration). This lowest unit is the only part of the Tshirege in which vapor-phase alteration is absent. Although both the pumices and the groundmass are glassy and soft, this unit is generally resistant to erosion and it does form cliffs (probably due to the lack of differential hardness between groundmass and pumices, as well as the susceptibility of the glassy tuff to surface reactions and "case-hardening").

Underlying units (left uncolored in Plate 1 and Fig. 1)

The underlying units include a complex series reworked tuffs, Cerro Toledo fall out, and Otowi Member tuff exposed in Los Alamos Canyon. Excellent exposures of Cerro Toledo fall out occur within TA-41 and elsewhere along the walls of Los Alamos Canyon, but exposures of the other units beneath the Tshirege Member are generally poor.

3. Mapped Features

The discrete fault scarps that characterize the Rendija Canyon and Guaje Mountain faults north of Los Alamos are not observed in the map area around TA-55. There is abundant evidence, however, that broadly-dispersed flexure and some displacement of the Tshirege Member has occurred in the TA-55 area. The evidence leading to this conclusion is based in part on fracture analysis (see section 5.), but is also based on the following features shown in the geologic map (Plate 1):

Micrograbens. These features (see Fig. 1 for map explanation) are most prominent and concentrated in the northwest part of the Plate 1 map area. They are small graben-like structures, with down-dropped central blocks, that mostly occur along mesa margins in unit 3. The largest micrograbens are concentrated along the southern margin of South Mesa, between the Los Alamos County landfill (near TA-61) and the trailer park. Here the micrograbens may be over 20 ft across and 75 ft long. Actual displacements of the central blocks are difficult to measure because they have commonly been eroded by water flow from the mesa tops, but the relief between micrograben walls and central blocks is as much as 10 ft or more, particularly along the southern margin of South Mesa.

The significance of the micrograbens is in their apparent relation to the southern projection of the Rendija Canyon fault and splays from that fault. A set of micrograbens on the north side of Los Alamos Canyon lies directly along the projection of the Rendija Canyon fault through Ashley Pond, and contains the only known occurrence of gypsum along near-surface fractures in the Pajarito Plateau (probable deposits as a result of leaching and precipitation along the fault passing beneath Ashley Pond). The connection between micrograbens and Ashley Pond strengthens the likelihood that the original Ashley Pond was a sag pond.

To the south of South Mesa, micrograbens are fewer and more subdued. They appear to be more common toward the western part of the map area, and may in fact increase in abundance toward the Pajarito fault zone. Further mapping would be required to confirm this suggestion.

Zipper Joints. The term "zipper joint" is used to describe sets of incised joints that provide drainages off of the Pajarito Plateau mesa tops or off of the unit 2 erosional shelves into the canyon bottoms (see Fig. 1 for explanation of map symbol). These minor drainages do not follow one preferred joint orientation, but instead follow N-S to NE-SW channels with "zig-zag" pathways. The straight-line path segment of any particular "zig" or "zag" in the channel bottom is seldom longer than 5-10 ft, a distance much shorter than the traces of joints that cross the channels. This observation strongly suggests that individual joints are not capable of channeling flow off of the mesa tops, but channels form instead along chains of joint segments, where N-S to NE-SW trending lines of deep-seated displacement have offset and weakened the overlying joints.

On a broad scale, the zipper joints are dispersed across the map area. However, the most prominent zipper-joint drainages occur along Twomile Canyon between TA-48 and TA-66, along Pajarito Canyon below TA-46, and along Threemile Canyon north of TA-15. These locations are generally to the south and east of the areas where micrograbens tend to be most prominent; it is possible that micrograbens tend to develop on mesa surfaces closet to the Rendija Canyon - Guaje Mountain and Pajarito fault systems, whereas zipper joints tend to develop farther from these major faults.

4. Fault Projections

The Rendija Canyon Fault (RCF) and the Guaje Mountain Fault (GMF) project across the Los Alamos townsite toward the map area of Plate 1. Based on the mapping and fracture studies completed for this project, the traces of these faults can be extended south through TA-48 (RCF) and TA-2/TA-35/TA-15 (GMF). These projections are not of discrete surface ruptures, but rather represent the likeliest axial trace of broadly dispersed surface effects above the extensions of these faults south of Los Alamos Canyon.

The Rendija Canyon Fault (RCF) appears to have at least two major splays south of the Los Alamos townsite. One of these splays passes through a major slide block in the north wall of Los Alamos Canyon and passes to the west of TA-48. The other splay may pass much farther to the south, crossing Los Alamos Canyon after passing beneath Ashley Pond, passing beneath TA-48, and extending south beneath a major zipper-joint drainage, a small micrograben, and an area where large blocks of tuff have fallen into a tributary to Twomile Canyon. Where these splays cross Pajarito Road near TA-48, they are defined by zones of abundant and open fractures in units 4 and 3 of the Tshirege.

The Guaje Mountain Fault (GMF) appears to project across Los Alamos Canyon just to the west of TA-2. The northern wall of Los Alamos Canyon at this point has a large slide block that is beginning to form near the fault projection. This slide block is still ~150 ft above the canyon floor, but has slipped ~13 ft along its bounding fractures. We estimate that the minimum mass of material held in this block above the western edge of TA-2 is 50,000 tons. It is probably not fortuitous that the two massive slide blocks in Los Alamos Canyon occur along the projections of the RCF and the GMF.

South of Los Alamos Canyon, the GMF appears to pass through a major zipper-joint drainage opposite the turnoff to LAMPF from East Jemez Road. Fracture mapping indicates a zone of abundant and open fractures where this fault projection crosses the mesa. Further south, the fault projection passes through a major zipper-joint drainage in Mortandad Canyon, beneath TA-35, and into the bend in drainage where Twomile Canyon intersects Pajarito Canyon. At this point the GMF projection appears to disperse into a number of splays; the westernmost splay truncates a finger mesa and passes into Pajarito Canyon where a perched meadow has been incised by downcutting of the Pajarito Canyon drainage. The other two splays project toward a set of zipper-joint drainages north of TA-15.

5. Fracture Measurements

Fractures are a conspicuous feature of the Bandelier Tuff in the Los Alamos area. Most of these fractures are nearly vertical in orientation and divide the tuff into roughly polygonal-shaped, elongate blocks. The spacing of these fractures is visually regular on the order of about 5 to 10 ft. In the Baltz et al. (1963) and Dames and Moore (1972) reports the fractures are called "joints", a geological term that denotes fractures that are vertically oriented, passing across bedding planes, and along which there is no appreciable movement. This previous work further designated "master joints" as those that are most persistent in length, numerically predominate, pass through several stratigraphic subunits, and dip more than 85 degrees. "Minor joints" are those dipping from 40 to 70 degrees and found especially in unit 2a. The joints form "conjugate sets" with dominant strikes of NW and NE with about 60 degrees between the strikes, which Baltz et al. (1963) distinguish as developing from a preferred stress or structural orientation.

Vertical fractures are common features of welded tuffs and have been attributed to brittle failure of the tuff by cooling contraction. In general these fractures form nearly parallel to the local thermal gradient in the tuff while it is cooling. Nearly horizontal fractures also form in welded tuffs through cooling contraction as well as in response to overburden stress. Dames and Moore (1972) have distinguished these cooling fractures, which they also called joints, from tectonic fractures by their slight variance in orientation among stratigraphic units, as well as their occurrence in three general trends in strike: (1) N70W to N90W; (2) N10W to N30W; and (3) N30E to N50E. These workers noted typical dips in the range of 80 to 90 degrees and fracture widths of 0.25 to 2.0 inches.

Because the fractures are numerous, we have tested the hypothesis that they might be planes along which tectonic stress might be relieved. Accordingly, the abundance of these fractures, their width and filling material should vary across areas where there has been tectonic displacement. In this way we circumvent the need to distinguish cooling fracture joints from tectonic fractures in the field, leaving that problem to statistical analysis of their measurements

Method. In order to make statistical analysis of fracture characteristics, we make a linear analysis of fracture abundance, strikes, dips, and widths along lines crossing the fault traces hypothesized during geological mapping. Road cuts along Pajarito Road and East Jemez Road provided rock faces where these fracture measurements could be repeated in a systematical fashion. Because of irregular exposure and vegetation, these measurements were not attempted on cliff exposures in the canyons.

The line along Pajarito Road begins about 235 ft west of the blockade emplaced at the west end of the old turnoff to TA-48 (see map for locations) and runs eastward nearly 2,800 ft to a point along a line drawn from the southeastern fence of TA-55. From the geological map (Plate 1), this line crosses the southern extension of the Rendija Canyon Fault (RCF). The line along East Jemez Road begins about 200 ft east of the turnoff to the dirt access road going down South Mesa (where the 7,255 foot contour crosses the road), and the line continues nearly a mile down East Jemez Road past the LAMP turnoff to where the 7,000 ft contour crosses the road. The middle section of this line cuts across the southerly trace of the Guaje Mountain Fault (GMF). 704 fractures are documented along the Pajarito Road line, and 921 fractures are documented along the East Jemez Road line.

Fractures are documented by fracture maps, constructed from polaroid photo- mosaics (Plates 3 and 4). Each photo covers about 15 ft of rock exposed along measured lines. Gaps in road-cut exposures have been measured such that the fracture data can be analysed as a continuum. The photomosaics have attached maps with traced fractures that have been numbered for specific documentation in field notes and a data base. Fracture strikes and dips were measured with a Brunton compass (accuracy of 2 degrees), and fracture widths by ruler to within 2 mm accuracy. Because all variations of fracture visibility were encountered, only fractures that these measurements could be made were included in the study. The fracture data were entered into an RS/1 data base for analysis (ESSXRF VAX, RS/1 directory = [WOHLETZ.RSUSERHOME]@ken@ta55).

Fracture Abundances. In order to asses linear variations of fracture abundances, called linear density, the number of fractures encountered in 10 and 100 ft intervals around each fracture were calculated by a RS/1 procedure called "DENS." These data are shown as a function of location along each of the two measured lines (Figures 4 and 5). The 10-foot linear density curve best represents what a casual observer would see along these road cuts, which is that there is no apparent variation in linear density along the lines. However, the 100-foot density curve shows some important peaks.

Along Pajarito Road (Figure 4), two peaks occur, one near the old turnoff to TA-48 and one just south of TA-55. The latter of these peaks with values of 25 to 40 fractures per 100-foot interval is along strike of the RCF, while the former on the western part of the line corresponds to a possible fault branch of the RCF that was mapped by alignment of downthrown blocks micrograbens and zipper joints. Figure 4 also shows 100-foot fracture density curves (p1 and p2) measured along corresponding parts of the line at cuts along the other side of the road. These curves show similar trends as the previous curve, which supports the uniqueness of the data in a sense that the linear data likely represents data for an aerial distribution of fractures.

The East Jemez Road line shows two peaks, one at the western edge and an apparent peak between 1,600 and 2,400 ft east where there is also a gap in data because of a lack of a road cut exposure there. This latter peak (24 to 50 fractures per 100-foot interval) corresponds in location to the trace of the GMF. The former peak might reflect the proximity of the RCF, which is projected to be about 1,000 ft west of this line, or possibly a branch fault running west-northwest along the road connecting the RCF and the GMF.

For both lines, gaps in the data set occur near the projection of the RCF and GMF, because of a lack of road-cut exposure. These gaps are not surprising if one assumes that erosion of the mesa tops has produced notches where fracture density is highest.

Fracture Strikes and Dips. Table 2 lists average strikes and dips for fractures measured along Pajarito Road and East Jemez Road. If all the fractures belong to conjugate NE and NW trending sets caused by cooling contraction, an approximately equal number of each is expected. However this is not the case for the data set gathered. Of the 704 fractures measured along Pajarito Road, 460 belong to the NE set and 244 to the NW set.

Table 2. Fracture Data*.

		Number	Strike	Dip	Width	Cumulative Width
Pajarito Road						
	All	704	N16E (48)	76 (19)	1.81 (4.52)	905.85
	NE	460	N45E (25)	73 (20)	1.81 (5.14)	585.40
	NW	244	N39W (27)	81 (14)	1.81 (3.04)	320.45
East Jemez Road						
	All	921	N4E (48)	75 (18)	0.92 (1.74)	850.85
	NE	520	N39E (26)	75 (18)	1.01 (1.89)	524.85
	NW	401	N42W (27)	75 (18)	0.81 (1.53)	326.00

* Strikes and Dips are in degrees with standard deviations shown in parentheses. Widths are in cm, and cumulative widths for Pajarito Road line exclude measurements on sections P1 and P5, which cover area along the line already included.

For the 921 fractures measured along East Jemez Road, 520 are NE and 401 are NW. Over the RCF zone NE fractures outnumber NW fractures by about 2.16:1, and over the GMF zone, this ratio is 1.69:1. Over areas not suspected of being affected by fault zones, such as along section 4 on the East Jemez Road, the ratio of NE to NW fractures is 1.26:1. This observation suggests that fault zones have affected the ratio of NE to NW fractures. For the areas through which the RCF and GMF are projected on these lines (RCF - 1,800 to 2,700 ft east, Figure F4; GMF - 1,000 to 2,600 ft east, Figure 5), 158 fractures of varying strikes over the RCF average 1.58 cm wide and dip 72.5 degrees (east or west of strike), and 199 fractures over the GMF average 0.90 cm wide and dip 74.9 degrees (east or west of strike).

Histograms of fracture strikes (Figures 6 and 7) show an almost continuous distribution of strikes from -90 degrees (West) north through 0 degrees to 90 degrees (East) with only a slight preference in frequency of fractures trending northeast. These data are illustrated with linear distance in Figures 8 and 9.

Along Pajarito Road, the dominant fracture strike is about N16E with the northeast set averaging around N45E and the northwest set averaging around N39W. There is little apparent variation in fracture strikes across the trace of the RCF (1,900 to 2,400 ft east) and over the fault branch (100 to 500 ft east).

The East Jemez Road line shows average fracture strikes just 4 degrees east of north with NE fractures averaging N39E and NW fractures averaging N42W. In these data only a change from a dominance of NE fractures to a dominance of NW fractures gives an indication of the presence of the GMF.

Fracture dips average 76 degrees (73 along NE sets, 81 along NW sets) on the Pajarito line, and they average uniformly 75 degrees along the East Jemez line. These dips are dominantly 1 to 10 degrees to the northwest or northeast of vertical (80 to 89 degrees) for the fault zones along Pajarito Road (Figure 10), whereas in between these zones the dips are more nearly vertical with a southeast or southwest dipping tendency. Where NE trending fractures dip further from vertical so does the NW set, but in the opposite direction. For the East Jemez Road line (Figure 11), there is no apparent variation in fracture dips across the projection of the GMF.

Fracture Widths and Fill. Fracture opening widths average 1.81 cm for both fracture sets along the Pajarito Road line (Table 2) with noticeable increases across the RCF and its fault branch (Figure 12). The cumulative fracture opening along this line is 9.06 m, 3.56 m accounted for across the RCF branch and 2.45 m across the RCF. Figure 13 shows fracture opening per 100-foot interval along the Pajarito line, and noticeable peaks occur over projected fault traces. Across the RCF opening of NW fractures is greater than that of NE fractures. The opposite relationship however is apparent across the fault branch, with NE fractures showing the greatest opening.

There are several zones along the Pajarito Road line of notable fracture openings where fractures are filled with or adjacent to brecciated rock and possibly gouge. Figure 14 shows the locations and openings of fractures that are filled with over 10 cm of breccia or detritus for the Pajarito Road line. There are noticeable occurrences over the RCF and the RCF branch. Specific examples over the RCF branch include fracture number 22 (Plate 2, section P2A), which consists of two fractures separated by 1.26 m of detrital fill and breccia, fracture 43 (Plate 2, section P2A) with an opening of 15 cm filled with breccia, and fracture 4 (Plate 2, section P1), which is two fractures separated by a 68 cm wide zone of rubble, and a zone of completely broken tuff 2 m wide but with no measurable fracture surfaces between fractures 6 and 7 (Plate 2, section P3A). Possible fault breccia and gouge zones over RCF exist between fracture 5 and 6 (Plate 2, section P4A), between fractures 54 and 68 (Plate 2, section P4A), and between fractures 83 and 88 (Plate 2, section P4B). Across Pajarito Road from sections P4A and P4B, a brecciated zone 90 cm wide exists between fractures 5 and 6 (Plate 2, section P5A), another breccia zone over 1 m wide exists between fractures 23 and 26 (Plate 2, section P5A), fracture 39 (Plate 2, section P5B) has 15 cm of breccia fill, and a breccia zone between fractures 64 and 65 (Plate 2, section P5B) has 5 parallel fractures in a crumbled zone about 1 m wide. These zones on section P5A and P5B correlate in relative location to zones identified in sections P4A and P4B.

Along the East Jemez Road line, average fracture opening widths (Figure 15) are about 0.9 cm. There is an apparent decrease in width to about 0.4 cm in crossing the GMF from west to east. In general NW fractures are opened slightly more than NE ones, although for the cumulative fracture opening along this line of 8.51 m, 5.25 m is accommodated by the NE set while only 3.26 m is due to the NW set (Table 2), because there are fewer NW fractures than NE ones. Figure 16 shows fracture opening per 100-foot interval along this line, but there is little indication of greater opening across the GMF, probably as a result of the lack of road-cut exposure there.

Along East Jemez Road (Figure 17) only one fracture opening greater than 10 cm was noted over the trend of the GMF while several were noted on the west end of the line, possibly a response to the proximity of the RCF. These fractures are noted as fractures 54, 67, and 69 (Plate 3, section E1A) and fracture 36 (Plate 3, section E3A).

Vertical Displacements. There are very few fractures along which vertical displacement can be confidently recognized; where we have noted features, such as lithic fragments broken and displaced, movement is a few cm or less. In order to assess potential vertical displacement accommodated by fractures, we make a trigonometric assumption that fracture opening widths have occurred in response to vertical movement along those fractures. Based upon fracture data along Pajarito Road where over the projection of the RCF (distance = 1,800 to 2,700 ft east, Figure 4) dips average 72.5 degrees and fracture openings average 1.58 cm, a trigonometric relationship suggests that this average fracture opening is achieved by 6.25 cm of vertical displacement per average fracture. For the 158 fractures observed in this span of 900 ft the total cumulative vertical displacement is 8.30 m (27.2 ft). This same calculation for measured fractures along East Jemez Road where it crosses the projection of the GMF (average fracture dip = 74.87 degrees, average opening = 0.90 cm, 199 fractures) indicates a total cumulative vertical displacement of 6.86 m (27.6 ft) over 1600 ft horizontal distance (1,000 to 2,600 ft east, Figure 5).

Conclusions. Fracture data measured along lines running parallel with Pajarito Road and East Jemez Road suggest that the presence of the Rendija Canyon Fault and Guaje Mountain Fault have caused notable increases in the abundance of fractures in the Bandelier Tuff where the lines cross traces of these faults. In addition there is an apparent increase in average and cumulative fracture opening widths across these fault projections. Fracture strike and dip data provide no conclusive evidence. Appearance of rock brecciation and gouge zones of up to a meter wide along some fractures is is added indication of surface rupture that has been tectonically caused along these faults.

The increase in abundance of fractures over the fault zones and the likelihood of average displacement on the order of a cm on each of these fractures are an indication that if the calculated vertical movement of several m or more has occurred in bedrock below the tuff along the fault traces, its surface manifestation has been spread out over zones of several hundred feet across the fault, so that surface rupture is diffuse and difficult to recognize.

6. Topographic Gradients

Topographic gradients are commonly affected by fault movements. Along mesa tops where the regional gradient slopes at a few degrees easterly, there are a few very gentle inflection points of this gradient. Along stream beds, topographic inflections caused by fault movement are termed "nick points." Several such features of up to 10 ft vertical relief were noted in canyons. We plot mesa top gradients and stream gradients to see if inflection points correspond to fault zone projections.

Mesa Top Gradients. Even though surface displacement of mesa tops by the RCF and GMF is likely diffused over distances of several hundred feet, there might be slight changes in topographic gradient. Figure 18 shows mesa top elevations from west to east on Los Alamos Mesa (Trinity Drive - DP Road), South Mesa, Sigma Mesa, and Mesita Del Buey (Pajarito Road). Topographic gradient inflections are prominent at areas where the RCF and GMF are projected. The same is true for Twomile Mesa, Twomile Mesa (south), and Pajarito Mesa (Figure 19). While the topographic effect of the RCF is greatest to the north it becomes less distinct to the south, while the opposite is true for the GMF, which is expressed by captured drainages canyons that develop on its trace.

Although it is difficult to prove that these topographic gradient inflections are an indication of the presence of the faults, the gradient along Trinity Drive - DP Road is especially interesting in the area just west of Ashley Pond (Figure 20). Gardner and House (1987) and Wachs et al. (1988) extend the RCF south to Ashley Pond, and just west of the point the mesa top takes a very unusual dip towards the west. In Figure 17 the average topographic gradient west of Ashley Pond is compared with that to the east of the pond. A down drop of nearly 150 ft to the west can explain the discontinuity in the generally east dipping mesa top gradient. This discontinuity extends over nearly 1 mile from Diamond Drive to Ashley Pond, covering the zone where the RCF might split into several fault branches. If this 150 ft of apparent downdrop to the west over the RCF is in fact realistic, we need to consider reasons why this amount of vertical displacement is not apparent south of Los Alamos canyon. In our mapping in Los Alamos canyon, we did observe southwest-trending splays of the RCF running about 500 ft west of its main trace (just west of the Los Alamos Inn). Along these fault splays is noticeable topographic downthrow to the west. Another SW-trending splay of the RCF may branch off in Pueblo Canyon and pass on either side of the LAAO DOE building, curving up Los Alamos canyon towards the Pajarito Fault zone. It is possible that these fault splays might in fact accommodate much of the vertical offset seen along the RCF north of Los Alamos canyon.

Stream Gradients. Stream gradients in the area of Plate 1 may have some inflections that reflect the positions of the RCF and GMF (Figs. 21-25). The Sandia Canyon gradient (Fig. 22) and the Mortandad Canyon gradient (Fig. 23) both have sharp increases where the streams crosses the GMF projection. These gradient increases are entirely within the tuffs of unit 2, and are thus unlikely to be due to stratigraphic transitions in tuff physical properties. The Twomile/Pajarito gradient (Fig. 24) has inflections where secondary drainages meet the main channel, as well as where the RCF and GMF projections intersect; these inflections are perhaps less easy to interpret, since both drainage and fault effects may have contributed to the gradient changes.

7. Recommendations

To further substantiate the above fracture data that indicate the diffuse presence near TA-55 of surface rupture associated with the trends of the Rendija Canyon and Guaje Mountain faults, additional fracture measurements should be made. These measurements can not be confidently made on cliff exposures because of vegetation, soil and rock cover, and the irregular faces of the cliffs. We suggest that blade cut of sufficient depth (about 1 foot) to expose solid tuff be made on mesa tops near TA-55 and that the cuts be washed clean by water hoses. This method could expose fractures in a regular fashion such that measurements could be made similar to those on road cuts.

Further work should be done in Los Alamos Canyon. In particular, the large slide block forming above TA-2 has been mapped only in reconnaissance scale. This block is the most prominent example in the map area of potential mass-wasting hazards to established sites (in this case, the reactor at TA-2). It is likely that similar slide blocks exist near other laboratory technical areas, and these require hazard study as well.

Related work that can further document the seismic hazard in the mapped area includes study of geomorphic surfaces (e.g., raised meadows and terraces in canyons) and detailed topographic surveys of stratigraphic markers over the fault zones. This is work we also strongly recommend.

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Baltz, E. H., Abrahams, J. H., Jr., and Purtyman, W. D., 1963, Preliminary report on the geology and hydrology of Mortandad Canyon near Los Alamos, N. Mex. with reference to disposal of liquid low-level radioactive waste. U. S. Geol. Surv. Open File Report, 105 pp.

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Gardner, J. N. and House, L., 1987, Seismic hazards investigations at Los Alamos National Laboratory, 1984 to 1985. LA-11072-MS, 76 pp., 7 maps.

Wachs, D., Harrington, C. D., Gardner, J. N., and Maassen, L. W., 1988, Evidence of young fault movements on the Pajarito Fault System in the area of Los Alamos, New Mexico. LA-11156-MS, 23 pp.

Figure Captions

Plate 1. Geological map of the Pajarito Plateau around TA-55.

Plate 2. Fracture maps along Pajarito Road. Green lines denote NW striking fractures, red lines denote NE striking fractures.

Plate 3. Fracture maps along East Jemez Road. Green lines denote NW striking fractures, red lines denote NE striking fractures.

Fig. 1. Composite stratigraphic column showing the schematic stratigraphy of the Tshirege Member of the Bandelier Tuff in the TA-55 area. This column serves as a key to the geological map (Plate 1.)

2. Stratigraphic section of the Tshirege Member near TA-55.

3. Stratigraphic section of the Tshirege Member near TA-40.

4. Plot of linear fracture density along Pajarito Road. Curves for sections p1 and p5 parallel the line and show the repeatability of fracture abundances along strike with the inferred tectonic fabric.

5. Plot of linear fracture density along East Jemez Road.

6. Histogram of fracture strikes along Pajarito Road.

7. Histogram of fracture strikes along East Jemez Road.

8. Variation of fracture strikes along Pajarito Road, showing averaged (smoothed) trends for all fractures and for NE and NW sets.

9. Variation of fracture strikes along East Jemez Road, showing averaged (smoothed) trends for all fractures and for NE and NW sets.

10. Variation of fracture dips along Pajarito Road showing smoothed trends for all fractures, the NE set, and the NW set. The dips are expressed such that 0 degrees is vertical and 90 (-90) is horizontal.

11. Variation of fracture dips along East Jemez Road showing smoothed trends for all fractures, the NE set, and the NW set. The dips are expressed such that 0 degrees is vertical and 90 (-90) is horizontal.

12. Variation of averaged fracture widths along Pajarito Road.

13. Variation in cumulative fracture opening for 100 foot intervals along Pajarito Road.

14. Plot of fractures having openings of 10 cm or more along Pajarito Road.

15. Variation of averaged fracture widths along East Jemez Road.

16. Variation in cumulative fracture opening for 100 foot intervals along East Jemez Road.

17. Plot of fractures having openings of 10 cm or more along East Jemez Road.

18. Plot of topographic gradients of mesa tops for Trinity Drive - DP Road (Los Alamos), South Mesa, Sigma Mesa, and Pajarito Road (Mesita Del Buey).

19. Plot of topographic gradients of mesa tops for Twomile Mesa, Twomile Mesa southern branch, and Pajarito Mesa.

20. Detailed plot of topographic gradient along Trinity Drive - DP Road showing the prominent break in slope near Ashley Pond where the Rendija Canyon Fault zone runs. Linear fits to gradient segments on either side of the RCF show that up to 150 ft of downdrop to the west could have caused this break in slope.

21. Los Alamos canyon gradient.

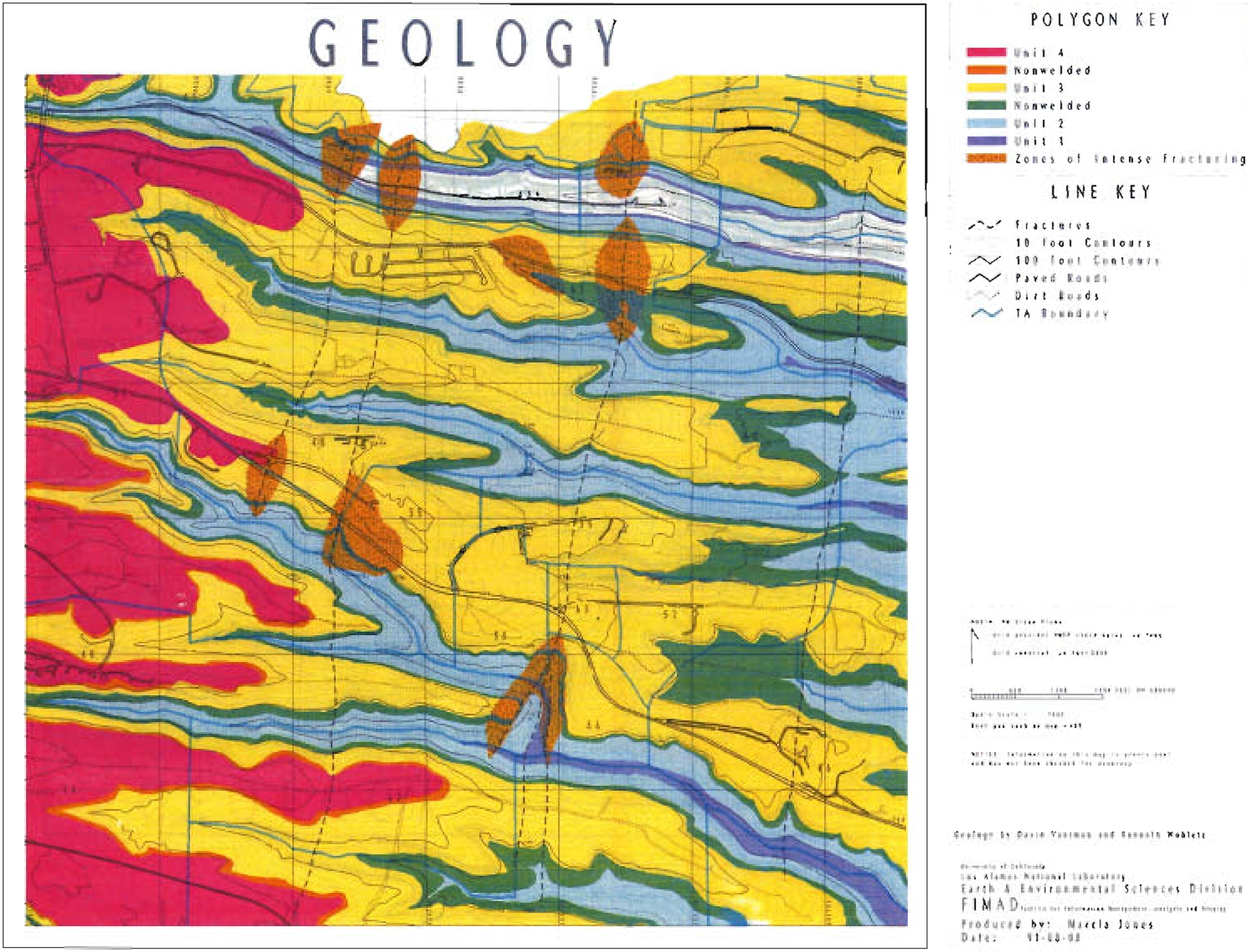
22. Sandia canyon gradient.

23. Mortandad canyon gradient.

24. Two mile/Pajarito canyon gradient.

25. Pajarito canyon gradient.

Plate I


GEOLOGY
POLYGON KEY
Unit 4
Nonwelded
Unit 3
Nonwelded
Unit 2
Unit 1
Zones of Intense Fracturing
LINE KEY
Fractures
10 foot Contours
100 foot Contours
Paved Roads
Dirt Roads
TA Boundary
Geology by David Vaniman and Kenneth Wohletz
Los Alamos National Laboratory
Earth & Environmental Sciences Division
FIMAD
Produced by: Marcia Jones

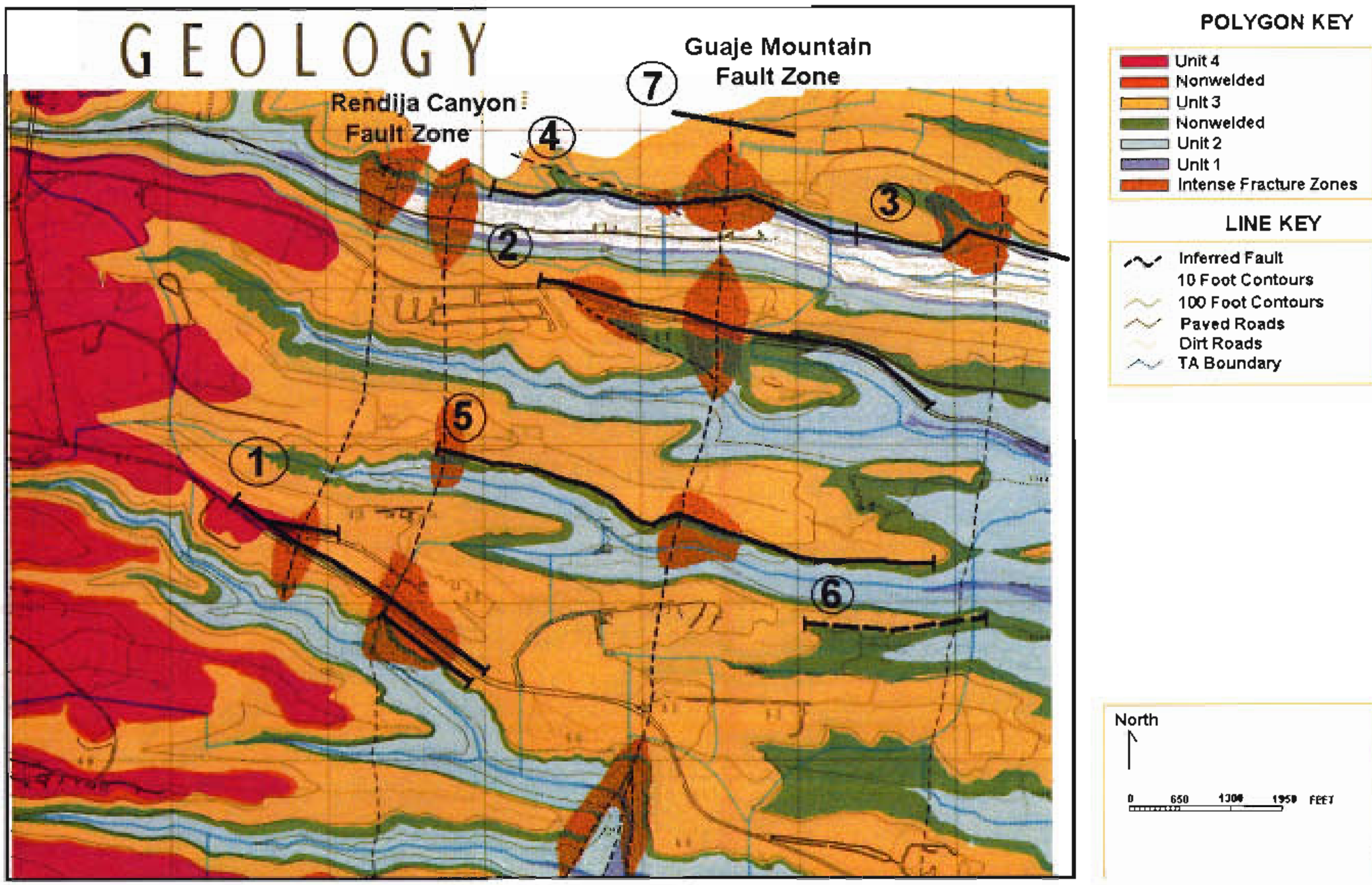

GEOLOGY
Rendija Canyon
Fault Zone
Guaje Mountain
Fault Zone
1
2
3
4
5
6
7
POLYGON KEY
Unit 4
Nonwelded
Unit 3
Nonwelded
Unit 2
Unit 1
Intense Fracture Zones
LINE KEY
Inferred Fault
10 Foot Contours
100 Foot Contours
Paved Roads
Dirt Roads
TA Boundary
North
0 650 1300 1950 FEET

Plate I

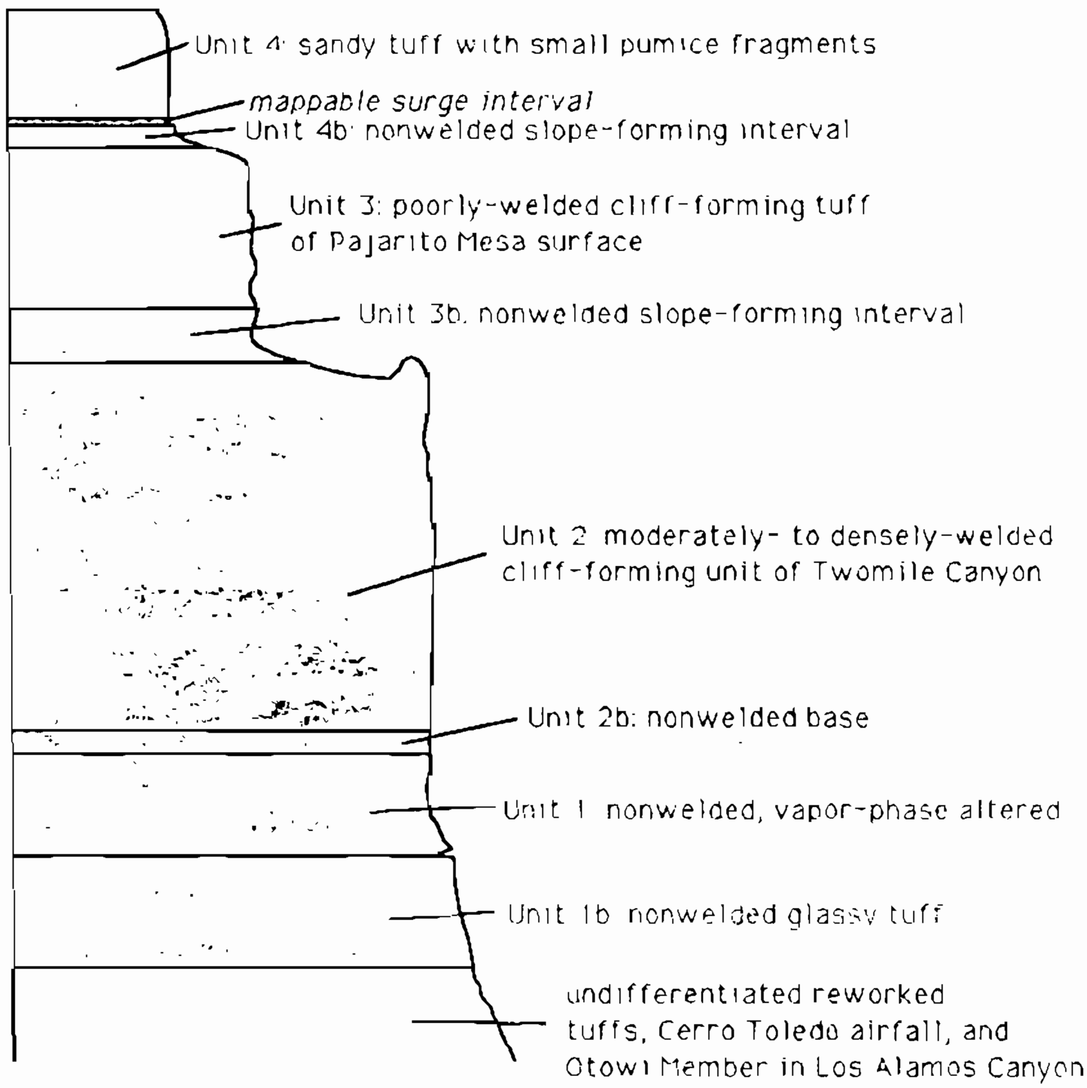
Plate II

Large scale photomosaic map on file with Sesimic Hazard Program

Plate III

Large scale photomosaic map on file with Sesimic Hazard Program

Schematic Stratigraphy of the Tshirege Member in the TA-55 Area



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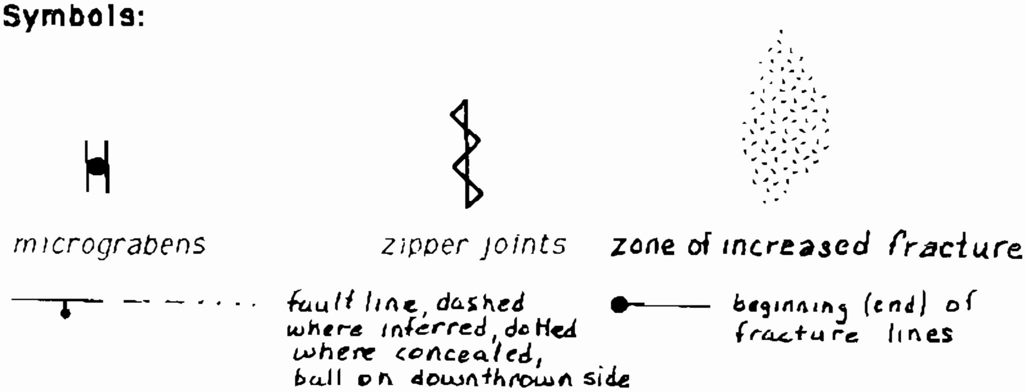


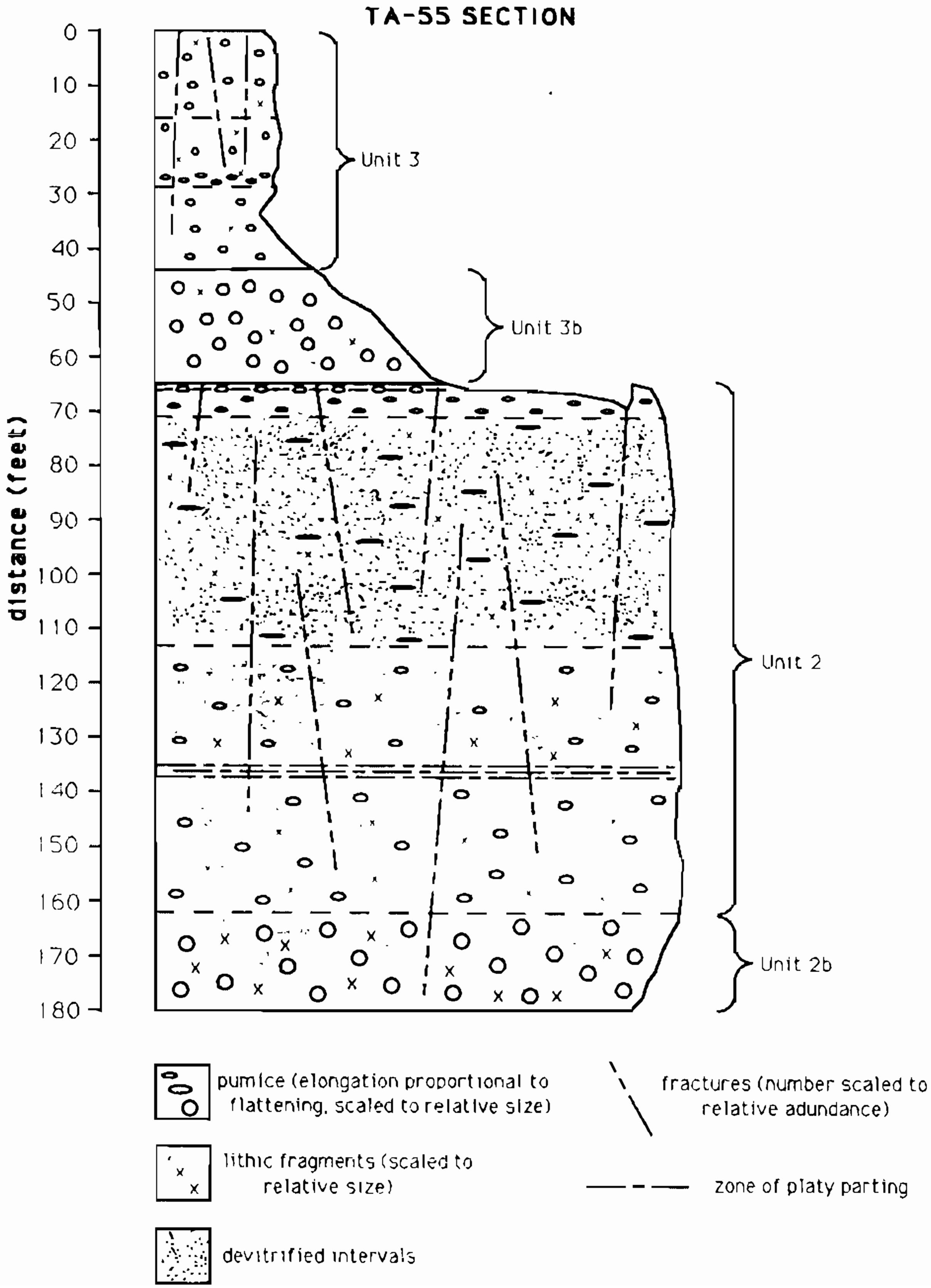
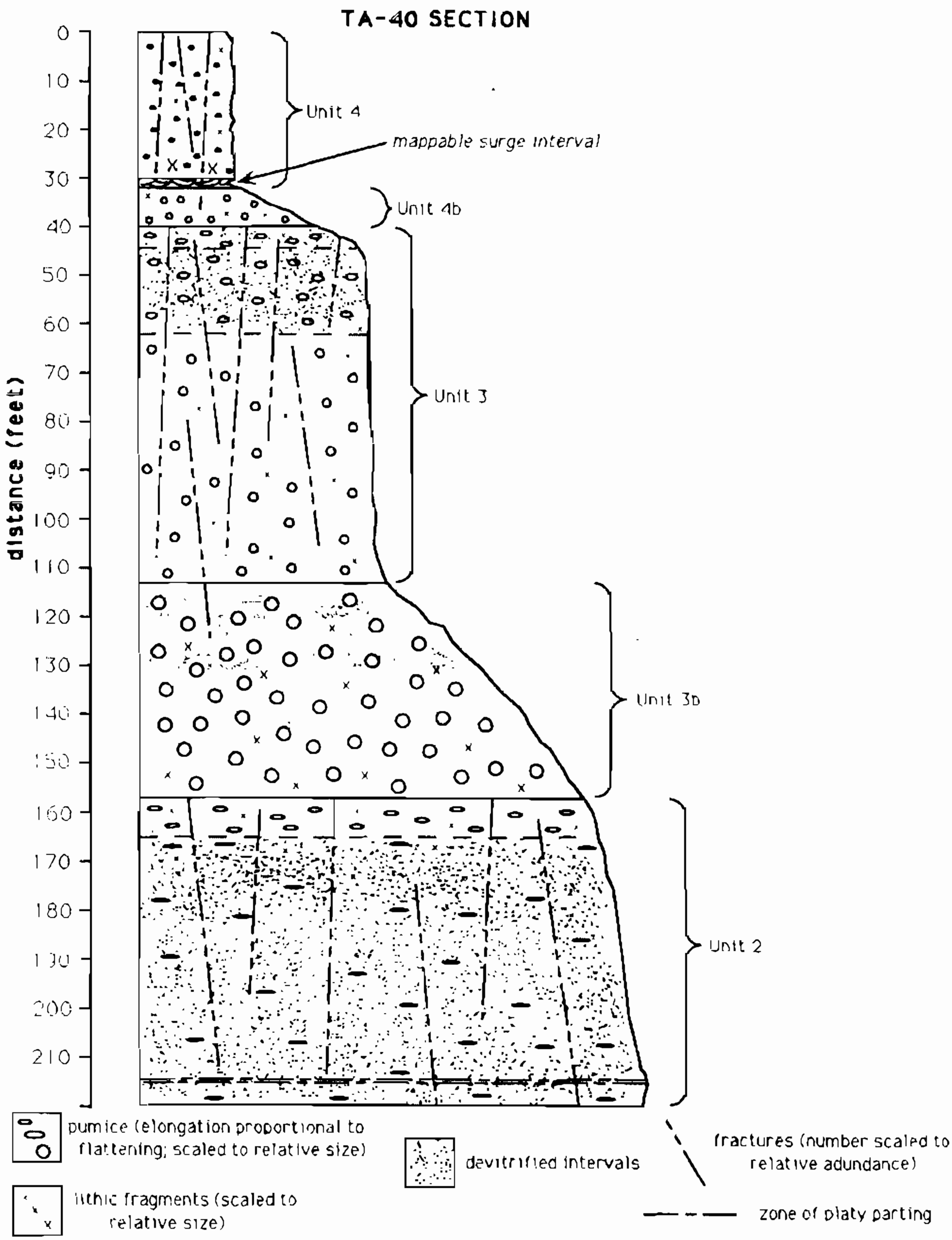
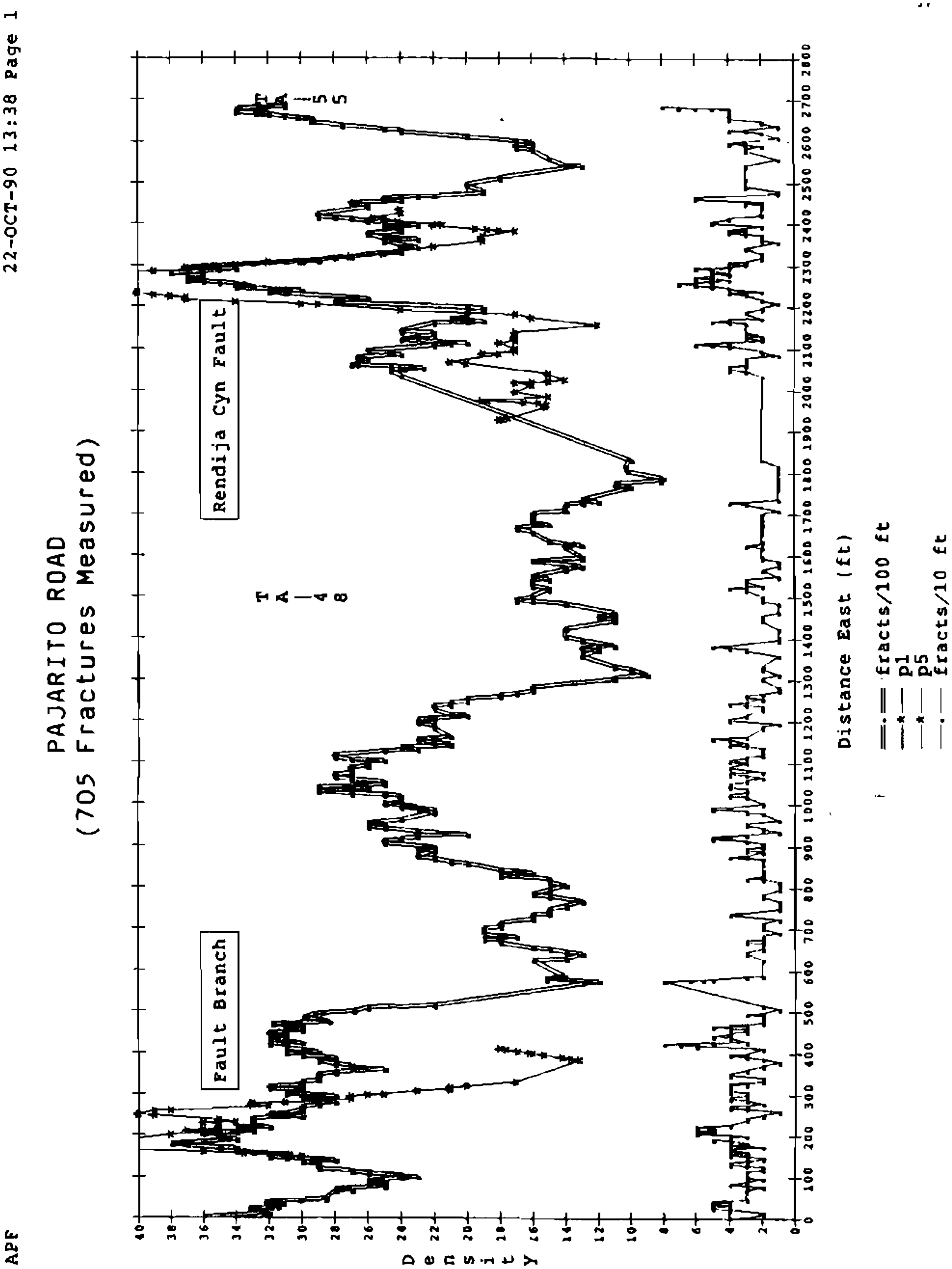
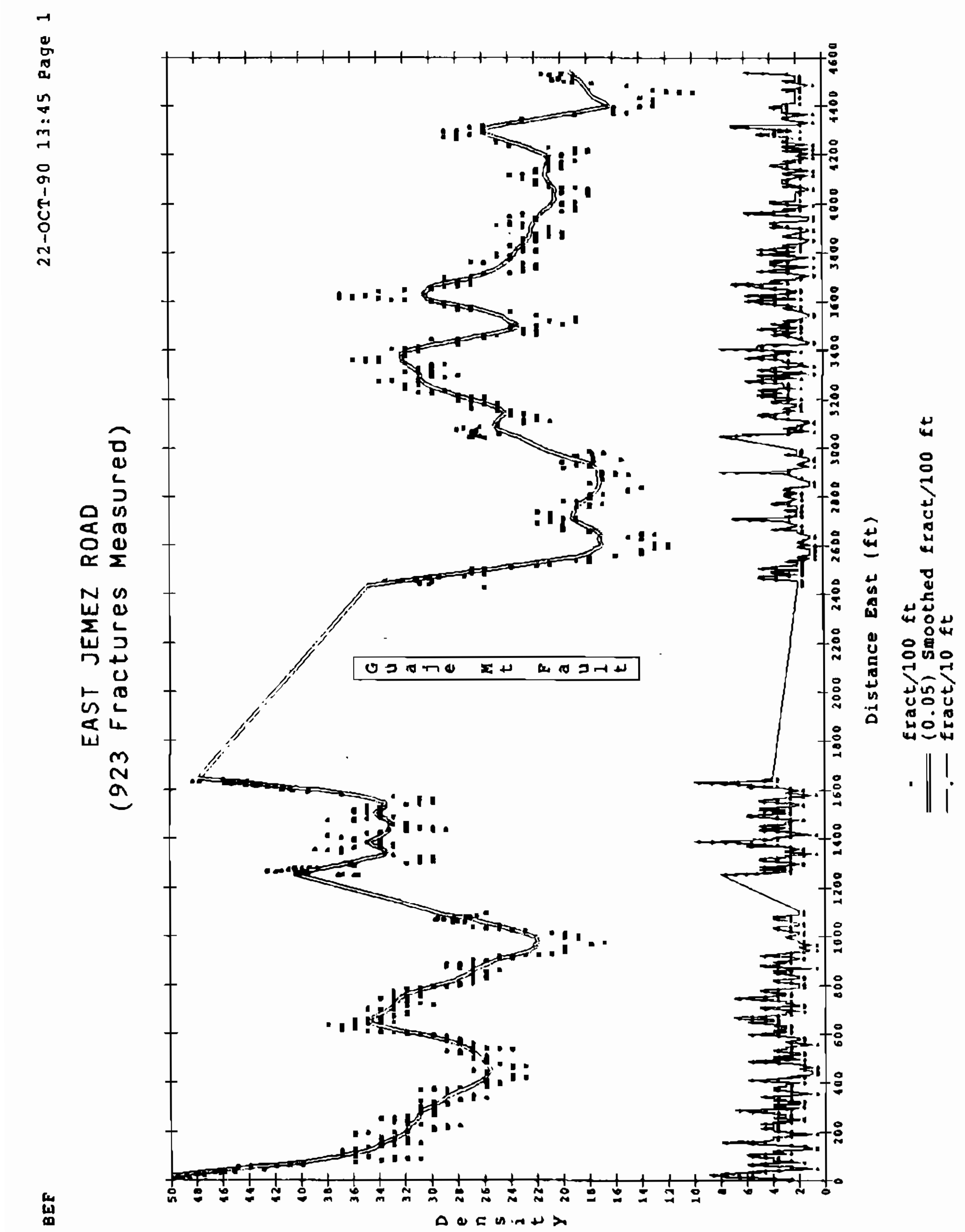

TA-55 SECTION
distance (feet)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
Unit 3
Unit 3b
Unit 2
Unit 2b
pumice (elongation proportional to flattening, scaled to relative size)
fractures (number scaled to relative adundance)
lithic fragments (scaled to relative size)
zone of platy parting
devitrified intervals

Figure 3


TA-40 SECTION
distance (feet)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
Unit 4
mappable surge interval
Unit 4b
Unit 3
Unit 3b
Unit 2
pumice (elongation proportional to flattening; scaled to relative size)
devitrified intervals
fractures (number scaled to relative adundance)
lithic fragments (scaled to relative size)
zone of platy parting


22-OCT-90 13:38 Page 1
PAJARITO ROAD
(705 Fractures Measured)
Fault Branch
Rendija Cyn Fault
TA-48
TA-55
Density
Distance East (ft)
fracts/100 ft
p1
p5
fracts/10 ft
APF


22-OCT-90 13:45 Page 1
EAST JEMEZ ROAD
(923 Fractures Measured)
Guaje Mt Fault
Density
Distance East (ft)
0 200 400 600 800 1000 1200 1400 1600 1800 2000 2200 2400 2600 2800 3000 3200 3400 3600 3800 4000 4200 4400 4600
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50
fract/100 ft
(0.05) Smoothed fract/100 ft
fract/10 ft
BEF

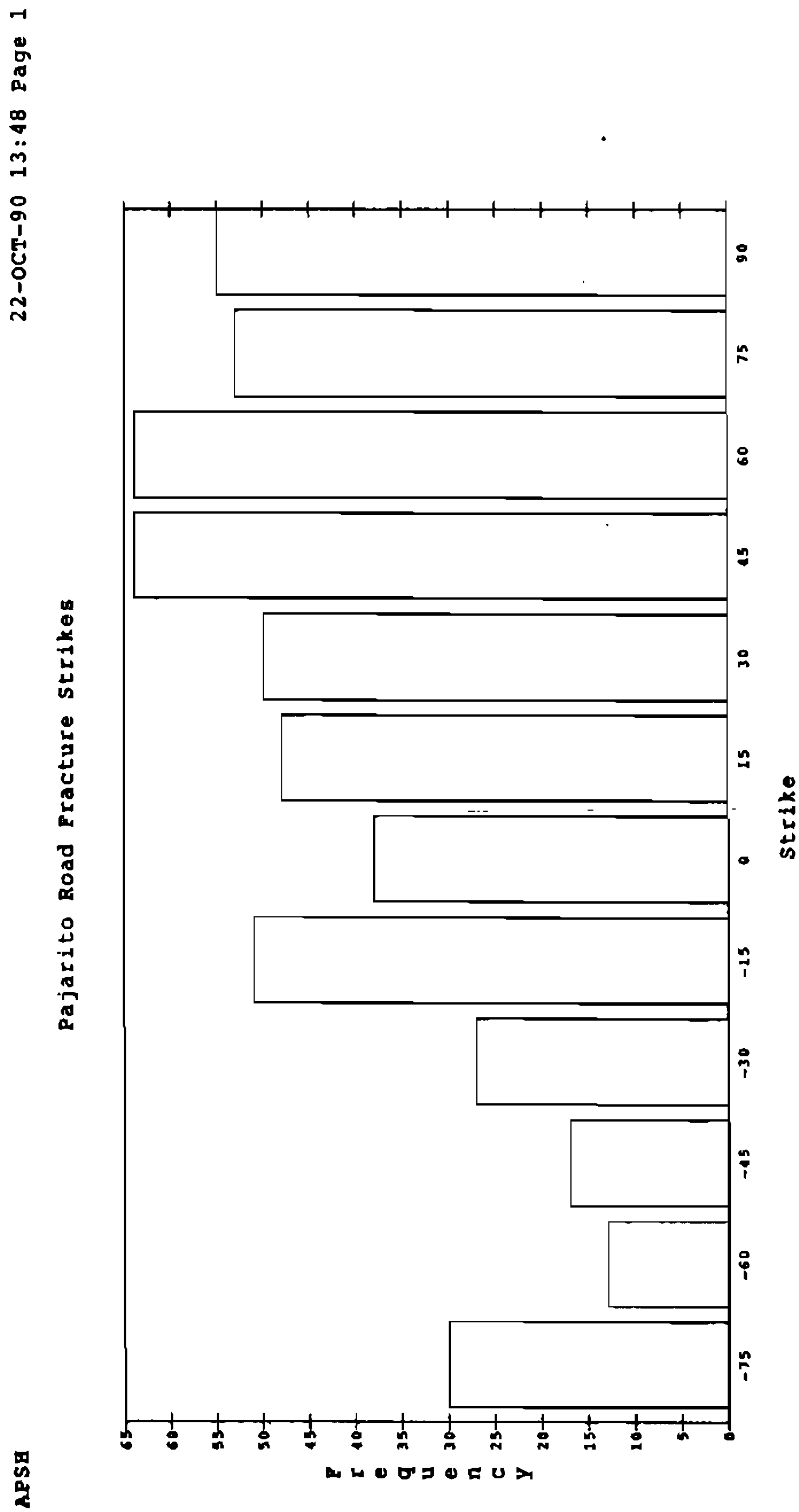
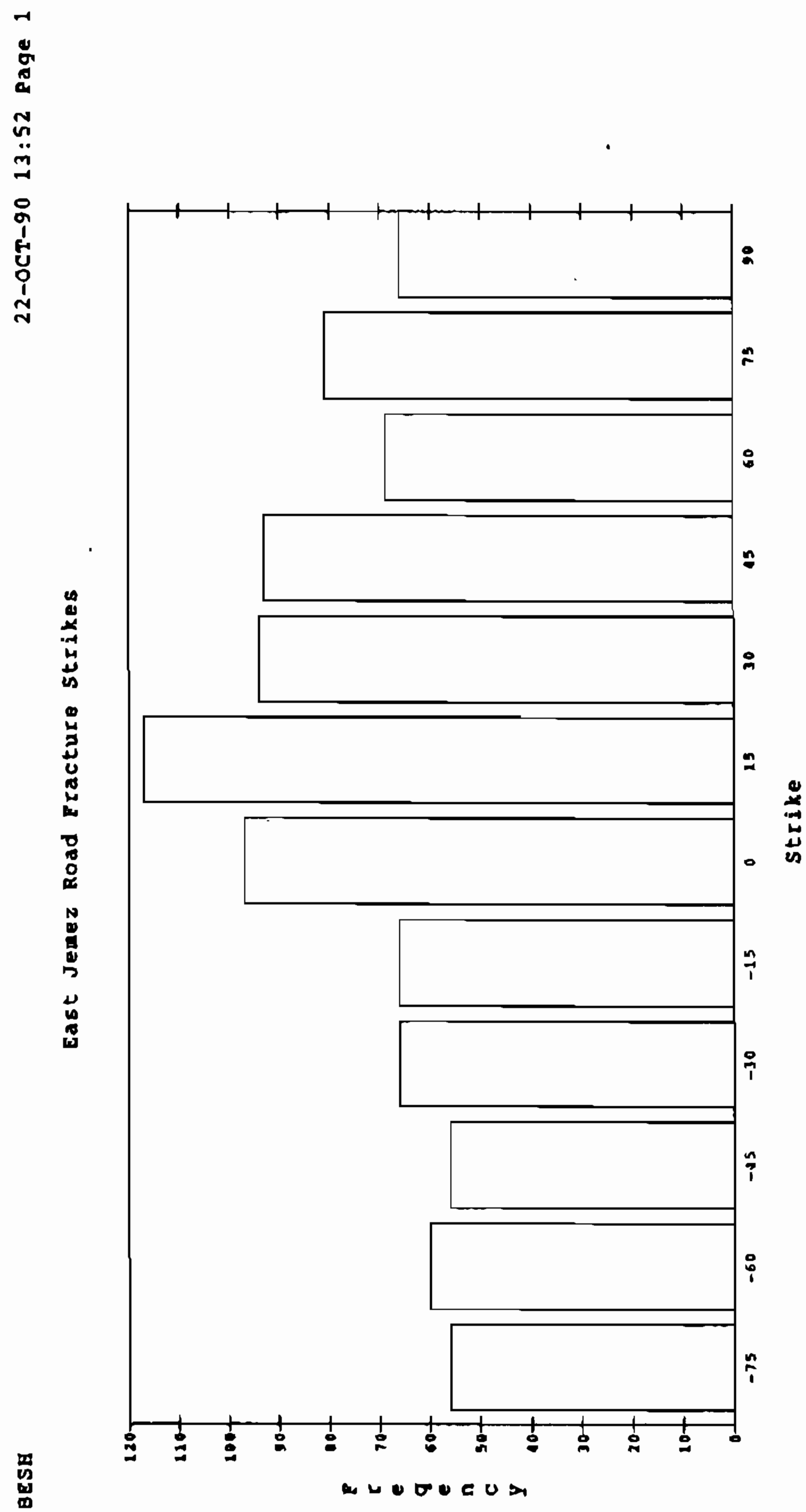
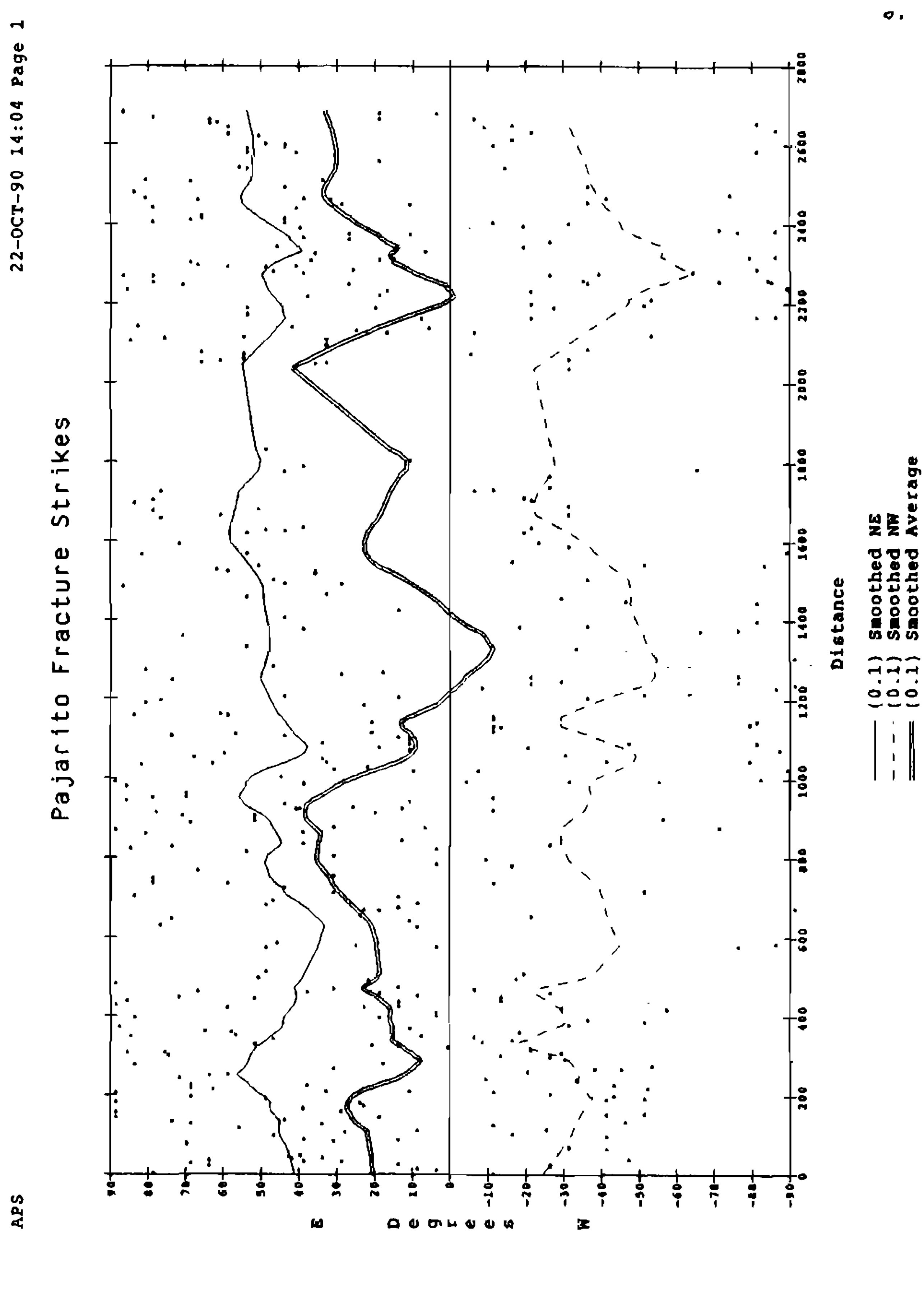
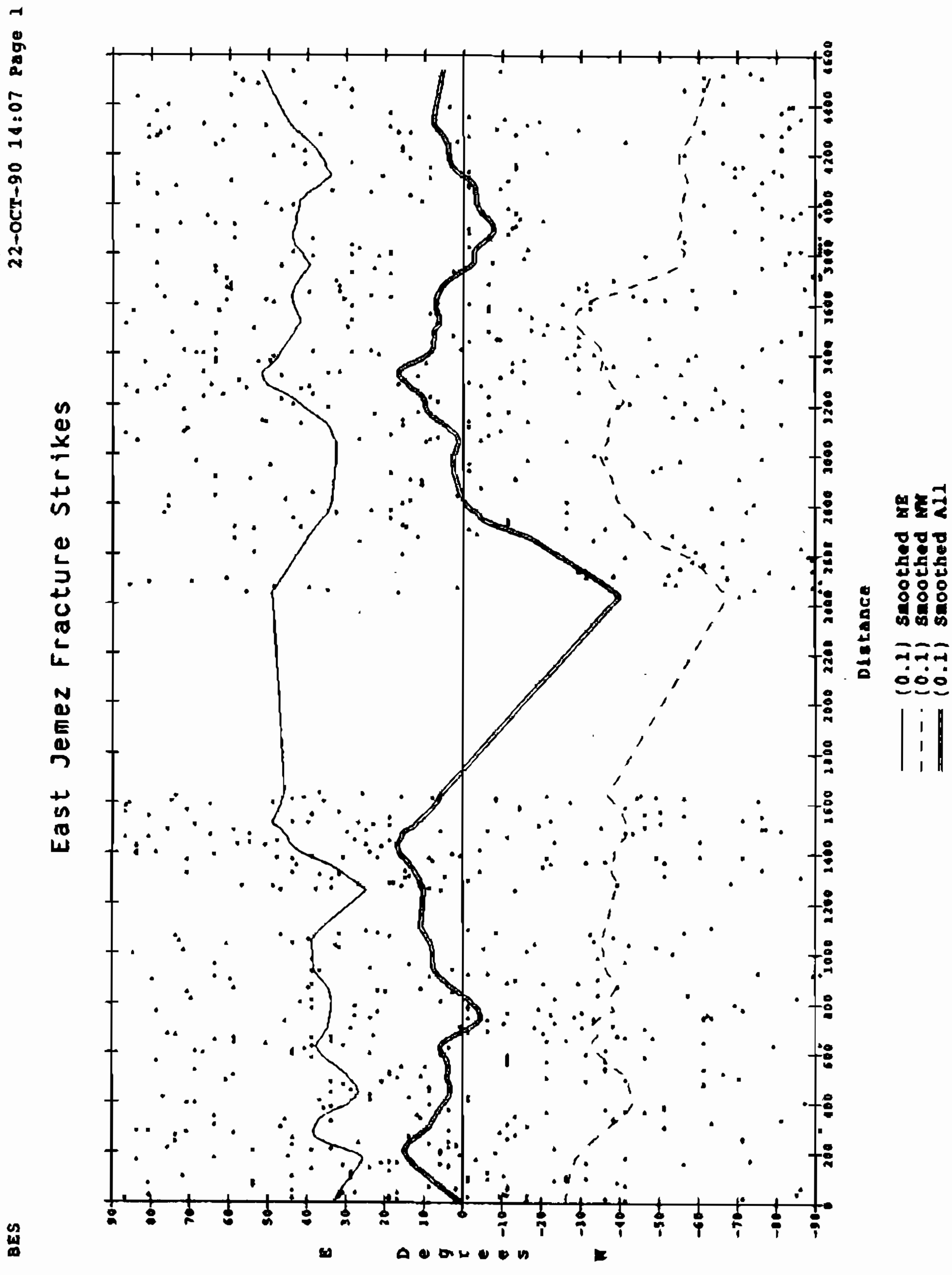

22-OCT-90 13:48 Page 1
Pajarito Road Fracture Strikes
APSH
Frequency
0
5
10
15
20
25
30
35
40
45
50
55
60
65
Strike
-75
-60
-45
-30
-15
0
15
30
45
60
75
90

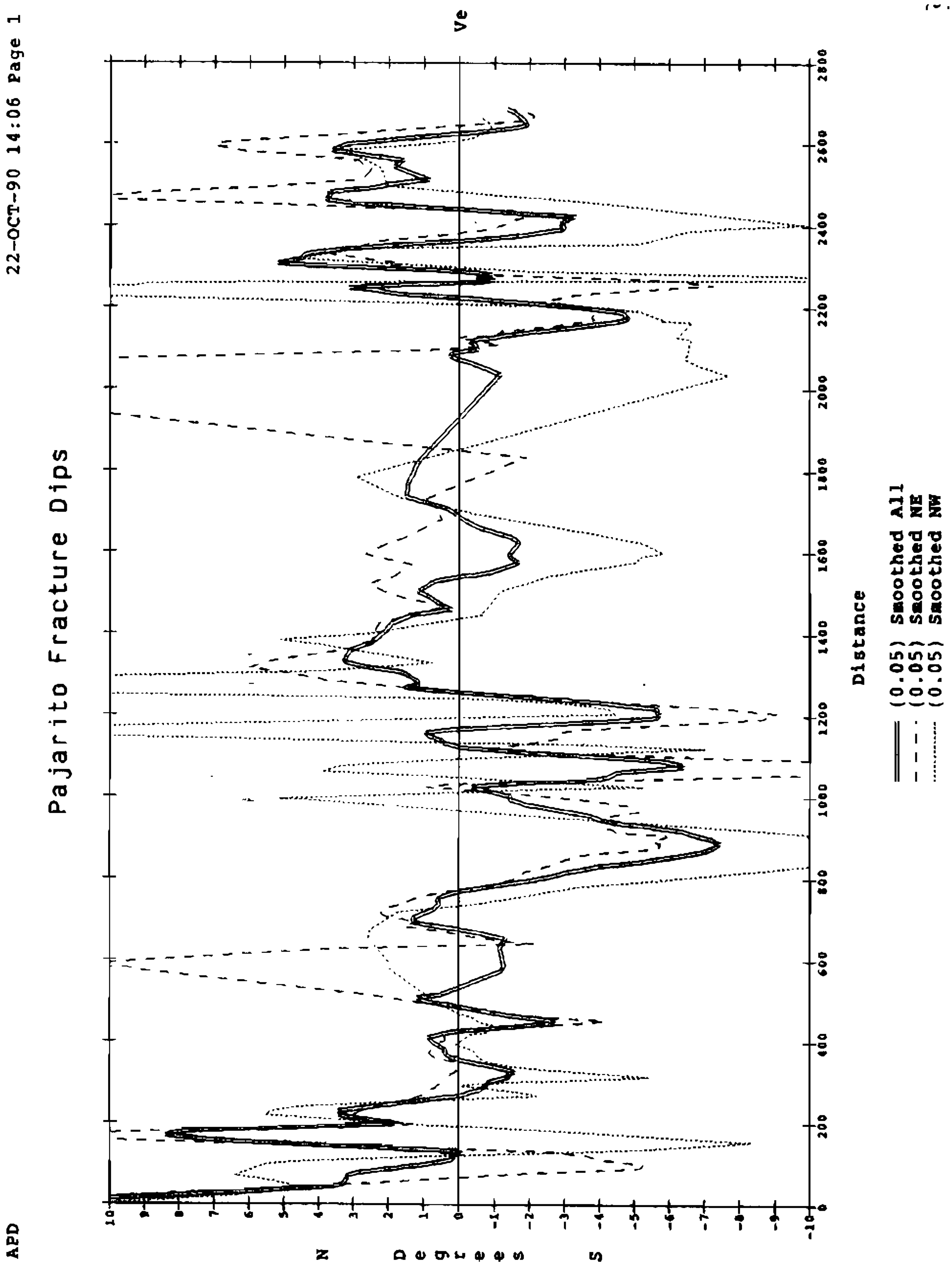
Figure 7



22-OCT-90 13:52 Page 1
East Jemez Road Fracture Strikes
Strike
Frequency
BESH
-75 -60 -45 -30 -15 0 15 30 45 60 75 90
0 10 20 30 40 50 60 70 80 90 100 110 120


22-OCT-90 14:04 Page 1
Pajarito Fracture Strikes
APS
E
Degrees
W
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
Distance
(0.1) Smoothed NE
(0.1) Smoothed NW
(0.1) Smoothed Average


22-OCT-90 14:07 Page 1
East Jemez Fracture Strikes
BES
E
Degrees
W
Distance
(0.1) Smoothed NE
(0.1) Smoothed NW
(0.1) Smoothed All


22-OCT-90 14:06 Page 1
Pajarito Fracture Dips
APD
Ve
N Degrees S
Distance
(0.05) Smoothed All
(0.05) Smoothed NE
(0.05) Smoothed NW

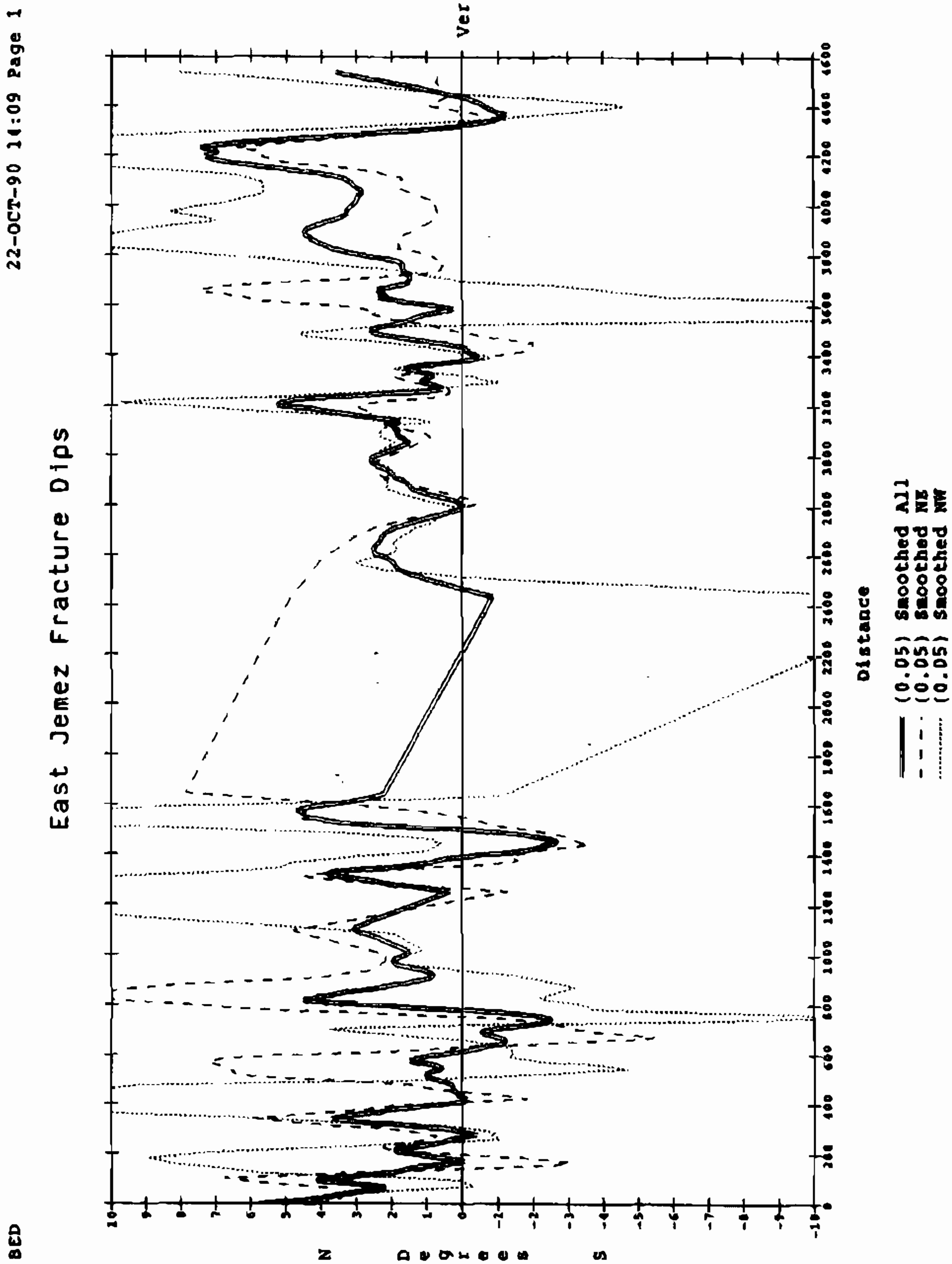

East Jemez Fracture Dips
22-OCT-90 14:09 Page 1
Ver
BED
N Degrees S
Distance
(0.05) Smoothed All
(0.05) Smoothed NE
(0.05) Smoothed NW

Figure 12 (missing)

Figure 13

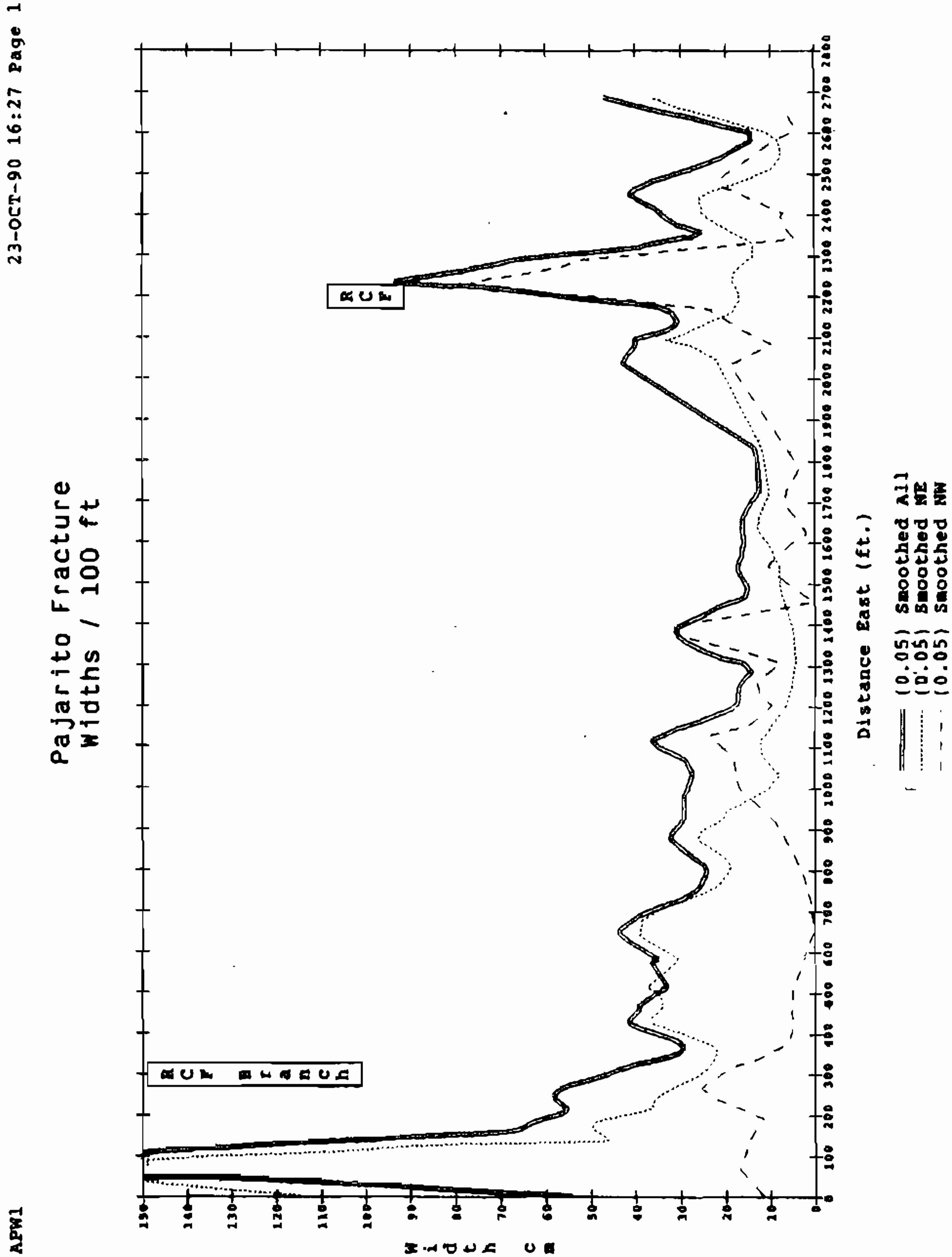
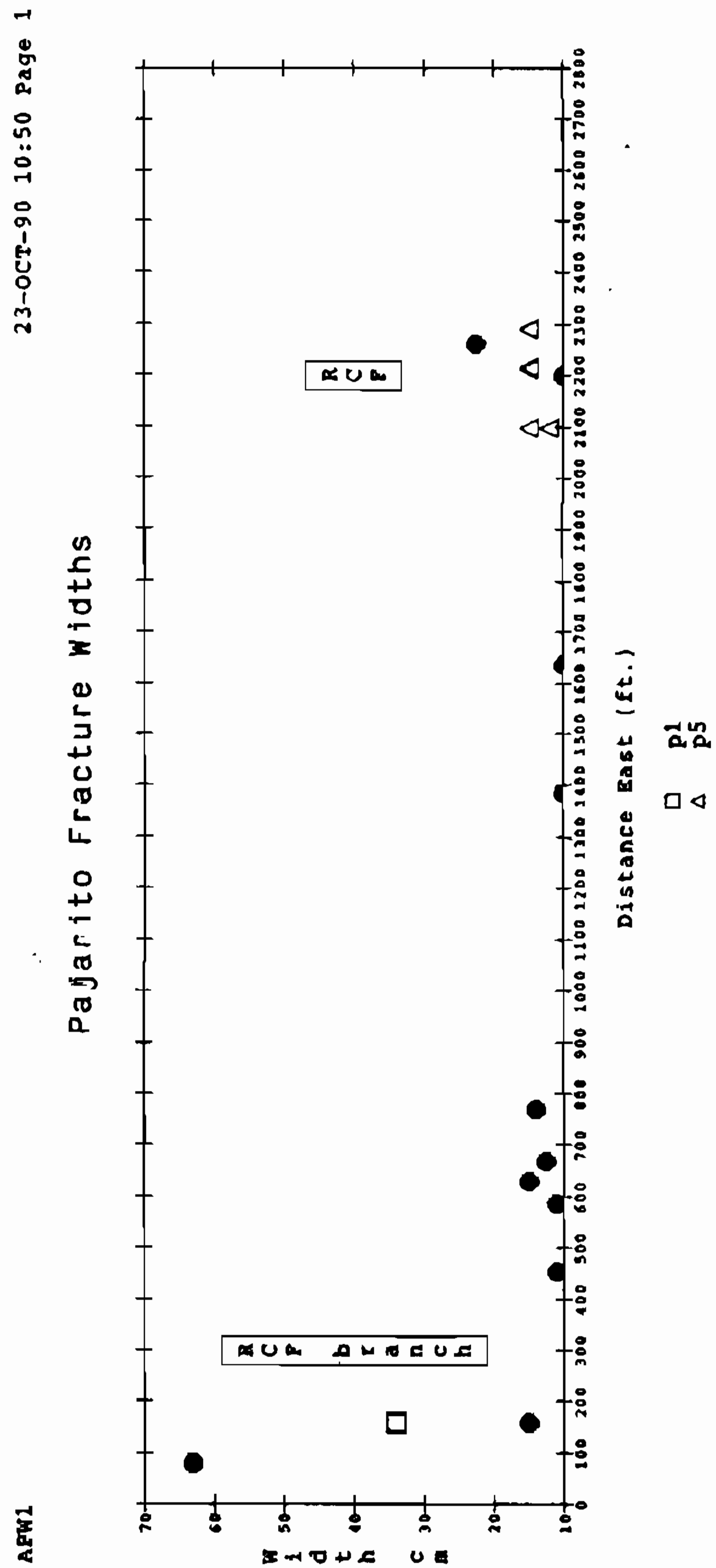

23-OCT-90 16:27 Page 1
Pajarito Fracture
Widths / 100 ft
RCF Branch
RCF
Width cm
Distance East (ft.)
(0.05) Smoothed All
(0.05) Smoothed NE
(0.05) Smoothed NW
APW1

Figure 14


23-OCT-90 10:50 Page 1
Pajarito Fracture Widths
AFW1
Width cm
Distance East (ft.)
RCP branch
RCP
p1
p5
70
60
50
40
30
20
10
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
2200
2300
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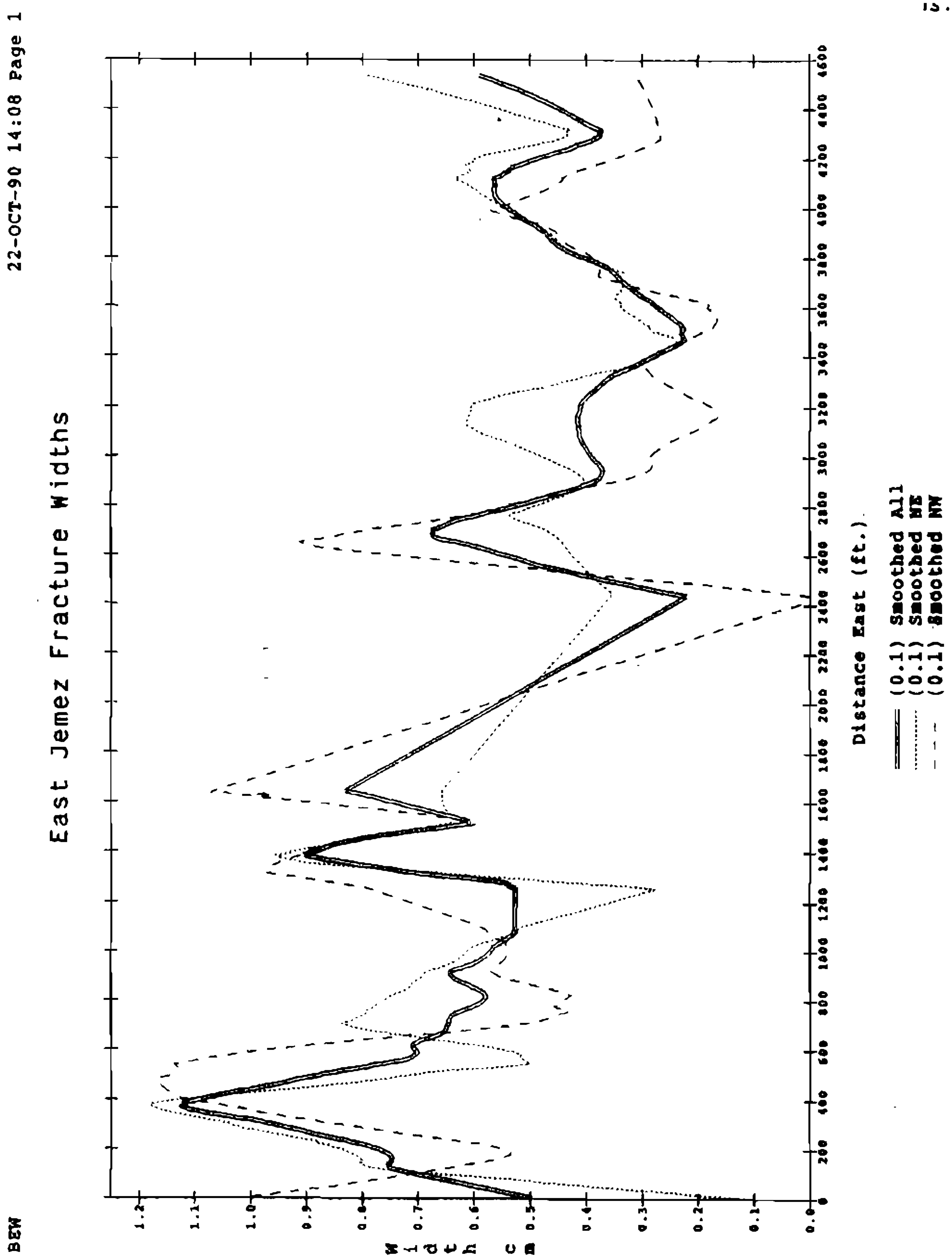
2500
2600
2700
2800


22-OCT-90 14:08 Page 1
East Jemez Fracture Widths
Distance East (ft.)
(0.1) Smoothed All
(0.1) Smoothed NE
(0.1) Smoothed NW
Width cm
BEW

EES1-SH90-17

Figure 16

16.

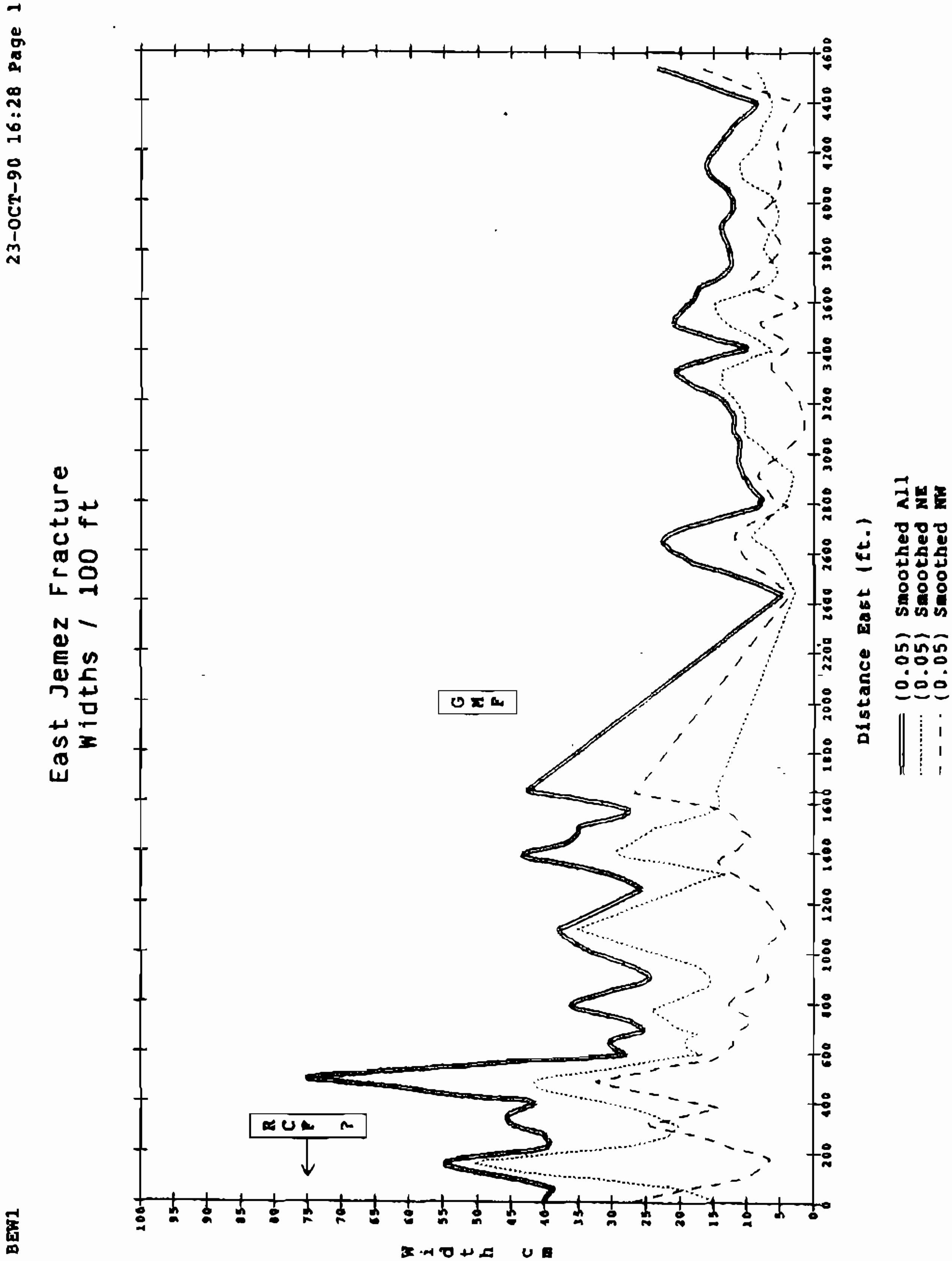
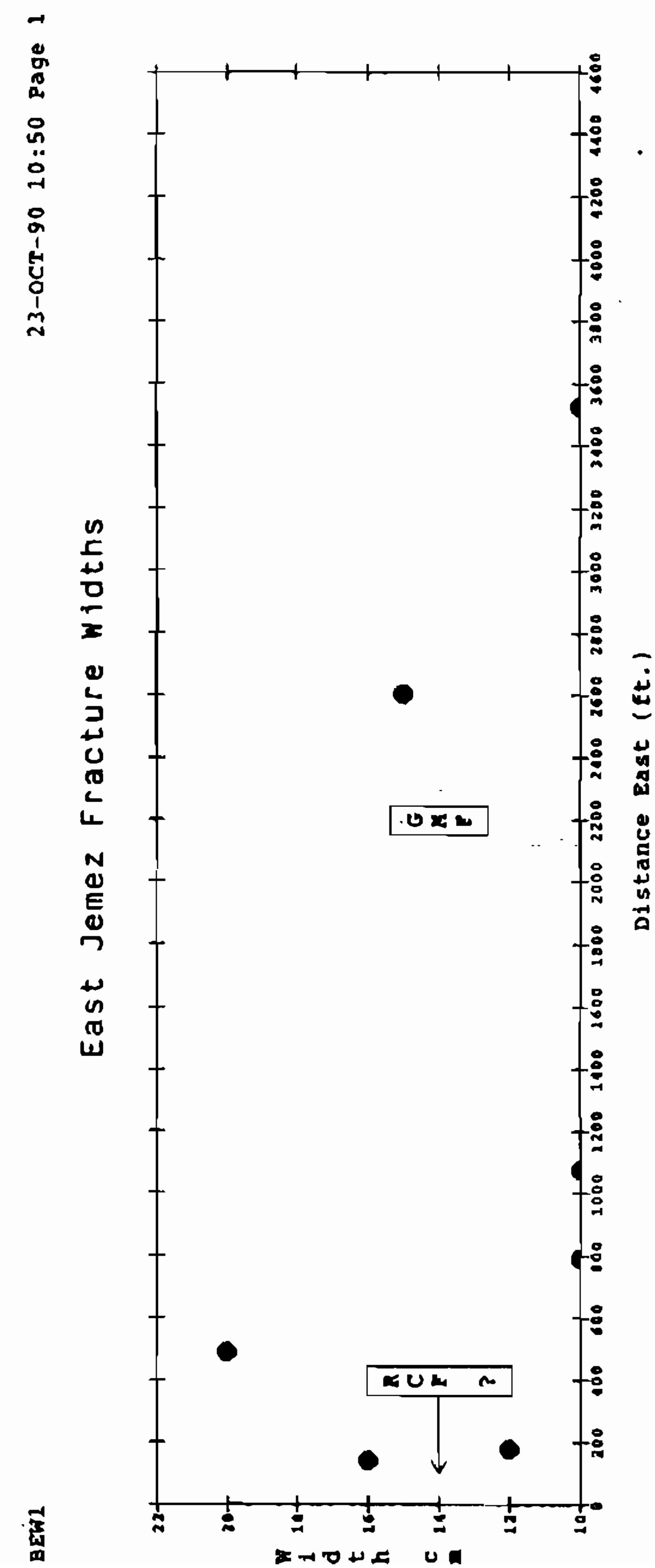


Figure 17


East Jemez Fracture Widths
23-OCT-90 10:50 Page 1
BEW1
Width cm
Distance East (ft.)
GXF
RCF ?

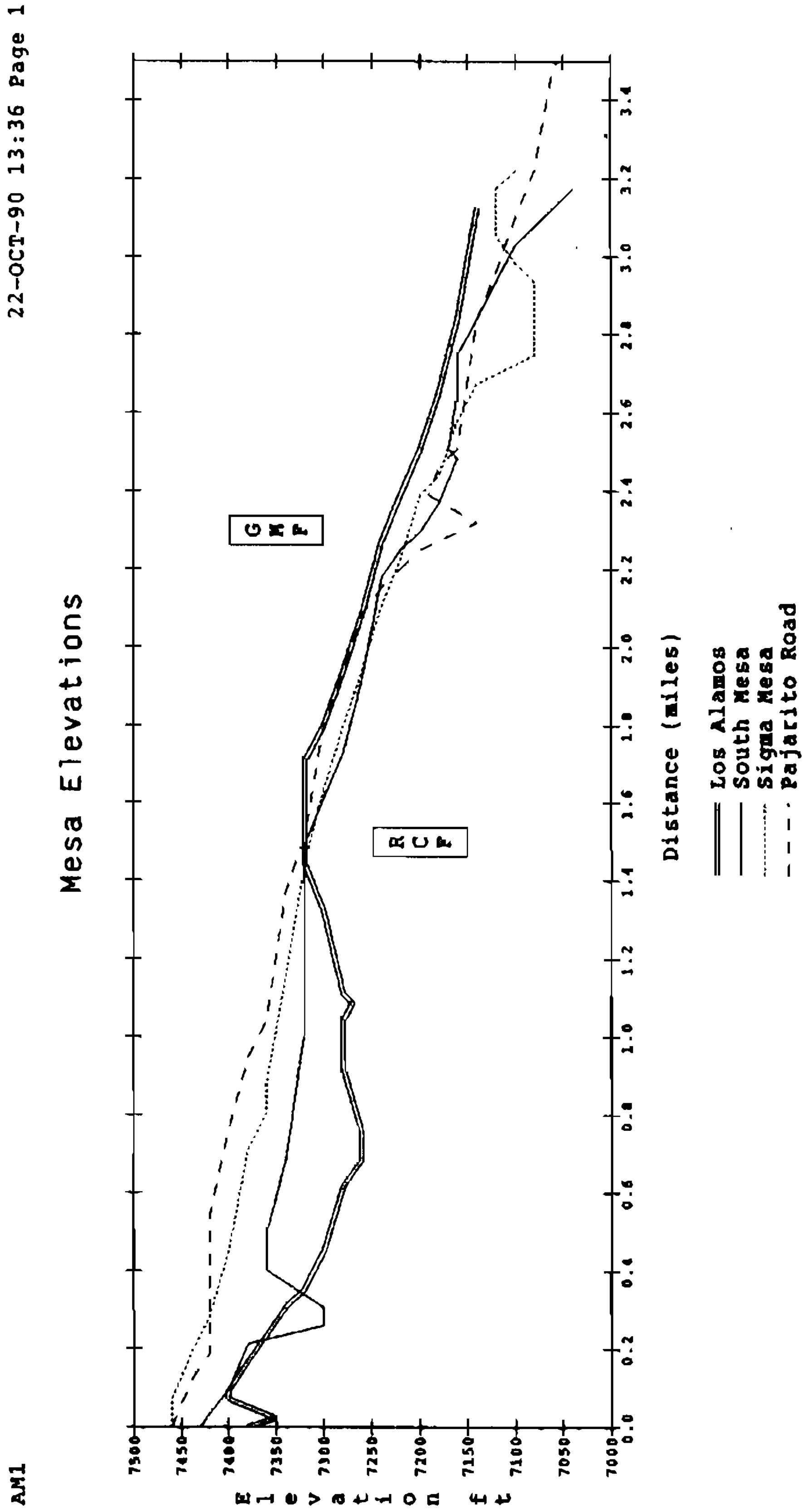
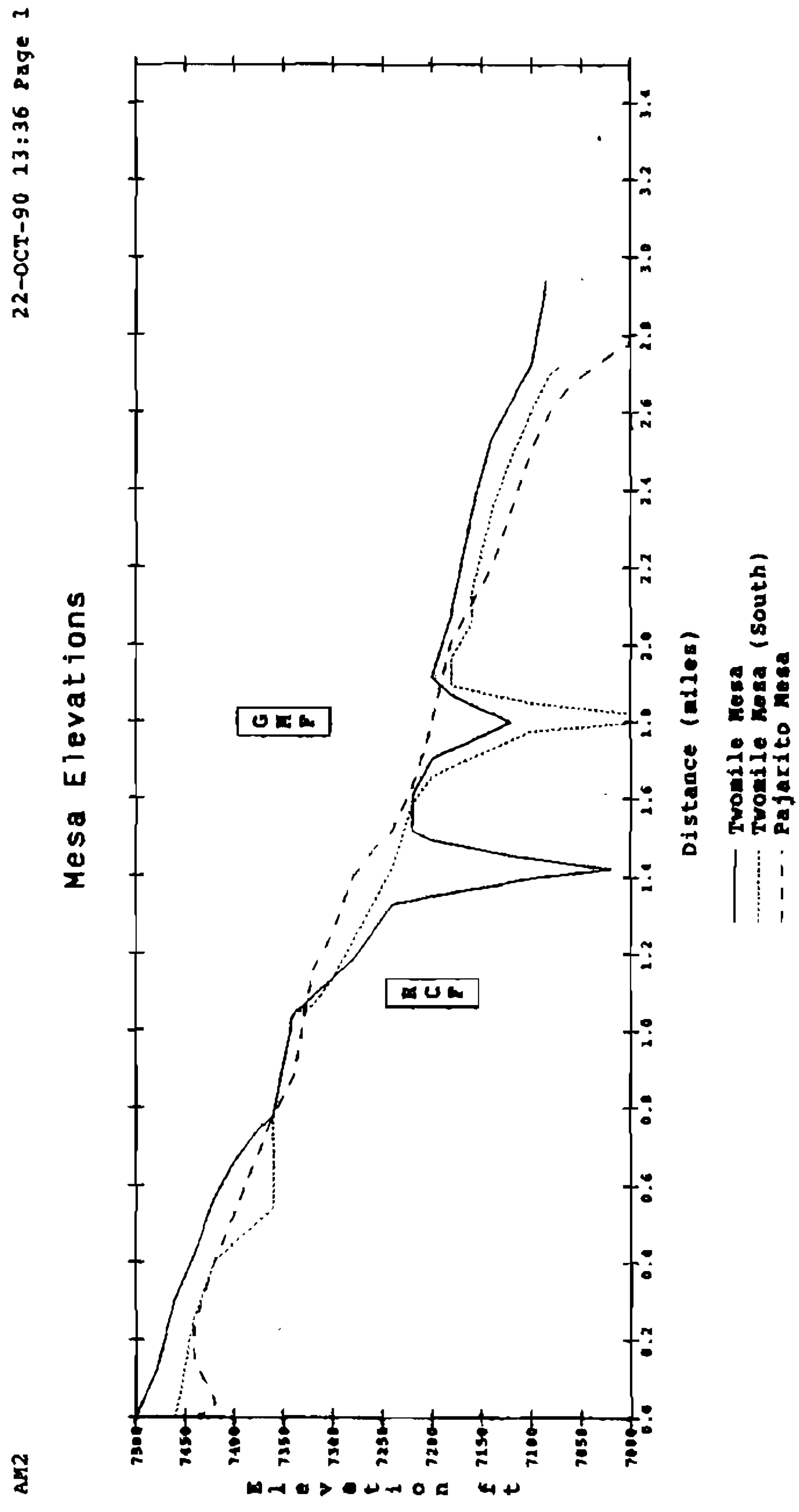

Mesa Elevations
22-OCT-90 13:36 Page 1
AM1
Elevation ft
7500
7450
7400
7350
7300
7250
7200
7150
7100
7050
7000
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.4
Distance (miles)
G
M
F
R
C
F
Los Alamos
South Mesa
Sigma Mesa
Pajarito Road

Figure 19


22-OCT-90 13:36 Page 1
Mesa Elevations
GMF
RCF
Distance (miles)
Elevation ft
Twomile Mesa
Twomile Mesa (South)
Pajarito Mesa
AM2

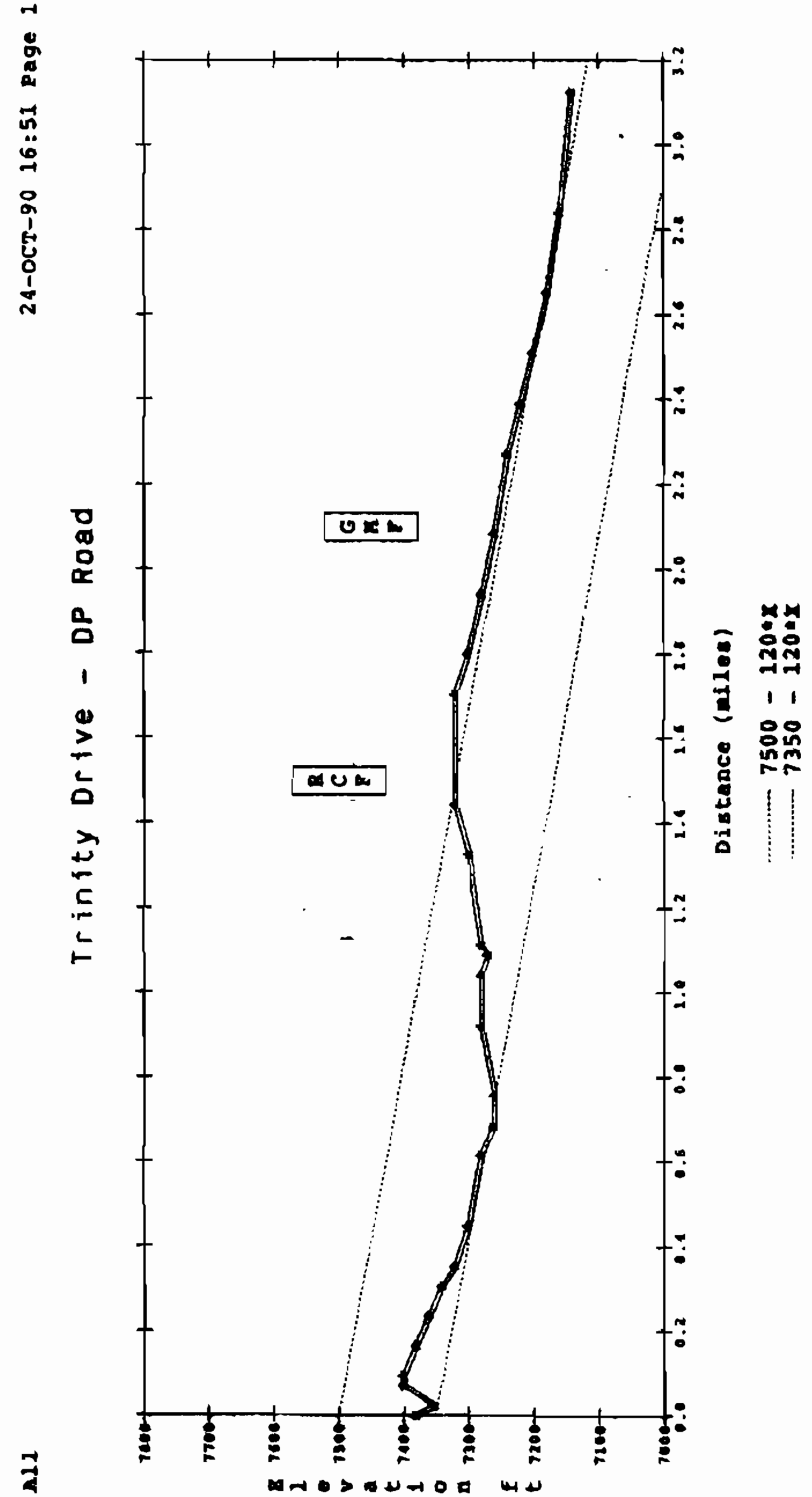
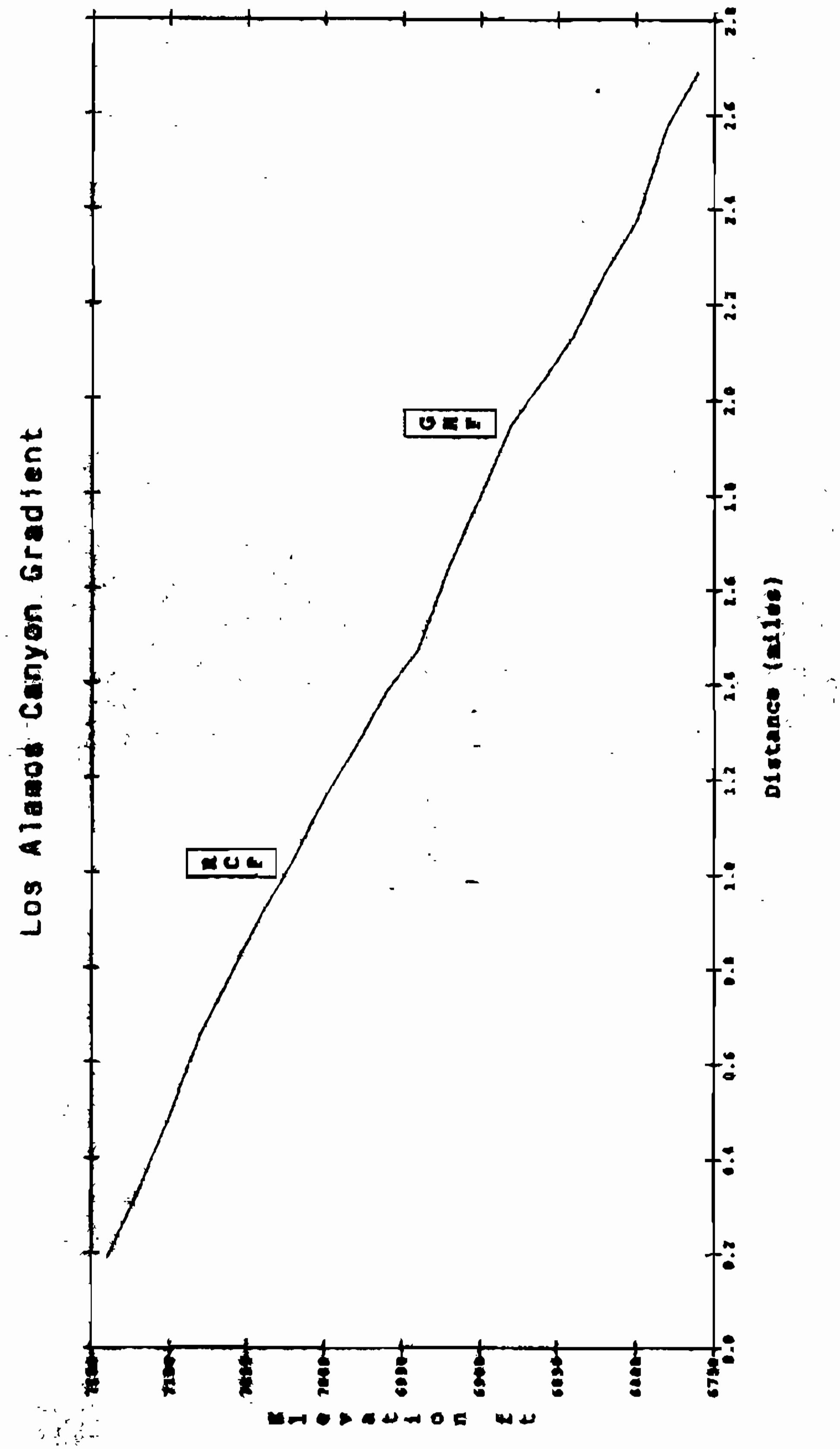
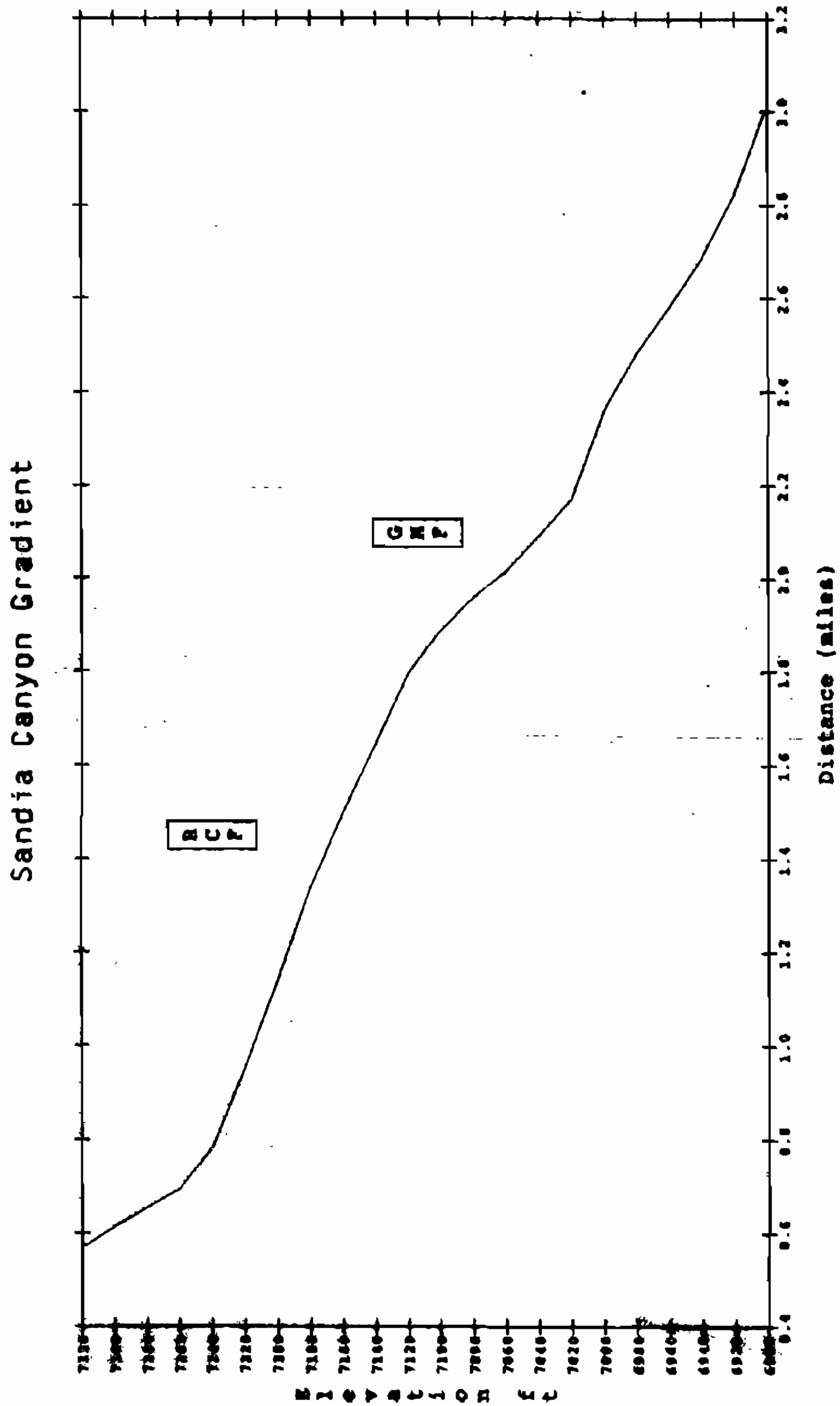
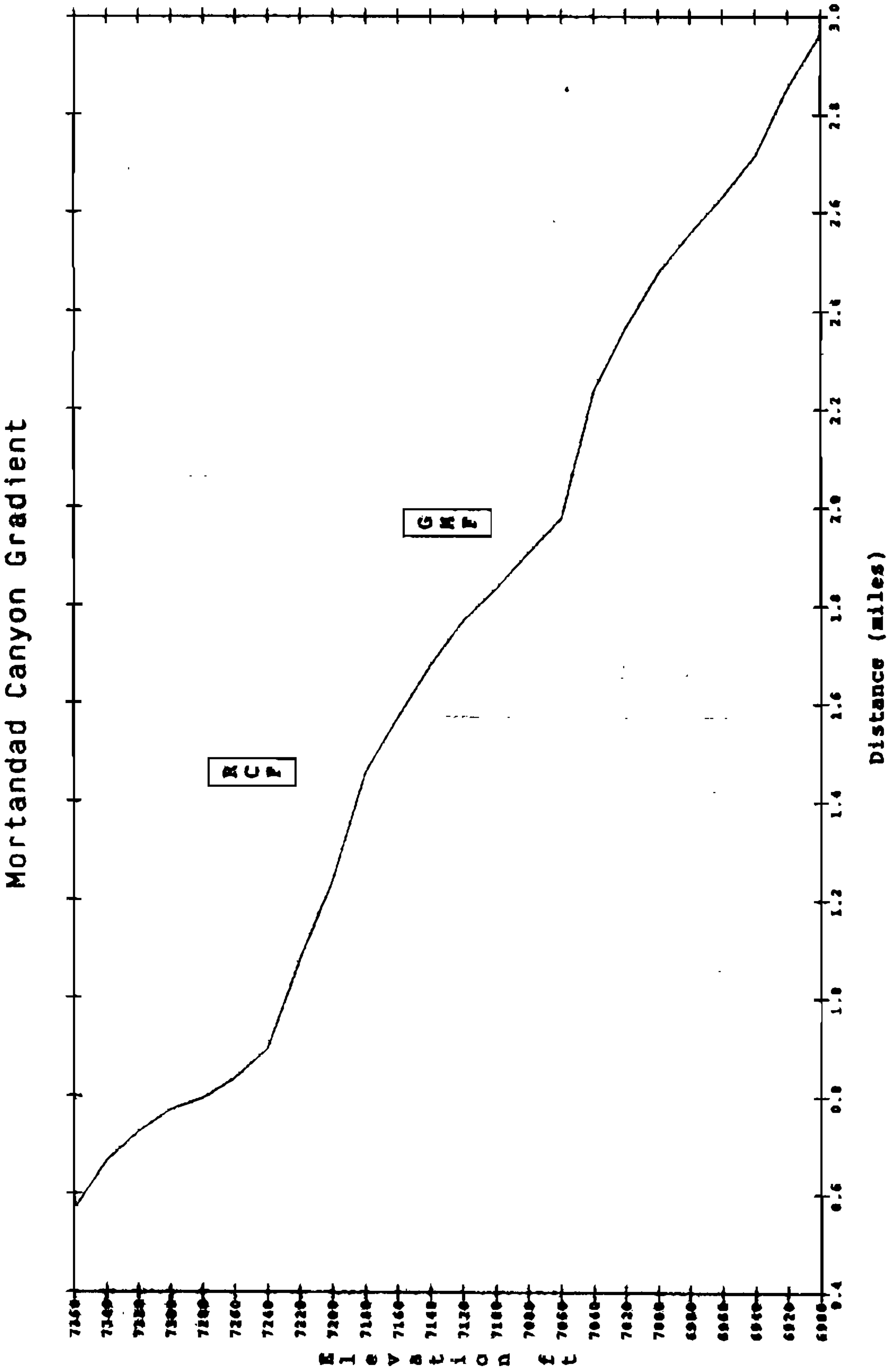
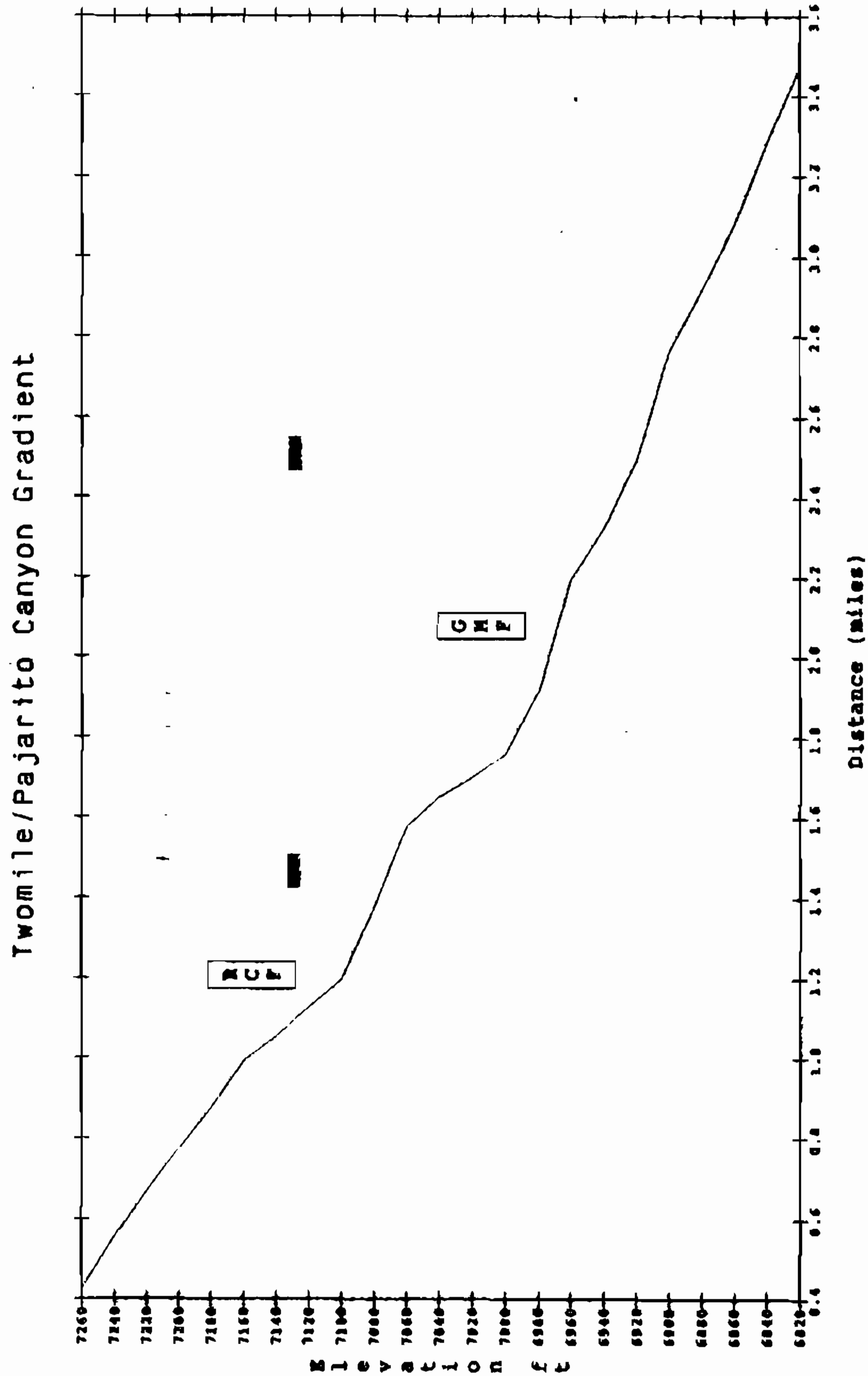

24-OCT-90 16:51 Page 1
Trinity Drive - DP Road
All
Elevation Ft
RCF
GMF
Distance (miles)
7500 - 120*X
7350 - 120*X

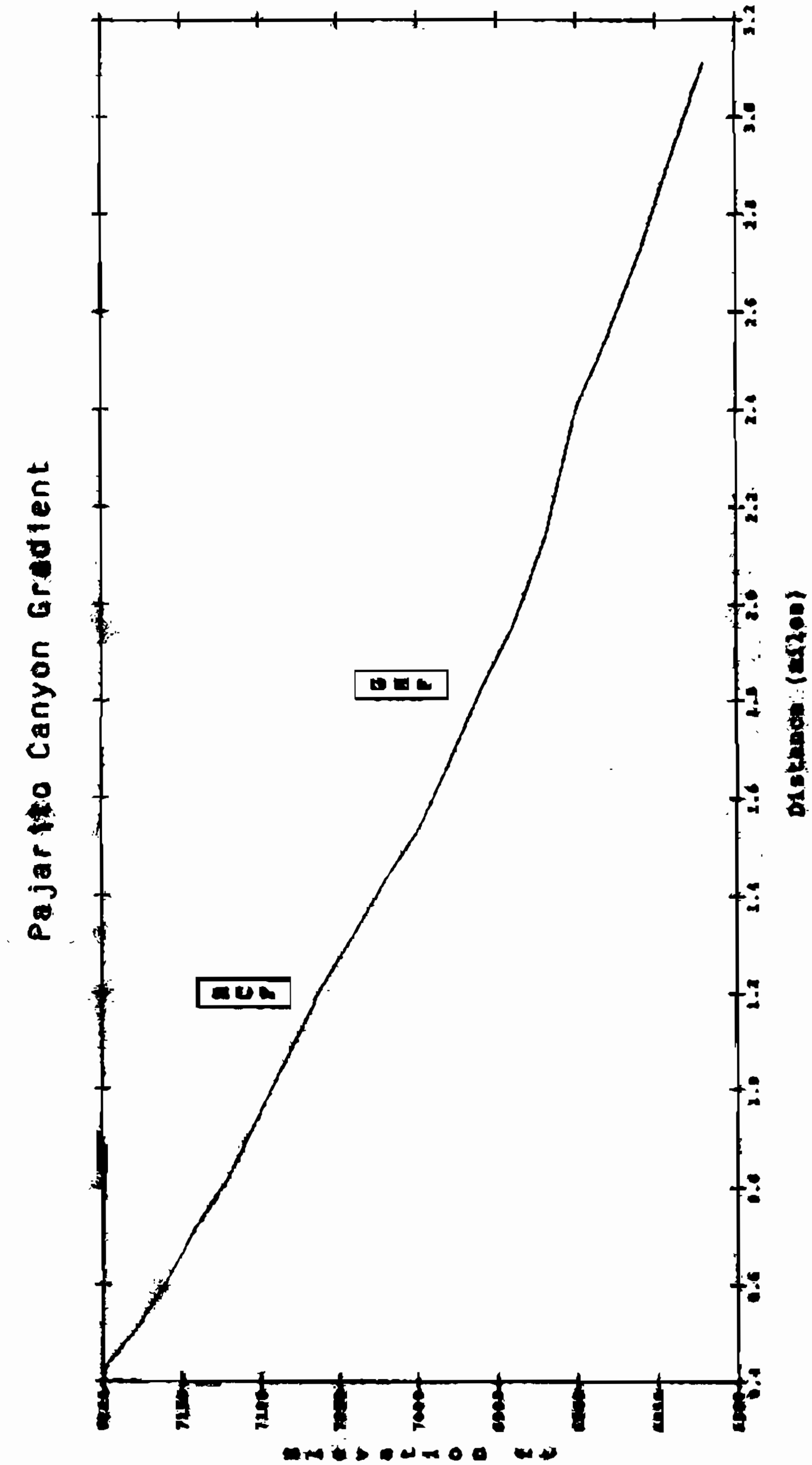
Figure 21


Los Alamos Canyon Gradient
GRF
RCF
Distance (miles)
Elevation ft


Sandia Canyon Gradient
Distance (miles)


Mortandad Canyon Gradient
RCF
GRF
Distance (miles)
Elevation ft


Twomile/Pajarito Canyon Gradient
Distance (miles)
Elevation ft
RCF
GHF


Pajarito Canyon Gradient