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SUBSURFACE GEOLOGY OF THE PAJARITO PLATEAU, ESPAÑOLA BASIN, NEW MEXICO

by

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ABSTRACT

Integration of data from wells, geophysical surveys, and surface exposures has enabled construction of structure contour and paleogeologic maps of the pre-Bandelier Tuff surface beneath the Pajarito Plateau. Numerous faults of the Rio Grande rift system cut the pre-Bandelier Tuff surface, and most have down-to-the-west displacements. Cumulative down-to-the-west movements across these faults from the Rio Grande on the east to the Rendija Canyon fault zone on the west exceed 600 ft (185 m). All faults in the area show evidence of recurrent activity, with increasing displacements of progressively older rock units. The southern Pajarito fault zone has over 600 ft (185 m) of pre-Bandelier Tuff down-to-the-east movement. The Pajarito fault zone and a major pre-Bandelier Tuff fault identified herein may constitute the local boundaries of the southern continuation of the intra-rift Velarde graben. The paleogeologic map shows that three major rock units (Cerros del Rio basalts, Tschicoma Formation dacites, and Puye Formation gravels) underlie the Bandelier Tuff and interfinger beneath the central Pajarito Plateau.

INTRODUCTION

Los Alamos National Laboratory lies on the Pajarito Plateau, which is an apron of Bandelier Tuff that spreads from the Jemez Mountains on the west into the Española Basin of the Rio Grande rift on the east. The rift is a complex system of north-trending basins (Fig. 1) that have formed by still active down-faulting of large blocks of the earth's crust in response to greater than 30 Myr of extensional tectonic activity (Chapin 1979; Sanford et al. 1979; Cash et al. Aldrich and Laughlin of the Los Alamos National Laboratory also provided data, 1984). Geologic evidence indicates that the vicinity of Los Alamos has experienced intense and nearly continuous volcanic and tectonic activity since

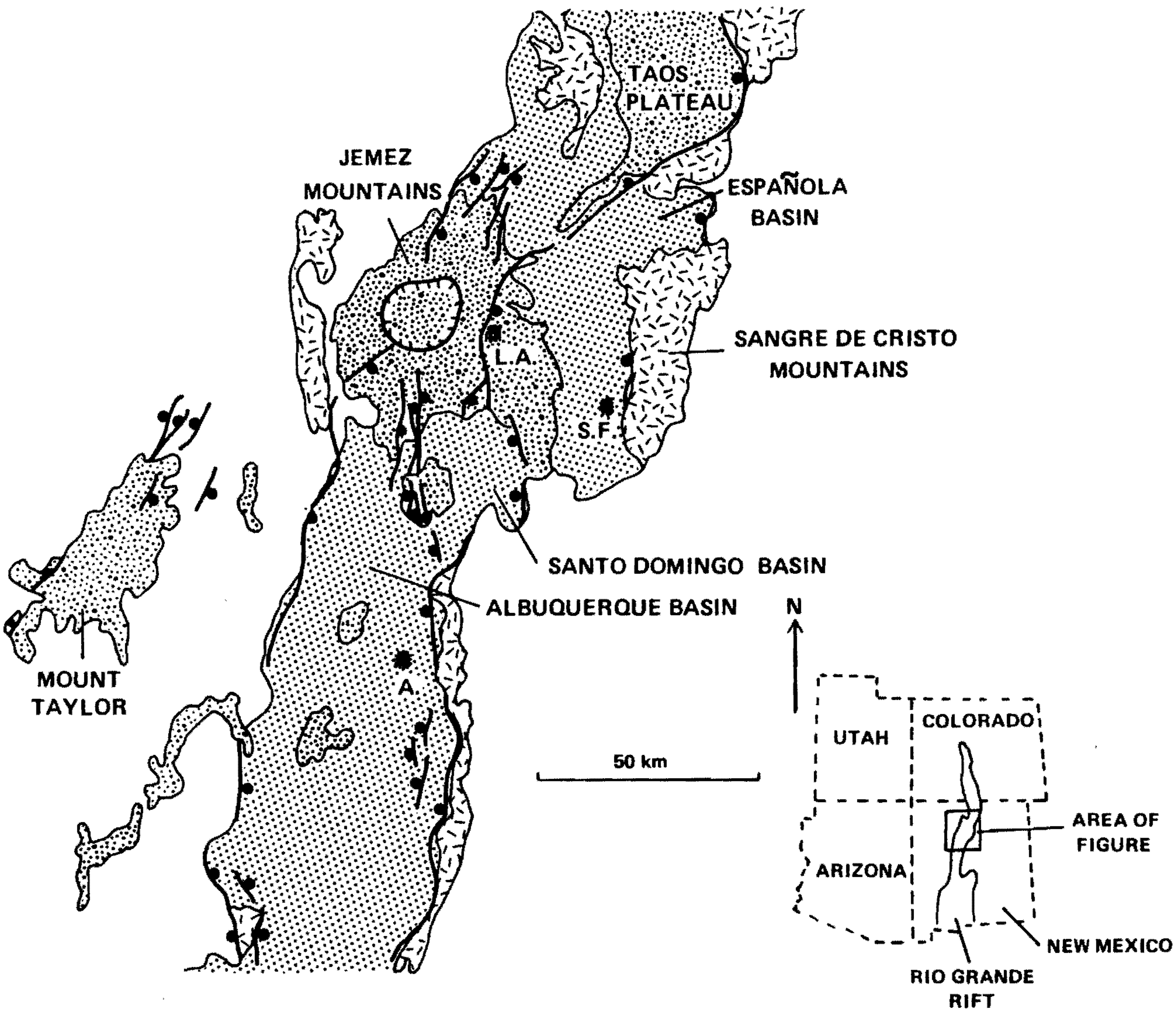

Figure 1: Generalized map showing relation of the Pajarito Plateau (L.A.) to local Rio Grande rift basins and extent of the Rio Grande rift in New Mexico and Colorado (inset). Major fault zones are shown schematically. Random dash = Precambrian rocks; coarse, regular stipple = Tertiary-Quaternary rift-fill sediments; irregular stipple = Tertiary-Quaternary volcanic rocks; L.A., S.F., and A are Los Alamos, Santa Fe, and Albuquerque, respectively (from Gardner and Goff 1984).

>13 Myr ago (Gardner and Goff 1984). Although active faults and fault zones exposed at the surface bear obvious seismic potential, it is possible that faults that do not displace surface rocks may also be re-activated in the future. Some such faults may be manifested at the surface as fracture zones or air photo lineaments, but they may not qualify as capable faults according

to the Nuclear Regulatory Commission's 10CFR100. These faults are, however, integral parts of the fault systems that have formed the active Rio Grande rift, and as such, these faults must be identified and considered to be potential sources for earthquake generation and surface rupture (Slemmons 1977).

The purpose of this study, part of the Laboratory's Seismology and Geology Studies for Earthquake Risk Assessment program, is to delineate by integrating data from drill holes and water wells, seismic and gravity surveys, and geologic maps those faults beneath the Pajarito Plateau that do not break the surface. Based on these data, a structure contour map (Map 1), constructed on the unconformity below the Pleistocene Bandelier Tuff, is the basis for determining the locations of and displacements along faults that have not cut through surface strata. Based on lithologic data from wells and surface exposures, we present a paleogeologic map (Map 2) of the pre-Bandelier Tuff surface beneath the Pajarito Plateau that will aid siting recording devices to measure the seismic response of the area. Maps 1 and 2 are located in the pocket on the inside back cover of this report.

Because most of the data used to generate the two maps of this report were originally reported in nonmetric units of measurement, we use the English system first, followed by the metric equivalent. In our discussions, we use the terms conservative and liberal to mean modeling of data minimizing the number of or displacements on faults and maximizing the number of or displacements on faults, respectively. We use the term subsurface to refer to features that are not exposed at the surface and the term surface to refer to those features that postdate the Bandelier Tuff.

POST-BANDELIER TUFF (SURFACE) FAULTS AND PREVIOUS WORK

The surface geology of the Pajarito Plateau has been mapped and discussed in detail by Griggs (1964) and Smith et al. (1970). Gardner and Goff (1984) included a discussion of the structure and stratigraphy of the plateau in their treatment of the Jemez volcanic complex. Golombek (1981; 1983) provided some topical studies on the Pajarito fault zone, and Budding and Purtymun (1976) discussed some geologic implications for seismicity in the Los Alamos area. Four main fault zones cut the surface in the immediate vicinity of Los Alamos, as follows (see Fig. 2): the Pajarito, Water Canyon, Guaje Mountain, and Rendija Canyon (new name, this report) fault zones.

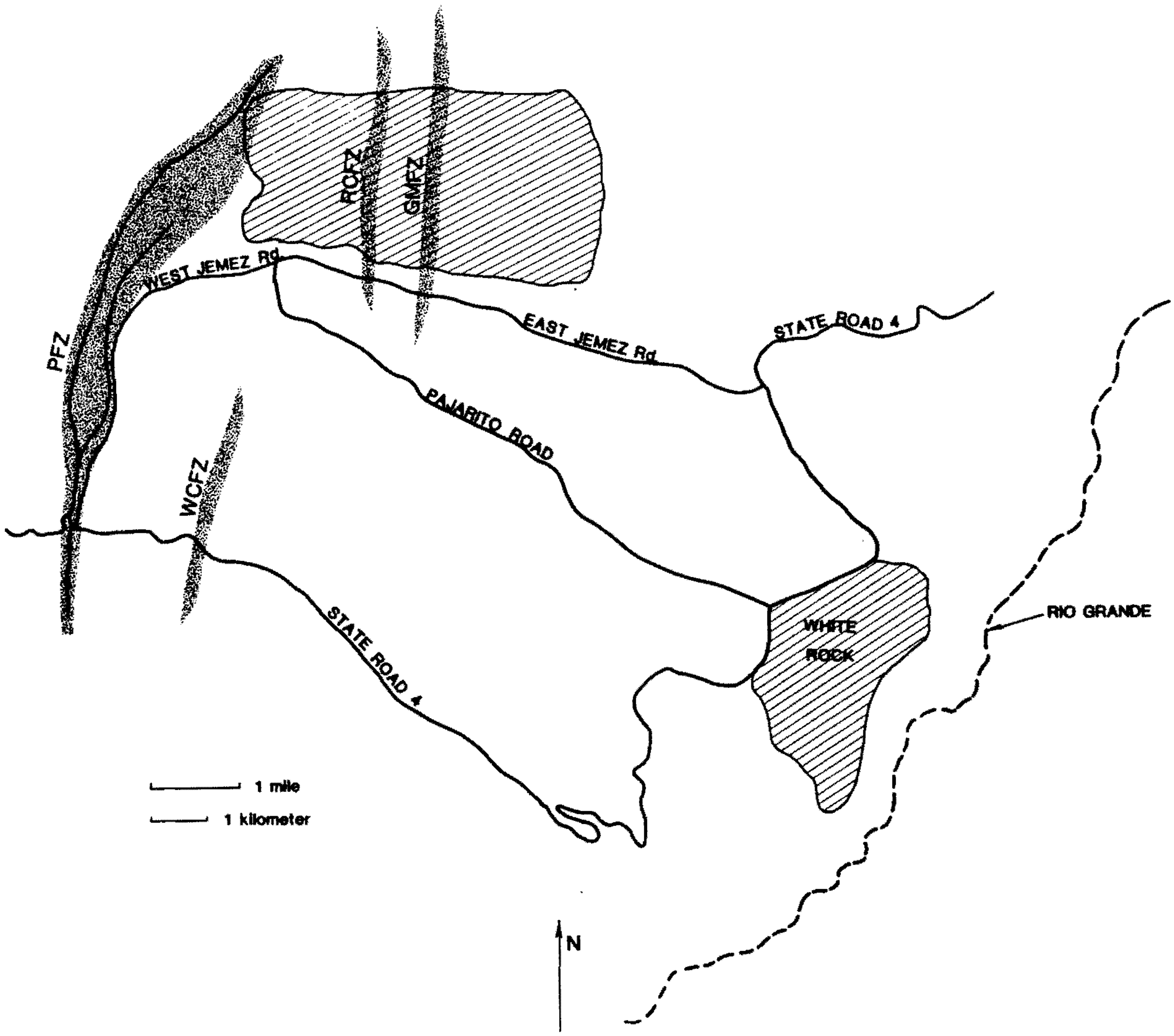

Figure 2: Known surface exposures of major fault zones (stippled) of the Pajarito Plateau. Roads, Rio Grande, and communities of Los Alamos and White Rock (ruled) shown for reference. PFZ = Pajarito fault zone; WCFZ = Water Canyon fault zone; GMFZ = Guaje Mountain fault zone; RCFZ = Rendija Canyon fault zone.

The Pajarito fault zone (Fig. 2) is a north-northeast-trending series of en echelon faults along the eastern flank of the Jemez Mountains, New Mexico, that is the active boundary fault along the western edge of the Española Basin of the Rio Grande rift (Golombek 1981; Gardner and Goff 1984). The main fault scarp exhibits up to 300 ft (100 m) of displacement in the 1.1 Myr old Bandelier Tuff (Griggs 1964; Doell et al. 1968) and skirts much of the western side of Los Alamos National Laboratory. North of Los Alamos, the Pajarito fault zone has sustained movements at least as recently as 500 000 years ago, and related faults have experienced movements less than 22 000 years ago (Aldrich and Harrington 1984; Harrington and Aldrich 1984). Fault activity along the Pajarito fault zone has been recurrent, with displacements at depth greatly exceeding those observed at the surface (Griggs 1964; Kelley 1979; Golombek 1981).

The Rendija Canyon and Guaje Mountain fault zones are part of the down-to-the-west system of faults that contribute to the asymmetry of the Española Basin noted in various geophysical studies (Budding 1978; Cordell 1979; Williams 1979; see also discussions of Goff and Grigsby 1982 and Gardner and Goff 1984). These fault zones show vertical displacements of 60-130 ft (20-40 m) (Golombek 1981; Maassen and Gardner, Los Alamos National Laboratory, unpublished mapping, 1984) in Bandelier Tuff and persist to the south as fracture zones and air photo lineaments across the Pajarito Plateau and Los Alamos National Laboratory.

The Water Canyon fault zone is a relatively small fault that cuts Bandelier Tuff with about 30 ft (10 m) of down-to-the-east displacement (Budding and Purtymun 1976; Goff and Gardner, Los Alamos National Laboratory, unpublished mapping, 1984). This fault zone persists farther north from exposures on State Road 4 as an air photo lineament.

Manley (1979) suggested that the intra-rift Velarde graben extends south through the Española Basin and is bounded on the west by the Pajarito fault zone in the Los Alamos area. She noted a lack of exposed border faults along the eastern margin of the southern Velarde graben. Kelley (1979) described the tectonic features of the area with respect to the central Rio Grande rift, and Gardner and Goff (1984) proposed a model relating tectonic and volcanic development of the Jemez Mountains to the history of the north-central Rio Grande rift.

Purtymun (1984) correlated the subsurface stratigraphy of the Pajarito Plateau to the regional stratigraphy and produced, using data from well logs and core samples, a contour map on the main aquifer. Gravity studies of the Los Alamos area, conducted by Budding (1978), Cordell (1979), and Williams (1979), have resulted in various interpretations of subsurface structure in the Española Basin. Using the positions of gravity inflections, Budding (1978) constructed cross sections across the Pajarito Plateau showing a deep, western side of Los Alamos National Laboratory. North of Los Alamos, the Pajarito fault zone has sustained movements at least as recently as 500 000 years ago, and related faults have experienced movements less than 22 000 years ago (Aldrich and Harrington 1984; Harrington and Aldrich 1984). Fault activity along the Pajarito fault zone has been recurrent, with displacements at depth greatly exceeding those observed at the surface (Griggs 1964; Kelley 1979; Golombek 1981).

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METHODS

Data from 25 wells (Table I) and 6 seismic lines were compiled on the geologic base map of Griggs (1964) (scale 1:31,680). With few modifications,

TABLE I
SUMMARY OF FORMATION AND/OR LITHOLOGIC DATA, USED IN THIS REPORT, FROM WELLS ON THE PAJARITO PLATEAU

Well Notation	Elevation of the Base of the Bandelier (feet above sea level)	Underlying Formation
PM2	6283	Basalt [a]
PM1	6355	Basalt
T4	6848	Puye [b]
T3	6450	Puye [c]
T7	6180	Basalt
T2	6583	Puye
H19	6706	Tschicoma [a]
T6	6420	Puye
T5	6421	Basalt
LA06	6404	Basalt
B1	6575	Puye
B3	6545	Puye
B4	6593	Puye
T8	6382	Puye [c]
DT9	6090	Puye [b]
DT10	6150	Puye [b]
DT5A	6210	Puye [b]
PM3	6450	Puye [c]
PM4	6317	Basalt [a]
PM5	6354	Basalt [a]
HH (EGH-LA1)	6360	Puye [c]
G	6458	Basalt
TA46	6370	?
TW1	6350	?
(Unnamed)	6380	?

[a] Overlies Puye.
[b] Overlies Tschicoma.
[c] Overlies Basalt.

elevation data from surface exposures of the base of the Bandelier Tuff and surface traces of faults were taken from the geologic map of Griggs (1964). Geologic logs of wells, compiled by Cooper et al. (1965), John et al. (1966), Purtymun (1967), and Purtymun et al. (1983, 1984) provided much of the control for constructing the subsurface base of the Bandelier Tuff.

Seismic lines LAC-1 and SR-4 (Map 1), interpreted by Reynolds (no date), provided both the depth to the base of the Bandelier and the locations of probable faults. Data from seismic lines TA-49 and TA-44 are considered to be of poor quality (Reynolds, no date) and were not used. Although the data retrieved along line SR-4 is of relatively good quality, the shot-point locations had to be shifted in order to properly align the surface trace of the Water Canyon fault on the seismic line with the location of the surface scarp exposed on State Road 4. Structure contours based on this line are the result of a three shot-point shift of data to the east. In addition, the eastern half of this seismic section exhibits superfluous noise, probably because the seismic line was shot along a curving road, which nearly parallels the Water Canyon fault for a short distance on the downthrown block. The paucity of recognizable reflectors east of the fault presents problems in determining the elevation of the pre-Bandelier surface.

Longer deep seismic reflection lines, lines 1 and 2 (Map 1), through Los Alamos and Mortandad Canyons (CXC, Inc., 1979), show excellent reflectors at depth, but generally lack consistent shallow reflectors which might represent the base of the Bandelier Tuff.* Therefore, these reflection lines could not be used to determine the depth to the pre-Bandelier surface. Both lines 1 and 2 show numerous breaks or offsets of reflectors, strongly suggesting an abundance of subsurface faults. Only faults that exhibit substantial offset (i.e., greater than 50 ft or about 15 m) in both deep and shallow horizons were plotted on the structure contour map. Fault offsets were conservatively approximated from the estimated velocity/depth profile compiled by Homuth.* Where line LAC-1 and line 1 overlap, LAC-1 was used because it shows higher resolution at shallow levels.

Aerial photographs and published Bouguer gravity anomaly maps were used only to check for features suggesting the presence of faults where the contoured data imply their existence. Field reconnaissance was employed to verify stratigraphic and structural relationships where possible.

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*Information provided by E.F. Homuth, Los Alamos National Laboratory (1984).

Structure contours were drawn at 20-ft (6-m) intervals, beginning in areas of greatest control and extrapolating into the areas of little to no control. Dashed contours represent inferred elevations, while questioned contours indicate total lack of data. For areas with little or no data, the contoured morphology represents the simplest, most consistent form that fits the nearest area with better control. Mapped faults in the area are nearly vertical; therefore we assume that the subsurface fault traces are nearly coincident with their surface traces. The completed map was reduced to a scale of 1:62,500 to be compatible with other maps being generated in the Seismology and Geology Studies for Earthquake Risk Assessment program.

Because the pre-Bandelier surface is an unconformity developed on a variety of lithologic units, there is no single topographic signature that is consistent over the entire map area. Therefore, an abrupt change in geomorphology alone is not necessarily indicative of faulting. Every effort was made to contour data without faults.

A general paleogeologic map was constructed of the pre-Bandelier surface to better understand the control each formation exerts on subsurface topography and to aid in assessing the material properties of the Pajarito Plateau in future studies. Contacts are based on well information (Table I) and surface exposures.

SUBSURFACE FAULTS

One potentially major zone of subsurface faulting is strongly suggested by both seismic and well data (Map 1). The northeast-trending master fault of this zone extends southward from Pueblo Canyon (T19N, R7E, Sec. 17) for at least 6 miles (9.5 km). West-side-down displacement along the fault increases southward, from approximately 60 ft (18.5 m) in Los Alamos Canyon to about 180 ft (55 m) between wells PM2 and T6. Displacement may increase to nearly 400 ft (123 m) at the fault's southernmost mapped extent. Several smaller faults parallel the northern portion of the major fault, one of which is antithetic and shows about 100 ft (30 m) of displacement in seismic line LAC-1. Faults apparent in deep reflection seismic lines 1 and 2 show estimated shallow displacements of up to 150 ft (46 m), and most of these faults have down-to-the-west sense of movement. Estimates of offsets at depth indicate that many of these faults sustained over 200 ft (60 m) of displacement in the past, some of which occurred before the Cretaceous. In addition to the mapped subsurface faults, seismic lines demonstrate that several faults of less than 50 ft (<15 m) of displacement exist beneath the Pajarito Plateau.

On comparison with the gravity inflections from cross sections of Budding (1978), Williams (1979), and Cordell (1979), the inflection marking the eastern boundary of the prominent gravity low in the Pajarito Plateau area lies extremely close to the trace of the major easternmost subsurface fault. Cordell (1979) states that faults might be placed with some degree of assurance at the inflection points in gravity profiles. The coincidence of these two features suggests that the subsurface fault could be one of the graben-bounding faults along the eastern margin of the Velarde graben.

The three surface faults east of the Pajarito fault, Water Canyon, Guaje Mountain, and Rendija Canyon faults, continue some distance through the map area in the subsurface before apparently dying out. These faults were extended into the subsurface along prominent aerial photo lineaments, which probably represent eroded fracture zones. In addition, the Guaje Mountain and the Rendija Canyon faults appear in deep seismic reflection lines 1 and 2, south of their surface exposures. The combined surface displacement of these two faults approaches 130 ft (40 m) (Golombek 1981). Griggs (1964) asserts that the subsurface displacement may reach 500 ft (150 m). Contouring revealed displacements averaging 110 ft (34 m) per fault in the pre-Bandelier surface (Map 1), supporting the idea that substantial recurrent movement has occurred along these two faults. The displacement along the southern end of the Guaje Mountain fault should be considered a minimum. More liberal contouring in the southwest corner of the map, which may actually be more consistent with Tschicoma Formation topography, could indicate up to 200 ft (60 m) of displacement along this fault.

The Water Canyon fault, which exhibits approximately 50 ft (15 m) of down-to-the-east surface displacement, offsets the pre-Bandelier surface about 70 ft (21 m) in seismic line SR-4. This displacement value is a minimum estimate, because of the noise problems mentioned above, in the eastern half of the seismic line. Some speculation exists as to whether the reflector picked to the east of the fault is the same reflector as that chosen to the west. If a slightly deeper reflector in the downthrown block is correlative with the reflector in the upthrown block, then the subsurface displacement along the Water Canyon fault could reach 250 ft (77 m). In either case, movement diminishes to the north, where the fault is expressed as an air photo lineament.

The southern portion of the Pajarito fault exhibits over 600 ft (180 m) of pre-Bandelier displacement near State Road 4. Measurable surface offset in the Bandelier Tuff equals 300 ft (100 m) at this location (Griggs 1964).

PALEOGEOLOGY

The geology of the pre-Bandelier unconformity consists of three major lithologic units, each with a unique topographic expression (Maps 1 and 2). The Puye Formation, a large alluvial fan derived from volcanic highlands to the northwest, covers most of the northern half of the map area. Elongate, generally east-west-trending lobes characterize these conglomeratic deposits. Extensive basalts of the Cerros del Rio basalt field flowed to the west-northwest into the map area from vents near the Rio Grande. Broad shields of basalt flows and possible vents produced a series of relatively low relief hills over most of the southeastern portion of the map. The Tschicoma Formation underlies the Bandelier Tuff along the western border of the map as a series of steep, lobate dacite flows, derived from the west. According to well data, the Puye Formation interfingers with both the Cerros del Rio basalts and the Tschicoma Formation in the central portion of the map area. This relationship has been noted by Griggs (1964), Manley (1979), and Purtymun (1984). The pre-Bandelier geomorphology strongly resembles the present erosional surfaces developed on the Puye, the Cerros del Rio, and the Tschicoma formations.

DISCUSSION

The deepest part of the Española Basin lies along its western margin, but the specific nature and location of the possible intra-rift graben have been topics of much speculation. Manley (1979) has noted the absence of exposed faults bounding the rift along the eastern side of the Española Basin. She has suggested the continuation of the Velarde graben southward below the plateau with its eastern margin paralleling the Rio Grande gorge. Budding (1978) postulated the existence of a deep, central graben beneath the Pajarito Plateau.

Gentler gravity gradients to the east suggest that faults along the eastern margin of the basin tend to have smaller offsets than those along the western margin (Cordell 1979). This observation has led some to assert that the eastern portion of the Española Basin need not be faulted (Baltz 1978; Williams 1979). Other workers have mapped north-trending faults east of the Rio Grande, most of which show minor, west-side-down displacements (Spiegel and Baldwin 1963; Kelley 1979). It is possible that numerous step faults with relatively small displacements constitute most of the basin's eastern portion (Manley 1979; Cordell 1979).

The deep seismic lines across the Pajarito Plateau (lines 1 and 2) show that this portion of the Española Basin is characterized by a series of down-to-the-west faults of varying displacements. Both seismic and well data suggest the presence of at least one major subsurface fault, which extends north-south over the length of the plateau and shows up to 400 ft (123 m) of west-side-down displacement. This fault corresponds with the major inflection along the eastern side of the large negative gravity anomaly beneath the plateau. It is possible that this subsurface fault is a border fault along the intra-rift Velarde graben. If so, then the central graben is wider than that proposed by Budding (1978) and narrower than that proposed by Manley (1979).

The presence of a deep graben containing between 5000 and 8000 ft (1.5 and 2.5 km) of Tertiary basin-fill sediments has been proposed by Kelley (1979), Budding (1978), and Goff and Grigsby (1982). Based on this study, cumulative west-side-down displacement across the plateau at the base of the Bandelier exceeds 600 ft (185 m) along seismic line 1. If the graben is as deep as postulated, then any of four possibilities could account for the apparent discrepancy between the observed fault displacements and the hypothesized graben depth:

1. The eastern margin of the basin is step-faulted over most of its width; therefore displacement is distributed over a zone wider than the Pajarito Plateau.
2. The faults mapped show recurrent movements and exhibit much greater displacements with depth.
3. The major fault responsible for displacement along the eastern margin of the graben lies east of the extent of our data and will be discovered only with additional seismic or well data.

4. Faults responsible for most of the down-faulting of the western Española Basin lie west of the Pajarito fault zone (Gardner and Goff 1984).

No faults transverse to the north-northeast trend were delineated by subsurface data. This may be an artifact of the strictly east-west orientation of all seismic lines. Kelley (1979) has suggested the presence of structural features transverse to the rift trend. Smith et al. (1970) mapped a northwest-trending, north-side-down normal fault through Frijoles Canyon, immediately to the south of the study area. All gravity studies of the Los Alamos area show a steep gravity gradient along the northern margin of the basin, suggesting either that the basin plunges to the south or that a transverse normal fault forms its northern boundary. Cordell (1979) noted that the structural nature of the Española Basin is beyond the resolution of gravity data, suggesting the use of seismic reflection profiles to determine if the basin is fault-bounded. Shallow north-south seismic lines across the plateau would be extremely useful in ascertaining the presence of transverse faults.

CONCLUSIONS AND RECOMMENDATIONS

Analysis of subsurface data has shown that numerous faults cut across the Pajarito Plateau at the pre-Bandelier level. Most have down-to-the-west displacements averaging about 100 ft (30 m), totaling over 600 ft (185 m) of displacement across the plateau at the pre-Bandelier horizon. Some subsurface faults in the area have shown recurrent activity since the Cretaceous; therefore it is entirely possible that activity will be renewed.

Surface faults mapped by other workers show increased displacements with depth and continue along strike in the subsurface, with surface expressions as prominent air photo lineaments. Both the Guaje Mountain fault and the Rendija Canyon fault appear on seismic lines 1 and 2, necessitating the extension of these two faults beneath the Pajarito Plateau south of their surface exposures. Only conservative contouring in the southwest portion of the map allows these faults to show decreasing displacements to the south. The Pajarito fault shows 600 ft (185 m) of displacement at the base of the Bandelier Tuff, a value nearly twice its surface displacement.

The easternmost subsurface fault coincides with the gravity inflection along the eastern margin of the large negative gravity anomaly below the plateau. This major fault could represent the eastern fault bounding the intra-rift Velarde graben in this portion of the Española Basin.

Seismic lines 1 and 2 exhibit numerous subsurface faults, which were not implied by other data. Undoubtedly, shallow seismic reflection profiles across other portions of the Pajarito Plateau would illuminate additional faults. Future seismic lines should extend east-west from the Rio Grande across the Pajarito fault zone to characterize the intra-rift graben and north-south from Garcia Canyon through Frijoles Canyon to check for transverse structures. A useful seismic hazards analysis of the Pajarito Plateau will not be complete without such additional data.

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