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Title: Geomorphology and Structure of the Pajarito Fault Zone West of Los Alamos National Laboratory, New Mexico

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GEOMORPHOLOGY AND STRUCTURE OF THE PAJARITO FAULT ZONE WEST OF LOS ALAMOS NATIONAL LABORATORY, NEW MEXICO

Submitted to:
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April 9, 1997

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1. EXECUTIVE SUMMARY

Previous trenching investigations on the main trace of the Pajarito fault (WCFS, 1995) did not expose the "main fault" plane, and did not detect faulting younger than 50,000-60,000 years old (50-60 ka), despite the fact that both faults antithetic to the Pajarito fault display Holocene or late Pleistocene movement. This study was undertaken to locate the main fault plane and to define trench sites that might expose evidence of post-50 ka faulting (i.e., the most recent faulting event, or MRE), as well as to improve current estimates of recurrence times between large earthquakes on the Pajarito fault.

Based on 17 days of detailed field mapping, it appears that about 60% of the 50-100 m-high Pajarito fault scarp is a segmented monocline, i.e. the scarp face is underlain by one or more large east-tilted blocks of Bandelier Tuff at least 20-25 m thick. Vertical displacement in these reaches of the Pajarito fault has been accommodated at the surface by progressive eastward tilting or toppling of these blocks, accompanied by opening of large tension fissures at the scarp crest and between topple blocks. A basal normal fault zone exists at the toe of the scarp in most places, but its net throw is probably small compared to the height of the scarp. Given this geometry, it is unsurprising that WCFS trenches in the basal fault zone did not expose a "main fault" plane, because over most of the fault scarp no such plane exists. Instead, deformation over most of the fault trace has been partitioned among the basal fault zone, basal graben-bounding faults (particularly in the 2 km-wide fault zone south of Los Alamos Canyon), mid-scarp faults, interblock tension fissures, and small antithetic faults above the main fault scarp.

The remainder of the Pajarito fault scarp is composed of either high-angle faults displacing subhorizontal tuff, or large deep-seated rotational landslides (about 30% of scarp length, including large areas north of Water Canyon, near the Water Tanks trench site of WCFS, and near the mouth of Pajarito Canyon). Landslide areas should be avoided in future paleoseismic investigations, because landslide movement mimics fault movement and could be caused by many nonseismic triggering mechanisms.

In order to identify and date paleoearthquakes on the Pajarito fault and to identify the MRE, it is necessary to trench <u>all</u> the component structures at any given latitude on the fault zone. This can best be accomplished by an across-strike transect of multiple short trenches, one across each deformation zone. The four trenches of WCFS (1995) are poorly located to be the basis of such transects, being affected by landsliding. The best site for a paleoseismic transect is south of Los Alamos Canyon, where seven trench sites are proposed that would capture almost all faulting events at that latitude. A detailed task list and cost estimate for this transect is given in Sec. 8 of this report. A significant effort must be made towards precise dating of faulted deposits in each trench, since it is essential in multi-trench transects to correlate paleoearthquakes among trenches. Dr. S.L. Forman, who managed the dating work for the WCFS study, has agreed to lead this effort.

Seven additional trench sites are proposed for longer-term paleoseismic efforts, in case the first transect does not expose evidence of post-50 ka faulting. The recommended transects of trenches will greatly improve current estimates of paleoearthquake recurrence and elapsed time, and should improve current estimates of per-event displacement. The improved age control could support a calculation of conditional probability for future large earthquakes on the Pajarito fault.

2. INTRODUCTION

2.1 Goal of This Study

The geologic study described herein was undertaken to find out whether accurate and complete paleoseismic data could be collected on the main trace of the Pajarito fault zone. By paleoseismic data, I mean data to identify, date, and characterize the Holocene and late Pleistocene earthquakes that caused surface rupture on the main fault trace. The Pajarito fault is the largest contributor of potential seismic hazard to the Los Alamos National Laboratory, but to date has been poorly characterized (Woodward-Clyde Federal Services, 1995). Thus, I examined previous investigations and performed detailed mapping to ascertain why previous studies had been unsuccessful in deciphering the recent history of large earthquakes on this fault.

2.2 Scope of This Study and Previous Work

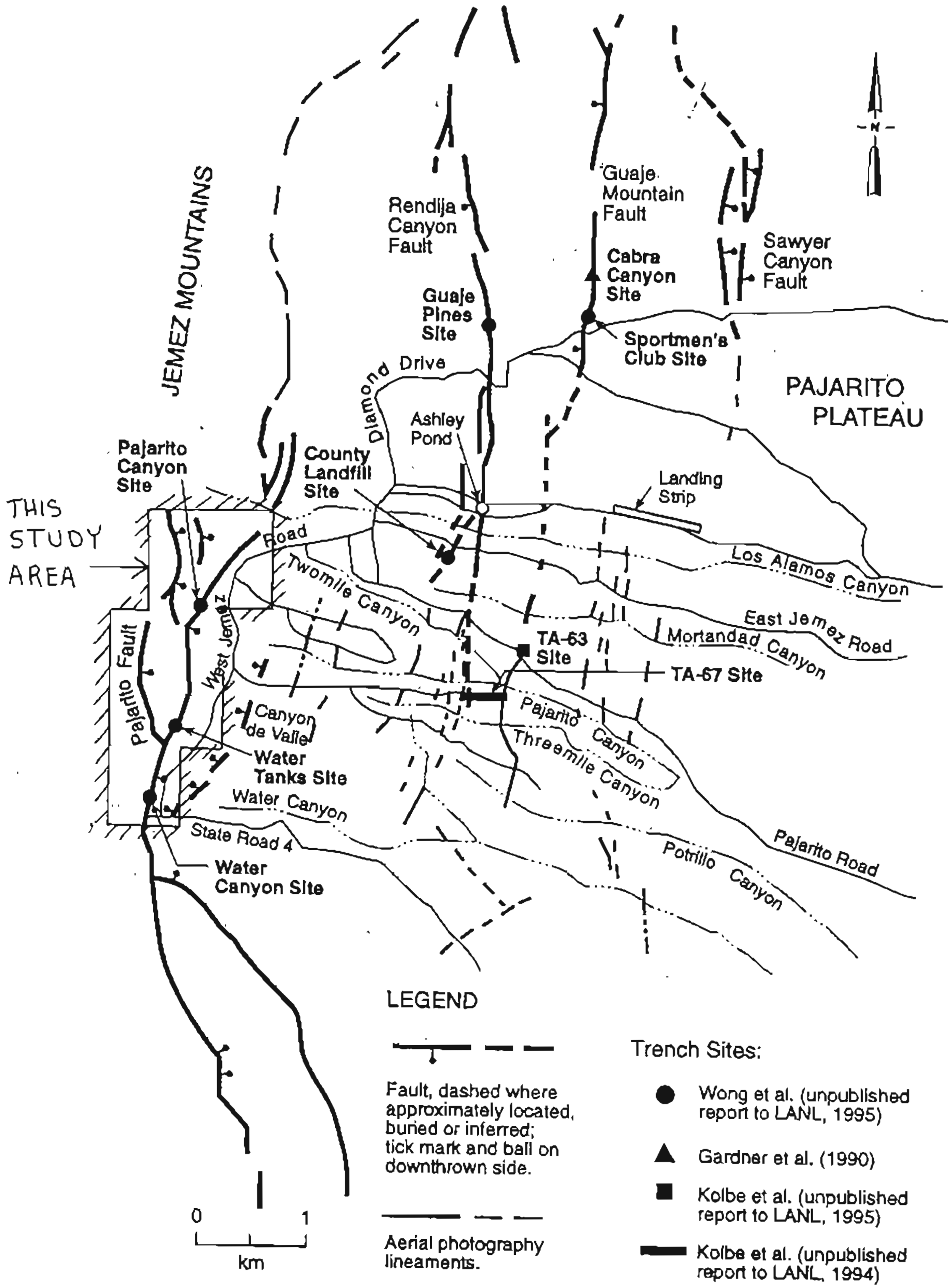
This study had two primary goals. The first was to understand why previous trenching investigations (WCFS, 1995) had failed to expose the main trace of the Pajarito fault, nor had identified any Holocene surface-rupture events on that trace. The second goal was to locate optimum sites for additional trenches that might yield the data previously missed.

The main paleoseismic work on the Pajarito fault zone was performed in 1993-95 (WCFS, 1995). In that study, WCFS excavated four trenches on the main trace of the Pajarito fault (Fig. 1). These trenches all lay at the toe of the ca. 100 m-high scarp of the Pajarito fault, and none of them ascended more than 20 m vertically up the scarp. Although all four trenches contained small-displacement faults and fractures, none exposed a major fault zone with many meters of offset. Reviewers of the WCFS draft report (WCFS, 1993) concluded that none of the trenches extended far enough up the scarp to expose the main fault trace.

In the spring of 1996 the author was asked to perform a reconnaissance of the main scarp of the Pajarito fault to determine where the main fault trace might be located, and whether it could feasibly be exposed in a trench. I spent May 1-2, 1996 examining the main scarp, accompanied in part by J. Gardner, S. Reneau, and E. McDonald of LANL, and reported my findings on June 9, 1996 (GEO-HAZ, 1996). My main conclusions were that the escarpment is mainly a segmented monocline, with a small-displacement normal fault at its base, a variable number of faults of unknown displacement on the scarp face, and large tension fissures at the crest of the moncline. Given this geometry, it is not surprising that WCFS failed to expose a large-displacement fault at the toe of the escarpment. However the structure of the escarpment seemed to vary greatly along strike. Therefore, my prime recommendation was to make a detailed geomorphic/structural map of the main fault scarp, to document the structures and mass-wasting features, and to locate potential trench sites. A key criteria for siting trenches was to expose the fault trace that ruptured last on the main fault trace, to date that rupture event, and to decide whether that event corresponded with Holocene paleoearthquakes dated on the antithetic Rendija Canyon and Guaje Mountain faults (WCFS, 1995).

The detailed mapping of the escarpment was performed by the author from Sept. 19- Oct. 11, 1996, the results of which are reported here. The study area ranged from Highway 4 on the south to Los Alamos Canyon on the north (Fig. 1).

Fig. 1. Location map showing the limits of detailed mapping in this study, and the sites of trenches excavated on the main fault trace by Woodward-Clyde Federal Services (1995).



2.3 Methods

Preliminary photogeologic mapping was performed on 1:6000- scale color aerial photographs provided by LANL. I also referred to the 1:12,000- scale surficial geologic mapping between Twomile Canyon and Pajarito Canyon by WCFS (1995), unpublished Quaternary geologic mapping of Reneau (1996), and unpublished landslide mapping of J. Gardner (LANL). My mapping was placed on 1:1200- scale topographic base maps with a 2 ft contour interval, provided by LANL. These maps were printed on mylar so they could be overlaid onto color orthophotos of the same scale. Fig. 1 shows the areal limits of the 12 map sheets used in this study. Full-scale copies of each 1:1200 geologic map are included as Plates 1-12 in this report.

Most mapping was performed in the field, during traverses up, down, and across the escarpment. Approximately 17 days were spent in the field.

3. STRATIGRAPHY OF THE PAJARITO FAULT ZONE

3.1 Bedrock Stratigraphy and Structure

The main scarp of the Pajarito fault zone is composed of the 1.1- 1.2 Ma Bandelier Tuff. This moderately to densely welded tuff is very hard and resistant to weathering, although pervasively jonted. In order to decipher the structures and deformation of this bedrock exposed in the main scarp, we need to understand the physical stratigraphy of the tuff.

3.1.1 Primary (cooling?) structures

The Bandelier Tuff exposed on the scarp face and in canyons cut into the scarp exhibits pyroclastic bedding in unwelded units, from which the original depositional attitude may be inferred. In some subunits of the Tuff, closely-spaced parallel, subhorizontal fractures give the rock a "flaggy" appearence (Fig. 2). These parallel fractures are thought to be either bedding-plane partings in pyroclastic units or cooling fractures parallel to the ground surface at the time of tuff depostion. Such fractures (partings) are the main field criteria for assessing the structural attitude of the tuff in outcrop. The other indicator of "bedding" in the tuff, fiamme or flame structures, are rarely visible in outcrop. Where they are observed, they are parallel to partings.

At numerous roadcuts and quarry cuts I observed 5-20 cm-wide zones of intense subvertical fracturing that were restricted to individual beds in the tuff 1-2 m thick. These zones had steep dips, but were truncated at top and bottom against parting fractures at the boundary with over-and underlying tuff beds (Fig. 3). In detail, the fractures begin to curve as they approach the over-and underlying units, and become asymptotic to the "bedding-plane" partings. Viewed in plan, the shear-fractures are more circular than planar, forming a columnar zone of deformation. Fractures radiate outward from the axis of the column. Notably, where the largest of these shear-fractures cut across subhorizontal partings and joints, the latter show no vertical displacement (Fig. 4). The lack of vertical continuity and displacement across these features seems to suggest that they may date from the initial placement and cooling of the tuff, perhaps due to the presence of a pre-Bandelier fault scarp at this site (Fig. 5).

Fig. 2. Outcrop of " flaggy"-weathering Bandelier Tuff. This is within cooling unit 4 as defined by Reneau and McDonald (1996) and probably equivalent to "unit E" of Rogers (1995). In this report it is map unit B4.

Fig. 3. Example of anomalous "shear-fractures" that are truncated by overlying beds in the tuff. The intense fracturing to the left and right of the trowel (at center, 20cm long) stops abruptly near the upper edge of the photo. Photo taken in the quarry at the mouth of Canyon de Valle.

Fig. 4 Large shear- fracture exposed in the wall of the quarry at the mouth of Canyon de Valle. Brunton compass at bottom is 7 cm in diameter. Note that subhorizontal fractures are not offset.

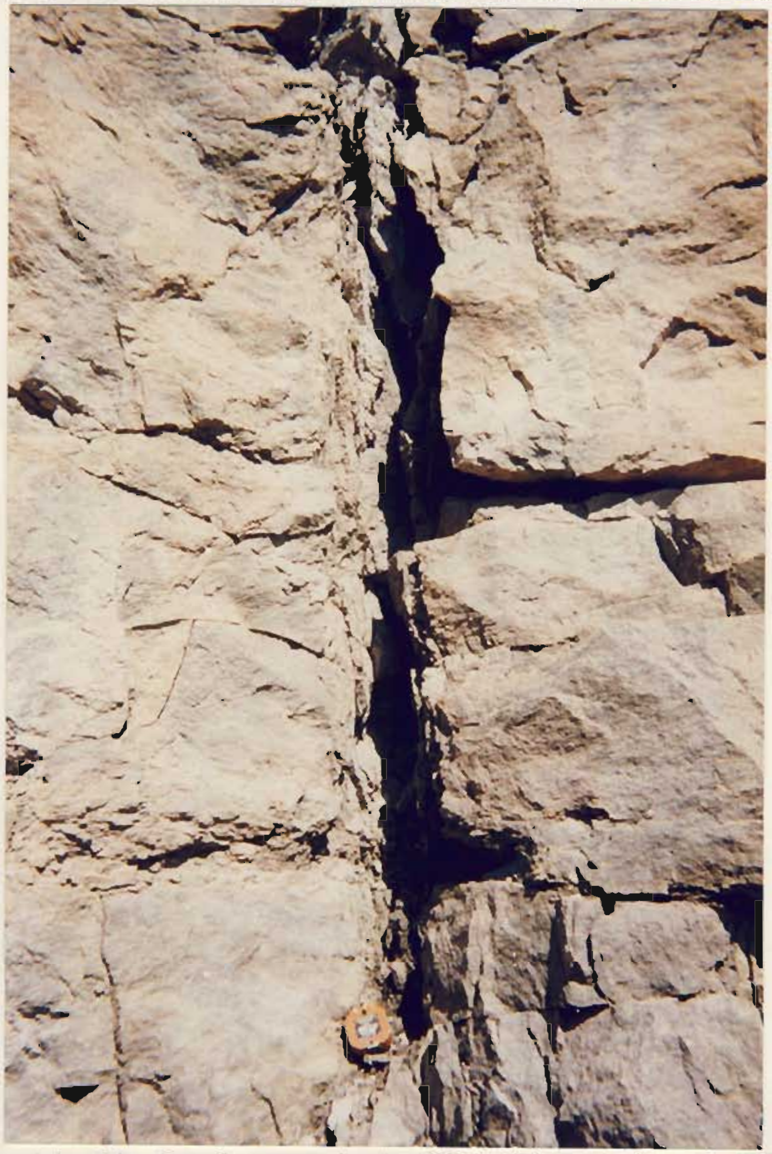
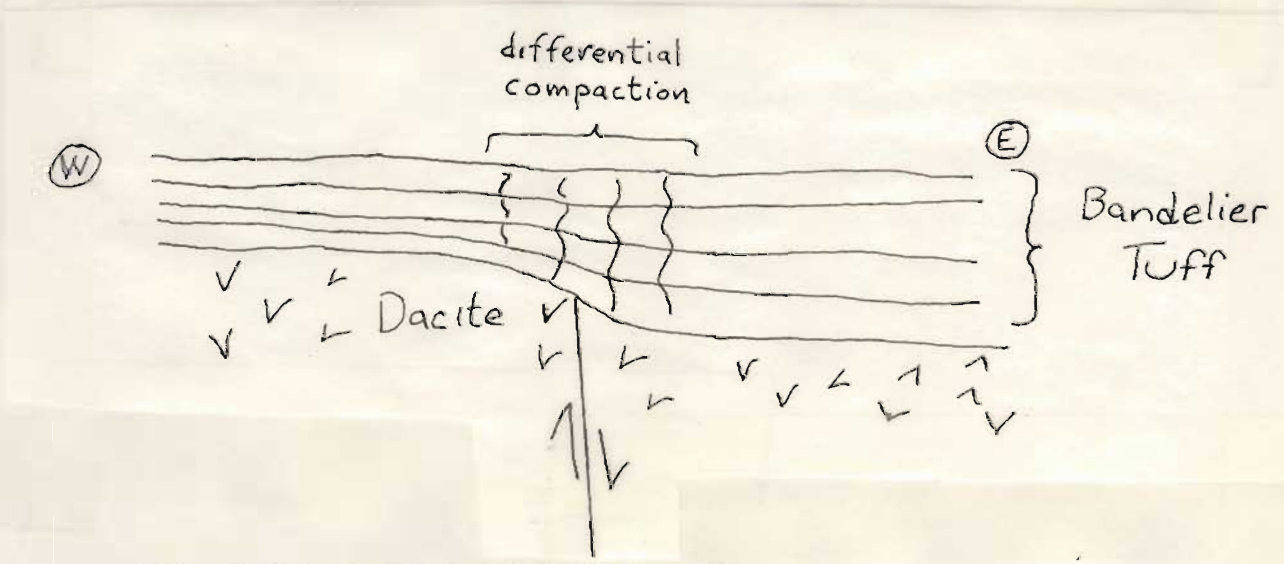


Fig. 5. Possible origin of the shear-fractures related to differential compaction and cooling as the Bandelier Tuff was deposited over a preexisting scarp in the underlying Tschicoma Dacite. Not to scale.



3.1.2 Jointing and exfoliation

The Bandelier Tuff near the Pajarito fault scarp typically contains three sets of orthogonal joints. The first set is subhorizontal (typical dip 1-4 degrees east) and generally parallels the boundaries of the major cooling units and compositional beds in the tuff (Fig. 6). The other two sets are subvertical away from the scarp and roughly orthogonal. The NE-trending set strikes N 45-50°E and the NW-trending set strikes N 20-25°W. These two joint sets seem to form a conjugate pair symmetrical with the strike of the Pajarito fault scarp, e.g., where the scarp trends N 15-20°E south of Los Alamos Canyon (Fig. 7). Finally, a more rare fourth joint set parallels the general strike of the fault scarp.

Except in areas of shear-fracturing or later tectonic fracturing, the subhorizontal joint set has a closer joint spacing that the subvertical sets. This distinction usually permits one to infer the structural attitude of tuff outcrops on the scarp face. For example, on much of the scarp face the best-developed joint set approximately parallels the ground surface (Fig.8), and the bedrock outcrops compose meter-scale slabs that pave the scarp face.

At first glance it is not clear whether many of these slabs are in-situ bedrock or loose slabs. Even if outcrops are in-situ, it is unclear whether the prominent ground-parallel joint set is the same one that dips 3-4 degrees elsewhere, or whether it is an exfoliation joint set that may have developed in response to the local slope.

I spent considerable effort to understand these ambiguous structural relationships, assisted by numerous roadcuts and streamcuts into the scarp where the third (depth) dimension could be observed. Based on these field observations, I created a three-fold classification of Bandelier Tuff outcrops on and near the main fault scarp (Fig. 9). Two map units are defined where sufficient vertical exposure exists to track joints downward for several meters. In map unit Bi (Fig. 9b), the prominent parting-bedding joint set dips <10 degrees east (typically 3-4 degrees E; e.g. Fig. 6). This dip is thought to represent the original depositional attitude of the tuff, unaffected by deformation associated with the Pajarito fault.

However, field observations show that many parts of the scarp face underlain by gently east-dipping tuff are composed of slabby tuff outcrops, the tops of which parallel the ground surface which slopes 25-40 degrees east (Fig 9b). For example, such slabs occur throughout the upper scarp face ascended by Ski Hill Road (Fig. 10), where roadcuts (Fig. 6) clearly show that dominant jointing is subhorizontal. Close inspection of Figs. 10 and 11 shows there are prominent subhorizontal joints on the scarp face, and that the slab tops cut across them at a high angle. Deep cuts in the scarp (e.g. Fig. 11, left background) fail to reveal any joints parallel to the surfaces of these slabs. Therefore, I conclude that these "false slab tops" result from some weathering process, rather than comprising joint surfaces. The process that forms these ground-parallel planar outcrops presumably originates at the ground surface. For example, in Fig. 10 the slab at top center has a prominent bevel about 30 cm high, above which the tuff is darker, rougher, with higher lichen cover than below. This micromorphology suggests that the lower, smoother surface was previously covered by colluvium which has now been washed away by

Fig. 6. The dominant subhorizontal partings in cooling unit 4 near the crest of the main Pajarito fault scarp dip 3 degrees-4 degrees east. Roadcut on Ski Hill Rd, looking south. The cut is about 3.5m high.

Fig. 7. Sketch of joint sets in relation to strike of the fault scarp, with data taken from south of the Los Alamos Canyon. The crestal toppling fissures here turn down-scarp to follow the joint directions.

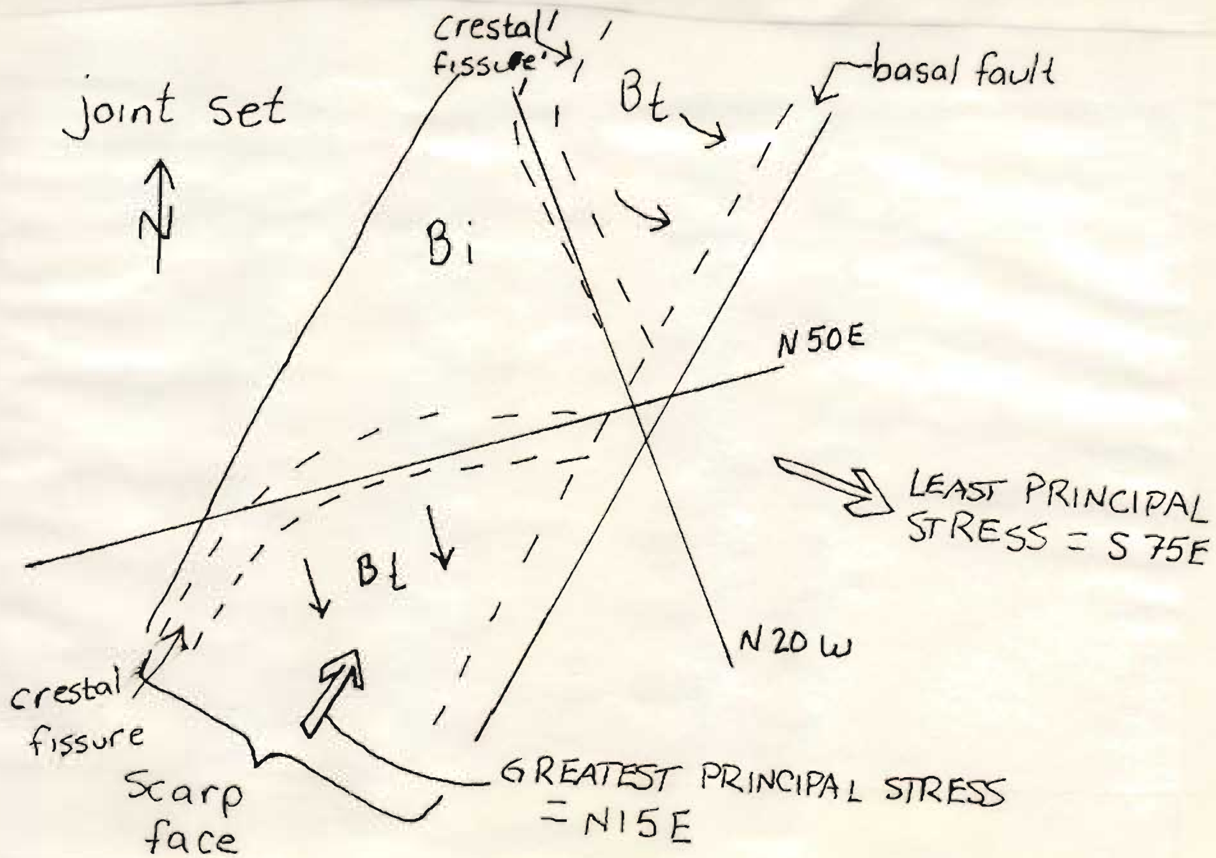


Fig. 8. Outcrop of Bandelier Tuff on the main scarp face downhill on Ski Hill Rd. Joints orthogonal to bedding dip into the hillside at about 60 degrees. This area is mapped as forward-toppled tuff (Bt).

Fig. 9. Map units representing Bandelier Tuff outcrops on the Pajarito fault scarp. (a) slabs of tuff (map unit Bs). This designation is purely descriptive, and is used for areas where the depth dimension cannot be observed. Thus, it could represent either loose slabs of tuff lying on the scarp face, overlying in-situ tuff of any orientation, or forward-toppled in-situ tuff. (b) low-dip bedrock (map unit Bi), where the prominent joint set is interpreted as "bedding" and dips <10 degrees (typically 3 degrees-4 degrees). Due to granular disintegration a false slab top can develop on Bi parallel to the ground surface. (c) toppled bedrock (map unit Bt). Mapped where vertical exposures show that east-dipping prominent joints extend to depth, and other joint sets are orthogonal to that set.

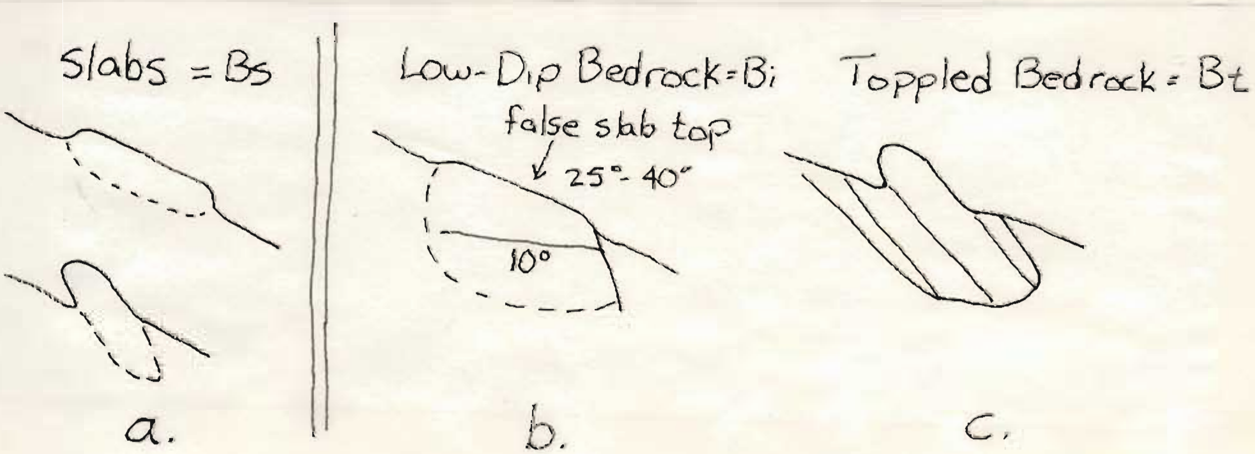


Fig. 10. Area of ground-parallel slabs sloping 30 degrees E on the upper scarp face at Ski Hill Rd. These are false slab tops. Note subhorizontal joints above clipboard.

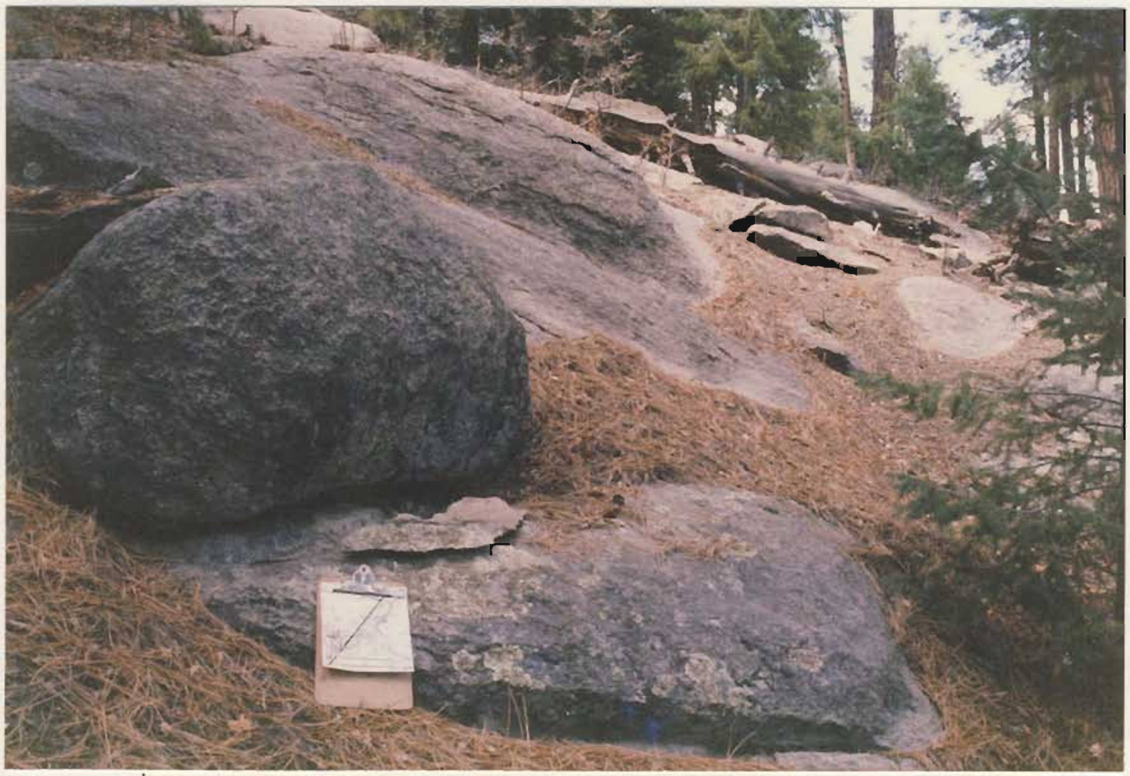


Fig. 11. Ground-parallel slabs (foreground) sloping 30 degrees E south of Twomile Canyon. Deeply-incised gully in left shows only horizontal jointing, indicating outcrop surface is not joint controlled.

sheetwash or rillwash. The bevel may have been developed by chemical and/or physical weathering enhanced by moist colluvium being in contact with tuff. As in most arid and semi-arid climates, weathering is accelerated where bedrock is kept in contact with a moisture-retaining regolith, as opposed to emergent outcrops which dry rapidly after each rainfall event. Therefore, it is possible that existence of a thin negolith layer on the scarp face induces granular disintegration of the underlying tuff along a surface parallel to the ground surface. If erosion strips away the regolith, the underlying tuff surface is exposed.

A second map unit is used where the prominent joint set dips 25-40 degrees E, and where vertical exposures show this trend persists downward for several meters (i.e., it is not a surface weathering effect). Fig. 12 shows a typical gully exposure into this unit, mapped as a toppled bedrock (Bt). Where dip in the tuff is approximately parallel to the surface on the scarp face and there are no vertical exposures, this unit is difficult to distinguish from loose slabs of tuff simply lying on the surface. In that case, I mapped a descriptive unit of bedrock slabs (Bs; Fig 9a) which might represent either possibility. In many cases, however, either the vertical exposures do exist, or the tuff outcrops are defined by prominent joints that are <u>steeper</u> than the ground surface (e.g., Figs. 9c, 13). Where joints dip more steeply than the ground surface, tuff outcrops make small "fins" that stuck out of the ground as shown in Fig. 13. This geometry would be difficult to create with loose slabs of tuff that were creeping down the scarp face; those would tend to remain parallel to the surface slope.

Another criteria to distinguish map units Bi and Bt is the dip of joints orthogonal to the prominent set. Where tuff has been truly forward-tilted to 25-40 degrees, these joints dip into the scarp face at 50-65 degrees, maintaining a perpendicular orientation to the "bedding" joints. In untoppled areas, these joints remain nearly vertical.

3.1.3 Bedrock map units

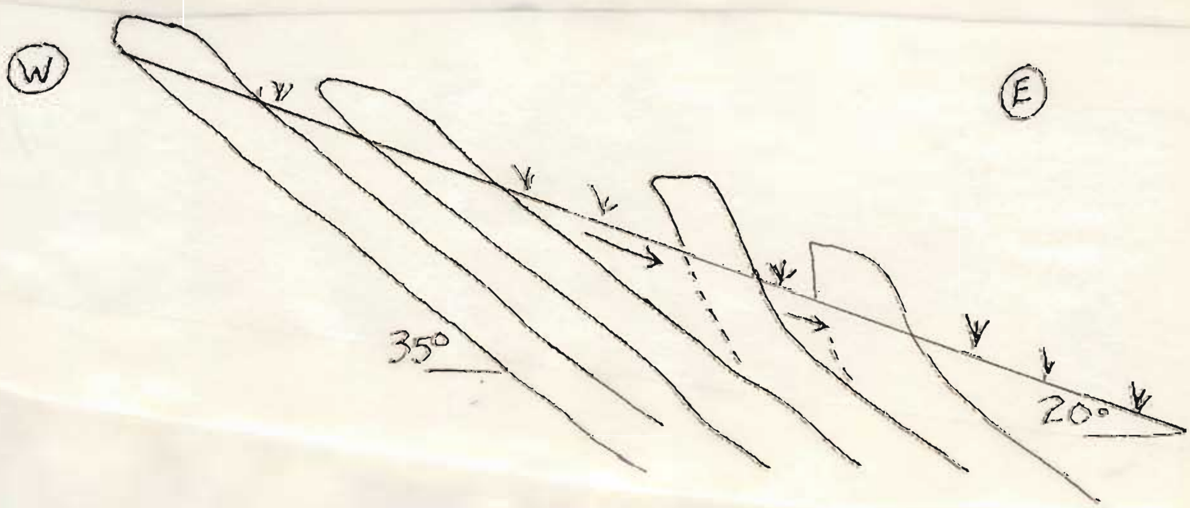
3.1.3.1 In-situ map units (Bi, Bw, Bn, Bf, B5, B4)

I mapped six units in the tuff where exposures showed that either bedding in surge beds or prominent "bedding" joints were nearly horizontal. The generic unit for this condition is Bi, or in-situ bedrock. In some areas the tuff is distictly orange, soft and "punky" (equivalent to the "thud" rock units of Rogers, 1995), a product of vapor-phase alteration. I mapped this rock type as Bn, or nonwelded tuff. It's much harder ("ping") counterpart was mapped as Bw, or welded tuff.

Near the crest of the scarp I was able to define two units which corresponded to Reneau and McDonald's (1996) cooling units 5 and 4 (my units B5 and B4). Unit B5 is typically a massive welded to punky tuff, whereas unit B4 displays a "flaggy" appearance caused by parallel jonts 3-8 cm apart (see Fig. 2). Where this same flaggy appearance was observed farther down the scarp, where correlation with cooling unit 4 was less certain, I mapped the tuff with the descriptive designation Bf (flaggy tuff). My use of these six units was somewhat arbitrary along strike, and I may have mapped similiar rock as either B4 or Bf, or Bi/Bw/B5 in different places along strike. The important meaning of these map units is less in representing their proper position in the stratigraphic sequence (of which I am unsure in many areas), as in showing that the tuff has not been significantly rotated by Quaternary deformation.

Fig. 12. Typical gully exposure of Tuff on the scarp face where the prominent joint set dips 25-40 degrees E, or roughly parallel to the surface of the scarp face. Clipboard at bottom is 60 cm square.

Fig. 13. Schematic diagram showing the shape of tuff outcrops where the prominent joint dip (35 degrees here) is steeper than the surface slope (20 degrees). The two tuff "fins" at left protrude above the surface at the ambient dip angle. The two fins at right have been bent forward and steepened by downslope creep of the regolith.



3.1.3.2 Toppled map units (Bt)

The toppled map unit is mapped over about 2/3 of the upper (bedrock) portion of the main scarp face. In these areas the prominent joint set dips 25-40 degrees east, and the other prominent joints are orthogonal to it. Over most of the extent of the scarp face mapped as Bt, there is a prominent tension fissure at the crest of the scarp. This rubble-filled fissure separates a terrain of horizontal tuff above the scarp from a domain of east-tilted tuff on the scarp face. This relation between horizontal tuff, large fissure, and east-tilted tuff is best exposed where Highway 4 ascends the main fault scarp, and is described in detail in Sec. 4.2.3.

3.1.3.3 Bedrock in ambiguous structural position (Bs)

Many areas of the scarp face are not dissected enough, or lack any artificial cuts, so that the vertical continuity of surface-parallel slabs cannot be checked. In other words, I do not know if the ground-parallel slabby outcrops represent a surface weathering phenomenon (as in Bi), joint-controlled weathering in a toppled terrain (Bt), or merely loose slabs of tuff embedded into regolith and presumably creeping down the slope (colluvial unit cb). Due to this ambiguity, I mapped these areas as Bs, or slabby-weathered tuff.

I was quite happy with the above-described three fold classification of tuff outcrops on the scarp face until I encountered the small outcrop on the north side of Pajarito Canyon (Fig. 14), which I term the "disturbing outcrop". This particular outcrop, which is about 2.5 m square, shows mainly ground -parallel joint on the outside, grading to horizontal joints on the inside. This pattern is what I feared might be occurring all over the fault scarp, i.e., that most joints visible were exfoliation joints that had developed parallel to the modern ground surface. If this were true, then joints could not be used to define structural domains.

However, in 17 days of traversing up and down the scarp this outcrop was the only one I observed with this unusual gradational pattern of jointing. All the other outcrops examined contained consist joint sets. The only other place where joints diverge is next to the shear fractures described in Sec. 3.1.1. Therefore, the most reasonable explanation for the disturbing outcrop is that one or more shears once existed adjacent to the outcrop, and have now been eroded away.

3.2 Stratigraphy of Unconsolidated Deposits

3.2.1 Alluvium

Alluvium in the fault zone includes stream channel deposits (ax) and alluvial fans (afx). Stream alluvium is subdivided by age, with map unit a1 representing active channel alluvium, a1.5 and ay low terraces (Holocene). Unit a2 represents slightly higher, incised terraces that are younger than the El Cajete pumice (50-60 ka; Reneau and McDonald, 1996, p. 40). A small area of alluvium exposed in roadcuts on West Jemez Road is composed almost entirely of pumice; this is map unit ae. Beneath this unit, also mainly exposed in deep roadcuts, is the oldest alluvium in the area (a3, a3d). This alluvium is composed almost entirely of dacite gravel, much of which must predate the deep incision of modern canyons into the main fault scarp.

Fig. 14. The "disturbing outcrop" on the north side of Pajarito Canyon. Jointing in the interior of the outcrop is mainly vertical and horizontal, but gives way to more surface-parallel jointing at right. These two joint sets clearly cross-cut each other. Outcrop pictured is about 2 m high.

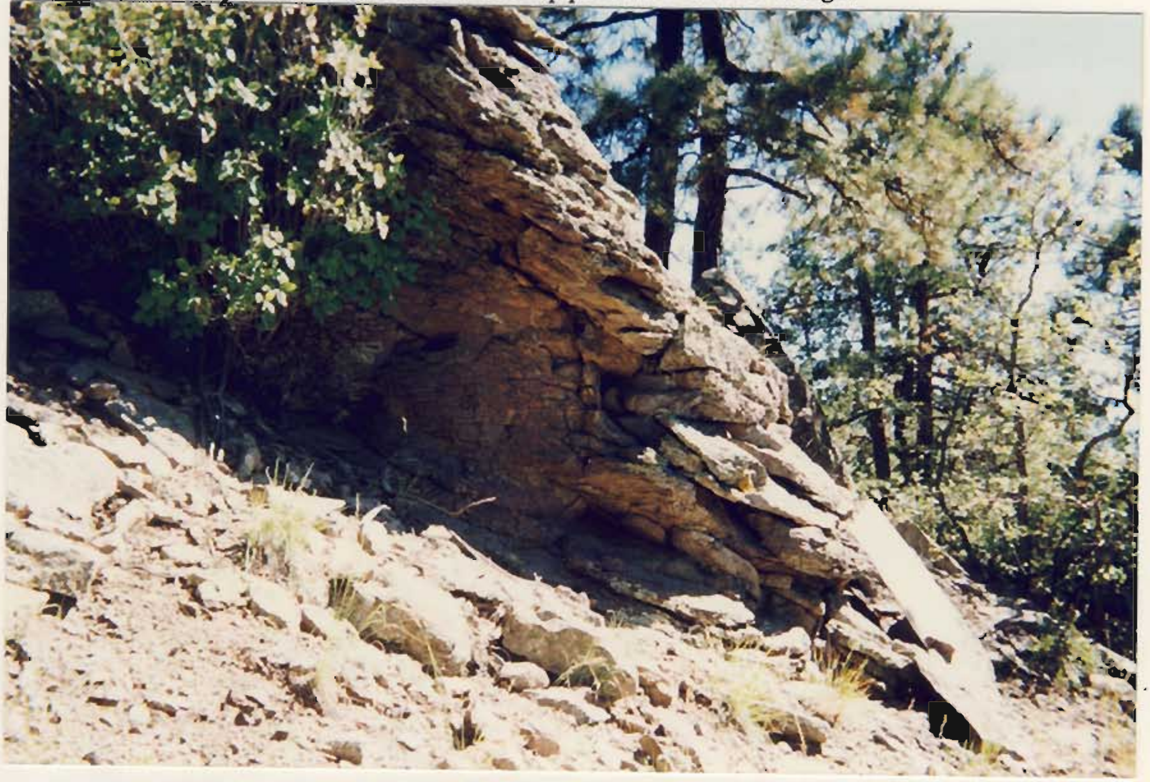
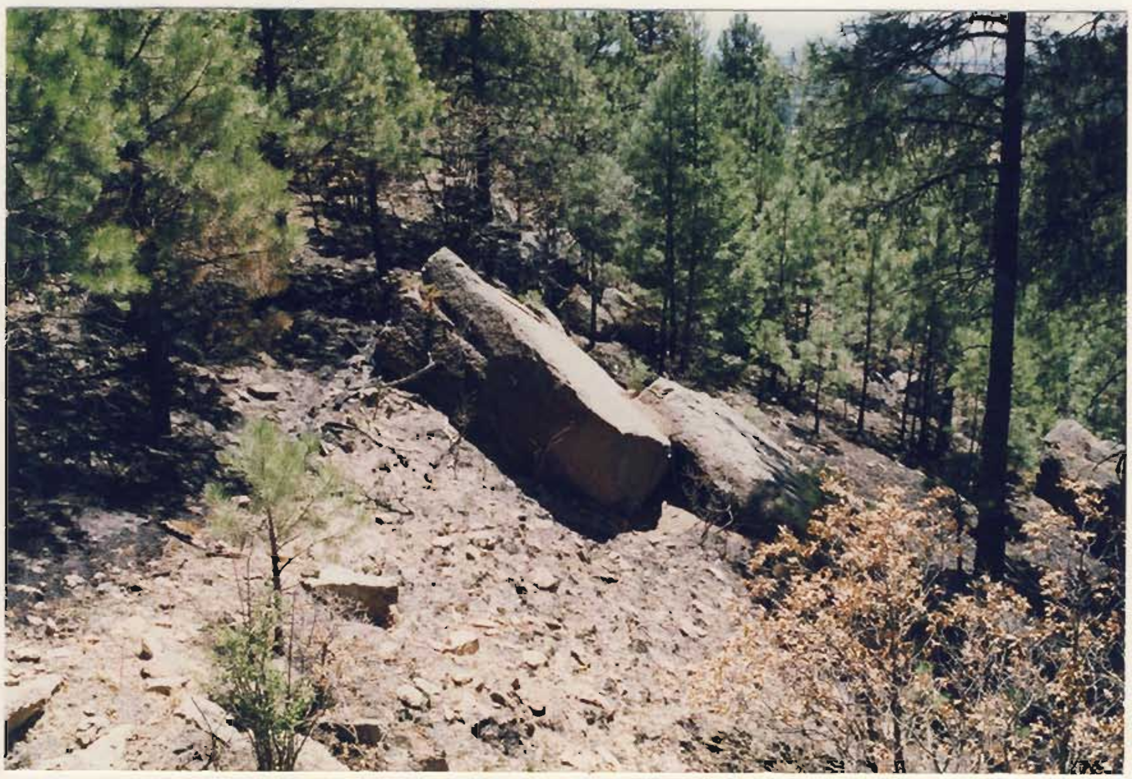


Fig. 15. Detached slabs of Bandelier Tuff on the ground surface, upper north slope of Canyon de Valle, above the quarry. The local dip of in-situ bedrock here is 3 degrees-4 degrees E (view is looking E), whereas the slabs are lying on a south facing slope.



Alluvial fans are likewise subdivided byage, into young (afy, afy1, afy2), internmediate (afi, afi1, afi2), and old (afo) fans. Young fans are Holocene, intermediate-age fans are late Pleistocene (post El Cajete). The age of old fans is unknown, but is apparently pre-El Cajete.

Due to the prevalence of sheetwash processes over much of the scarp between major drainages, it is sometimes difficult to decide whether sediments at the scarp toe were deposited by concentrated runoff (alluvium) or by sheetwash and creep (colluvium). Therefore I have defined a map unit of alluvium-colluvium (ac, acy) where this ambiguity cannot be resolved.

3.2.2 Colluvium

Most of the lower half of the fault scarp is mantled by colluvial deposits. Because colluvium accumulates by vertical accretion and dissection on the scarp face is minimal, only the youngest colluvium is typically exposed at the surface. Therefore, I subdivided colluvial units by grain size rather than by age.

The coarsest colluvium is map unit cm, composed of megablocks of tuff several meters in diameter. This map unit includes the very coarse grained fills of crestal tension fissures, such as the one transected by Highway 4 (see photo in Reneau and McDonald, 1996, p. 81). In most areas of toppling the toppled zone consists of rubbly fissure fill mixed with quasi-intact blocks and domains of blocks of forward-tilted tuff. Even with a good roadcut exposure, like that along the face of the scarp ascended by Highway 4, it is often unclear how large a tuff block to include in colluvium or how small an outcrop to map as toppled bedrock (Bt). This distinction becomes even more difficult on the scarp face where there are no vertical exposures. The key criterion for identifying megablock colluvium is a relatively abrupt end to intact bedrock in the dowmslope direction, and a parallel zone of large tuff blocks of various orientations embedded in the scarp surface, which grades downslope into more normal bouldery colluvium in which most clasts are oriented parallel to the ground surface. Bouldery colluvium may contain large detached slabs of Bandelier Tuff which are clearly not in-situ (Fig. 15). Finer colluvium is mapped as gravelly colluvium (cg) in which clasts >15 cm long are rare.

A final colluvial map unit is colluvium derived almost entirely from the El Cajete pumice (ce). I mapped very little primary pumice because most of the pumice observed in outcrop showed signs of downslope transport (cut-and-fill structures, etc.). Map unit ce appears to outcrop as a band relatively high on the colluvial apron, and is overlain to the east (downslope) by younger, non-pumiceous colluvium (usually map unit cg). This geometry suggests that there may be an age progression of colluvium on the colluvial apron, with successively younger deposits eastward (Fig. 16). This geometry would require that the colluvial layers dip more steeply than does the present ground surface. One way that this could happen is if the ground surface was regraded to a lower angle by erosion after the deposition of the pumice. Regrading would be expectable under the following scenario. First, the scarp was blanketed with pumice, which incidentally killed most of the vegetation. Second, rainstorm events washed huge volumes of pumice off the scarp face, which was deposited on the colluvial apron. Third, the scarp

Fig. 16. Schematic cross-sections showing the geometry of colluvial units at the toe of the scarp near Highway 4. (a) inferred geometry soon after deposition of the El Cajete pumice. (b) geometry after slope regrading.

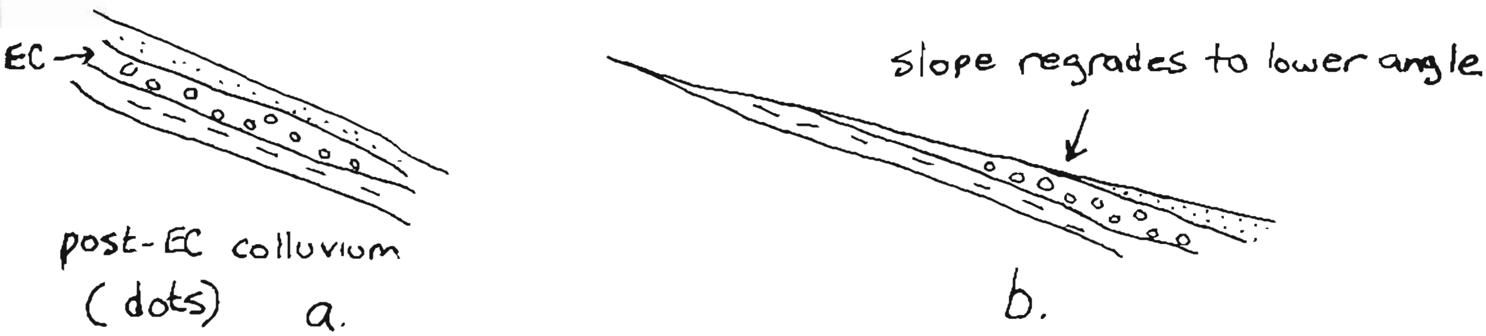
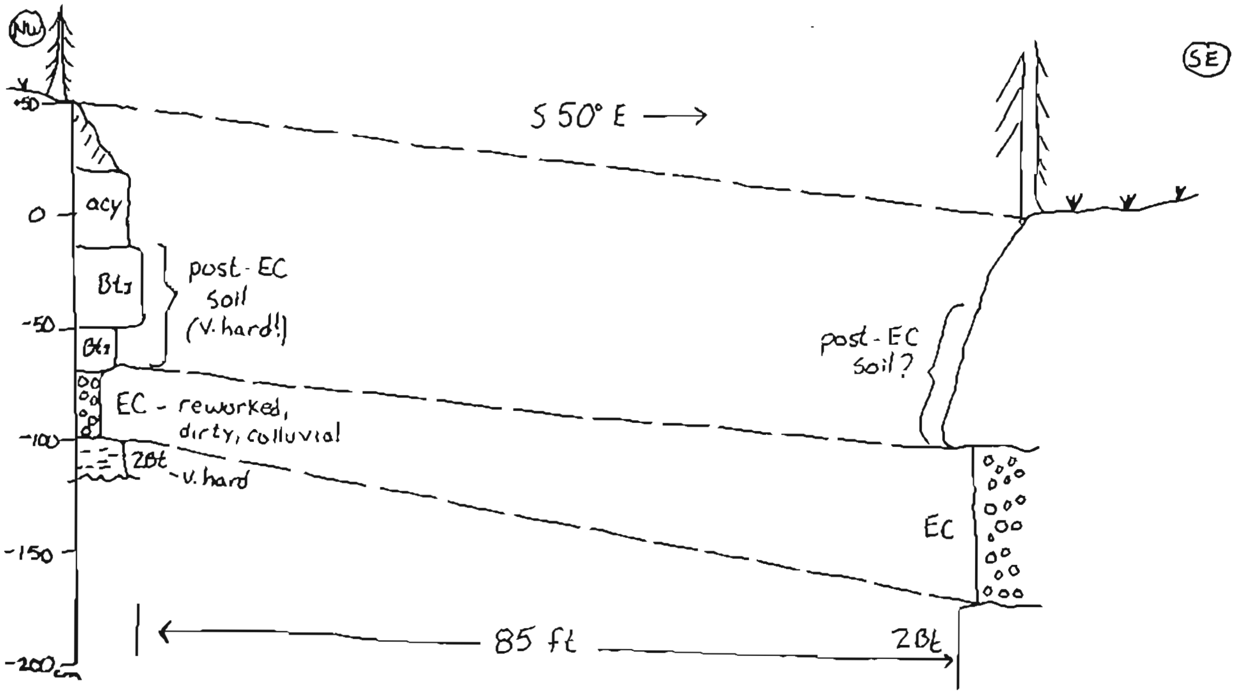


Fig. 17. Correlation of El Cajete pumice and associated colluviums across Ski Hill Road, in the graben south of Los Alamos Canyon.



revegetates, and future runoff carrying much less sediment erodes and redeposits the colluvium farther valleyward, thus regrading the slope to a lower angle.

In grabens such as the wide one south of Los Alamos Canyon, the retransported El Cajete pumice appears as a distinct layer sandwiched between sandy and gravelly colluvium (map unit cg). Well-developed soil horizons, especially beneath the El Cajete pumice, indicate a long period of landscape stability prior to 50-60 ka. The geometry of pumice and bracketing colluviums can be seen in roadcuts on the east and west sides of Ski Hill Road in the graben (Fig. 17). The retransported pumice thickens eastward across the road from 30 cm to 50 cm, and is under- and overlain by soils developed in sandy colluvium.

In addition to the El Cajete pumice an older pumice is exposed just south of the hairpin curve in Highway 4 as it ascends the fault scarp (Fig. 18). This pumice has not been previously described, so its age and origin is unknown. J. Gardner (pers. comm. 1996) suggested that the pumice may be fractionally younger than the main eruption of the Bandelier Tuff. The pumice is restricted to deep toppling fissures, which suggests that toplling may have immediately preceeded pumice eruption. If this outcrop is typical of topple fissure fills, then the toppling process may have initiated sooin after initial post-Bandelier faulting, and fissures of various ages may be filled with pumice and colluvium of many ages.

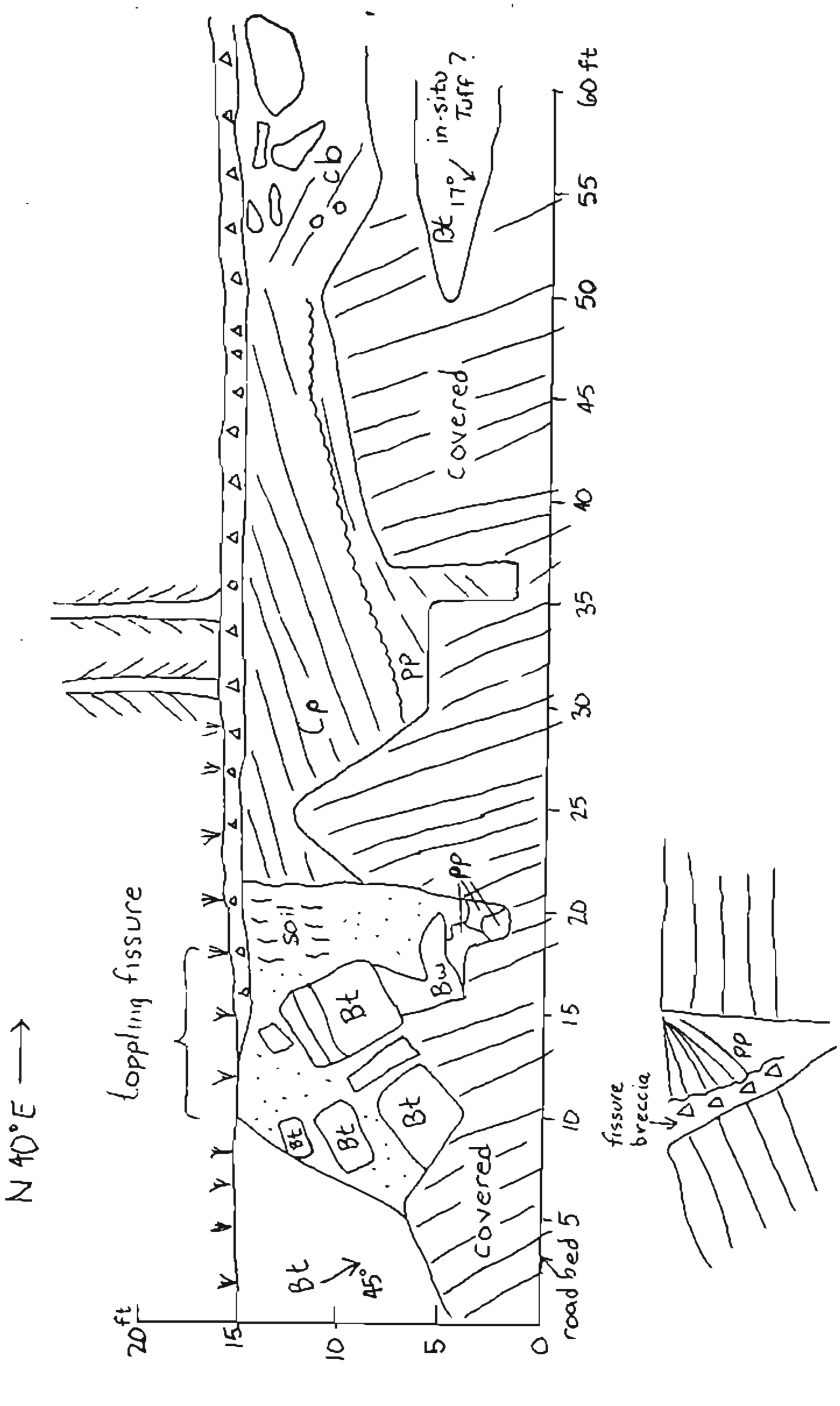
3.2.3 Landslide deposits

Much of the Pajarito fault scarp has clearly been subject to deep-seated landsliding. Evidence for landsliding includes: 1) the scalloped nature of the scarp crest, 2) below the scallops, anomalous benches and back-tilted tuff blocks, and 3) masses of tuff at the scarp toe that protrude farther east than usual (several of these are cut by West Jemez Road). Deep-seated landslides thus appear to be rotational slumps composed of quasi-intact masses of tuff. These landslides are subdivided according to inferred age, based on the freshness of morphologic features such as headscapes, lateral margins, and how well drainage is integrated on the slide. For a discussion of morphologic dating of landslides, see McCalpin (1984). No very young (Holocene) deep slides were mapped; lBi represents intermediate-age slides and lBo older slides.

Several thinner slides appear to be composed of more rubblilized, unconsolidated material; these are simply mapped as "l". Finally, several areas of thin debris sliding of colluvium over bedrock were noted; these are mapped as debris slides (ld).

A final category of colluvium is isolated huge boulders of tuff that lie near the toe of the colluvium apron. These boulders appear to sit on the ground surface or are slightly embedded into it. They presumably rolled down the scarp face, perhaps originating from zones of "cm" farther upslope. These rocks may have been dislodged by earthquake shaking, in which case they would be useful paleoseismic indicators if they could be dated. Given the number of loose colluvial boulders on the modern scarp face, and the violent shaking to be expected in a surface-rupturing earthquake, it is surprising that there are so few large erratic boulders on the colluvial apron. One explanation would be that the most recent faulting event is quite old (pre-Holocene), and most of the previously rolled boulders are buried by later colluvium. This explanation would support the contention of WCFS (1995) that the last surface-rupturing earthquake occurred prior to

Fig. 18. Sketch of the roadcut immediately south of the lowest hairpin turn on Highway 4 as it ascends the fault scarp. The roadbed is drawn as horizontal, but actually dips 3 degrees to the right. Bt, toppled blocks of Bandelier Tuff; Bw, welded tuff; pp, primary (airfall) pumice, very clean and well-sorted; cp, colluviated (reworked) pumice; cb, bouldery colluvium containing little or no pumice. The inset at lower left shows how the primary pumice (pp) may have accumulated in an open toppling fissure.



deposition of the El Cajete pumice. The existence of many loose rocks on the scarp face also suggests the latest faulting is quite old, since that event presumably would have dislodged all the loose rocks existing at the time of the event. Thus, today's multitude of loose rocks must postdate the latest faulting event.

4. STRUCTURE OF THE PAJARITO FAULT ZONE

4.1 Structure of the Whole Fault Zone

The Pajarito fault zone is composed of a 50-100 m-high east-facing fault scarp (Fig. 19) , which breaks into multiple scarps along strike, and two antithetic faults, the Rendija Canyon and Guaje Mountain faults. In this study I only mapped the main scarp of the Pajarito fault between Highway 4 and Los Alamos Canyon (Fig. 1), including a prominent western splay fault north of Canyon de Valle, and the large graben and step faults south of Los Alamos Canyon.

On the latter area the fault zone is at its widest, measuring about 2 km wide between the farthest western and eastern fault traces. However, most of the vertical offset is contained on the main east-facing scarp, which is about 50 m high here. Fig. 20 schematically shows two possible subsurface geometries for the fault zone (minor splay faults are omitted for clarity). In both options, the scarp face is an east-tilted monolithic block of tuff strata, forming a large segmented monocline with a tension (toppling) fissure at the scarp crest. In option 1 there is a normal fault zone at the base of the 50 m high scarp, thus making the adjacent sediment-filled depression a true graben. In option 2 this fault does not exist, and the depression is a half graben with a deep thickness of fill at its eastern margin. I propose to run a seismic refraction survey prior to trenching in this graben, since the two geometries outlined above would dictate very different trenching strategies (see section 6.2).

4.2 Structure of the Main Scarp

Most of the effort in this study was devoted to mapping the main fault scarp of the Pajarito fault. Although the heavily forested scarp looks uniform from a distance, detailed mapping shows that it is composed of several structural elements which vary in importance along strike. In some areas, such as near Canyon de Valle, the scarp is a simple scarp with gently east-dipping tuff truncated by a single high-angle normal fault near the center of the fault (Fig. 21). In other areas the scarp face is composed of one or more east-tilted monolithic blocks with large tension fissures at the crest (see Fig. 20). These two geometries comprise structural end-members, but there are intermediate geometries. For example, the main scarp south of Los Alamos Canyon is composed of two east-tilted blocks each with its own crestal tension fissure (Fig. 22). Within each block dips appear to steepen eastward. A basal normal fault zone probably exists at the toe of the main scarp.

In the following section I describe the four main structural elements of the main scarp, i.e. the basal fault zone, mid-fault scarps, tension/toppling fissures, and transverse (E-trending) structures.

Fig. 19. Photograph of the main scarp of the Pajarito fault, looking south across Canyon de Valle. The scarp at this location is 115+/- 24m (WCFS, 1995, Table 4-1). The scarp in the middle distance is south of the study area, and ranges from 75 to 90 m high.

Fig. 20. Schematic cross-sections of the Pajarito main scarp and graben south of Los Alamos Canyon. Units B5 and B4 refer to Bandelier Tuff, cooling units 5 and 4 as defined by Reneau and McDonald (1996). Stippled pattern shows alluvium and colluvium in the graben; triangles indicate coarse rubble in tension fissures. The existence of the basal fault zone in option 1 is uncertain, as is its throw.

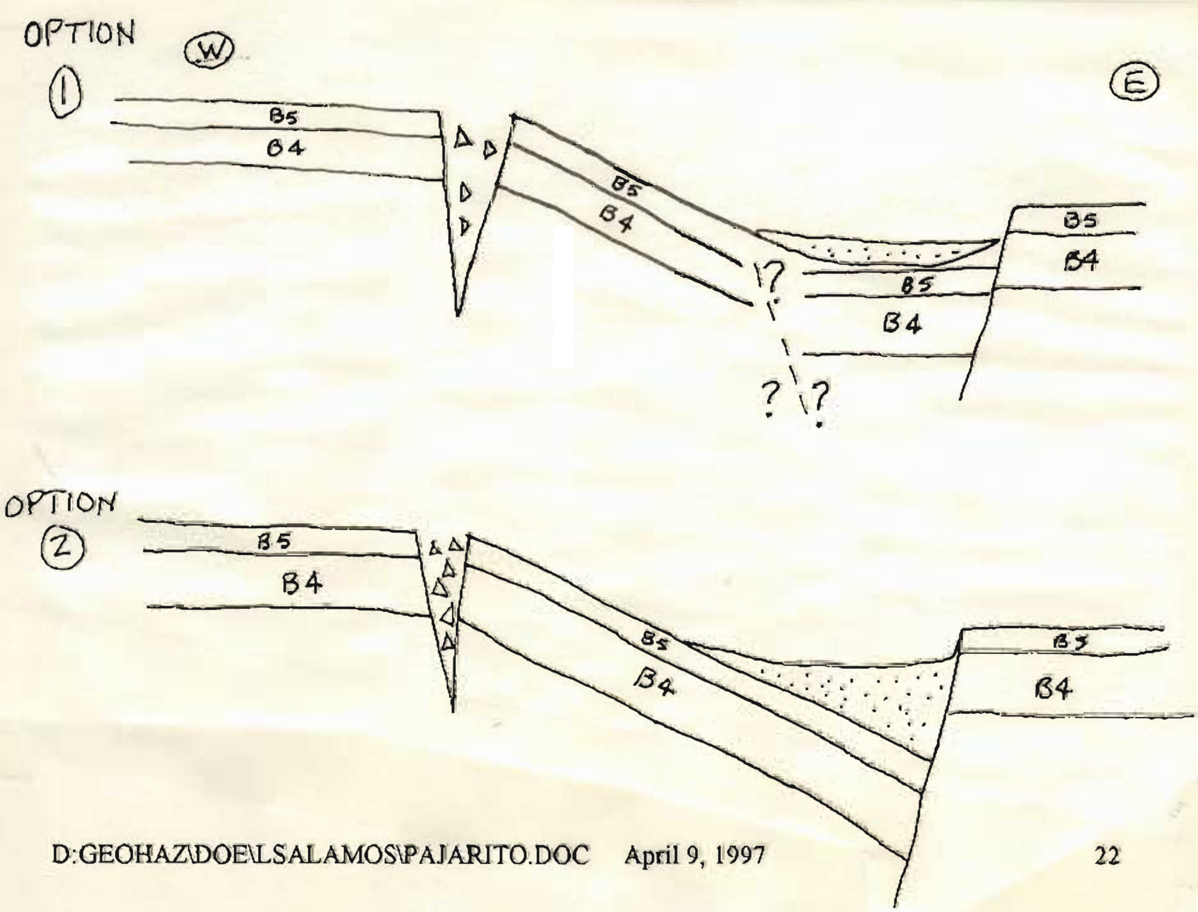
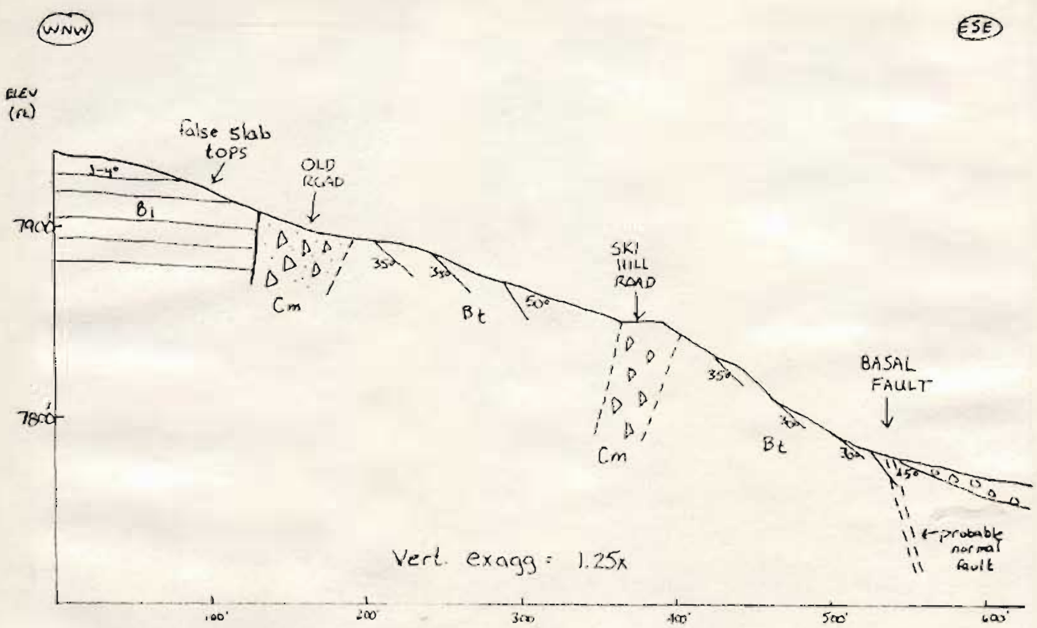


Fig. 21. Photograph of the main scarp looking north across Canyon de Valle. The unvegetated area at lower center is a quarry, which at its eastern end exposes the main fault zone. Tuff at the scarp crest dips 3-4 degrees east, but is broken up by several troughs paralleling the scarp crest. These troughs probably represent extension and normal faulting due to gravitational spreading or incipient landsliding toward the east. However, the scarp face here is very planar and shows no signs of deep-seated landsliding.

Fig. 22. Cross-section of the main scarp in the vicinity of Ski Hill Road. Dips are from field measurements. cm = megablock colluvium; Bt = tilted Bandelier Tuff; Bi = intact (untilted) Bandelier Tuff. Circles at far right indicate graben fill (alluvium and colluvium).



4.2.1 Basal fault zone

The basal fault zone describes a normal fault zone typically located at the base of the scarp, at the head of the colluvial apron (i.e. at the bedrock/colluvium contact). Sometimes this so-called basal fault zone is 1/3 or more up the scarp face, due to the height of the colluvial apron. This fault zone is known to exist only at the sites of the four WCFS trenches, and is inferred to exist at the bedrock/colluvium contact elsewhere. Below I describe exposures or geomorphic expressions of this fault, from south to north.

Downslope of the lowest hairpin curve in Highway 4, runoff diverted from the highway has incised a gully which flows over the bedrock-colluvium contact, forming a waterfall (Fig. 23). Downslope of the waterfall Bandelier Tuff is fractured and faulted with about 5-15cm between fault traces. The bedrock-colluvium contact steps down to the east before disappearing beneath the elevation of the gully bottom. This site is tentatively proposed for future trenching (see Sec. 6.3).

The deepest exposure of the basal fault zone, although not the best exposed, is in the quarry wall at the mouth of the Canyon de Valle (Fig. 24). The zone of deformation is roughly 30 ft wide (Fig. 25) and is composed of increasingly fractured tuff blocks which give way eastward to detached blocks dipping about 60 degrees E. The contact between these detached blocks and true colluvium is indistinct.

At the large drainage that cuts through the scarp south of Ski Hill Road, the basal fault zone is reflected by an abrupt termination of bedrock outcrops (Fig. 26). This geomorphic expression is typical, and suggests that the throw on the fault is at least as great as the depth of the valley east of the contact, since no bedrock outcrops on valley walls there.

In the second small gully south of Ski Hill Road the basal fault zone truncates east-dipping tuff (Fig. 27). The geomorphic expression of the fault is a overhanging outcrop that dips into the hillslope at 50 degrees-60 degrees. Where gullies cross this contact it is possible to stand beneath the overhang, where gully erosion has removed colluvium on the downthrown side. The zone immediately downslope from the overhang often displays large tuff blocks in various orientations, mapped as "cm".

Figs. 28 and 29 show poorly-exposed east-dipping zones of fractures and faults that coincide with the bedrock-colluvium contact, and are thus thought to represtent the basal fault zone. These east-dipping fractrures are anomolous with respect to most of the exposures on the scarp face upslope, and in places clearly crossscut the ambient three joint sets (e.g. Fig. 28).

4.2.2 Mid-scarp faults

Mid-scarp faults are poorly exposed and the ones described in this section may not be representitive of faults all along strike. Typically mid-scarp faults can only be detected in gullies cut into the scarp face, where residuum and colluvium does not mantle the surface. Where exposed, these fault zones resemble the basal fault zone, i.e. a 1-2 m wide zone of closely spaced fractures that dip 60 degrees-80 degrees E (Fig. 30).

In other areas the center of the scarp appears to be deformed in a wide zone of discrete fractures, across which the tuff abruptly steepens in dip by 5 degrees (Fig. 31).

Fig. 23. Hand-cleaned exposure of the basal fault zone downslope from the lowest hairpin curve on Highway 4.

Fig. 24. Photograph of the north wall of the quarry at the mouth of Canyon de Valle. The basal fault zone is located at right center. Fig. 25 shows the inferred structures in this poorly-exposed cut.

Fig. 25. Sketch of structural relations in the north wall of the quarry at the mouth of Canyon de Valle. Heavy lines bound the deformation zone.

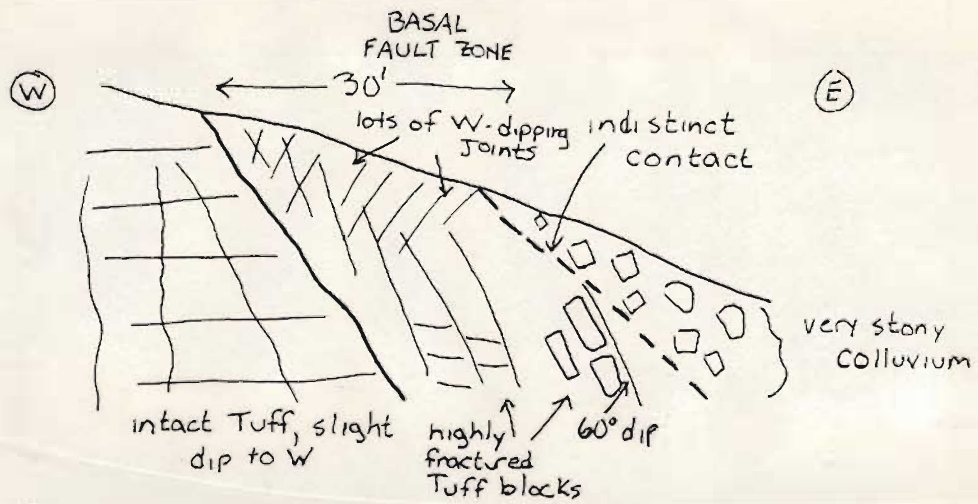


Fig. 26. Photograph of the south wall of the large drainage that cuts through the fault scarp south of Ski Hill Road. Horizontally bedded tuff on the right is abruptly truncated, presumably along a steeply-dipping basal fault zone.

Fig. 27. Photograph of the geomorphic expression of the basal fault zone in the second small gully south of Ski Hill Road. The fault zone creates on overhanging bedrock-colluvium contact defined by the orthogonal joint set which dips about 60 degrees into the hillslope.

Fig. 28. Photograph of the anomalous east-dipping fractures at the base of the main scarp, south of Ski Hill Road. Clipboard is 60 cm square.

Fig. 29. Photograph of the anomalous east-dipping fractures at the base of the main scarp in the first small gully south of Ski Hill Road. Clipboard is 60 cm square. Both the spacing and orientation of fractures here is anomalous with respect to the rest of the scarp.

Fig. 30. Photograph of a mid-scarp fault zone in a gully on the scarp face, south of Los Alamos Canyon: Note the anomalous close fracture spacing near the clipboard (60 cm square) and the increase in fracture spacing to the left (east).

Fig. 31. Schematic sketch of the wide deformation zone exposed in Twomile Canyon where it cuts through the main fault scarp. The structural domains are separated by wide, rubble-filled fractures up to 1.5 m wide, probably produced by toppling.

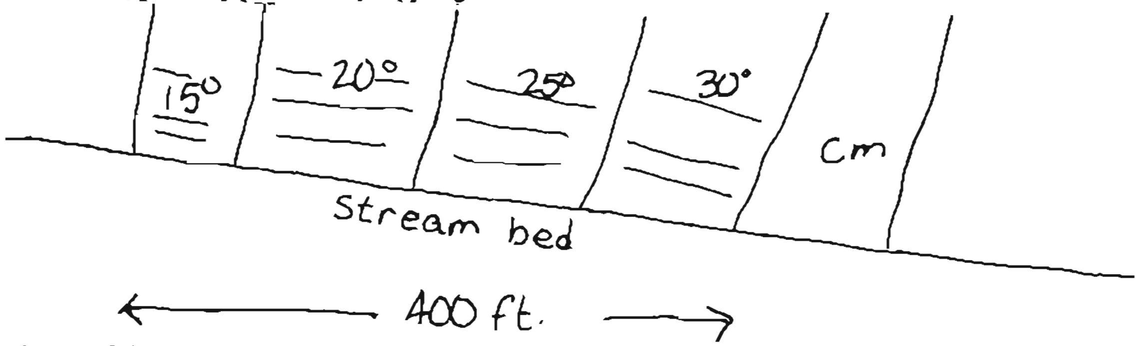


Fig. 32. Schematic diagram of the large topple fissure exposed in the roadcut on Highway 4 near the scarp crest. If the boundaries of the fracture remain planar, it implies that: 1) the fracture would be ca. 50 ft wide at the ground surface, not accounting for erosion, 2) the fracture would taper to zero width about 40 ft below the roadway, and 3) the toppled block of tuff is about 70ft thick.

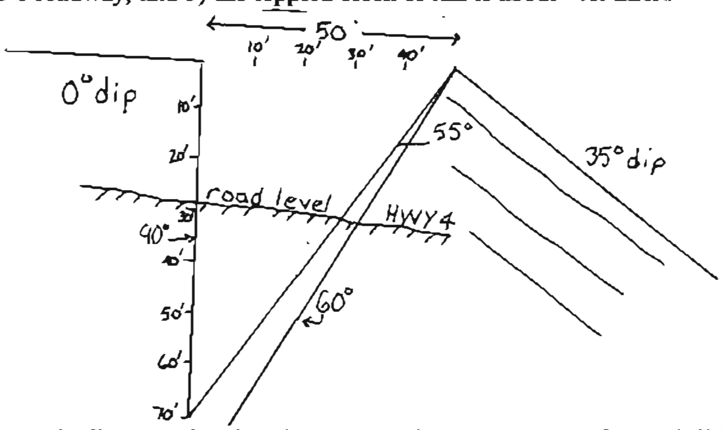
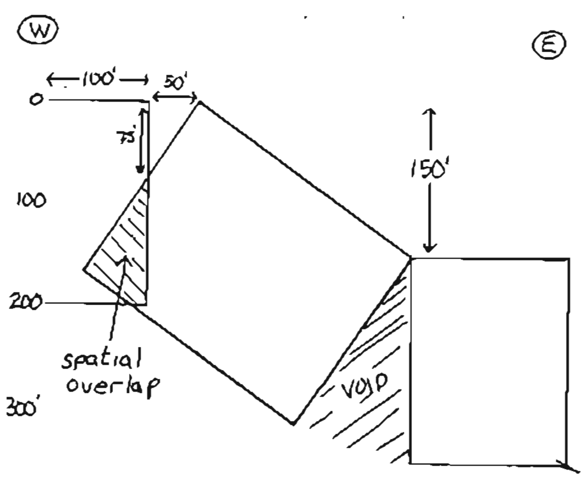


Fig. 33. Schematic diagram showing the space problems created by forward tilting of a 200 ft-thick slab of Bandelier Tuff at the main fault scarp. To avoid creation of large spatial overlaps and void spaces, the style of deformation must change to more vertical faulting at depths greater than 75 ft.



Each domain of constant dip is separated from the next by a rubble-filled fracture up to 1.5 m wide, down at canyon bottom level. If these fractures formed by the eastward toppling of blocks, then they presumably widen upward, but cannot usually by traced up onto the colluvium-covered scarp face. This diffuse style of deformation results in splintering nearly the entire width of the fault scarp into separate topple blocks. The existence of megablock colluvium (cm) at the eastern end of the transect suggests that a larger-displacement fault truncates the 30 degree-dipping tuff.

4.2.3 Tension fissures and topple blocks

Over most of the main scarp eastward toppling appears to be the main mode of accomodating vertical deformation (see Fig. 20). The best exposures of this deformation style are on Highway 4. On the south facing roadcut horizontally bedded tuff on the west is separated from 35 degree east dipping tuff by a rubble-filled crack that is about 10 m wide at road level. The western boundary fracture of the crack is vertical and the eastern boundary crack dips 55 degrees W, perpendicular to "bedding" in the toppled eastern block (Fig. 32). If this geometry is correct then the toppled slab is only 70-80 ft thick, or only about 1/4 as thick as the scarp is high here. Given this thickness, what is the style of deformation below 70-80 ft depth? A simple geometric model (Fig. 33) shows that there are severe space problems with tilting forward a slab as thick or slightly thicker than the scarp height. Perhaps some of the space problem is solved by the transition and rotation of smaller and smaller fault-bounded topple blocks. Such pervasive deformation is observed in the toppled zone along Highway 4 (Fig. 34), so it is presumably as or more common in the subsurface.

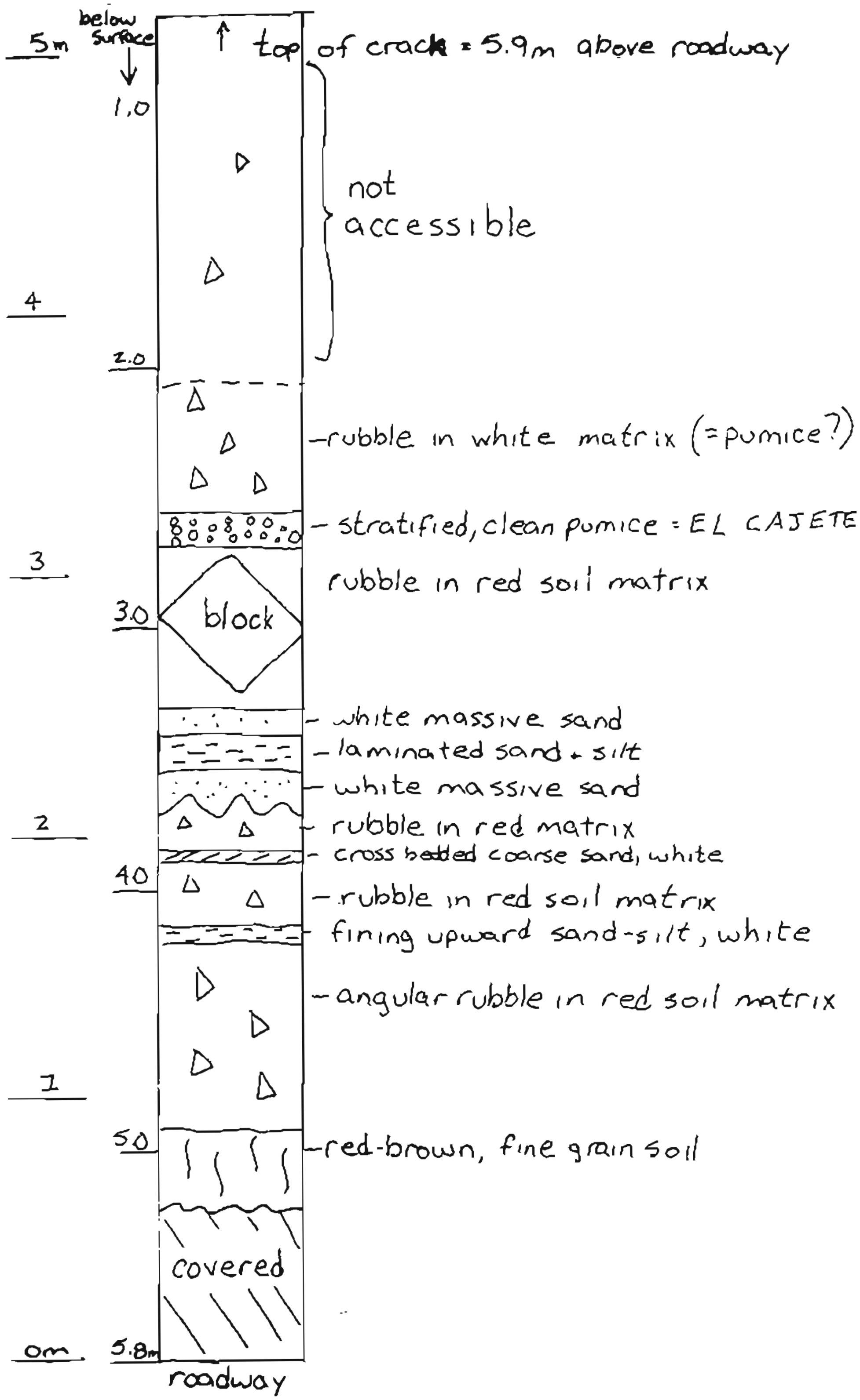
The 10 m-wide topple fissure fill on Highway 4 exhibits no internal structure, being a diamicton-like mass of angular tuff blocks encased in a fine red sandy matrix. However, some smaller tension fissure fills do display stratification and soil development. At the inside of the right-angle curve in Highway 4 near the crest of the scarp, a 1 m-wide fissure is filled with horizontally stratified sands and silts (Fig. 35). The fill is both internally faulted by small-displacement conjugate normal faults, and sheared in 10 cm-wide zones next to the bedrock walls. The upper part of the fissure fill appears to be a buries soil, although it is not clear how a soil would form in a fissure 3-4 m below the ground surface.

Even narrower tension fissures have mappable stratigraphy. Immediately west of the lower hairpin curve on Highway 4, a 6 m-high, 30 cm-wide tension fissure is filled with at least 13 mappable subhorizontal strata (Fig. 36). Four types of units can be distinguished: 1) stratified, well sorted sands and silts presumably deposited by running water, 2) pumice beds, 3) diamicton-like rubble which presumably fell into the crack, and 4) red-brown, massive buried soils. Unlike the fissure fill previously described, this fill is not sheared near the bedrock contact, nor does it contain internal faults. Thus, it may be a purely tensile crack. It is unknown whether the crack opened to its entire 30 cm width in one initial episode, after which it slowly filled, or whether the crack opened incrementally while filling. Unfortunately, few paleoseismic investigations have concentrated on deciphering fissure fills, so we have a limited conceptual framework with which to interpret them.

Fig. 34. Photograph of the south-facing roadcut of Highway 4 near the scarp crest, east of the large topple fissure. Note the 35-40 degree east dip of the prominent joint set, and the 50-55 degree west dip of orthogonal joints and secondary, rubble filled topple fissures (center and left). The white rod at bottom center is 3m long.

Fig. 35. Photograph of the filled fissure on the inside of the right-angle curve in Highway 4 near the crest of the scarp. The fill is well-stratified and ranges from very coarse sand (lighter brown colors) to silt (red). The fill is crisscrossed by numerous small-displacement conjugate normal faults. The upper part of the fill visible here has soil ped structure which obscures all stratification.

Fig. 36. Measured section of strata in a 30 cm wide fissure fill immediately west of the lower hairpin curve in Highway 4. No deformation was visible at the edges of the fissure, suggesting that this fissure resulted from pure tensile opening.



The main part of Highway 4 that crosses the fault scarp parallels a zone of toppling and yields many exposures of topple cracks. My reconnaissance observations suggest that cracks may progressively widen as toppling continues, which leads to rotation of topple cracks to lower angles (Fig. 37). On the northern end of the study area , where Ski Hill ascends the scarp, topple fissures stand open and have not been filled with sediment (Fig. 38).

Over most of the fault scarp topple fissures are not fortuitously exposed by roadcuts, and their existence must be inferred from the morphology of the scarp face. For example, the topple fissure exposed in the Highway 4 roadcut can be traced northward onto the scarp face, where it defines a 35 ft-wide bench (Fig. 39). Immediately east of the bench is a hogback-like ridge of tuff (Bf, or flaggy-weathering tuff) with fractures dipping 30-40 degrees E. To the west of the bench is a long colluvium-covered slope, which terminates in cliffs of horizontally-bedded tuff. A similar geometry is found near Twomile Canyon (Fig. 40).

Based on these two localities and many others, it is possible to define the common geomorphic elements of a topple fissure zone. First, upslope of the fissure tuff "bedding" is gentle and orthogonal joints are tight (Fig. 41). Second, orthogonal joints become progressively more open as the topographic bench or trough is approached (see Fig 38). Third, bedrock outcrops abruptly end on the margin of the troughs, often with overhanging faces. Fourth, a linear bench or trough parallels contours on the scarp face. The surface here exposes red-stained rubble but no in-situ tuff outcrops. Fifth, the downslope side of the bench is a linear, hogback-type ridge of tuff dipping ~30 degrees E. All of these surface features can be related to the subsurface features visible in the Highway 4 roadcut (Fig. 32).

4.2.4 Transverse structures

The alternation of toppled zones with non-toppled zones along strike on the scarp face suggest that some kind of transverse structures must exist, along which differential movement is accommodated. Only a few of these zones were observed in the field. One zone north of Canyon de Valle separates a domain of horizontal tuff (to the south, including the mouth of Canyon de Valle) from 20 degree-dipping tuff to the north. The contact between the two domains is abrupt, defined by a narrow rubble-filled gully no more than 1 m wide (Fig. 42). A better exposure of a suspected transverse structure exists about 100 m N of the site of Fig. 42, where a gully bottom exposes a peculiar narrow pillar of tuff bounded by E-W-trending fractures (Fig. 43). The subhorizontal fractures in the tuff flanking the pillar bend upward as they approach the pillar. If subhorizontal fractures in the tuff date from its cooling, then their bent shape implies that they were bent while the tuff was still hot. This further implies that there was movement on the transverse structure at this time. The structure pictured in Fig. 43 did not have any zones of breccia or rubble associated with it, such as would be produced by brittle fracturing. Thus, it is not clear exactly how the transverse zones behave rheologically. One possibility is that there are multiple transverse zones that effect a transition from domains of horizontal to toppled tuff. In other words, the along-strike transition in dip might be accomplished piecemeal, like the across-strike increase in dip shown in Fig. 31. However, the only two suspected transverse structures were not 1.5 m-thick rubble-filled

Fig. 37. Schematic diagrams showing how topple fissures might evolve through time. In the earlier stage, fissures are narrow and dip steeply into the slope. As the block on the right progressively tilts more and more, the topple fissure widens and is rotated to a lower dip angle.

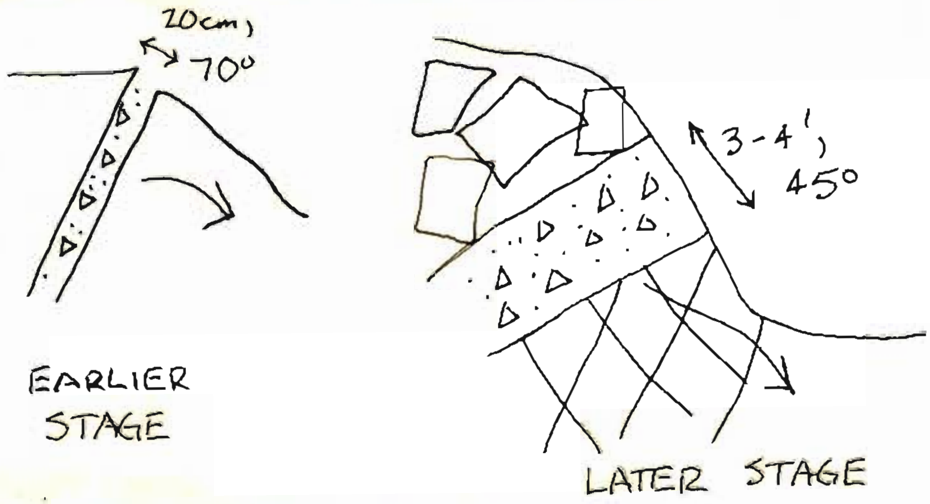


Fig. 38. Photograph of open topple fissures on the main scarp south of Ski Hill Road. The open void at center has not yet been filled in with sediment.

Fig. 39. Schematic section across the filled topple fissure, roughly 100 m north of the Highway 4 roadcut. This is a proposed site for future paleoseismic trenching.

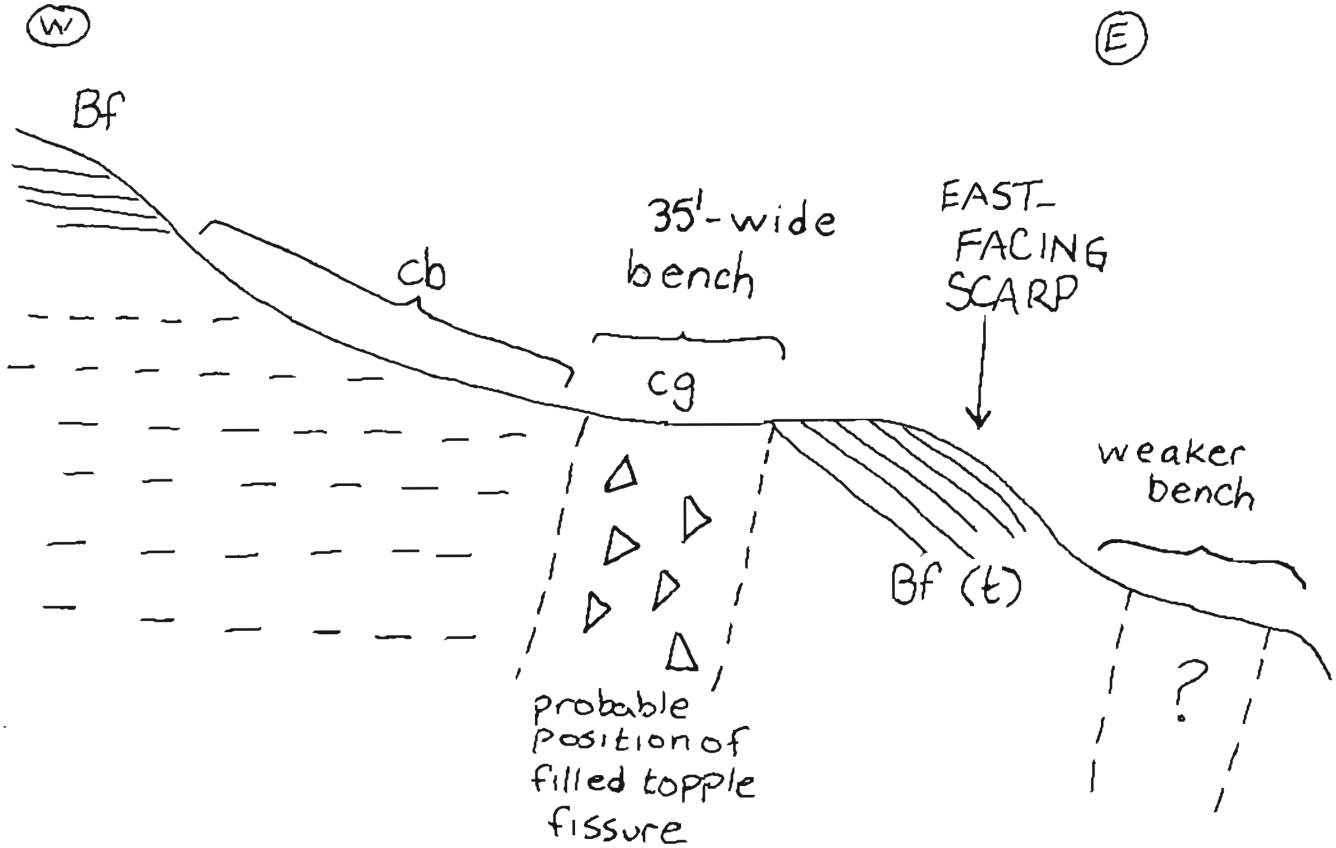


Fig. 40. Schematic section across a filled topple fissure on the north side of Twomile Canyon. An old dirt road takes advantage of the bench underlain by colluvium (cg.).

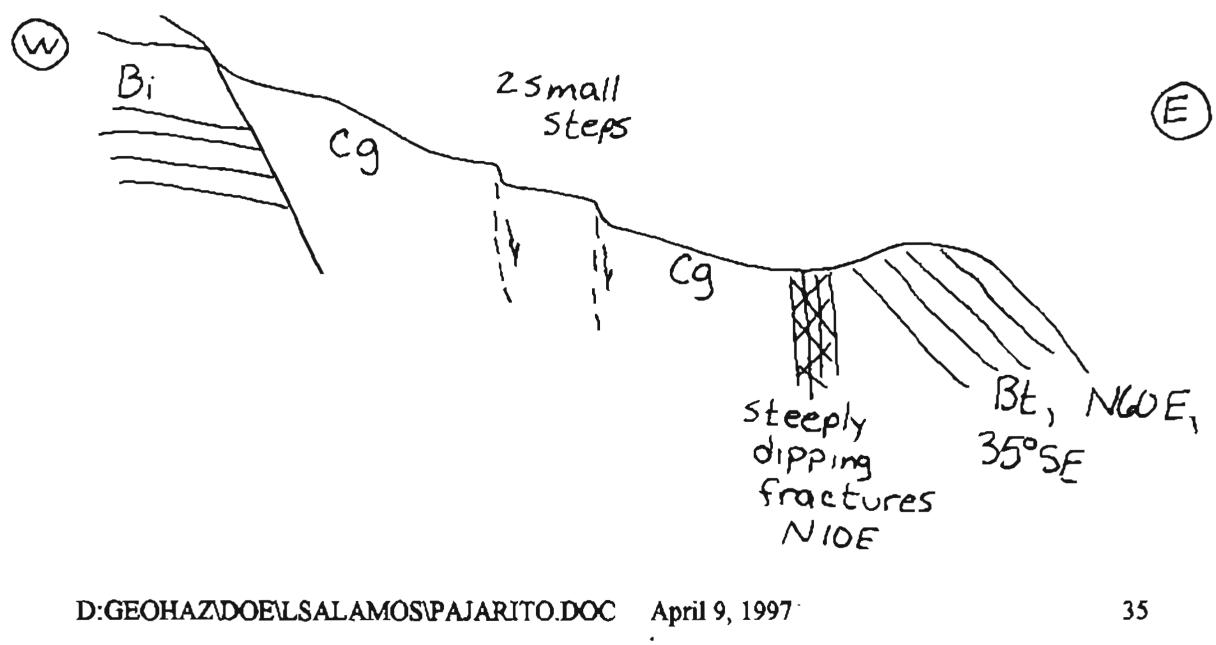


Fig. 41. Schematic diagram showing the common surface morphologic features over a topple fissure. See text for details.

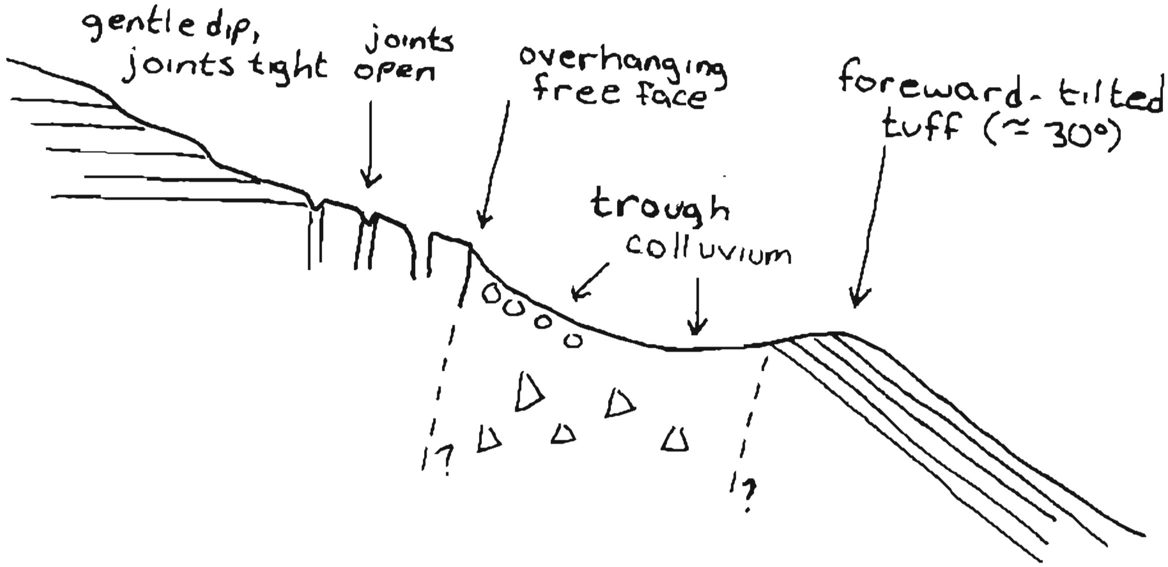


Fig. 42. Photograph mosaic of a suspected transverse structure that separates a domain of horizontal tuff (left) from 20 degree- dipping tuff (behind and right of the clipboard). The boundary lies immediately to the left of the clipboard.

Fig. 43. Photograph of a suspected transverse structure at 7835 ft elevation on the scarp face about 200 m north of Canyon de Valle. Folding shovel is 70 cm long.

fractures, but much narrower zones of fracturing. This narrowness could be explained from the fact that transverse zones must accommodate mainly strike-slip movement between in-situ and eastward toppled domains.

5. GEOMORPHOLOGY OF THE PAJARITO FAULT ZONE

Although the major landforms in the fault zone are clearly of tectonic origin (e.g. the main fault scarp), many smaller-scale features appear to be of gravitational or mass-wasting origin. This duality should not be surprising, since the current 100-125 m-high fault scarp is a very steep slope near the angle of repose, and slopes like this even of nontectonic origin are subject to slope failures.

5.1 Tectonically-controlled landforms

The large and linear scarps in the Pajarito fault zone are all of inferred tectonic origin, although the presence of tectonic faults can only be confirmed where deep trenches or roadcuts exist. Criteria for tectonic origin of landforms include: 1) long linear extent, and 2) lack of a high nearby slope that could induce gravitational stresses. For smaller-scale landforms on the scarp itself, it is often difficult to determine whether the underlying deformation is tectonic or gravitational. This question of course has profound impacts on any paleoseismic investigation of the scarp.

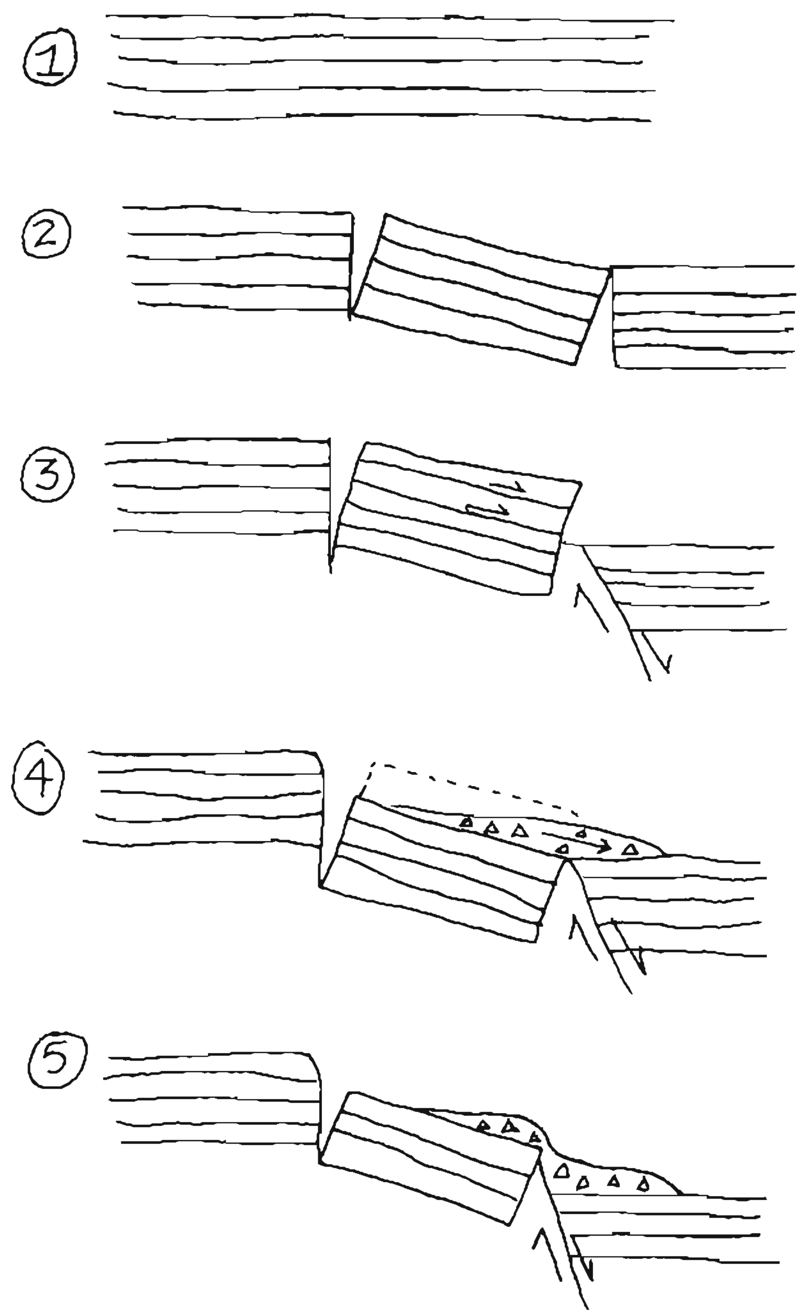
5.2 Mass wasting-controlled landforms

The most obvious mass wasting-controlled landforms are small- to medium-size translational and rotational landslides on the scarp face. These slides possess many characteristics of landslides, i.e. a curved headscarp, a hummocky body sharply delimited from the adjacent smoother topography, and a protruding toe. Examples of such small landslides include: 1) in the center of the scarp upslope from Highway 4, 2) 1 km south of Pajarito Canyon, and 3) the thin debris slides north of Canyon de Valle.

More ambiguous are those parts of the main fault scarp that appear to consist wholly of deep-seated rotational landslides, such as: 1) the section between Water Canyon and a large unnamed drainage 0.5 km to the north, 2) a 0.5 km long part of the scarp centered on the Water Tanks trench site of WCFS, south of Canyon de Valle, and 3) a 0.5 km reach south of Pajarito Canyon. In these reaches the scarp face is composed of slopes and benches, rather than a smooth east-facing slope. The toe of the scarp is composed of lobe-like areas of bedrock that protrude farther east than usual, separated by poorly-defined reentrants. The crest of the scarp is slightly scalloped. All these landforms are suggestive of deep-seated rotational slumping.

The geometry of the failure plane and its stratigraphic setting can only be guessed at. Given the segmented-monocline structure of the scarp in many places, the central east-tilted block could be undermined by slip on the basal fault zone (Fig. 44). This undermining would most likely create translational bedrock slides rather than slumps. The existence of landforms such as benches and slope-parallel trenches suggests a strong rotational component to sliding in places, which requires a curved failure plane. Such a curved failure plane could conceivably be created by a complex linkage between 25-40 degree dipping partings and subvertical fractures and fault zones.

Fig. 44. Schematic diagrams showing the inferred evolution of the main scarp and how it could lead to landsliding. (1) pre-faulting geometry of the tuff; lines show boundaries of cooling units; (2) dip-slip faulting creates a segmented monocline; (3) continued displacement on the basal fault zone "daylights" bedding plane structures in the tuff (i.e. weak unwelded strata, surge beds, etc.); (4) the undermined slabs slide downslope as translational bedrock slides: some rubbilization occurs; (5) further displacement on the basal fault zone offsets the landslide mass. This sequence was based on field relations observed south of Pajarito Canyon.



Deep-seated slumping is rare elsewhere in the upper 100 m of the Tshirege member of the Bandelier Tuff, even on the steep canyon sidewalls of the Pajarito Plateau. This lack of sliding is understandable, since the rocks in the upper 100 m of the tuff contain no clayey interbeds or altered horizons that might have low enough shear strength to permit sliding (Rogers, 1995). The question thus arises, why is slumping so common on the Pajarito fault scarp? One obvious answer is that faulting and toppling of the scarp has broken up the tuff into many fissure-bounded blocks on the scarp. Due to the 25-40 degree eastward dip of strata in most of these blocks, downslope movement (not necessarily rotational) is inevitable. Thus dip-slip faulting created large-scale toppling, and that toppling set up favorable conditions for landsliding. An additional factor must be the availability of groundwater in the region of the scarp, due to infiltration from precipitation at higher elevations on the rim of the Valles caldera. However, one would imagine that the deep dissection of the scarp at Water Canyon, Canyon de Valle, and Pajarito Canyon would have locally lowered the water table to near the base of the scarp. Ironically, it is in these three areas that landslides are most common.

This interplay of faulting, toppling, and landsliding constitutes a major source of ambiguity in interpreting faults exposed in cuts or trenches. At any one site, how do we distinguish a tectonic fault, a fissure caused by toppling, or shears and fissures caused by landsliding? The best criterion is the geomorphic setting of the exposed fault or fissure. If the fault has a steep east dip and bounds domains of near-horizontal tuff, it is probably a tectonic fault. If the fault or fissure separates horizontal from east-tilted tuff, it is probably related to toppling. If the shears occur at the scalloped head or margins of a benched area on the scarp with a protruding toe, then a landslide origin is indicated.

One area where the ambiguity is greatest is at the crest of the scarp, where scarp-parallel troughs and benches are common (Fig. 45). In some areas these troughs occur upslope of obvious large landslides, such as north of Water Canyon and above the Water Tanks area. These troughs are presumably incipient landslides features. In other areas, such as north of Canyon de Valle, the scarp face below the troughs is relatively planar and is not mapped as containing landslides. What then is the origin of these troughs?

First, troughs are in the proper structural position to overlie crestal tension fissures, such as described in Sec. 4.2.3. This seems to be the case north of Canyon de Valle, where the tuff above the scarp is horizontal but on the scarp face dips 25-30 degrees east. However, the crestal topography is often more complex and chaotic than the simple bench landforms previously defined as overlying topple fissures (Figs. 39-41). Troughs often form an anastomosing network that isolates raised tuff blocks and they divert or behead small drainages from above the scarp. It appears that the troughs outline blocks of tuff, usually bedded horizontally, that are being separated by nearly horizontal extension toward the scarp face. In places small blocks of tuff are rotated back into the scarp, as if responding to rotational slumping (Fig. 46).

The small landforms at the scarp crest (1-2 m wide, tens of meters long) could conceivably represent tectonic faulting, toppling, or landsliding. The landforms are youthful, i.e. scarps are steep (although vegetated), drainages are beheaded, and closed depressions occur. Although a rigorous program of dating was beyond the scope of this study, the landforms are sufficiently fresh to suggest Holocene movement, or even

Fig. 45. Photograph of scarp-parallel troughs at the crest of the scarp north of Canyon de Valle. Drainage in the troughs is not integrated, suggesting recent movement.

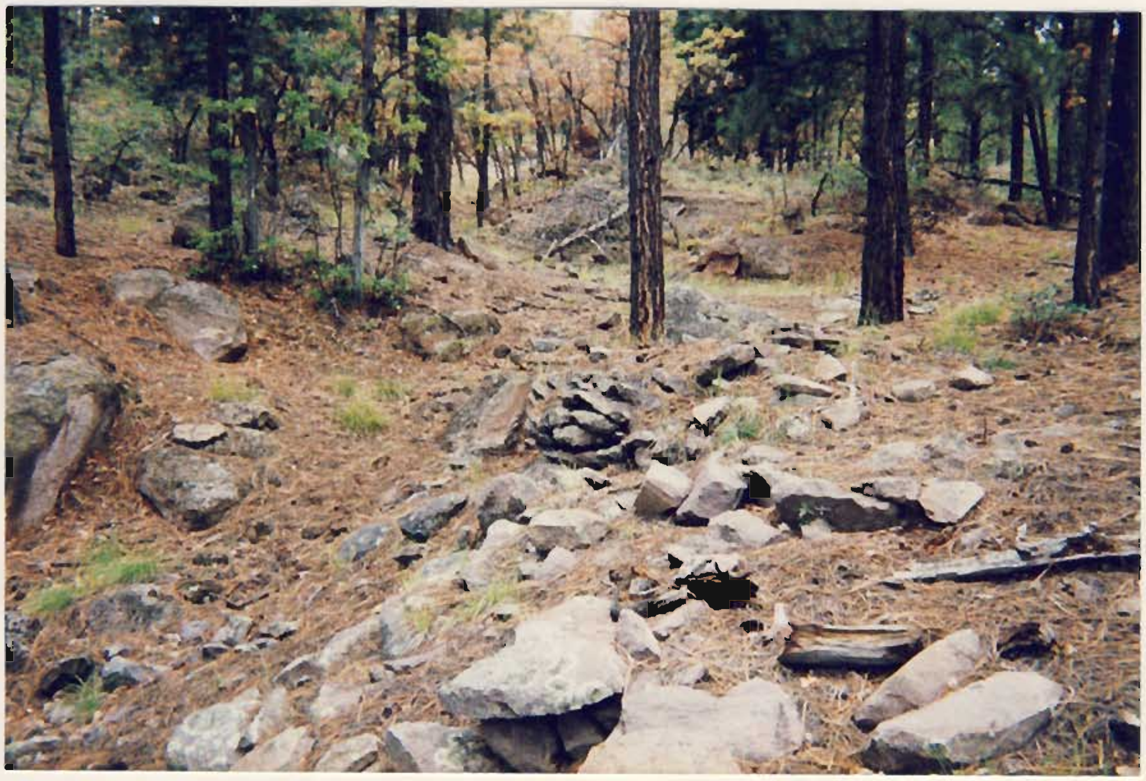
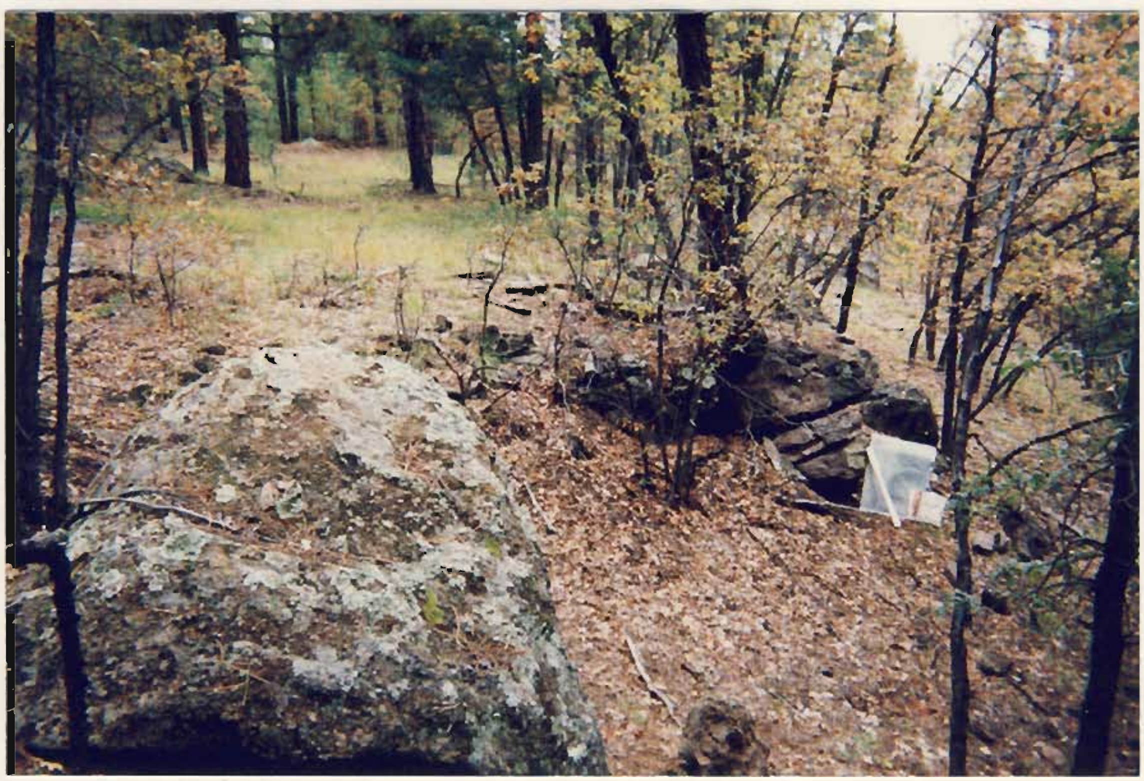


Fig. 46. Photograph of benched terrain at the crest of the main fault scarp north of Canyon de Valle. The block against which the clipboard is leaning displays prominent bedding-type joints dipping 25 degrees W, or back into the slope, as if the block has been back-rotated.



ongoing slow movement. If such deformation is tectonic, then it conflicts with the conclusion of WCFS (1995) that the youngest faulting on the main scarp is of pre-El Cajete age. If the deformation is gravitational in origin, it could be of any age.

A final source of ambiguity concerning troughs and benches on the main scarp is the triggering mechanism for movement. Even if the landforms are created by gravitational processes such as landsliding or toppling, both processes can be caused by seismic shaking or by nonseismic causes such as intense rainstorms or rapid snowmelt. Thus, once the scarp has reached its present height of 100+ meters, toppling could proceed either under the force of gravity, accelerated by rises in groundwater level, or by intense shaking during surface-rupturing earthquakes. Because many topple fissures probably formed to accommodate vertical displacement, and may be connected to steeply-dipping faults at depth, during a given earthquake movement on a topple fissure might be classified as either primary fault deformation or as secondary induced landsliding (after the classification of McCalpin and Nelson, 1996).

Due to the ambiguity about the genesis of troughs and benches, and their triggering mechanisms, paleoseismic investigations should avoid areas of suspected landsliding. It is interesting to note that, according to my detailed mapping , the two Water Tanks trenches dug by WCFS are in a landslide block, and the Pajarito Canyon trench is in an area of complex splay faulting and landsliding. Only the Water Canyon trench is located where deformation is relatively simple, but it probably did not extend far enough west to intersect the main fault zone.

6. POTENTIAL SITES FOR TRENCHING INVESTIGATIONS

6.1 Philosophy of Trench Siting

My philosophy of trench siting on the Pajarito fault scarp is based on three concepts. First, trenches should avoid areas of clear or even suspected landsliding, since we cannot know whether such landsliding was triggered nonseismically or seismically. Second, on each tectonic landform trenched we should attempt to expose most of the paleoseismic record, i.e. trench as completely as possible though the colluvial wedge. Due to the depth limitation of backhoes, this means that smaller scarps make better trenching targets than larger scarps. Third, we wish to identify and date the most recent faulting event on the main fault trace, to determine whether the main and antithetic faults rupture simultaneously.

These three concepts dictate that we avoid the ~30% of scarp length affected by deep-seated landsliding. The remainder of the scarp exhibiting a planar scarp face is too high, however, to be completely trenched without creating a costly, dangerous, and obtrusive hole on the scarp. For example, where the fault scarp is relatively planar 200-500 m south of the Water Tanks, the colluvium-bedrock contact is 100 ft above the level of West Jemez Road. Thus a megatrench that exposed the entire colluvial wedge would have to be about 100 ft deep. Excavating such a trench would be similar to creating an open-pit mine. An alternative would be to dig a 5-6m-deep trench and expose only the effects of the latest few events on that fault trace, but even this would be difficult.

An attractive option would be to trench the fault zone south of Los Alamos Canyon, where the vertical displacement is partitioned among many east-facing and west-facing scarps. This approach has both advantages and disadvantages, as outlined below.

6.2 Transect South of Los Alamos Canyon

My preferred option for detecting the most recent faulting event on the Pajarito fault, as well as for refining estimates of recurrence, is to trench multiple scarps in a transect south of Los Alamos Canyon. This option follows the philosophy established in many prior trenching investigations, where different types of sites are considered superior for deciphering the timing of faulting events as opposed to measuring displacement (Weldon et al., 1996). Since our main concern is in identifying and dating the most recent (and earlier) faulting events, we wish to locate sites along the fault zone where faulting is widely distributed, i.e. not where successive events on a single fault trace successively overprint earlier events. Where successive surface faulting is widely distributed, it is more likely that new faults will be created and older faults not reactivated. Where this happens the age of faulting is constrained by the stratigraphic level at which the various faults terminate. This approach is the main one used at classic trench sites on strike-slip faults such as the San Andreas fault in southern California (Sieh, 1978; Fumal et al., 1993; Weldon et al., 1996).

On the Pajarito fault the widest deformation zone (2 km wide) is found immediately south of Los Alamos Canyon. The main structural components there are the 50 m-high main scarp (i.e., less than half the typical height of the scarp elsewhere), and adjacent 170 m-wide graben. The structure of the main scarp is shown in Fig. 22. East of the graben is a 100-200 m-wide horst, bounded by low east-facing scarps. West of the main scarp are several poorly-expressed fault traces; the one 240 m west of the main scarp crest forms a well-preserved 2 m-high west facing scarp. The locations of seven potential trench sites were laid out and flagged by the author and J. Gardner on 25 Nov. 1996 (Fig. 49).

The main advantage to trenching the multiple faults in this area is that most scarps are small and can be completely trenched. On the main scarp the basal fault zone will require about a 6 m-deep trench to expose colluvium from the latest few events (Fig. 47). This trench must excavate through the farthest-downslope toppled block in order to capture the entire basal deformation zone. (In contrast, the Pajarito Canyon trench of WCFS stopped about 0.5m downslope of this contact, and thus did not expose the main basal fault plane.) In order to conform to OSHA standards, a 6 m-deep trench must either be shored or benched with 5 ft-high benches (Fig. 48).

An additional advantage of this transact for identifying many paleoseismic events is the 170 m-wide graben. It is likely that a graben of this width contains internal faults that are not expressed at the ground surface (e.g. similar to the many small faults observed in WCFS trenches). Grabens are preferred locations on normal faults for dating paleoearthquakes because alternating distributed secondary faulting and graben deposition creates upward fault terminations at different stratigraphic levels. Also, tilted subdomains within the graben can create angular unconformities, with dips increasing with depth (e.g. McCalpin et al., 1994). The ambiguity of origin associated with fault traces on a 100 m-high fault scarp does not exist for shears in the 170 m-wide graben; it is very unlikely that shears in graben could be created by landsliding or toppling, since they are so

Fig. 47. Schematic diagram showing how the proposed 6 m-deep trench at the basal fault zone must dig into the lowest toppled block of tuff. Tuff is represented by parallel lines representing bedding fractures; colluvuim at right has no pattern.

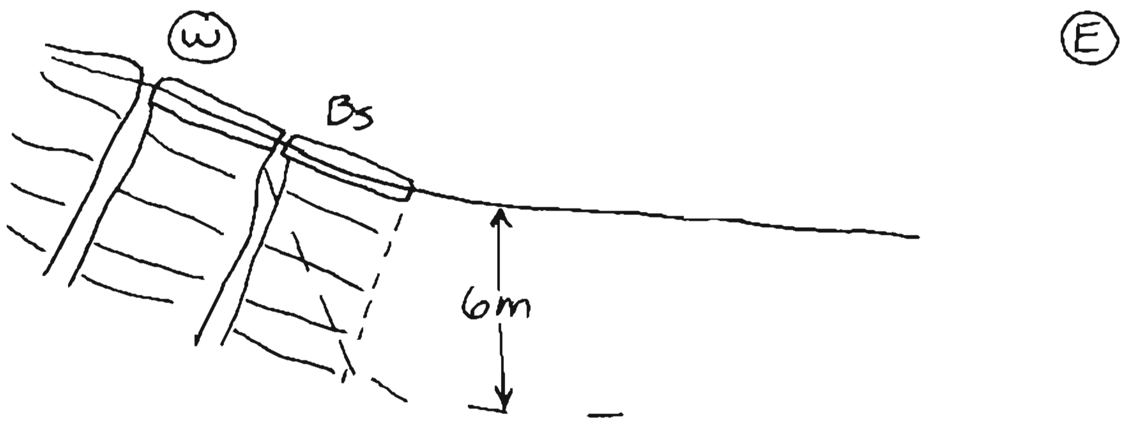


Fig. 48. Schematic cross-section of a 20 ft (6 m) deep trench showing the upper 10 ft can be benched. The lower 10 ft must be shored.

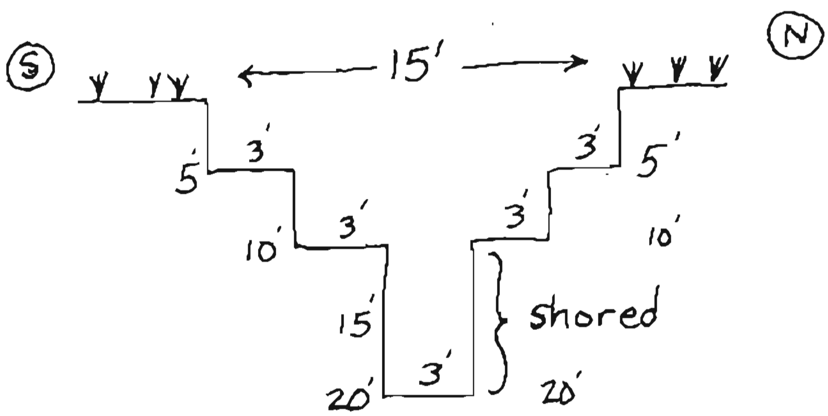
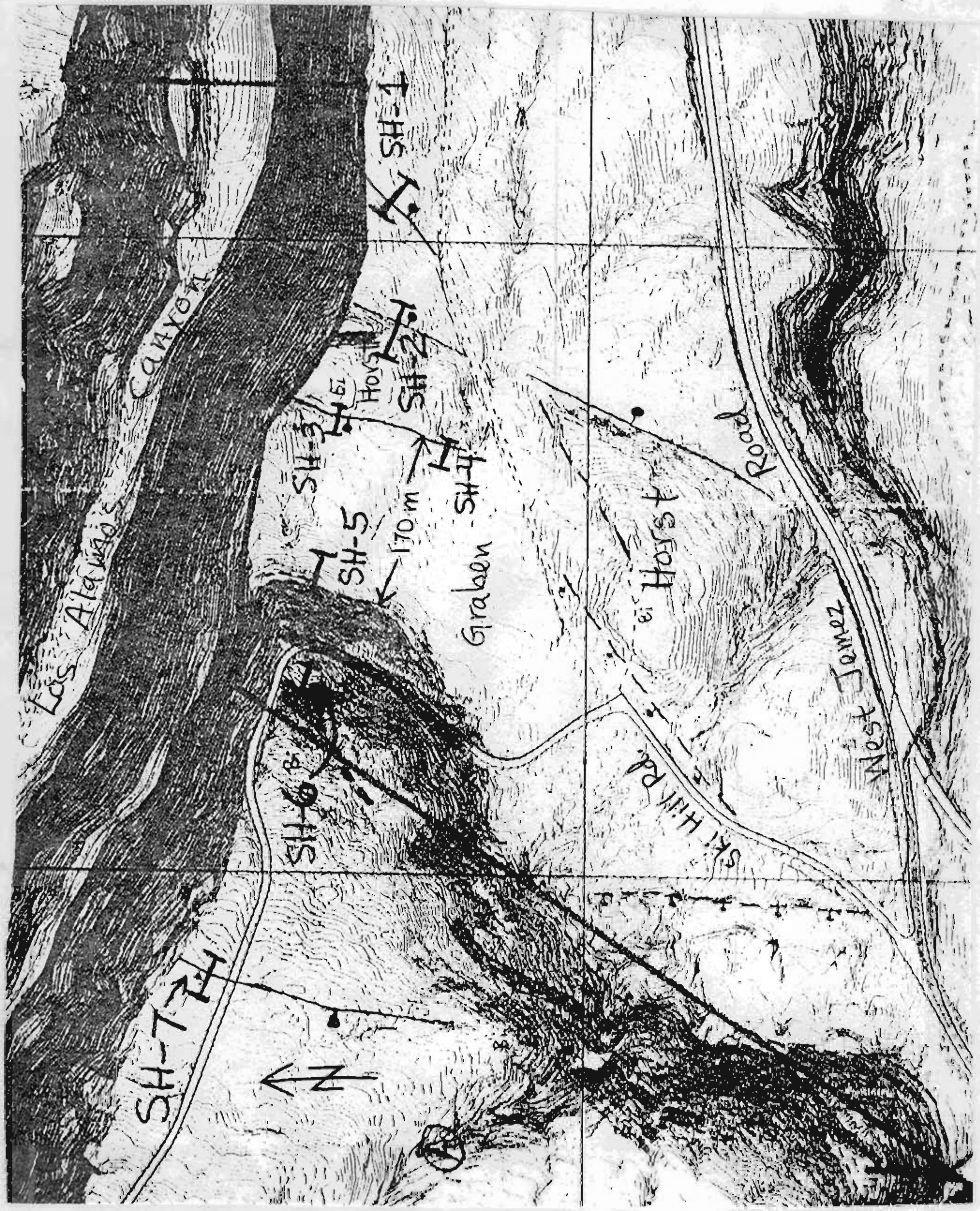


Fig. 49. Topographic map of the Pajarito fault zone south of Los Alamos Canyon, showing the locations for the seven trenches in the transect. Contour interval = 2 ft; 10 ft between bold contours. Bar-and-ball are on the downthrown side of the scarp.



far from slopes.

Due to the promising nature of the graben for preserving paleoseismic evidence, I recommend performing a seismic refraction survey of several lines across the graben. This survey should show any abrupt changes in depth to bedrock that might be caused by hidden intragraben faults. In addition, the survey would tell us how thick the graben fill is, and this information would be good to know before excavating the two trenches at the eastern and western margin of the graben.

The one disadvantage of trenching the transect here is that displacement has died down considerably from the maximum. WCFS (1995) inferred that some component of displacement at this latitude is being transferred to the Rendija Canyon fault. The manner in which displacement might be transfered from the Pajarito fault to the antithetic fault is critical to paleoseismic interpretation. If every surface rupturing event on the Pajarito fault ruptures as far north as Los Alamos Canyon, but displacement per event decreases northward, then evidence for every paleoearthquake should be present in the scarps to be trenched on our transect. In contrast, if the decreased net throw at Los Alamos Canyon is caused by some paleoearthquake ruptures transferring from the Pajarito Fault to the Rendija Canyon fault south of our transect, then those rupture events will not be present in our trenches. From this perspective, it would be advantageous to trench south of Pajarito Canyon, which is south of the rapid drop in net throw on the main scarp (WCFS, 1995, Fig. 4-3a). However, the scarp south of Pajarito Canyon contains flaws for paleoseismic study, as previously described.

If one or more paleoearthquakes transferred rupture to the Rendija Canyon fault south of our transect, we will not know it, since such events will not be present in our trenches. Conversly, if we identify a post-El Cajete rupture in our trenches, we can safely assume that it continued on the Pajarito fault for some distance south of our transect. Thus, failure to identify a post-El Cajete rupture in our transect does not prove that there were no such ruptures on the Pajarito fault south of the transect. If this is the result of trenching the transect near Ski Hill Road, then the only remaining test for post-El Cajete rupture on the Pajarito fault would require trenching farther south on the fault zone.

6.3 Trenches on the Highway 4 Facet

The fault scarp ascended by Highway 4 possesses the best existing artificial exposures of toppling-related deformation. However, these exposures do not typically expose the interaction of the fissure with the modern ground surface. This relation is critical for determining the age of latest movement on the fissure. Fortunately, the large topple fissure near the crest of the scarp forms a bench on the scarp face (Fig. 39) that is easily accessed by an old jeep road that switchbacks up the scarp. This surface expression of the fissure is superior to the one that must be trenched in the transect at Ski Hill Road, which was disturbed by road-building, so I propose that a trench here would be optimum for defining the general usefulness of toppling fissures in paleoseismic investigations.

The basal fault zone is also well-exposed below Highway 4 (Fig. 23). The site can also be accessed via an old jeep trail at the foot of the scarp, so constitutes a good trenching site.

The remaining deformation on the Highway 4 scarp is accommodated by a wide zone of complex toppling deformation exposed in roadcuts. Much of this deformation could be documented by logging roadcuts, and manually digging trenches just upslope of the roadcut. However, logistical considerations might limit the latter approach. In addition, an unknown proportion of the deformation lies south of the large Highway 4 hairpin curve, in Bandelier National Monument (this area was not mapped in this study). Trenching would probably not be possible within the Monument.

In summary, there are two good trench sites on the Highway 4 facet, but there are also additional zones of deformation that cannot be exposed. If post-El Cajete displacement is not observed in the two trenches, we will not know if such events never occurred here, or whether they might have ruptured a mid-scarp location that cannot be trenched. For this reason the Highway 4 facet is inferior to the Ski Hill Road tracsect for detecting young displacement.

6.4 Other Trench Sites

During November 1996 I flagged five additional trench sites that might contain evidence for post-El Cajete displacement. The first is a small alluvial fan at the foot of the 35 m-high western splay fault scarp north of Canyon de Valle. The intermediate age fan is apparently offset by a NNW-trending 3 m-high scarp fronted by a graben 25 m wide (Fig. 50). An alternative interpretation here is that the alluvial fan is draped over a smaller fault scarp at the foot of the larger scarp. If the fan is faulted, and the assignment of intermediate (post-El Cajete) age is correct, then this location has evidence for post-El Cajote faulting which has so far not been documented on the higher main scarp, which lies about 450 m farther east.

Four additional trench sites were located in the large alluvial fan complex 350-650 m SW of the mouth of Pajarito Canyon (Fig. 51). Three of the trench sites are located across subtle down-to-the-east flexures across an intermediate age alluvial fan (map unit afi2). These flexures may be caused by small displacement faulting of the fan, by draping of fan deposits over preexisting scarps, or by purely depositional processes. The alluvial fan here is in a reentrant caused by a 40 degree change in strike of the fault scarp. In such structural reentrants it is common to have distributed small faults which "cut the corner" between the linear scarps to the north and south. In addition, trench site AF-1 is across a flexure which is on-strike with a N-S-trending linear gully farther south. This incised gully parallels the fault scarp, rather than flowing away from it, and so is presumed to follow a fault or fissure. The other two flexures at AF-2 and AF-3 parallel scarps on the north side of the reëntrant. Once again, if these flexures are underlain by faults, and the fan is post-El Cajete in age, then post-El Cajete faulting is demonstrated.

The final trench site (AF-4) is located west of sites AF 1 through 3, and traverses a 12 m-high scarp which is rather unusual on the Pajarito fault zone. No Bandelier Tuff is exposed on the scarp face, and the scarp profile has a rounded convex-concave profile shape typical of scarps developed entirely in unconsolidated deposits. The nature of the unconsolidated deposit faulted is unknown. The geomorphic surface above the scarp is mantled by old dacite gravels (map unit a3d), so perhaps the smooth scarp appearance results from reworking of dacite gravels over the scarp face between faulting events. The main reason this location was selected for trenching is that the colluvial wedge

Fig. 50. Geologic map of the central part of the western splay fault north of Canyon de Valle, showing the proposed trench site across a short 3 m-high scarp and adjacent graben in an intermediate-age alluvial fan (afi). The scarp is evidently composed of a 60 ft-high western scarp and a 20-30 ft-high eastern scarp. **Burial of the latter by the alluvial fan may be causing the flexure in the fan.**

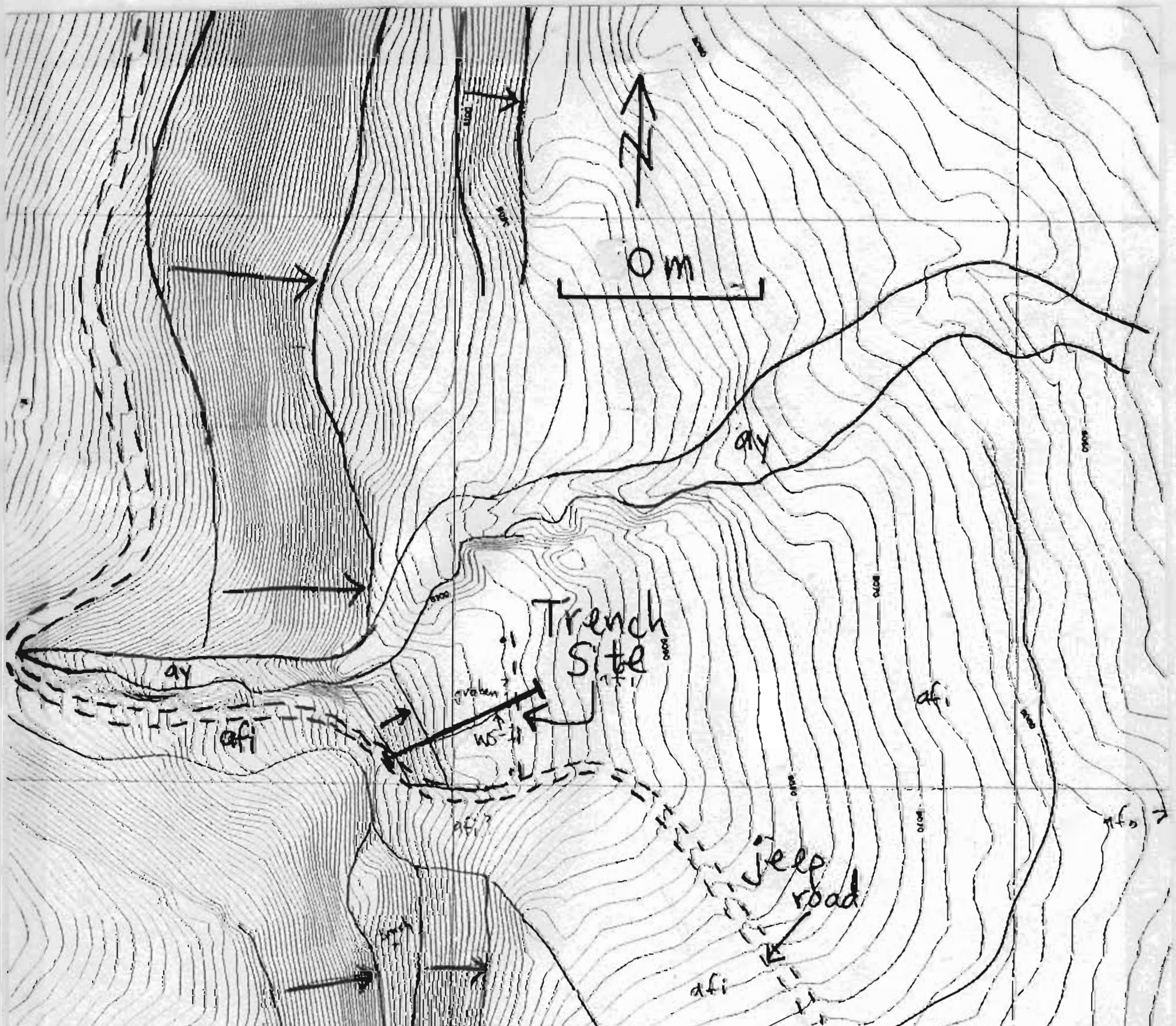


Fig. 51. Geologic map of the head of the large alluvial fan complex about 0.5 km SW of the mouth of Pajarito Canyon. Three trench sites (AF-1, 2, and 3) are located across subtle down-to-the-east flexures on an intermediate-age alluvial fan (afi2). Trench AF-4 is located farther west between old alluvium (a3d) and suspected slide block.

stratigraphy here may be similar to that examined in most other paleoseismic studies, having been derived by reworking an unconsolidated deposit. In contrast, most of the fresh rupture free faces elsewhere on the Pajarito fault scarp would have exposed only thin colluvium overlying bedrock in the post faulting free face, and this might lead to minimal colluvial sedimentation at the base of the rupture. However, it is acknowledged that even trenches AF-1 through 4 do not constitute a complete transect across the fault zone at this latitude. The highest scarp, downslope from AF-4, is not proposed for trenching because it may be a slide block. However, that same scarp could be trenched on the north side of the local drainage where it is easily accessible via a jeep road, if a complete transect here was deemed desirable.

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8. TASKS FOR TRENCHING THE PAJARITO FAULT, SUMMER 1997.

8.1 List of Tasks for Excavating 7 Trenches In the Ski Hill Road Transect

1. Obtain permits for excavating the 7 trench sites from USFS and/or Los Alamos County.

2. Arrange for a track-mounted backhoe to be at the trench sites on July 8, 1997. Preferred size is Caterpillar 230, Komatsu 220C, or equivalent. Note: Backhoe must be capable of cutting through small thicknesses of weathered Bandelier Tuff (= bedrock), and also ascending some slopes as steep as 20 degrees. Backhoe must dig the following 7 trenches, which I assume will be the transect south of Los Alamos Canyon (trench locations are shown on maps mailed 2 weeks ago to Eric McDonald)..
Trench 1-- 55 ft long, 8 ft deep, easy access, gentle terrain.
Trench 2-- 135 ft long, 12-14 ft deep, easy access, moderately sloping terrain.
Trench 3-- 57 ft long, 12-14 ft deep (possibly deeper), easy access, gentle terrain.
Trench 4-- 35 ft long, 12-14 ft deep, easy access, gentle terrain.
Trench 5-- 80-100 ft long, 16-20 ft deep, easy access, steep terrain.
Trench 6-- 65 ft long, 10-12 ft deep, easy access, steep terrain.
Trench 7-- 45 ft long, 12-14 ft deep, easy access, gentle terrain.
TOTAL Trench Length= 492 ft.

3. PERFORM SEISMIC REFRACTION PROFILING ACROSS GRABEN SOUTH OF LOS ALAMOS CANYON (SITES OF TRENCHES 3, 4, AND 5) IN ADVANCE OF TRENCHING. USE GEOMETRONICS ES-1220 12-CHANNEL SIGNAL ENHANCEMENT SEISMOGRAPH. PERSONNEL= J.P. MCCALPIN, HIRED GEOPHYSICIST. ESTIMATED TIME= 2 DAYS.

4. Excavate trenches. Will probably take full working 3-4 days.

5. Trenches must be shored to the appropriate safety standards required by LANL. Based on a spacing of 6 ft between shores, I estimate that approximately 82 shores will be needed.

6. Trenches must be fenced and posted with No Trespassing signage.

7. TRENCH WALLS WILL BE CLEANED AND GRIDDED WITH A STRING GRID. TRENCH WALLS WILL BE LOGGED, AND THEN SAMPLED FOR GEOCHRONOLOGY. TRENCHES WILL BE PHOTOGRAPHED. PERSONNEL=J.P. MCCALPIN, M.E. BERRY. ESTIMATED TIME= 22 DAYS

8. Geochronology samples must be dated. C-14 samples should be sent to a reputable lab (I use Beta Analytic, Miami, FL). TL samples will be analyzed by Steve Forman. Forman will collect samples on-site.

9. FIELD REVIEW OF TRENCHES FOR LANL PERSONNEL AND OTHERS. PERSONNEL= J.P. MCCALPIN, M.E. BERRY. ESTIMATED TIME= 4 DAYS.

10. Take down fences, remove shoring, backfill trenches, grade terrain, reseed and mulch.

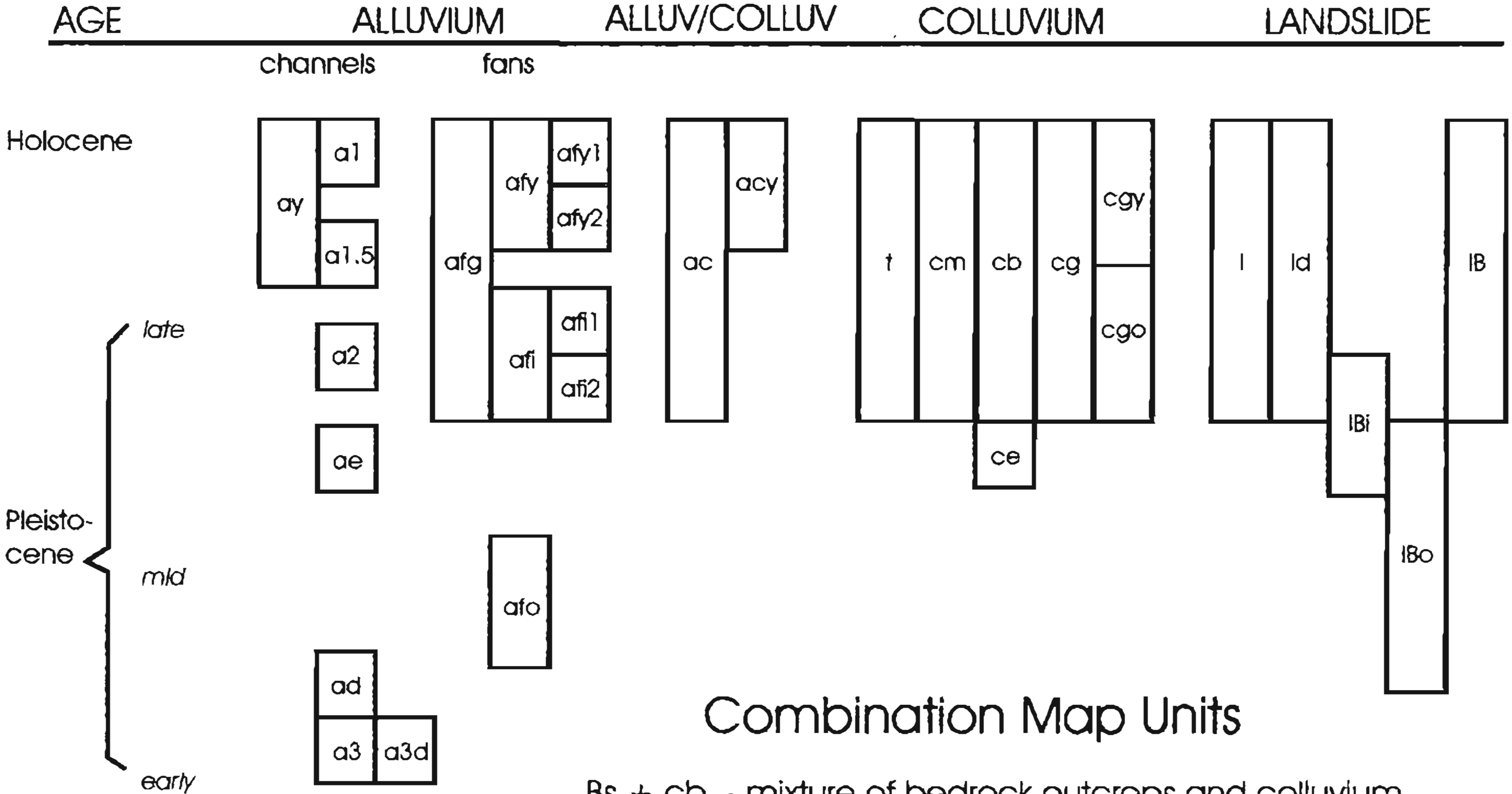
11. PREPARE WRITTEN REPORT ON THE TRENCHING CAMPAIGN, INCLUDING RESULTS OF GEOCHRONOLOGY ANALYSES. ALL TRENCH LOGS TO BE PROVIDED IN DIGITAL FORMAT. ESTIMATED TIME= 3 WEEKS. PERSONNEL= J.P. MCCALPIN, M.E. BERRY

8.2 Estimated Costs for Trenching the Transect

The following cost breakdown is for trenching the Ski Hill Road transect of scarps only (seven trenches). Trenching the additional seven trenches described in Secs. 6.3 and 6.4 would require about the same expenditure, but cannot be performed by GEO-HAZ during the summer of 1997 due to time limitations.

Task	Estimated Cost
1. Obtain Permits	$ 0.00
2. Arrange for Backhoe	$ 0.00
3. Perform Seismic Refraction Survey	$ 11,027.00
4. Excavate Trenches	$ 3,200.00
5&6. Shore trenches and fence	$ 23,100.00
7. Clean, grid, log, sample trenches	$ 40,749.00
8. Geochronology (S.L. Forman)	$ 24,968.00
9. Field review of trenches	$ 8,180.00
10. Remove shores and fences, backfill trenches, reclaim sites	$ 8,720.00
11. Prepare Report and trench logs	$ 24,900.00
TOTAL ESTIMATE	$144,844.00

CORRELATION OF MAP UNITS-- Unconsolidated Units



Combination Map Units

Bs + cb - mixture of bedrock outcrops and colluvium

$\frac{c\ b}{(B4)}$ Phrase in parentheses indicates parent material of colluvium

$\frac{c\ g}{B4}$ indicates thin cover of top unit over bottom unit

Appendix 2
EXPLANATION OF MAP SYMBOLS

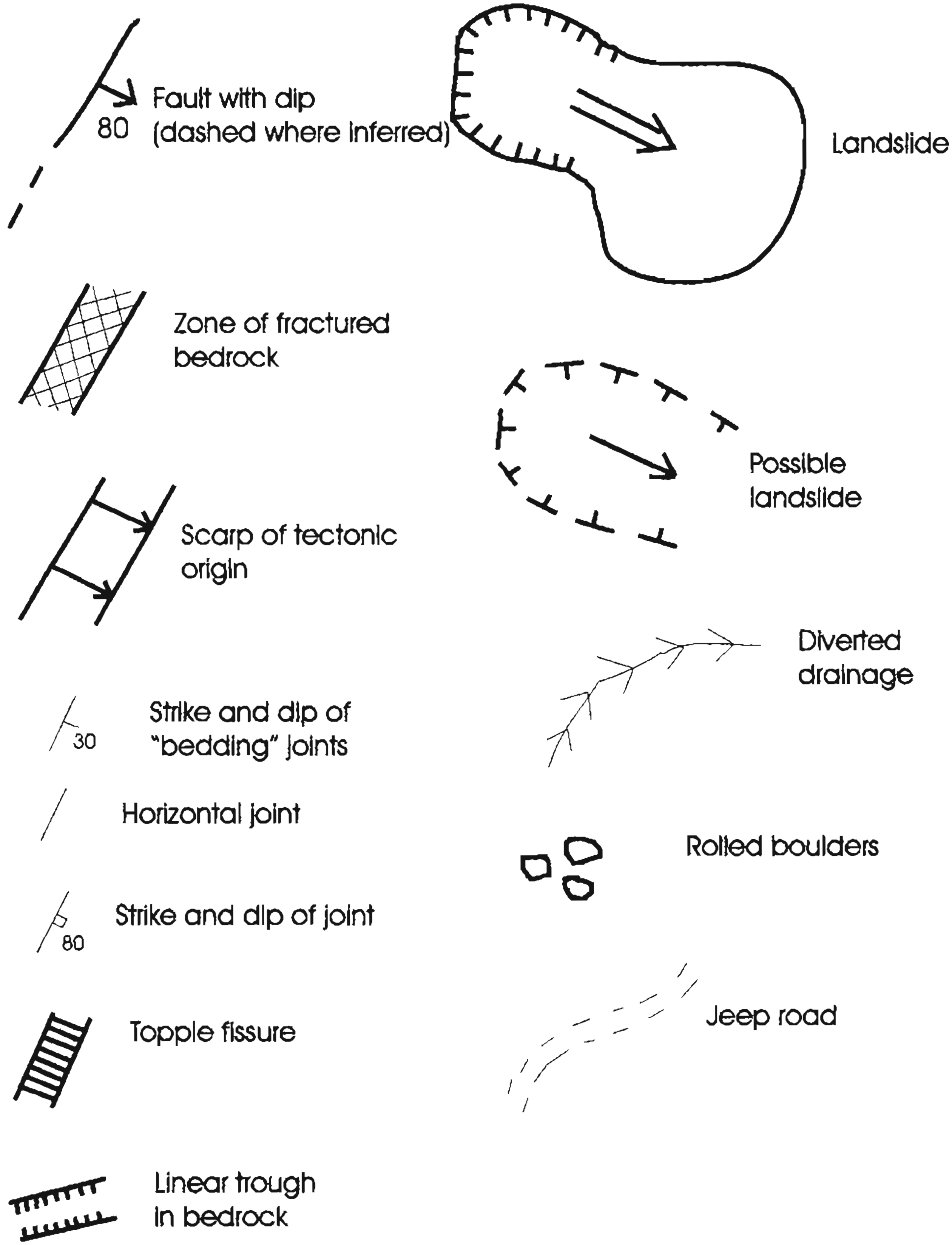


PLATE 1 in GEO-HAZ, 1997

PLATE 2 in GEO-HAZ, 1997

MAP 2

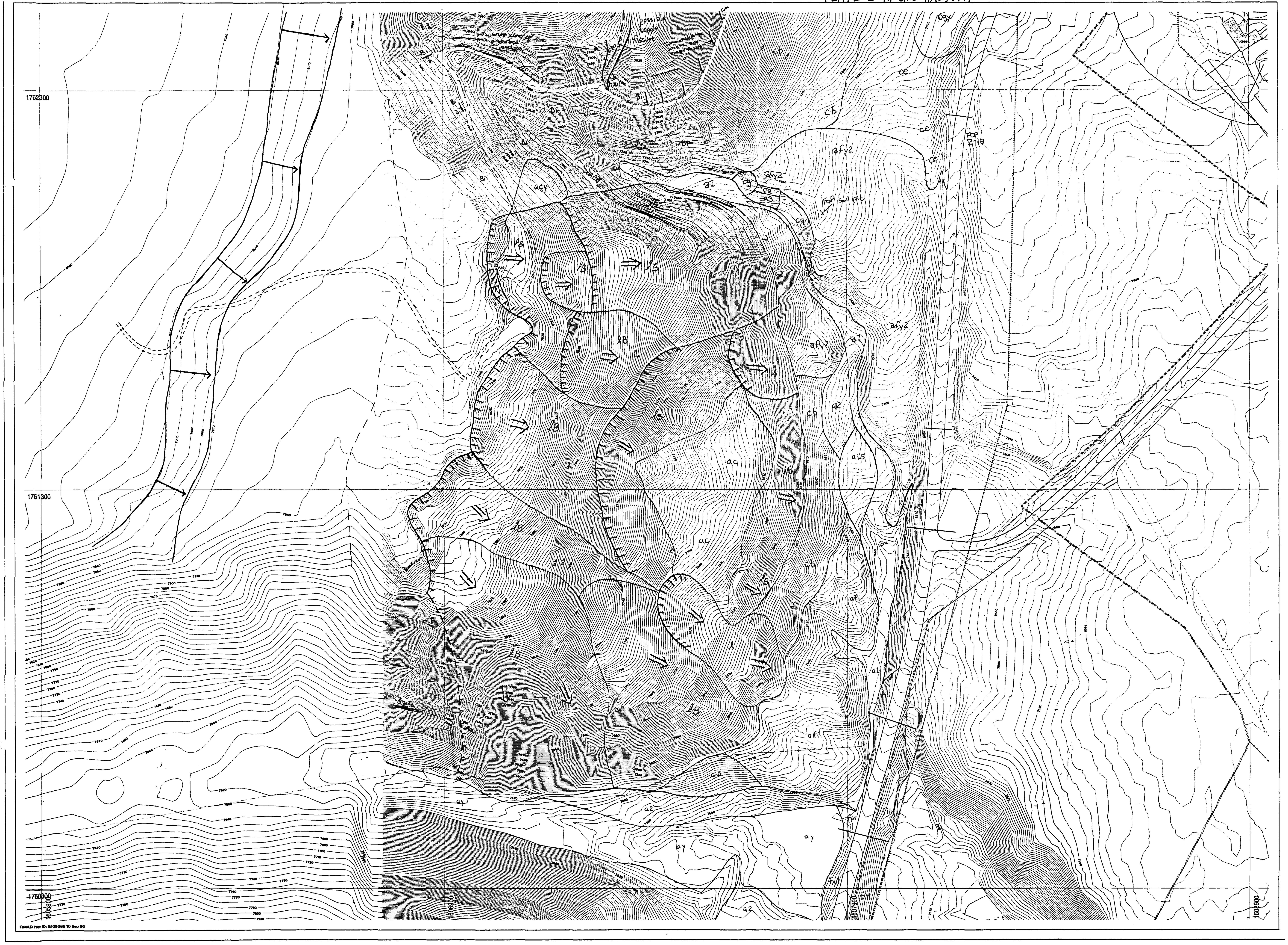
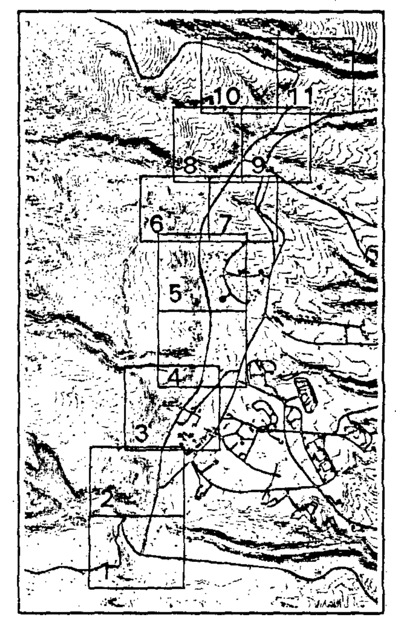


PLATE 4 in GEO-HAZ, 1997

Pajarito Fault Survey Map 4

LEGEND

- Contours, 2 foot
- Contours, 10 foot
- Cooling Lines
- Electrical > 13.2 kV
- Electrical < 13.2 kV
- Fence, Industrial
- Fence, Security
- Gas Line
- Industrial Waste Line
- LabNET Fiber Optic Cable
- Radioactive Liquid Waste Line
- Roads, Dirt
- Roads, Paved
- Road/Trail
- Sewer Line
- Steam Line
- Storm Drain/Culvert
- Telephone Line
- Water Line
- Building



FACILITY for INFORMATION MANAGEMENT ANALYSIS and DISPLAY
EARTH & ENVIRONMENTAL SCIENCES DIVISION (EES-5)

Produced by: Doug Walther
Date: September 10, 1996
FIMAD Plot ID: G105087

State Plane Coordinate System, New Mexico Central Zone.
1983 North American Datum

Grid provides NM State Plane coordinates in feet.
Grid interval, in feet: 1000
Feet per inch on map = 100

SCALE 1:1200

0 30 60 90 120 METERS

0 100 200 300 400 FEET

NOTICE: The information on this map is provisional. Feature locations are dependent on scale and symbology and their accuracy may not have been confirmed. Los Alamos National Laboratory boundary is based on legal description established in 1995. Contour data are from a September 1991 survey. All other data are from various sources and are part of the FIMAD repository.

FIMAD Plot ID: G105087 10 Sep 96

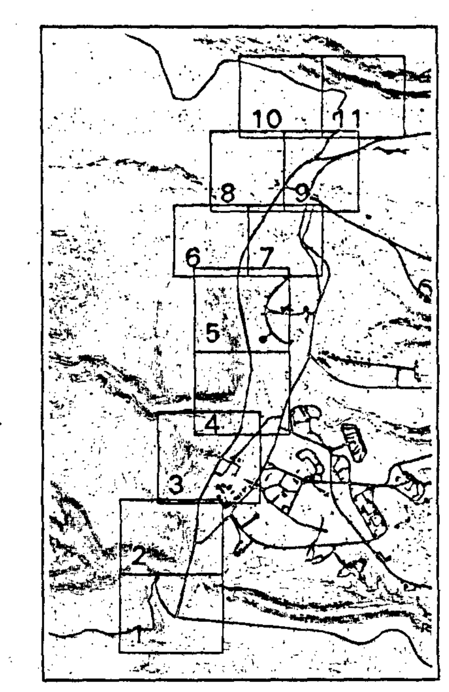
PLATE 5 in GEO-HAZ, 1997
Pajarito Fault Survey Map 5
LEGEND
Contours, 2 foot
Contours, 10 foot
Cooling Lines
Electrical > 13.2 kV
Electrical < 13.2 kV
Fence, Industrial
Fence, Security
Gas Line
Industrial Waste Line
LabNET Fiber Optic Cable
Radioactive Liquid Waste Line
Roads, Dirt
Roads, Paved
Road/Trail
Sewer Line
Steam Line
Storm Drain/Culvert
Telephone Line
Water Line
Building
1769100
1768100
1767100
1608200
1609200
1610200
Topography not correct
area not field checked
inferred buried fault
Note stepover
small grabens and ridges
FACILITY for INFORMATION, MANAGEMENT, ANALYSIS and DISPLAY
EARTH & ENVIRONMENTAL SCIENCES DIVISION (EES-5)
Produced by: Doug Walther
Date: September 10, 1996
FIMAD Plot ID: G105088
State Plane Coordinate System, New Mexico Central Zon
1983 North American Datum
Grid provides NM State Plane coordinates in feet.
Grid interval, in feet: 1000
Feet per inch on map = 100
SCALE 1:1200
METERS
FEET
NOTICE: The information on this map is provisional. Feature locations are dependent on scale and symbology and their accuracy may not have been confirmed. Los Alamos National Laboratory bound is based on legal description established in 1995. Contour data are from a September 1991 aerial survey. All other data are from various sources and are part of the FIMAD repository.

PLATE 6 in GEO-HAZ, 1997

Pajarito Fault Survey Map 6

LEGEND

- Contours, 2 foot
- Contours, 10 foot
- Cooling Lines
- Electrical > 13.2 kV
- Electrical < 13.2 kV
- Fence, Industrial
- Fence, Security
- Gas Line
- Industrial Waste Line
- LabNET Fiber Optic Cable
- Radioactive Liquid Waste Line
- Roads, Dirt
- Roads, Paved
- Road/Trail
- Sewer Line
- Steam Line
- Storm Drain/Culvert
- Telephone Line
- Water Line
- Building



FACILITY for INFORMATION, MANAGEMENT, ANALYSIS and DISPLAY
EARTH & ENVIRONMENTAL SCIENCES DIVISION (EES-5)

Produced by: Doug Walther
Date: September 10, 1996
FIMAD Plot ID: G105089

State Plane Coordinate System, New Mexico Central Zone.
1983 North American Datum

Grid provides NM State Plane coordinates in feet.
Grid interval, in feet: 1000
Feet per inch on map = 100

SCALE 1:1200

0 30 60 90 120
METERS
0 100 200 300 400
FEET

NOTICE: The information on this map is provisional. Feature locations are dependent on scale and symbology and their accuracy may not have been confirmed. Los Alamos National Laboratory boundary is based on legal description established in 1995. Contour data are from a September 1991 aerial survey. All other data are from various sources and are part of the FIMAD repository.

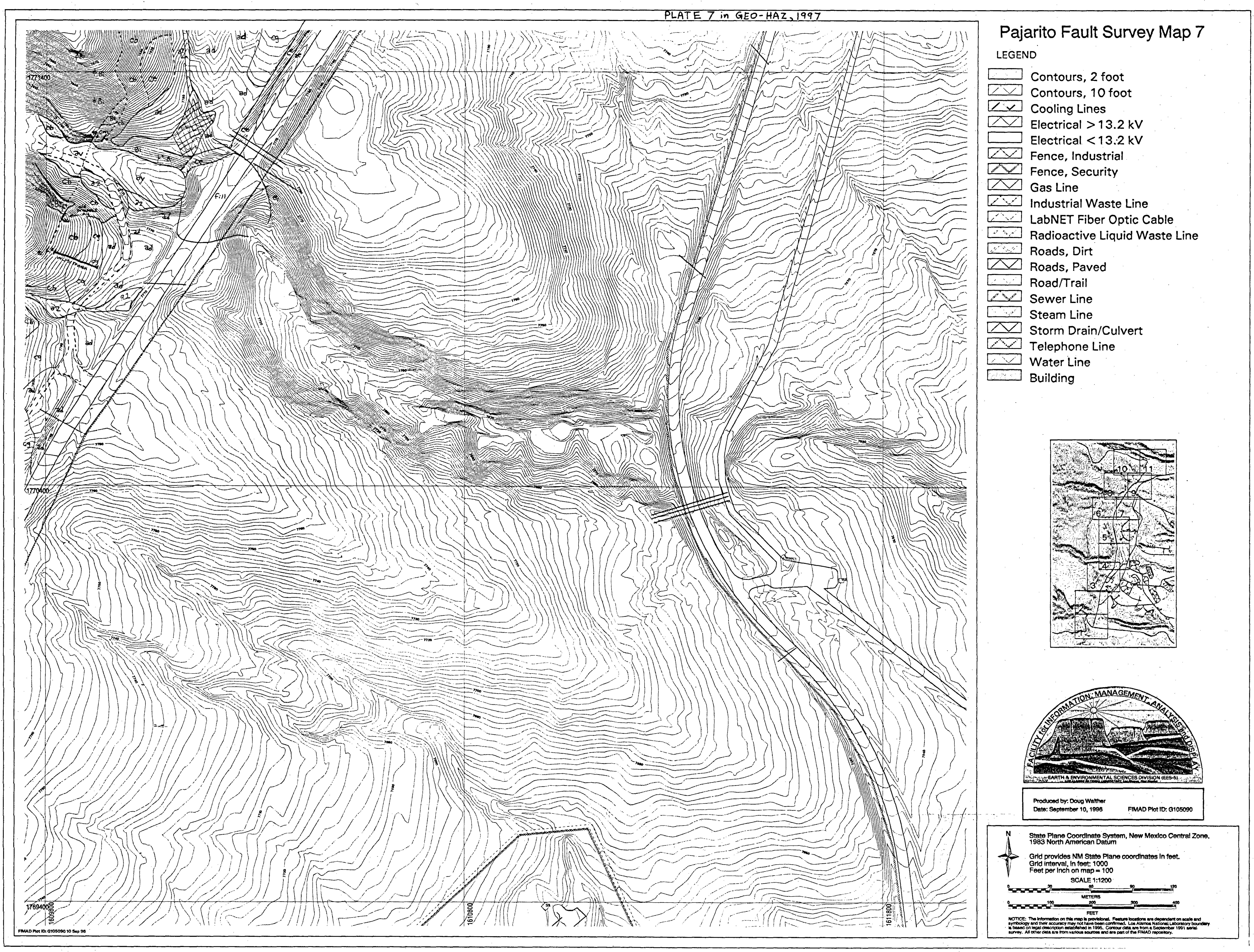
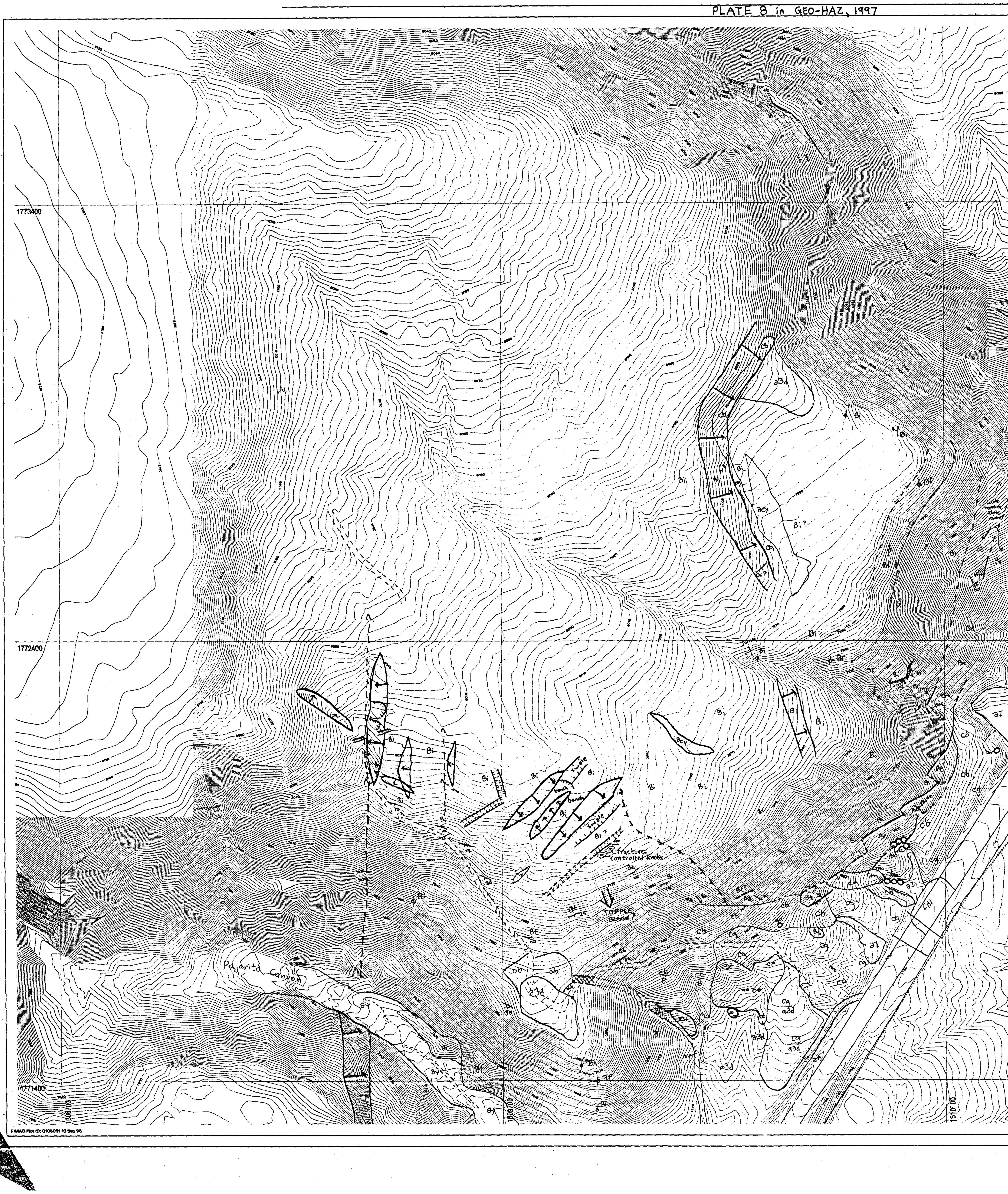


PLATE 7 in GEO-HAZ, 1997
Pajarito Fault Survey Map 7
LEGEND
Contours, 2 foot
Contours, 10 foot
Cooling Lines
Electrical > 13.2 kV
Electrical < 13.2 kV
Fence, Industrial
Fence, Security
Gas Line
Industrial Waste Line
LabNET Fiber Optic Cable
Radioactive Liquid Waste Line
Roads, Dirt
Roads, Paved
Road/Trail
Sewer Line
Steam Line
Storm Drain/Culvert
Telephone Line
Water Line
Building
FACILITY for INFORMATION MANAGEMENT, ANALYSIS and DISPLAY
EARTH & ENVIRONMENTAL SCIENCES DIVISION (EES-5)
Produced by: Doug Walther
Date: September 10, 1996
FIMAD Plot ID: G105090
N
State Plane Coordinate System, New Mexico Central Zone.
1983 North American Datum
Grid provides NM State Plane coordinates in feet.
Grid interval, in feet: 1000
Feet per inch on map = 100
SCALE 1:1200
0 30 60 90 120
METERS
0 100 200 300 400
FEET
NOTICE: The information on this map is provisional. Feature locations are dependent on scale and symbology and their accuracy may not have been confirmed. Los Alamos National Laboratory boundary is based on legal description established in 1995. Contour data are from a September 1991 aerial survey. All other data are from various sources and are part of the FIMAD repository.
1771400
1770400
1769400
1610800
1611800
FIMAD Plot ID: G105090 10 Sep 96

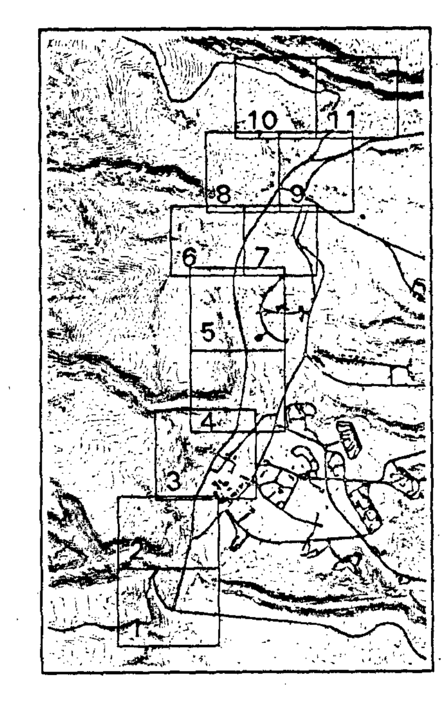
PLATE 8 in GEO-HAZ, 1997



Pajarito Fault Survey Map 8

LEGEND

- Contours, 2 foot
- Contours, 10 foot
- Cooling Lines
- Electrical > 13.2 kV
- Electrical < 13.2 kV
- Fence, Industrial
- Fence, Security
- Gas Line
- Industrial Waste Line
- LabNET Fiber Optic Cable
- Radioactive Liquid Waste Line
- Roads, Dirt
- Roads, Paved
- Road/Trail
- Sewer Line
- Steam Line
- Storm Drain/Culvert
- Telephone Line
- Water Line
- Building



FACILITY for INFORMATION, MANAGEMENT, ANALYSIS and DISPLAY

EARTH & ENVIRONMENTAL SCIENCES DIVISION (EES-5)

Produced by: Doug Walther
Date: September 10, 1996 FIMAD Plot ID: G105091

N

State Plane Coordinate System, New Mexico Central Zone.
1983 North American Datum

Grid provides NM State Plane coordinates in feet.
Grid interval, in feet: 1000
Feet per inch on map = 100

SCALE 1:1200

0 30 60 90 120
METERS
0 100 200 300 400
FEET

NOTICE: The information on this map is provisional. Feature locations are dependent on scale and symbology and their accuracy may not have been confirmed. Los Alamos National Laboratory boundary is based on legal description established in 1995. Contour data are from a September 1991 aerial survey. All other data are from various sources and are part of the FIMAD repository.

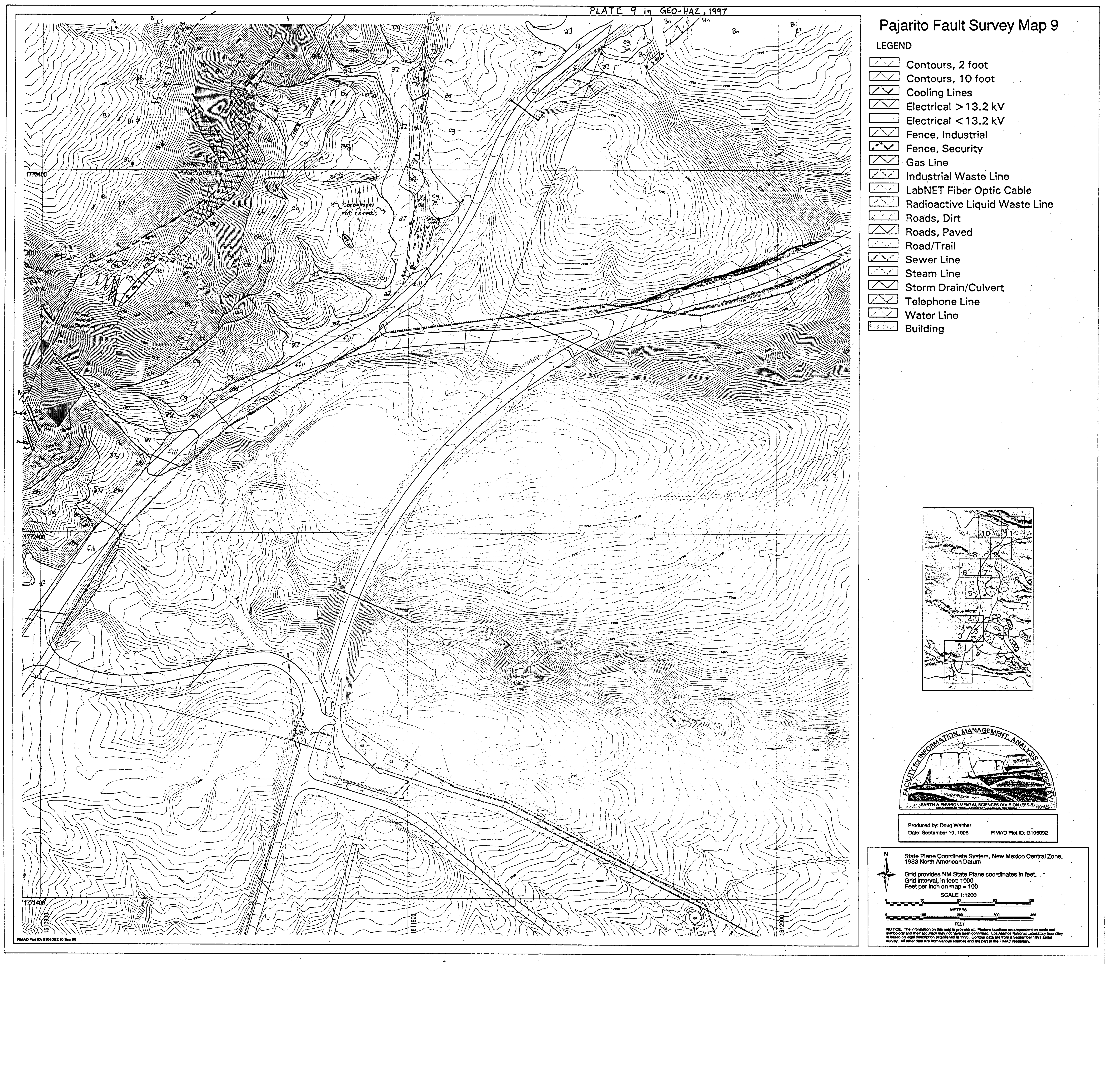
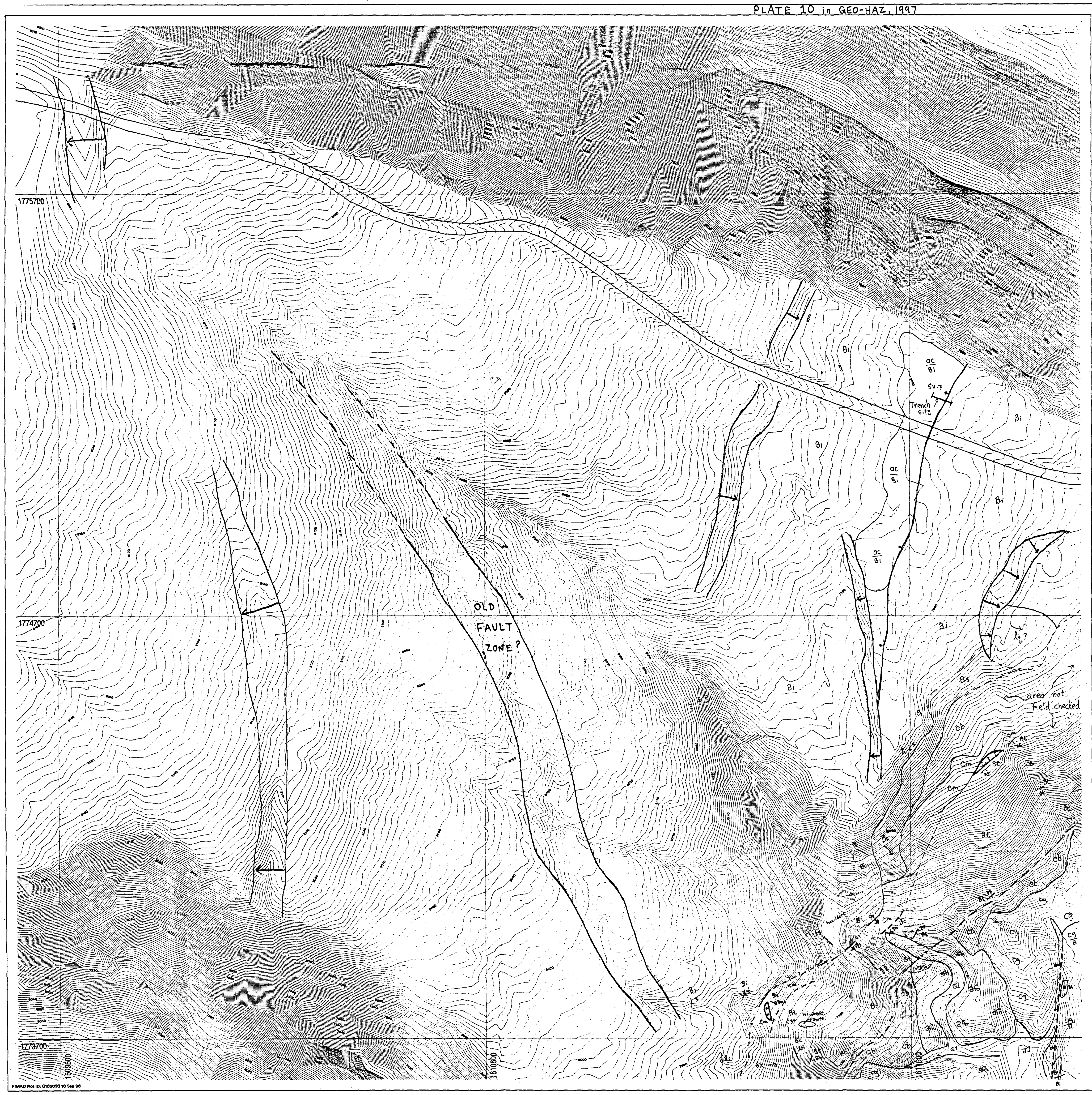


PLATE 9 in GEO-HAZ, 1997
Pajarito Fault Survey Map 9
LEGEND
Contours, 2 foot
Contours, 10 foot
Cooling Lines
Electrical >13.2 kV
Electrical <13.2 kV
Fence, Industrial
Fence, Security
Gas Line
Industrial Waste Line
LabNET Fiber Optic Cable
Radioactive Liquid Waste Line
Roads, Dirt
Roads, Paved
Road/Trail
Sewer Line
Steam Line
Storm Drain/Culvert
Telephone Line
Water Line
Building
zone of fractures
topography not correct
fill
FACILITY for INFORMATION, MANAGEMENT, ANALYSIS and DISPLAY
EARTH & ENVIRONMENTAL SCIENCES DIVISION (EES-5)
Produced by: Doug Walther
Date: September 10, 1996
FIMAD Plot ID: G105092
State Plane Coordinate System, New Mexico Central Zone.
1983 North American Datum
Grid provides NM State Plane coordinates in feet.
Grid interval, in feet: 1000
Feet per inch on map = 100
SCALE 1:1200
METERS
FEET
NOTICE: The information on this map is provisional. Feature locations are dependent on scale and symbology and their accuracy may not have been confirmed. Los Alamos National Laboratory boundary is based on legal description established in 1995. Contour data are from a September 1991 aerial survey. All other data are from various sources and are part of the FIMAD repository.

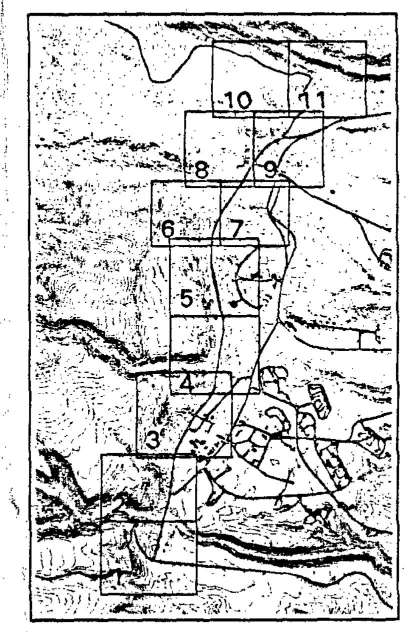
PLATE 10 in GEO-HAZ, 1997

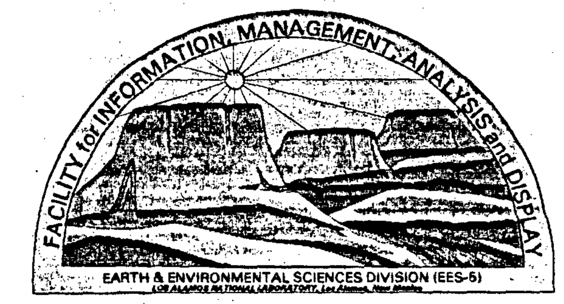


Pajarito Fault Survey Map 10

LEGEND

- Contours, 2 foot
- Contours, 10 foot
- Cooling Lines
- Electrical > 13.2 kV
- Electrical < 13.2 kV
- Fence, Industrial
- Fence, Security
- Gas Line
- Industrial Waste Line
- LabNET Fiber Optic Cable
- Radioactive Liquid Waste Line
- Roads, Dirt
- Roads, Paved
- Road/Trail
- Sewer Line
- Steam Line
- Storm Drain/Culvert
- Telephone Line
- Water Line
- Building





Produced by: Doug Walther
Date: September 10, 1996 FIMAD Plot ID: G105093

State Plane Coordinate System, New Mexico Central Zone.
1983 North American Datum

Grid provides NM State Plane coordinates in feet.
Grid interval, in feet: 1000
Feet per inch on map = 100

SCALE 1:1200

METERS: 0, 30, 60, 90, 120

FEET: 0, 100, 200, 300, 400

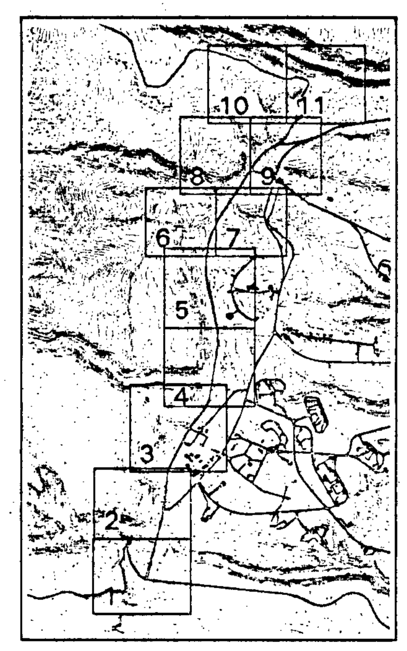
NOTICE: The information on this map is provisional. Feature locations are dependent on scale and symbology and their accuracy may not have been confirmed. Los Alamos National Laboratory boundary is based on legal description established in 1995. Contour data are from a September 1991 aerial survey. All other data are from various sources and are part of the FIMAD repository.

PLATE 11 in GEO-HAZ, 1997

Pajarito Fault Survey Map 11

LEGEND

- Contours, 2 foot
- Contours, 10 foot
- Cooling Lines
- Electrical > 13.2 kV
- Electrical < 13.2 kV
- Fence, Industrial
- Fence, Security
- Gas Line
- Industrial Waste Line
- LabNET Fiber Optic Cable
- Radioactive Liquid Waste Line
- Roads, Dirt
- Roads, Paved
- Road/Trail
- Sewer Line
- Steam Line
- Storm Drain/Culvert
- Telephone Line
- Water Line
- Building



FACILITY for INFORMATION, MANAGEMENT, ANALYSIS and DISPLAY

EARTH & ENVIRONMENTAL SCIENCES DIVISION (EES-5)

Produced by: Doug Walther

Date: September 10, 1996 FIMAD Plot ID: G105094

N

State Plane Coordinate System, New Mexico Central Zone.
1983 North American Datum

Grid provides NM State Plane coordinates in feet.
Grid interval, in feet: 1000
Feet per inch on map = 100

SCALE 1:1200

0 30 60 90 120 METERS

0 100 200 300 400 FEET

NOTICE: The information on this map is provisional. Feature locations are dependent on scale and symbology and their accuracy may not have been confirmed. Los Alamos National Laboratory boundary is based on legal description established in 1995. Contour data are from a September 1991 aerial survey. All other data are from various sources and are part of the FIMAD repository.