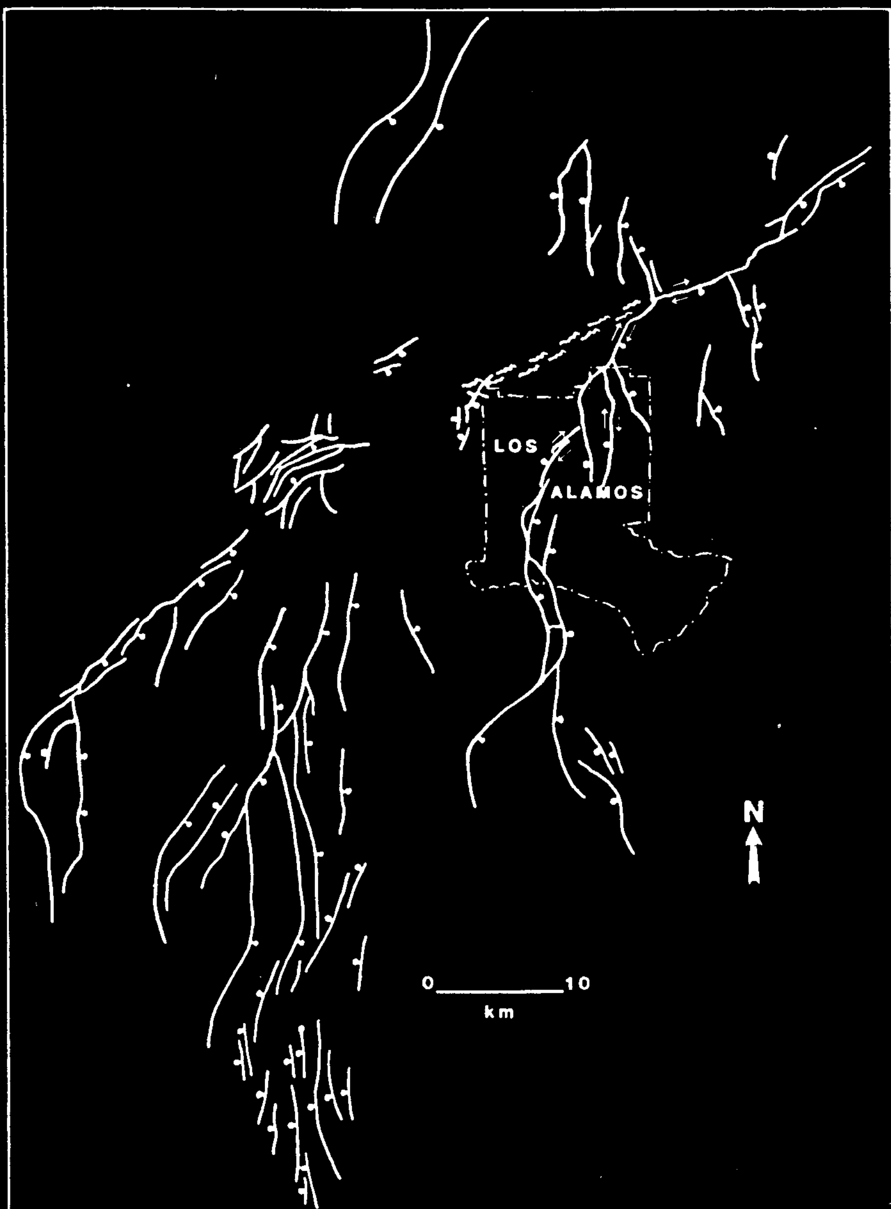
Los Alamos Environmental Restoration Records Processing Facility

ER Record I.D.# 0006682

LA-11072-MS

Seismic Hazards Investigations at Los Alamos National Laboratory, 1984 to 1985



Los Alamos

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

Los Alamos National Laboratory
is operated by the
Universit
for the
Departm
under contract W-

3467

LA-11072-MS

UC-11
Issued: October 1987

Seismic Hazards Investigations at Los Alamos National Laboratory, 1984 to 1985

Jamie N. Gardner
Leigh House

with contributions from

M. J. Aldrich, Jr.
W. S. Baldridge
D. Broxton
D. J. Cash
D. P. Dethier*
B. J. Dransfield**
F. Goff
C. D. Harrington
J. W. Hawley†
L. W. Maassen
D. Wachs‡

*Collaborator at Los Alamos. Department of Geology, Williams College, Williamstown, MA 01267.
**Guest Scientist at Los Alamos. Department of Geology, University of Alabama, University, AL 35486.
†Collaborator at Los Alamos. New Mexico Bureau of Mines and Mineral Resources, Socorro, NM 87801.
‡Collaborator at Los Alamos. Geological Survey of Israel, 30 Malkhe Yisrael Street, Jerusalem 95501, ISRAEL.

Los Alamos

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

CONTENTS

EXECUTIVE SUMMARY

Seismic hazards and risks at the Los Alamos National Laboratory have been addressed in a number of studies since the early 1970s. None of these studies have included recent seismic and geologic data and the new methods for evaluating seismic hazards or assessing seismic risks. Consequently, in April 1984 the Laboratory requested the Earth and Space Sciences Division to begin to reassess the earthquake hazards at the Laboratory.

This report describes our approach, earthquake models, and the tectonic setting of Los Alamos. We describe results of our field and seismological studies in the Los Alamos area. We present preliminary hazards maps and conclusions that are intended to provide tentative guidance for Laboratory planners.

Our investigation concentrates on the Pajarito fault system, part of which skirts the western boundary of the Laboratory. This system is a major, active structural element of the Rio Grande rift and represents a possible earthquake hazard to Laboratory facilities. Observed displacements in the area indicate that major movements have occurred on the fault system in the last 500,000 years. Current best estimates of expectable earthquake magnitude (Richter Scale) are from 6.5 to 7.8. Although these estimates need to be better constrained and the recurrence intervals for possible earthquakes determined, we conclude that the fault system is capable of an earthquake that will cause damage to the Laboratory.

SEISMIC HAZARDS INVESTIGATIONS AT
LOS ALAMOS NATIONAL LABORATORY, 1984 TO 1985

by

Jamie N. Gardner and Leigh House

ABSTRACT

The Pajarito fault system, part of which skirts the western boundary of Los Alamos National Laboratory, is a major, active structural element of the Rio Grande rift. We have mapped over 100 km of interrelated fault zones and traces that constitute the fault system in the vicinity of Los Alamos; however, estimates of total fault system length are unrealistic because faults of the Pajarito system connect with regional structures that show no clear terminations. The style of deformation in the fault system gradually transforms from normal slip, to normal oblique slip, to dominantly right lateral strike-slip motions from south to north. Most significant movements (>100 m) on the fault system in the vicinity of Los Alamos have occurred within the last 1.1 million years. Portions of the fault system may have associated microseismic activity. Available evidence indicates that major movements have occurred on the fault system in the last 500,000 years and as recently as 350,000 years ago, 240,000 years ago, 42,000 years ago, possibly <10,000 years ago, and 2,000 years ago. Clearly the fault system is capable in the sense of the Code of Federal Regulations definitions. Some limited, inferential field data imply the fault system generates characteristic earthquakes in the magnitude (Richter) range 6.5 to 7.8 (ideal correlation to Modified Mercalli Intensity VIII to X); however, these estimates need to be better constrained, and the recurrence interval for these earthquakes remains to be determined. Extrapolation of frequency-magnitude relations, derived from the 10 years of data from the Los Alamos seismograph net, to estimate large expectable earthquakes is unrealistic, and based on the findings of other workers the result is most likely a substantial underestimate. The subsurface geology of Los Alamos and seismic properties of the Bandelier Tuff, over which the Laboratory lies, are so variable that the responses of different sites within the Laboratory should be analyzed individually for design purposes.

CHAPTER I: INTRODUCTION

I-A: BACKGROUND

Seismic hazards and seismic risk at Los Alamos National Laboratory have been variably addressed in a number of topical studies since the early 1970s (see Appendix "Previous Studies"). However, since 1972 (Dames and Moore, 1972) there have been no comprehensive seismic hazards or risk analyses of the Laboratory that include the recently available seismic and geologic data and the new developments in the way these data are treated in determining seismic risk (e.g., see Tillson, 1984). In a 1985 review of major research and development activities of the Earth and Space Sciences (ESS) Division of Los Alamos, R. M. Hamilton, Chief Geologist of the U.S. Geological Survey, wrote the following to J. H. Birely (Associate Director for Chemistry, Earth, and Life Sciences at Los Alamos):

> "The only recommendation that I would like to make ... concerns seismic hazards in the LANL area ... fault offsets that have recently been studied in the area, and, more generally, the tectonic setting of the LANL area, appear to deserve attention. ESS staff are well qualified to investigate this problem. I recommend, therefore, that a project be established to investigate seismic hazards in the LANL region."

In April 1984, the ESS Division was asked by the Laboratory to begin seismological and geological studies related to earthquake hazards at Los Alamos. Activities were to include instrumental earthquake monitoring, revision of a Laboratory-specific response spectrum, analysis of existing seismic data, evaluation of past seismic hazards studies at Los Alamos, and new geologic mapping of fault zones, as necessary. On review of past studies in light of modern seismic hazards assessment methodologies, it became evident that much work beyond the scope of the original project would be necessary to provide a state-of-the-art seismic risk assessment of the Laboratory. Hence, tasks were modified, redirected, and/or added, and on-going research in other programs was incorporated into the program so as to provide as much useful information as possible within the two fiscal years (1984 and 1985) of the original program (see Section I-B: Approach).

In February 1985, we presented our preliminary results to representatives of Laboratory management and made recommendations for necessary additional work as a second phase of the program. Work on the second phase began in January 1986 and will continue for the next several years. Thus, this report is documentation of work still in progress. In this chapter we describe our approach, earthquake models, and the tectonic setting of Los Alamos. In Chapters II and III we describe results of our field and seismological studies in the Los Alamos area. We present preliminary hazards maps and conclusions that are intended to provide tentative guidance for Laboratory planners. The Appendix "Previous Studies" is a partially annotated bibliography of work relevant to seismic hazards at Los Alamos.

I-B: APPROACH

An important semantic distinction is the difference between a seismic hazards evaluation and a seismic risk analysis. A seismic risk analysis must include

1) a seismic hazards evaluation,
2) an evaluation of seismic designs and seismic exposures of facilities in light of probabilities of various seismic effects, and
3) a determination of acceptable risks to personnel, property, and the environment.

Our program addresses only Step 1, the seismic hazards evaluation. A seismic risk analysis for Los Alamos should include Laboratory management, engineers, and safety experts, as well as geoscientists, and is beyond the scope of the current program. Given the results of a risk analysis, structural upgrades, retrofits, remedial construction, and emergency contingency planning must be done to mitigate the risks that are determined to be unacceptable.

As closely as practical, the approach we have developed and the definitions we employ are based on the 1985 Code of Federal Regulations, Title 10 (Energy: Nuclear Regulatory Commission) Part 100, Appendix A., pages 818-826 (hereafter referred to as 10 CFR 100-A). The Nuclear Regulatory Commission's guidelines of 10 CFR 100-A provide a legally defined approach to investigation and quantitative assessment of seismic hazards at a nuclear facility. The guidelines of 10 CFR 100-A define a deterministic approach to seismic risk assessment. In that the scope of investigations required by 10 CFR 100-A is large and beyond the current level of effort of our program, we have placed highest priority on obtaining the deterministic data necessary for subsequent seismic risk assessment:

1) critical review of pertinent literature (10 CFR 100-A, Sec. IV);
2) determination of subsurface geology (10 CFR 100-A, Sec. IV, paragraphs a-1, a-2, and a-4);
3) identification of capable faults (10 CFR 100-A, Sec. IV, paragraph b-4);
4) for the capable faults, determination of the nature of associated earthquakes (see Section I-D: Seismic Hazards Earthquake Concepts), fault length, relations of faults to regional structures, and the nature, amount, and geologic history of displacements along the fault (10 CFR 100-A, Sec. IV, paragraphs a-8 and b-7);
5) evaluation of tectonic structures, underlying the site, whether buried or expressed at the surface, with regard to their potential for surface rupture (10 CFR 100-A, Sec. IV, paragraph b-2);
6) instrumental monitoring of seismic activity (10 CFR 100-A, Sec. VI); and
7) determination of seismic response of geologic materials at the site (10 CFR 100-A, Sec. V).

I-C: USAGE OF MAGNITUDE, INTENSITY, AND CAPABLE FAULT

Throughout this report, unless otherwise specified, we use the term magnitude to mean the Richter or local magnitude of an earthquake. Abundant deterministic, empirical data exist that allow estimation of the size of earthquakes, with numerical values on the Richter scale, from measurable fault parameters and seismic data. The intensity of an earthquake is a measure of its effect on humans, on human-built structures, and on the earth's surface at a given location. Intensity, with an upper-case "I," means the numerical value on the Modified Mercalli Intensity (MMI) scale (Table I). A capable fault is one with potential for generating earthquakes. A capable fault is a fault with demonstrable historic macroseismicity, recurrent movements within 0.5 Ma, and/or one movement within 0.035 Ma (10 CFR 100-A).

I-D: SEISMIC HAZARDS EARTHQUAKE CONCEPTS

Several concepts and models for earthquakes that are prevalent in seismic hazards analyses warrant discussion at this point. The "Safe Shutdown Earthquake" and the "Operating Basis Earthquake" are the earthquake models utilized in 10 CFR 100-A. The Safe Shutdown Earthquake (also called the "Design Basis Earthquake") is that earthquake which will produce maximum vibratory ground motion at the site, based on evaluation of regional and local

TABLE I: ABRIDGED MODIFIED MERCALLI INTENSITY SCALE (MMI) OF 1930 (FROM HOUSNER, 1970) WITH RICHTER'S (1958) IDEAL CORRELATION OF MAGNITUDE (M_L) TO INTENSITY

(MMI)		(M_L)
I	Detected only by sensitive instruments.	
		2
II	Felt by a few persons at rest, especially on upper floors; delicately suspended objects may swing.	
III	Felt noticeably indoors, but not always recognized as an earthquake; standing autos rock slightly, vibration like passing truck.	3
IV	Felt indoors by many, outdoors by a few; at night some awaken; dishes, windows, doors disturbed; cars rock noticeably.	
V	Felt by most people; some breakage of dishes, windows, and plaster; disturbance of tall objects.	4
VI	Felt by all; many are frightened and run outdoors; falling plaster and chimneys; damage small.	
		5
VII	Everybody runs outdoors; damage to buildings varies, depending on quality of construction; noticed by drivers of autos.	
		6
VIII	Panel walls thrown out of frames; walls, monuments, chimneys fall; sand and mud ejected; drivers of autos disturbed.	
IX	Buildings shifted off foundations, cracked, thrown out of plumb; ground cracked; underground pipes broken.	
		7
X	Most masonry and frame structures destroyed; ground cracked; rails bent; landslides.	
		8
XI	New structures remain standing; bridges destroyed; fissures in ground; pipes broken; landslides; rails bent.	
XII	Damage total; waves seen on ground surface; lines of sight and level distorted; objects thrown up into air.	

geology and seismology and specific materials properties of the site. In the absence of site-specific deterministic data for the site and/or faults near the site, the Safe Shutdown Earthquake is commonly taken to be the largest earthquake--or highest intensity of ground motion--known to have occurred within the site's tectonic province (see Tectonic Province of Los Alamos). Seismic design bases are then determined by assuming occurrence of the Safe Shutdown Earthquake at the point on the tectonic structure or tectonic province nearest to the site. Design of facilities for the Safe Shutdown Earthquake must assure that critical structures, systems, and components (such as containment and coolant systems) remain functional so as to have the capability to execute and maintain a safe shutdown, and to prevent or mitigate the consequences of accidents. Thus, critical components of nuclear facilities must be designed to survive the Safe Shutdown Earthquake and continue to function to the point of preventing or mitigating damage to personnel, property, and the environment.

The Operating Basis Earthquake (also commonly referred to as the "Probable Earthquake") of 10 CFR 100-A is that earthquake which, considering the regional and local geology and seismology and specific characteristics of local subsurface material, could reasonably be expected to affect the site during the site's operating life. The operating life of a nuclear power plant is usually taken to be 30 years. Seismic design for the Operating Basis Earthquake requires that all structures, systems, and components not only survive the earthquake itself but also sustain no damage sufficient to impair continued operation of the facility without undue risk to the health and safety of personnel, the public, and the environment.

Recent research on individual faults and segments of larger fault zones in California and Utah suggests that individual faults generate the same size earthquakes with a narrow range of magnitudes near the maximum and with similar time lapses between events (Schwartz et al., 1981; Schwartz and Coppersmith, 1984). These earthquakes, specifically their magnitude and recurrence, are referred to as the "Characteristic Earthquake" for the fault. Loosely, the Characteristic Earthquake is comparable to the Safe Shutdown Earthquake except that the Characteristic Earthquake has a specific probability (that is, recurrence interval), is fault-specific, and its magnitude approximates that of the maximum earthquake (Safe Shutdown Earthquake).

Thus, for Los Alamos with proximal or near-field capable faults (within 5 miles or about 8 km), we take the Characteristic Earthquake as the most realistic model for expectable large earthquakes. The Operating Basis Earthquake for Los Alamos may best be based on the regional historical and instrumental seismicity.

I-E: TECTONIC PROVINCE OF LOS ALAMOS

Los Alamos National Laboratory lies within the Rio Grande rift, which is a subprovince of the larger Basin and Range tectonic province. Some workers maintain that certain characteristics (particularly geophysical) distinguish the Basin and Range from the Rio Grande rift in southern New Mexico and Mexico (Seager and Morgan, 1979), but they imply that, if anything, the rift is the more tectonically active of the two. Certainly the Basin and Range and Rio Grande rift have remarkably similar tectonic and magmatic histories over the last approximately 30 million years (Atwater, 1970; Christiansen and Lipman, 1972; Crowe, 1978; McKee et al., 1970; Chapin, 1979; Chapin and Seager, 1975; Baldridge et al., 1980; Gardner and Goff, 1984; Gardner, 1985), and both share a genesis in the extensional deformation resultant from plate boundary interactions of the North American and Pacific plates (Atwater, 1970). The North American-Pacific plate boundary is active in the present day (San Andreas fault), and the deformation in the Basin and Range continues as well. Both the Basin and Range and the Rio Grande rift have experienced historic macroseismicity (for example, Wollard, 1968; Stein and Bucknam, 1985; Arabasz et al., 1979; Dames and Moore, 1972). Furthermore, the Basin and Range and Rio Grande rift show similar styles of deformation, present-day state-of-stress patterns, and both are microseismically active (for example, Smith and Bruhn, 1984; Wallace, 1984; Cash and Wolff, 1984; Zoback and Zoback, 1980; Aldrich and Laughlin, 1982). Hence, according to the definitions of 10 CFR 100-A the Basin and Range and the Rio Grande rift are one in the same tectonic province.

As discussed above, 10 CFR 100-A requires, in the absence of site-specific, deterministic data, the Safe Shutdown Earthquake for a given site within a tectonic province to be based on the history of the entire tectonic province. At least seven historical earthquakes with magnitudes greater than 7 have occurred in the Basin and Range since 1871 (DuBois and Smith, 1980;

Stein and Bucknam, 1985). One of these earthquakes, with an estimated magnitude of greater than 7.2, produced surface rupture that extended within a few kilometers of the intersection of the New Mexico-Arizona-Mexico borders in 1887 (DuBois and Smith, 1980). Furthermore, recent work on the paleoseismicity of some young faults in the central Rio Grande rift indicates they have repeatedly generated earthquakes with magnitudes of 6.8 to 7.1 (Machette, 1986). Hence, without the site-specific, deterministic data that we seek to obtain in this program, the Safe Shutdown Earthquake based on the tectonic province approach for Los Alamos would have to be greater than magnitude 7.

CHAPTER II:

FIELD STUDIES OF THE PAJARITO FAULT SYSTEM

II-A: INTRODUCTION

We use the term Pajarito fault system to refer to the series of faults and fault zones that define the active western and northwestern boundary of the Española Basin of the Rio Grande rift. Because of structural, geometric, and genetic relations of fault zones in the area, we conclude they all constitute the zone of active or potentially active rift-bounding deformation in the vicinity of Los Alamos, as suggested by Golombek (1981) and Gardner and Goff (1984). The Pajarito fault system consists of the faults and fault zones that comprise the structural elements of the intrabasin Velarde graben as proposed and/or discussed by Budding (1978), Manley (1979), Dransfield and Gardner (1985), and Aldrich (1986). In that these faults and fault zones constitute a single, albeit complex, structural entity, they all must be considered integral members of the same system (see below).

The Pajarito fault system includes four fault zones that have been active in the Quaternary (see below); however, in a regional context the Pajarito fault system is also related to the active Jemez fault zone in the western Jemez Mountains, the post-Pliocene Santa Ana Mesa fault zone in the southern Jemez Mountains, the inactive Miocene Cañada de Cochiti fault zone in the southern Jemez Mountains, the post-Pliocene La Bajada fault southeast of Cochiti, and the active eastern Embudo and Velarde fault zones north of Española (Smith et al., 1970; Dames and Moore, 1972; Muehlberger, 1978, 1979; Manley, 1979; Goff and Kron, 1980; Gardner and Goff, 1984; Manley, 1984; Gardner, 1985; Aldrich, 1986).

We divide the Pajarito fault system into three geographic segments for purposes of discussion (Figure 1). It must be emphasized that these segments are geographic, not structural. We make these divisions strictly for descriptive purposes and do not imply lack of continuity of the fault system. Each segment of the fault system has yielded different kinds and variable amounts of information relevant to seismic hazards. The southern segment extends from the Rio Grande near Cochiti on the south to the southern boundary of Los Alamos County on the north. The southern segment provides limited information on young fault movements, structural continuity with more regional faults, and well-preserved >100-m Quaternary fault scarps. The central segment includes all elements of the fault system within Los Alamos County. The central segment exhibits disrupted stream gradients across faults, 100-m Quaternary scarps, changes in sense of movement, and localities where vertical movements have dammed drainages. The northern segment comprises the fault system north of Los Alamos to the Rio Chama. In the northern segment there is abundant geomorphic evidence for young and recurrent movements in the fault system. In discussing each segment of the fault system, we provide brief descriptions of structural relations of faults and fault zones, relations to regional structures, results of field studies that constrain nature, history, ages, amounts, and/or rates of faulting, and areas where data are lacking. Table II provides a summary of some of the results of the field studies and their seismic hazards implications.

II-B: SOUTHERN SEGMENT OF THE PAJARITO FAULT SYSTEM

The southern segment of the Pajarito fault system as defined here stretches from State Highway 4 south across the east side of St. Peters Dome (MAP IV-A, Sheets 1 and 2). At this point the fault zone splays, with one group of faults continuing due south to south-southeast toward the La Bajada fault east of the Rio Grande and the other group of faults trending southwest for another 6 km. Smith et al. (1970) show the south-trending splay joining the La Bajada fault and show the southwest-trending splay bending south and dying out in Tertiary sediments in the northern Santo Domingo Basin. Along its entire 30-km length the southern segment of the Pajarito fault zone shows significant offset of stratigraphic units and zones of gouge and breccia in canyon exposures.

The oldest rocks in the southern segment area are west-tilted sandstones and conglomerates of the Eocene Galisteo Formation. This sequence is bounded on the east and southeast by the Pajarito fault zone and is unconformably overlain by non- to weakly indurated sandstones and siltstones of the Miocene Santa Fe Group. Many thin flows and pillow-palagonite zones of alkali basalt are scattered throughout upper horizons of the Santa Fe Group, and a K-Ar date on one of these basalts is 16.5 Ma (Gardner and Goff, 1984). Unconformably overlying the Santa Fe Group is the Keres Group, the earliest sequence of Jemez volcanic rocks. Volcaniclastic rocks of the Keres Group generally dip from 3° to 10°W, and the Keres Group sequence ranges in age from >13 to 6 Ma (Gardner et al., 1986).

Overlying the Keres Group is one flow of Tschicoma dacite (3.67 Ma; Dalrymple et al., 1967) of the Polvadera Group in upper Frijoles Canyon and flows and tuffs of the Tewa Group. Tewa Group rocks consist primarily of

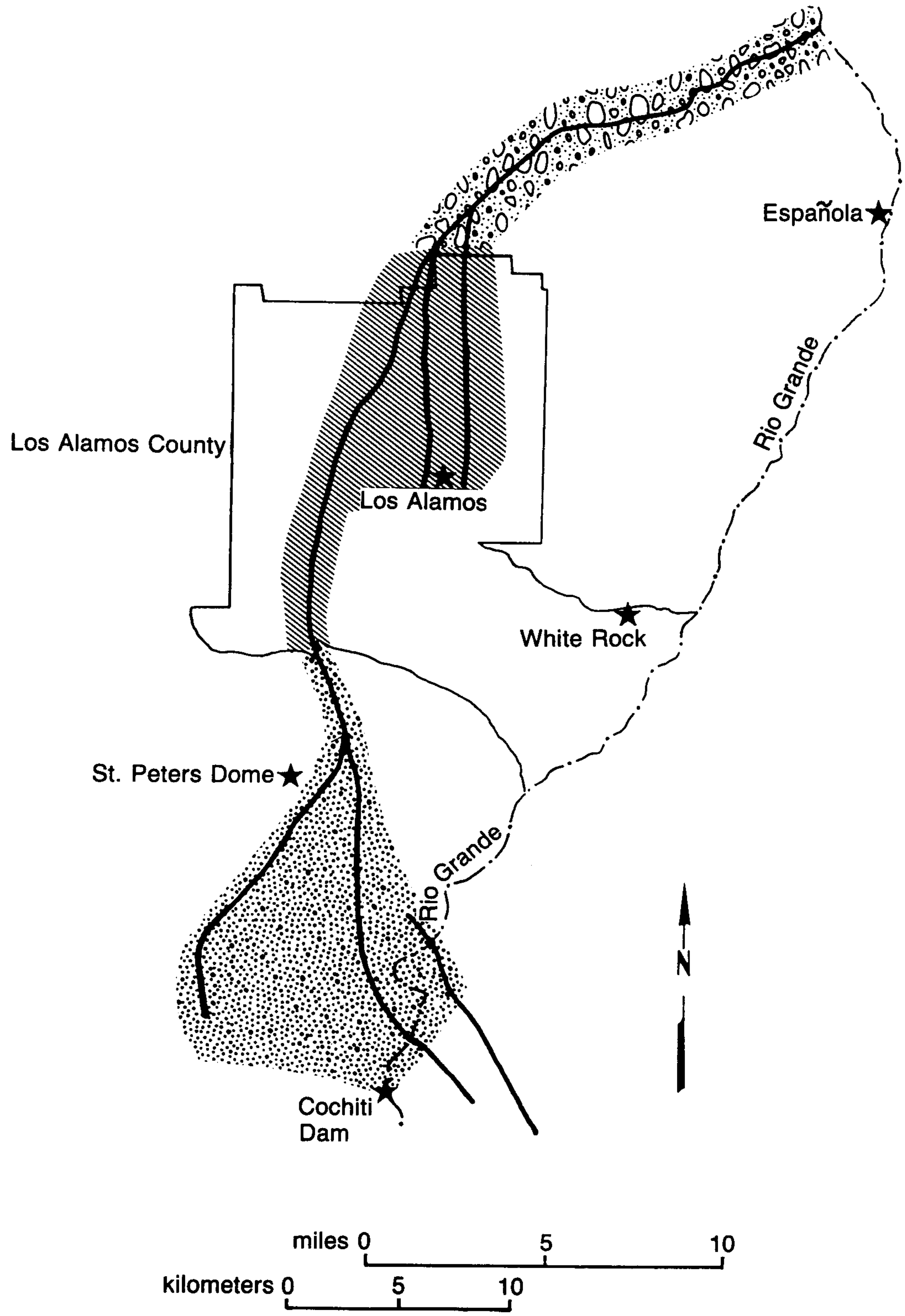


Figure 1a: Map showing southern, central, and northern segments of the Pajarito fault system, outline of Los Alamos County (thin solid line), and the Rio Grande (dot-dash line). Primary mapping responsibilities (MAP IV-A) are southern segment (coarse stipple) Gardner and Goff; central segment (diagonal rule) Broxton, Gardner, and Maassen; northern segment (open cobbles with fine stipple) Aldrich, Dethier, and Harrington.

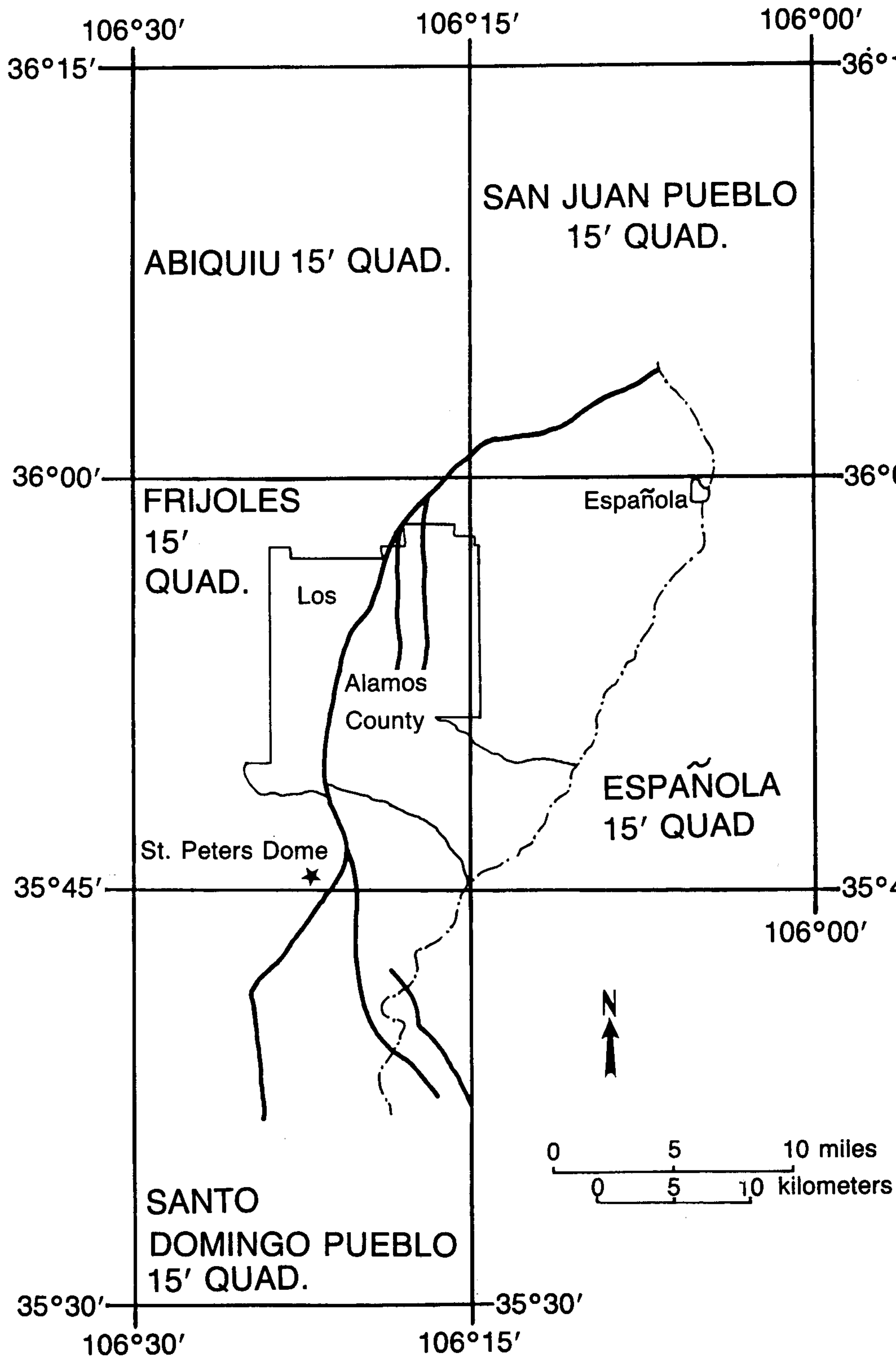


Figure 1b: Index of 15-minute topographic base maps of MAP IV-A, with St. Peters Dome (star), main trace of Pajarito fault system (heavy solid line), Rio Grande, and outline of Los Alamos County.

TABLE II: RESULTS FROM FIELD STUDIES WITH DIRECT SEISMIC HAZARDS IMPLICATIONS

RECENCY OF FAULT MOVEMENTS

Age	Remarks
<1.1 Ma	Offset Bandelier Tuff and younger rocks throughout entire fault system.
<500 Ka(?)	6-m offset of older alluvium, Pajarito fault in Bland Canyon; alluvium contains cobbles of Bandelier Tuff, but age otherwise not well constrained.
<600-350 Ka	Q_1 geomorphic surface deformed on Embudo and Pajarito faults.
<500-300 Ka	60 to 110 m drainage gradient disruption, Pajarito fault in Water Canyon.
<350 Ka	50-m downdropping of Q_1 geomorphic surface, Embudo fault.
<240 Ka	Faulted channel deposits younger than Q_2 geomorphic surface, Embudo fault.
<42 Ka	Faulted paleochannel surface, Arroyo de la Presa, Embudo fault.
Holocene (<10 Ka)	Dammed drainages and alluvial thicknesses, Rendija and Guaje canyons, Guaje Mountain fault; evidence indirect and not conclusive.
~2 Ka	Disrupted soil profiles, fault southwest of Hernandez.

ESTIMATES OF EARTHQUAKE MAGNITUDE BASED ON DISPLACEMENT PER EVENT RELATIONSHIP (Figure 25 of Slemmons, 1977)

Offset	Magnitude	Remarks
6 m	7.8	Based on assumption of one event causing entire offset of older alluvium, Pajarito fault in Bland Canyon.
0.5 m	6.8	Faulted paleochannel, Arroyo de la Presa, Embudo fault.
0.2 m	6.5	Faulted channel fill cut into Q_2 geomorphic surface, Embudo fault.

ESTIMATES OF MAGNITUDE AND RECURRENCE ASSUMING AVERAGE MINIMUM RATES OF MOVEMENTS REPRESENT STRAIN RATES (Based on Figure 2 of Slemmons, 1977)

Rate (cm/yr)	Magnitude/Recurrence	Remarks
0.2-0.4	6-6.3/100 yr	Water Canyon; average over 0.05 Ma; estimate utilizes nonconservative incision rates that may be unrealistic.
0.2	6/100 yr	Near Hernandez; average over 0.002 Ma.
0.02	6/1000 yr	South of Frijoles Canyon; average over 1.1 Ma.
0.02-0.04	6-6.5/1000 yr	Water Canyon; average over 0.5 Ma.
0.03	6.2/1000 yr	Santa Clara Canyon; average over 2 Ma.
0.02	6/1000 yr	Embudo fault; average over 0.25 Ma.
0.005	6.4/10,000 yr	Lobato Mesa; average over 10 Ma.
0.002	6/10,000 yr	Lobato Mesa; average over 1.1 Ma.
0.001	5.8/10,000 yr	Arroyo de la Presa; average over 0.042 Ma.

welded lower and upper Bandelier Tuffs (1.45 and 1.12 Ma respectively; Doell et al., 1968; Izett et al., 1980). Lower Bandelier Tuff (Otowi Member) is thickest northwest of St. Peters Dome suggesting it ponded in a low area between Valles caldera and the uplifted St. Peters Dome complex. Thin flows and tuffs of Cerro Toledo Rhyolite (1.43 Ma; F. Goff, unpub. data) outcrop between the Bandelier Tuffs in the northwestern part of Alamo Canyon. The youngest volcanic unit is the El Cajete pumice (0.13 Ma; Marvin and Dobson, 1979), which has accumulated in south- and east-facing slopes or forms a thin veneer on plateau tops.

Other Quaternary age units in the vicinity of the southern segment of the Pajarito fault system include landslide or mass-wasting deposits, colluvium, "older" alluvium, and active alluvium.

1. Faults

The northern half of the southern segment of the Pajarito fault system is a zone roughly 1 to 3 km wide marked by two parallel faults with down-to-the-east displacement of the upper member of the Bandelier Tuff. The maximum displacement of the Bandelier Tuff by the western fault is about 200 m based on scarp height on the mesa south of Frijoles Canyon (Figure 2). Maximum displacement of Bandelier Tuff by the eastern fault is about 90 m in the vicinity of the Stone Lions Shrine in Bandelier National Monument. At least three cross faults connect the major north-south faults along this part of the Pajarito fault system. Although the prominent geomorphic expression is the easiest way to locate the fault traces, exposures of fault gouge and breccia can be observed in the walls of Frijoles Canyon, Alamo Canyon, Capulin Canyon, and Hondo Canyon.

The western fault is covered by a large landslide on the northeast side of St. Peters Dome. South of the landslide the western fault juxtaposes both the Santa Fe Group and the Galisteo Formation against Upper Bandelier Tuff. Near Red Canyon, where it displaces Bandelier Tuff about 40 m, the western fault bends sharply southwest. Close to Red Canyon, west-dipping redbeds of the Galisteo Formation are sheared and drag-folded to the southeast into the fault zone, and the fault plane dips 70°SE. Farther to the southwest the fault generally juxtaposes flat-lying Bandelier Tuff (southeast) against Santa Fe Group, various Keres Group units, and, in one place, post-Bandelier Tuff alluvium. Maximum displacement is about 120 m in the Bandelier Tuff between

Figure 2: View, looking north, of main fault scarp from north of St. Peters Dome in Bandelier National Monument.

Cochiti and Bland Canyons. Maximum displacement in the older rocks is unknown but easily exceeds 300 m.

South of the Stone Lions Shrine, the east fault continues south to south-southeast, but displacements diminish rapidly and physiographic demarcation of the fault is much less obvious. The best place to observe the fault is in an unnamed side canyon west of Capulin Canyon where brecciated Bandelier Tuff can be seen in the canyon wall and Peralta Tuff (west) is faulted against Keres Group andesite and the Santa Fe Group in the canyon bottom. Maximum displacement in the Bandelier Tuff is no more than 20 m although displacement in the older rocks must be hundreds of meters. Farther south, the east splay of the zone is not easily located by surface mapping, but it apparently crosses the Rio Grande and joins the obvious fault scarp of the La Bajada fault. The La Bajada fault has not been studied in detail. Smith et al. (1970) show the fault with a down-to-the-west sense of displacement, younger than about 3 Ma, but older than Quaternary alluvium.

The angular unconformities between units have been caused by tilting of rock units with fault movements in the vicinity of St. Peters Dome. The Galisteo Formation dips 45° west-northwest, the Santa Fe Group dips 10-15° northwest, the Keres Group dips less than 5° northwest, and the Bandelier Tuff dips 3-5° southeast. Clearly these angular unconformities between rock units with amount of tilt increasing in progressively older units indicate recurrent fault activity since at least Santa Fe Group time. The prominent angular unconformity between the Eocene Galisteo Formation and the upper Santa Fe Group (16.5 Ma in the vicinity of St. Peters Dome; Gardner and Goff, 1984) together with offset Bandelier Tuff and Quaternary alluvium, indicates the southern segment of the Pajarito fault system has been recurrently active from at least 16.5 Ma through the Quaternary.

Style of Deformation

Brittle fracture data and field observations of fault plane attitude and displacement indicate the dominant style of deformation in the southern segment of the Pajarito fault system is normal faulting (Figure 3). The lack of piercing points makes estimation of any horizontal component to the movements difficult, but we have not recognized any features that indicate any horizontal component to movements in the Quaternary.

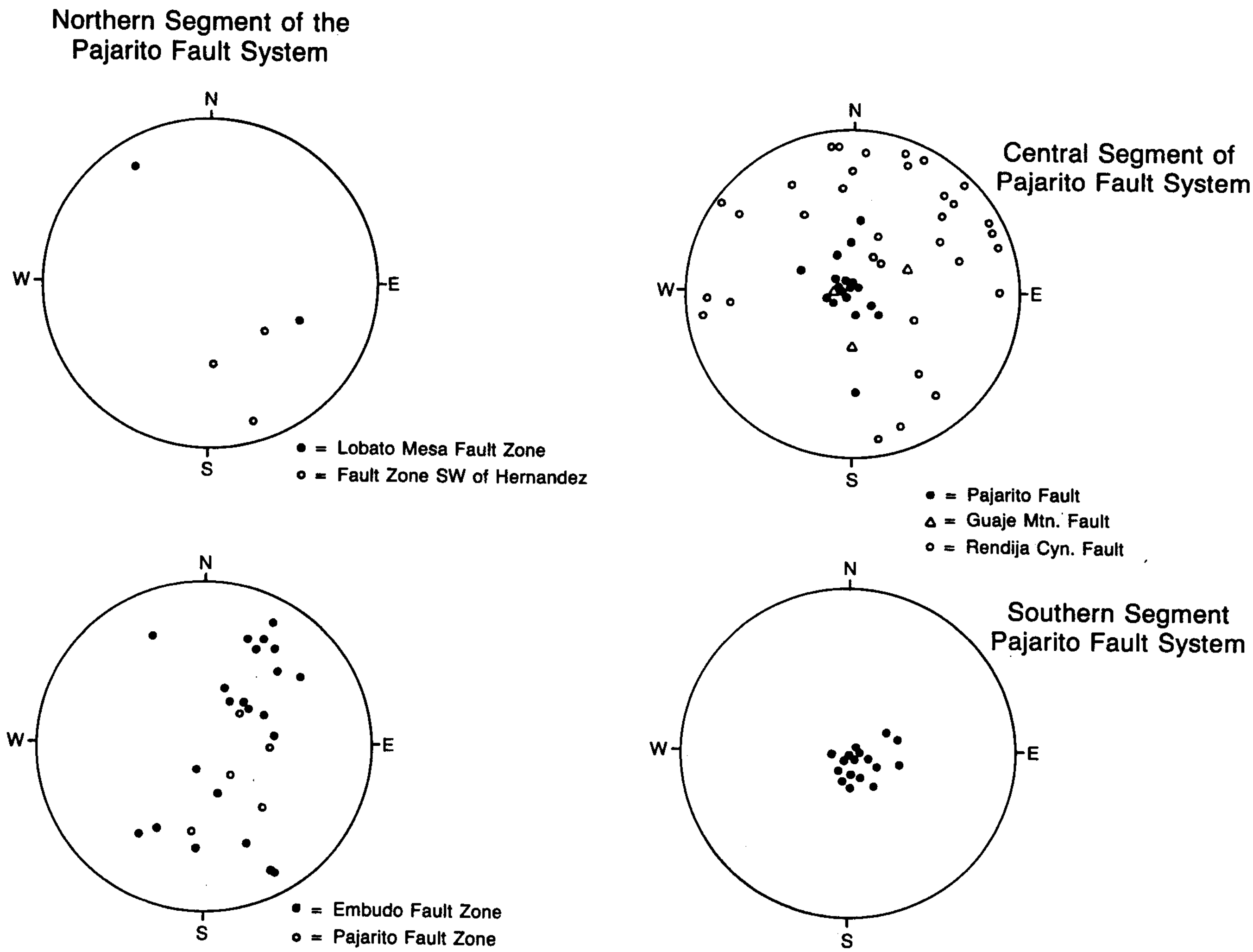


Figure 3: Lower hemisphere equal-area stereoplots of brittle fracture (slickensides and grooves) data for movements in different portions of the Pajarito fault system. [Some data from Golombek (1981) and Aldrich, unpub.]

3. Rates and Recency of Movements

Maximum displacement of Miocene and older rock units in the southern segment of the Pajarito fault systems exceeds 300 m, but evidence for episodic movements and lack of dated, correlated faulted units prohibit estimates of rates of fault movements based on these rocks. Although fault movements since deposition of the Bandelier Tuff have probably continued recurrently, a minimum, average rate of movement can be estimated for the last 1 million years. Since 1.1 Ma, when the upper Bandelier Tuff was erupted, a minimum, average rate of vertical displacement has been 200 m/1.1 million years or about 0.02 cm/yr.

At the mouth of Bland Canyon, the southwest splay of the Pajarito fault system crosses the canyon at right angles. On the north canyon wall, the fault forms a major bench in the Bandelier Tuff and juxtaposes Bandelier Tuff (east) against Peralta Tuff of the Bearhead Rhyolite (west). In the canyon bottom on the south side of Bland Creek, late Quaternary alluvium, which contains pebbles of Bandelier Tuff, is in fault contact with Peralta Tuff (6.81 ± 0.15 Ma; Gardner et al., 1986) (Figure 4). The fault plane dips about 70° to the southeast and is marked by slickensides between tuff and alluvium and by subtle drag-type deformation in the poorly bedded alluvium. The exposure indicates at least 6 m of displacement of the alluvium.

Three parallel seismic refraction profiles were done both upstream and downstream of the fault in Bland Canyon to locate the stream channel cut into bedrock, determine thickness of alluvium across the fault, and determine offset of the bedrock channel in the subsurface. Measured seismic P-wave velocities for the rock units are shown in Table III. The data indicate that alluvium overlying Peralta Tuff on the upthrown side of the fault is about 3 m thick (10 ft), whereas alluvium overlying Bandelier Tuff on the downthrown side is over 12 m (40 ft) thick (Figure 5). Hence, a scarp of about 9 m (30 ft) exists in the stream's bedrock channel.

A ground-penetrating radar profile that was obtained across the fault in Bland Canyon is shown in Figure 6. This profile suggests that at least the youngest alluvial strata (top several meters) are not disturbed by faulting. However, radar reflectors in the lower two-thirds of the profile are so weak, it is difficult to be conclusive. These reflectors could have been an artifact of the instrumentation.

Figure 4: Photograph, looking southwest, of the Pajarito fault near the mouth of Bland Canyon. Fault juxtaposes late Quaternary alluvium containing cobbles of Bandelier Tuff (left) against 6.8 million year old Peralta Tuff of the Bearhead Rhyolite.

TABLE III: SEISMIC P-WAVE VELOCITIES OF MAJOR GEOLOGIC UNITS, PAJARITO PLATEAU AREA[a]

Unit	P-Wave Velocity (ft/sec)	Locale	Remarks[a]
Active Alluvium	1100	Bland Cyn.	
	1800	Bland Cyn.	H_2O
	1150	Bland Cyn.	
	1175	Guaje Cyn.	
	1750	Guaje Cyn.	H_2O
	1200	Rendija Cyn.	
	2200	Rendija Cyn.	H_2O
	2400	Rendija Cyn.	H_2O
	1150	Rendija Cyn.	
	1900	Rendija Cyn.	H_2O
	1200	Rendija Cyn.	
	1900	Rendija Cyn.	H_2O
Bandelier Tuff	3700-5000(?)	Bland Cyn.	
	2500	TA-33	Vapor-phase altered
	3000	TA-33	Vapor-phase altered
	15000	W of S-Site	Densely welded
Puye Formation	4000	Guaje Cyn.	
Older Alluvium	4000	Guaje Cyn.	H_2O
Peralta Tuff	3500	Bland Cyn.	
	3400	Bland Cyn.	
	3900	Bland Cyn.	H_2O
	4000-5000(?)	Bland Cyn.	H_2O
Fractured Tschicoma	3300	Rendija Cyn.	
Formation Dacite(?)	3300	Rendija Cyn.	

[a] Question marks indicate uncertain unit assignment; H_2O in remarks column indicates measured unit was water bearing.

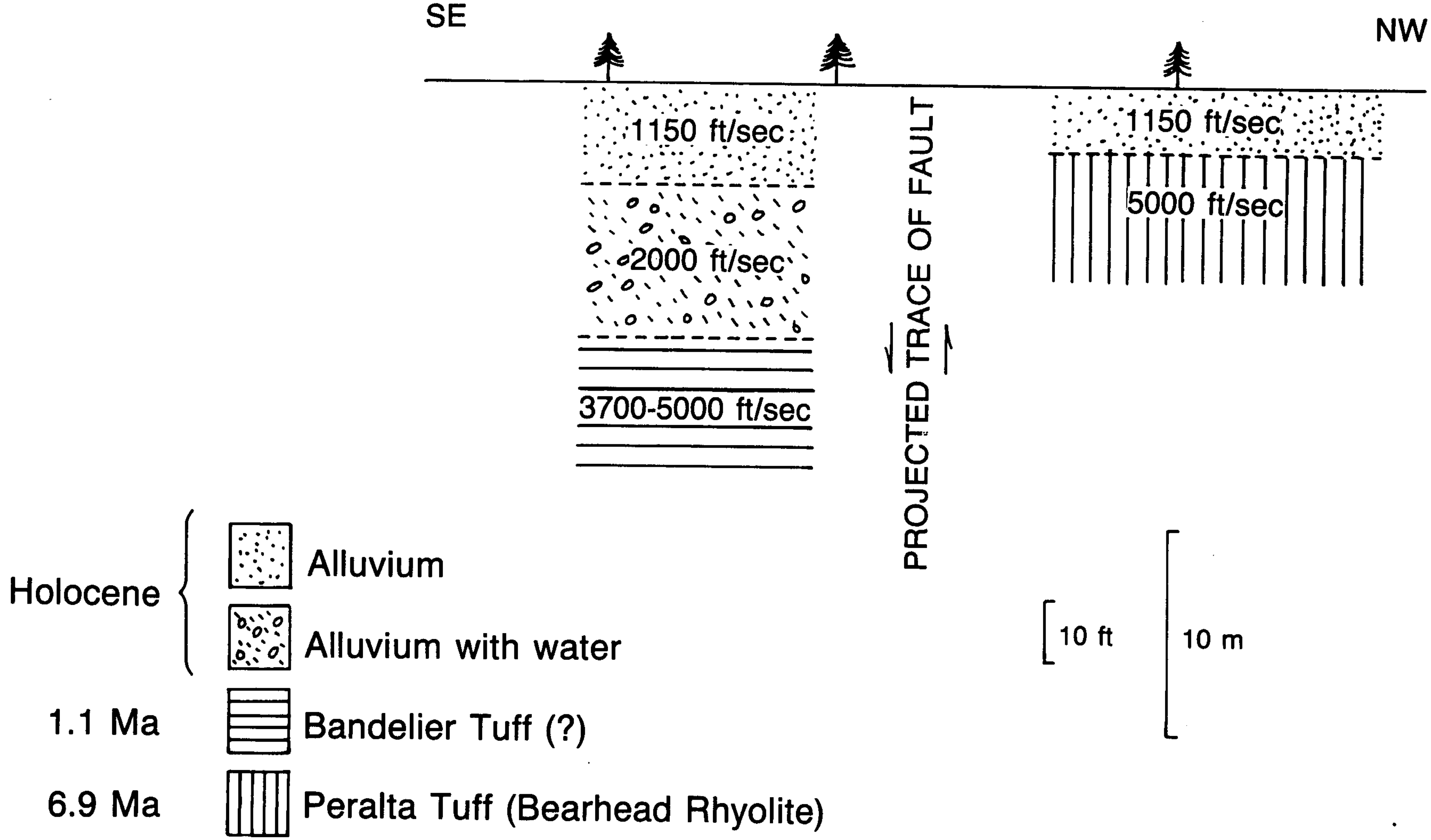


Figure 5. Cartoon cross section showing results of seismic refraction profiles in Bland Canyon.

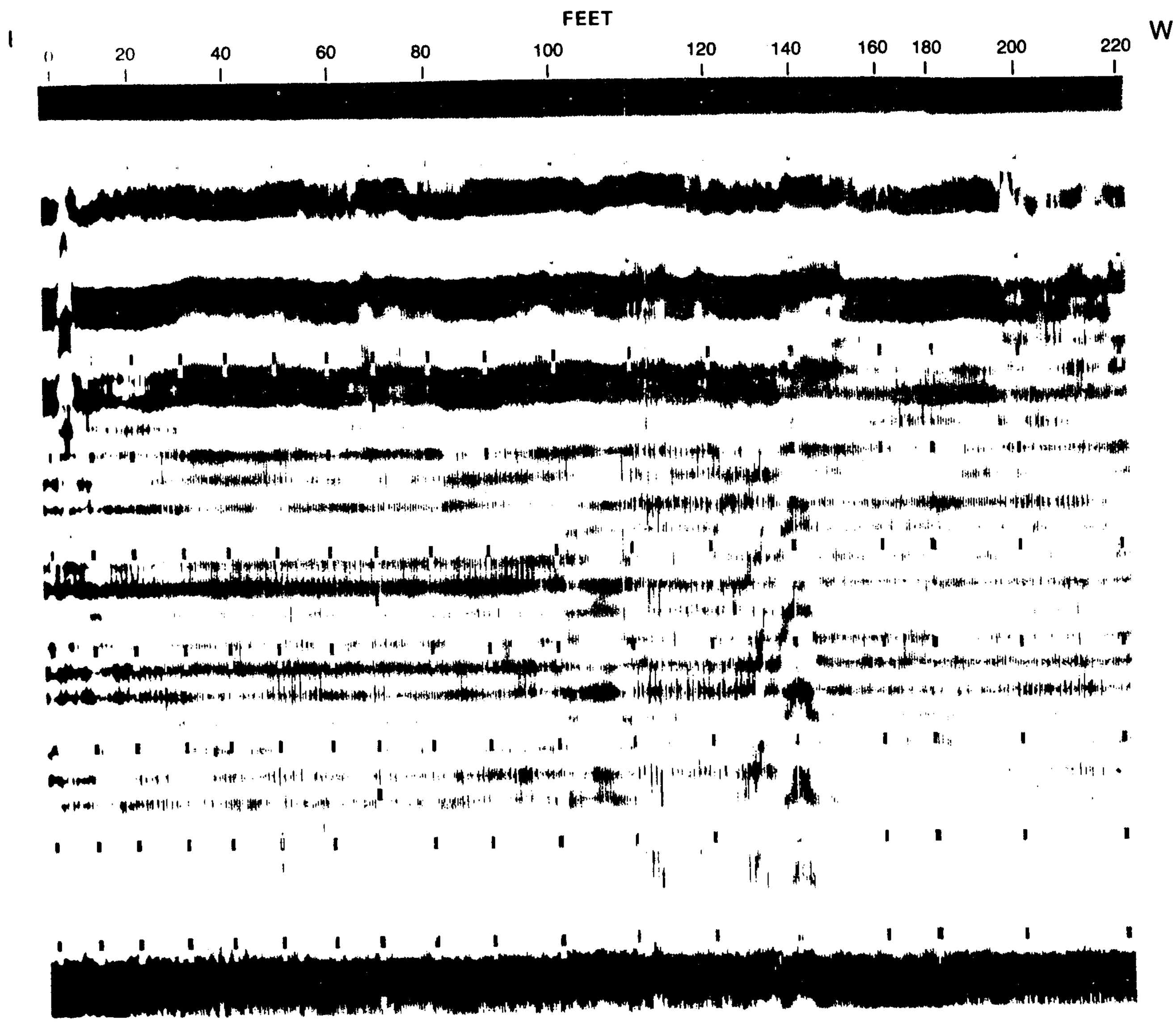


Figure 6: Ground-penetrating radar profile of active alluvium in Bland Canyon. Profile crosses projected trace of the Pajarito fault and apparently shows undisturbed layers in the top 15 ft (depth to prominant reflector at bottom of profile) of the alluvium. However, most reflectors in the bottom two-thirds of the profile are extremely weak and may have been an artifact of the instrumentation.

Exposures indicate that some "older alluvium," younger than Bandelier Tuff, has been faulted at least 6 m, but we do not yet know if this offset represents one or multiple movements. To be conservative we assume the entire 6 m represents one movement for the estimates shown in Table II. A radar profile suggests that the top 4.5 to 5 m of youngest alluvium in the canyon is not faulted. Hence, these data do not preclude additional offset of the "older alluvium" in the subsurface, nor do they constrain the age of faulting any better than information that may be obtained from exposures. Further work at this locality may be limited by private landownership. At the very least attempts should be made to better determine the age of the faulted "older alluvium." Rerunning radar profiles across the fault at a drier time of year (the one shown in Figure 6 was done during peak spring runoff) may allow greater depth of penetration and elucidation of displacements, or lack thereof, in the alluvium.

II-C: CENTRAL SEGMENT OF THE PAJARITO FAULT SYSTEM

The central segment of the Pajarito fault system is within Los Alamos County, and faults and fault zones of the central segment bound and/or underlie much of Los Alamos National Laboratory. The central segment includes the named Pajarito (also called "Los Alamos"; Kelley, 1978), Guaje Mountain, and Rendija Canyon (also called "Los Alamos"; Budding and Purtymun, 1976) fault zones (MAP IV-A, Sheet 2). The Guaje Mountain and Rendija Canyon fault zones are part of a series of down-to-the-west faults that contribute to the asymmetry of the Española Basin, with a deep intrabasin graben at the western boundary beneath the Pajarito Plateau (compare MAP IV-A, Sheet 2, and MAP IV-B; see discussions of Gardner and Goff, 1984, and of Dransfield and Gardner, 1985). Most of the down-to-the-west faults, except for the ones named above, do not break the Bandelier Tuff and are discussed in detail elsewhere (Dransfield and Gardner, 1985). These pre-Bandelier Tuff faults do nevertheless bear on certain aspects of seismic hazards at the Laboratory and are discussed in this regard in a later section (Chapter IV, MAP IV-D).

We have found Late Pleistocene to Holocene deposits and geomorphic surfaces that may yield better constraints on the history and recency of movements of the central segment of the fault system. We are currently remapping most of the central segment at a scale of 1:12,000 for purposes of selecting sites for further study by trenching.

1. Faults

Near the southern boundary of Los Alamos County, the Pajarito fault zone is a narrow swath of north-trending normal faults. The master fault of this portion of the fault zone offsets densely welded Bandelier Tuff (1.1 Ma) about 125 m. Although El Cajete pumice (0.130 Ma) is found within the fault zone, it is not clear if the pumice deposits have been faulted, as suggested in Keller (1968), or have simply accumulated on the lee-side of topographic obstructions in the El Cajete ejecta plume. The main fault scarp from State Road 4 to Los Alamos Canyon is steep (50° to 70° dip to the east) and surprisingly clear of talus or colluvium. A few small deposits of postscarp landslides too small to be shown on MAP IV-A have been noted, and one of these is cut by a north-trending linear of foliage. At least two postscarp alluvial fans built from Water and Pajarito canyons across the fault zone have been abandoned and are currently being incised. The postscarp deposits and features are the subject of on-going, detailed study.

In the vicinity of Los Alamos Canyon the fault zone widens, the dominant sense of movement apparently changes, and the clear geomorphic expression of the main fault scarp disappears.

Two fault segments are exposed in Los Alamos Canyon near the Los Alamos Reservoir. We call these the East Reservoir and West Reservoir faults. Both faults are well exposed in the north wall of the canyon; exposures on the south wall are covered by soil and colluvial deposits.

East Reservoir fault strikes north, following a shallow, linear gully up the north wall of the canyon. This gully empties onto the canyon floor at the picnic area about 100 m east of the reservoir spillway. The fault is recognized by drag folds within lavas of the Tschicoma Formation and by juxtaposition of lithologically distinct rock units.

Volcanic units on the east side of the fault consist of, in ascending stratigraphic order, coarsely porphyritic rhyolite, coarsely porphyritic dacite, and Bandelier Tuff. The coarsely porphyritic dacite is an excellent marker bed because it forms a prominent ledge and because it has a distinctive autoclastic rubble zone and vitrophyre at its base. On the western side of the fault, the stratigraphic succession is, in ascending order, moderately porphyritic dacite, sparsely porphyritic andesite, coarsely porphyritic dacite lava, and Bandelier Tuff. The coarsely porphyritic dacite is the same lava as that exposed beneath the Bandelier Tuff on the east side of the fault. However, below this distinctive marker bed, stratigraphic units are dissimilar across the fault.

The Tschicoma volcanic rocks in Los Alamos Canyon generally dip less than 20° toward the east or northeast. However, within 25 m of East Reservoir fault, rocks east of the fault are rotated to dips of up to 70°NW. The rubble zone at the base of the coarsely porphyritic dacite is displaced 60 m down to the east across the fault. The Bandelier Tuff is displaced 25 m down to east across the fault, indicating both recurrent movement and substantial displacement on the fault within the last 1.1 m.y. Foliations within the Bandelier Tuff are not rotated to steep dips like those within the underlying units on the east side of the fault.

The East Reservoir fault has had a history of recurrent movement with a significant component of vertical displacement. Certain features of the fault are also suggestive of a lateral component of displacement. These features include (1) drag folds on the east side of the fault that could be interpreted as indicating left lateral displacement, (2) reduction in the vertical displacement of the coarsely porphyritic dacite away from the fault, and (3) the presence of dissimilar stratigraphic units below the coarsely porphyritic dacite. These features are difficult to reconcile with vertical displacements only. A lateral component of movement cannot be clearly demonstrated from the limited exposures of this area, but oblique slip is probable.

The West Reservoir fault is located 200 m west of the East Reservoir fault and strikes north across the central portion of Los Alamos reservoir. This fault together with the East Reservoir fault bounds a narrow horst that strikes north.

The West Reservoir fault is recognized by drag folding within the Tschicoma coarsely porphyritic dacite described above, by juxtaposition of dacite against Bandelier Tuff across the fault, and by a prominent air photolinear cutting Bandelier Tuff north of Los Alamos Canyon. Stratigraphic units beneath the coarsely porphyritic dacite are not exposed in the vicinity of the fault because of thick deposits of colluvium. However, rhyolites clearly underlie the dacite about 300 m west of the fault, and andesites crop out beneath the dacite about 50 m east of the fault.

The coarsely porphyritic dacite on the downthrown western block is abruptly rotated to dips of 50°NE by the fault. East of the fault, this unit is subhorizontal. Vertical offset on this unit is about 70 m. The Bandelier Tuff (1.1 Ma) shows similar amounts of displacement across the fault.

From Los Alamos Canyon the Pajarito fault zone bends to the northeast and apparently becomes segmented into en echelon strands, which together with poor exposures, renders it difficult to trace. Also north from Los Alamos Canyon the Guaje Mountain and Rendija Canyon fault zones break the Bandelier Tuff (1.1 Ma) with a down-to-the-west sense of vertical displacement. Although vertical components to movements are easiest to document, air photostudies reveal drainages offset in a right lateral sense on the Pajarito, Rendija Canyon, and Guaje Mountain fault zones north of Los Alamos Canyon. The Guaje Mountain fault offsets the course of Guaje Canyon about 370 m. The canyon is cut through resistant dacite that is surrounded by more easily erodible gravels of the Puye Formation (MAP IV-A, Sheet 2). These relations together with data that suggest significant horizontal components to movements (Figure 3) indicate the canyon offset is due to fault movements and is not simply a fortuitous crook in the canyon's course. To the south, the fault offsets smaller drainages (presumably younger) cut in Bandelier Tuff about 60 m. The north wall of Pueblo Canyon is offset several meters in a right lateral sense by the Guaje Mountain fault (Figure 7). One splay of the Pajarito fault zone between Los Alamos and Pueblo canyons also shows right lateral movement of about 280 m, with a small north-trending drainage developed along the fault splay.

2. Style of Deformation

As discussed above, field evidence indicates the style of deformation within the fault system transforms from dominantly normal faulting in the southern part of the central segment to oblique slip in the northern portions of the central segment. These observations are consistent with the brittle fracture data shown in Figure 3. Although oblique slip for the northern portion of the central segment of the fault system is a plausible style of deformation in light of the data, we note that most slickensides in the northern portion of the central segment have near-horizontal orientations. This implies that the most recent movements have been dominantly horizontal, whereas older movements may have caused the vertical displacements.

3. Rates and Recency of Movements

A number of workers have reported evidence for recurrent movements along the central segment of the Pajarito fault system since at least Pliocene time

Figure 7: Oblique aerial photograph of the Los Alamos Ranch School (now downtown Los Alamos) taken looking east in about 1920. Arrow shows right lateral offset of the north cliff of Pueblo Canyon caused by lateral movements on the Guaje Mountain fault zone. (Photograph courtesy of Los Alamos Historical Society Archives)

(for example, Griggs, 1964; Golombek, 1981; Goff and Grigsby, 1982), and some workers have inferred multiple movements in the fault system within the last 1.0 to 0.5 million years (for example, Dames and Moore, 1972; Budding and Purtymun, 1976). Although the most recent movements within the central segment are the focus of ongoing studies, some preliminary information is presented here.

Based on information from 7.5-minute topographic maps, the gradients of the drainages of Water, del Valle, Pajarito, and Los Alamos canyons all change abruptly where the canyons cross the Pajarito fault zone. In that the gradient changes are substantial enough to be detected at the coarse resolution provided by the topographic maps and that the changes occur at the main trace of the fault zone, it is probable that at least some of the disruption of the gradients has been caused by young fault movements. We have examined one of these disrupted stream gradients, Water Canyon, in detail. We have noted that, on the Pajarito Plateau, portions of canyons away from faults and cut into Bandelier Tuff only are invariably about 150-200 m deep when V-shaped in cross section. The V-shape and low sinuosity of these canyons allow the reasonable assumption that most of the stream's erosive energy has been expended in downcutting. Hence, one may estimate an average, minimum stream incision rate into Bandelier Tuff to be about 0.02 cm/yr. In reality, these incision rates into Bandelier Tuff must be higher because of climatic variations in water supply with glacial and interglacial periods over the last 1 million years (age of the Bandelier Tuff of the Pajarito Plateau). Furthermore, the average minimum incision rate is very conservative because the Rio Grande drainages in this area have been actively downcutting only about 10,000 out of every 100,000 years (J. Hawley, pers. comm., 1986; C. Harrington, pers. comm., 1986); thus, one could argue that the average minimum incision rate of 0.02 cm/yr is low by at least one order of magnitude. For our purposes the more conservative rates are useful because estimates of, for example, timing of fault movements can only be maxima.

Water Canyon has a steepened gradient of about 6.5° cut into Bandelier Tuff immediately adjacent to and on the upthrown side (west) of the fault. Equilibrium gradients for Water Canyon are 2.25° in Bandelier Tuff on the downthrown (east) side of the fault and 3° in Bandelier Tuff in upper Water Canyon west of the steepened gradient (Figure 8). Geometric relations indicate, therefore, that the movements which disrupted Water Canyon's gradient

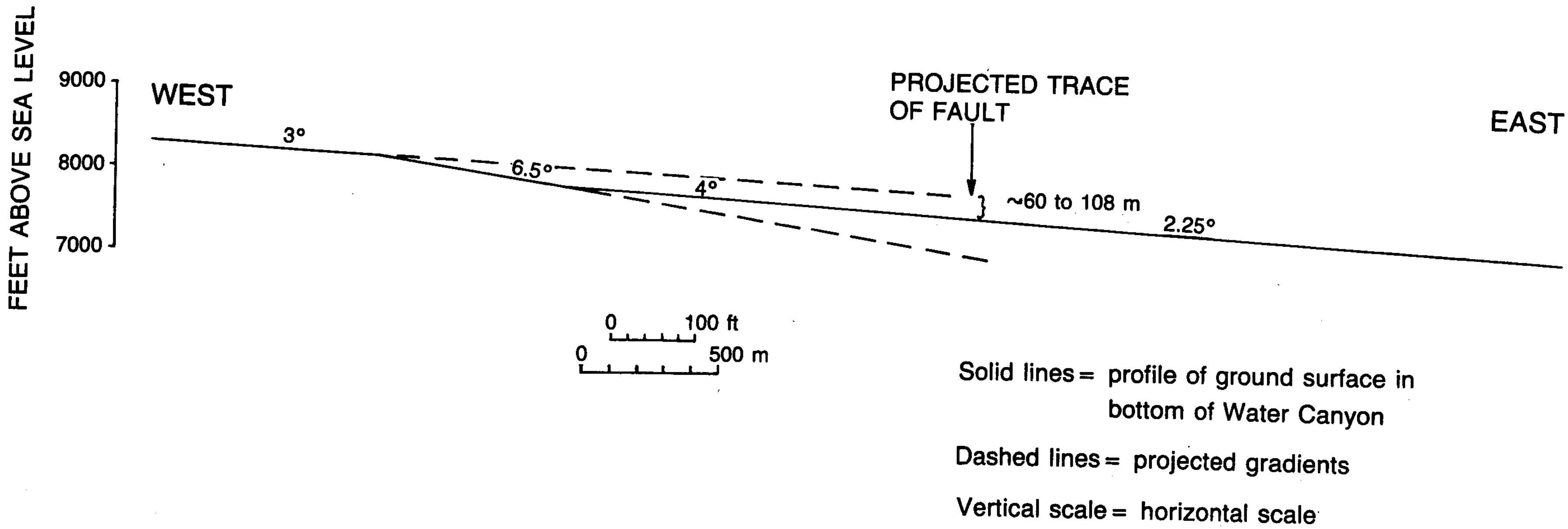


Figure 8: Stream gradient profiles of Water Canyon taken from 7.5-minute topographic maps. Steepened gradients of 4° and 6.5° occur immediately west of projected fault trace on the upthrown block.

caused 60 to 110 m of displacement and occurred less than 0.5 to 0.3 Ma. Significantly, these data indicate that most of the 125-m scarp at Water Canyon has been created within the last 500,000 to 300,000 years. Average minimum rates of fault movements, based on these data, are about 0.02 to 0.04 cm/yr for the Water Canyon locality.

Seismic refraction profiles were run across the Guaje Mountain fault zone to test the hypothesis that recent vertical fault movements (down-to-the-west) may have dammed the east-flowing drainages of Guaje and Rendija canyons. In Guaje Canyon alluvium has accumulated only on the upstream (west) side of the fault zone, suggesting that indeed young fault movements have dammed the drainage. Seismic refraction measurements indicate the alluvium accumulating upstream of the fault is about 2.5 m (8 ft) thick, and it overlies the Puye Formation (Table III).

In Rendija Canyon seismic refraction data indicate that the thickness of alluvium on the downthrown, upstream (west) side of the fault exceeds 12 m (40 ft), whereas on the upthrown side alluvium is only 6.8 m (22 ft) thick. Ground-penetrating radar profiles of the alluvium across the Guaje Mountain fault in Rendija Canyon show some interesting features (for example, Figure 9), but recent excavation of this area reveals most disrupted reflectors in the profile are alluvial channel scours.

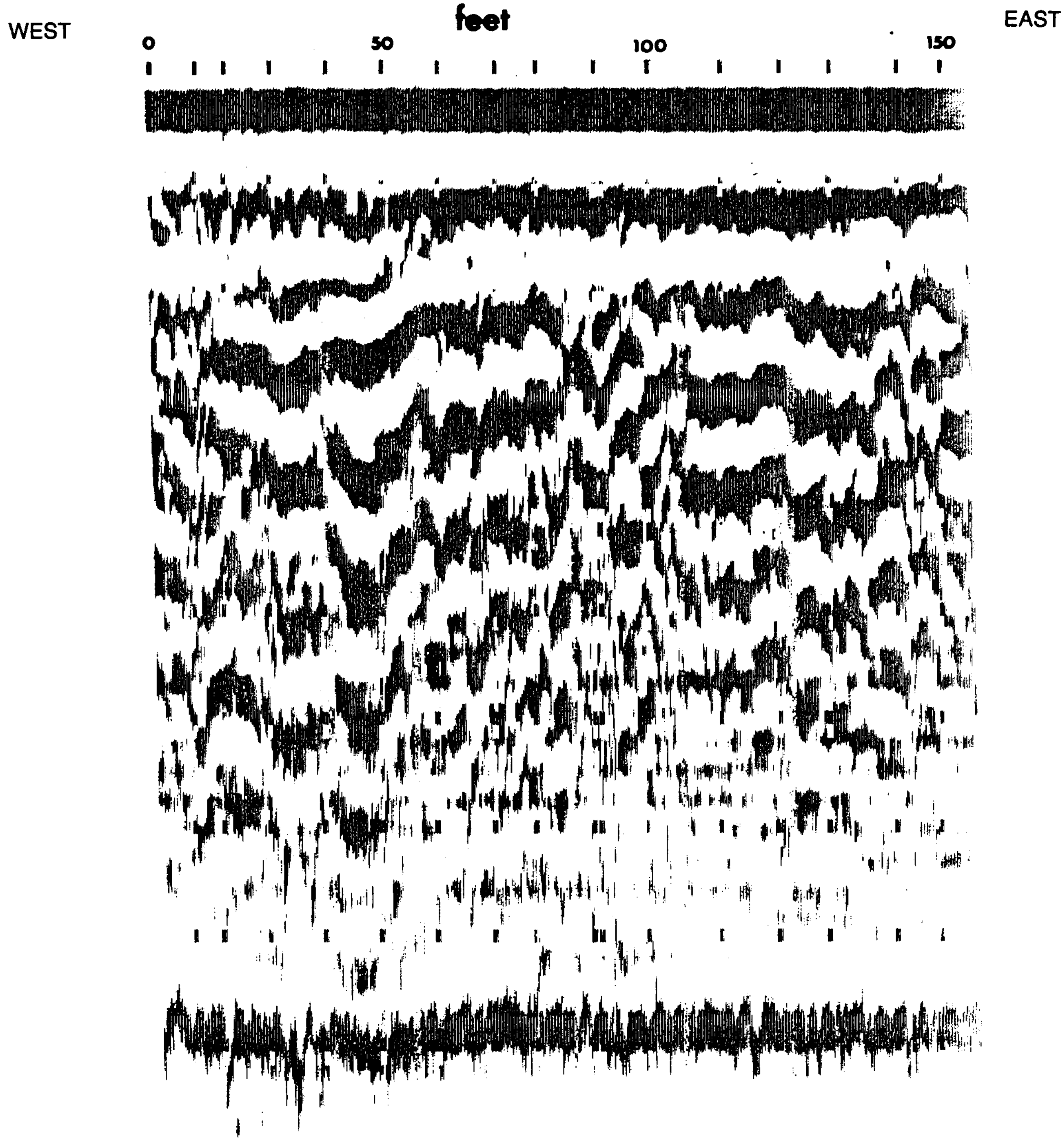


Figure 9: Ground-penetrating radar profile of active alluvium within the Guaje Mountain fault zone in Rendija Canyon. Recent excavation of this area reveals many of the reflectors in the profile show offsets which are the result of complex fluvial channel geometries. Lowest dark reflector at bottom of profile is about 15 ft deep.

II-D: NORTHERN SEGMENT OF THE PAJARITO FAULT SYSTEM

The northern segment of the Pajarito fault system extends north and northeast from Los Alamos County. In the northern segment the fault system includes the Pajarito fault zone (also called "Los Alamos," Kelley, 1978), the Lobato Mesa fault zone, the western Embudo fault zone (also called "Los Alamos," Kelley, 1978; also called "Santa Clara," Harrington and Aldrich, 1984), and the fault zone southwest of Hernandez (also called "north-trending," Harrington and Aldrich, 1984) (MAP IV-A, Sheets 3, 4, and 5).

1. Faults

From the northern boundary of Los Alamos County, near the intersection with the Rendija Canyon and Guaje Mountain fault zones, the trend of the Pajarito fault zone bends to the northeast. From this bend to where it intersects the Rio Chama, a distance of about 20 km, the fault zone bears the name "western Embudo fault zone." The distinction is purely semantic, in that there is no structural reason to distinguish the Pajarito and Embudo zones. We utilize both names only to assure geographic clarity and to emphasize continuity of the Pajarito system as the Embudo zone nearly to Taos. We have not studied the Embudo fault zone east of the Rio Chama in any detail. Muehlberger (1979), Manley (1984), Machette and Personius (1984), and Personius and Machette (1984) report recurrent Pleistocene to Holocene movements on the eastern Embudo fault zone.

The Lobato Mesa fault zone consists of a series of north-northwest-trending faults that splay from the western Embudo fault zone near Clara Peak. The Lobato zone clearly persists at least as far north as the town of Abiquiu. The Lobato Mesa faults have been mapped by Dethier and Martin (1984) and will not be discussed in detail here. Dethier and Martin (1984) report most tectonic activity in the Lobato Mesa zone was concentrated around 10 Ma, but they also report that at least one fault of the zone has Quaternary movements in that it offsets Bandelier Tuff less than 15 m. As discussed below, preliminary data suggest the Lobato Mesa, western Embudo, and southwest of Hernandez fault zones constitute integral parts of the fault system.

The fault zone southwest of Hernandez is a series of faults that intersect the western Embudo zone from the south, roughly 2 to 5 km southwest of the Embudo-Rio Chama intersection. The southern extent of this fault zone, south of the Santa Clara Indian Reservation, has not been mapped. As discussed below, these faults show abundant evidence for Quaternary movements.

2. Style of Deformation

All fault zones in the northern segment of the Pajarito fault system show evidence of movements with horizontal as well as vertical components (Figure 3). In fact, brittle deformation data indicate the most recent movements within these zones have been dominantly right slip. These data, together with the geometric relations of the fault zones, are what lead us to suggest that the Lobato Mesa, western Embudo, and southwest of Hernandez fault zones constitute integral parts of a fault system. The horizontal components to movements, the sense of movements, and the deformation of Quaternary geomorphic surfaces require that faults of the several fault zones must have operated in concert. The fault zones are parts of a complex rotational deformation of intrarift blocks of the Española Basin as discussed by Muehlberger (1979), Aldrich (1986), and Brown and Golombek (1986).

3. Rates and Recency of Movements

Topographic features along the Embudo fault zone and south of it and east of the Pajarito fault zone provide evidence that the fault system has been recurrently active during the last 0.5 Ma. Four erosional surfaces, from oldest to youngest designated Q_1, Q_2, Q_3, and Q_4, have formed across this portion of the northeastern Jemez Mountains during Quaternary time (MAP IV-G). The oldest, and highest, surface (Q_1) has been deformed by movements on the Pajarito fault zone and Embudo fault zone. This surface, formed 600 to 350 Ka (thousands of years before present) (Dethier and Harrington, 1986; Dethier, unpublished data), has been rotated by movements on the Embudo fault zone and Pajarito fault zone, decreasing the surface gradient and changing its slope direction from east to northeast (Figure 4 of and discussion in Harrington and Aldrich, 1984).

Evidence for additional deformation of the Q_1 surface by movement along the Embudo fault zone is a marked increase in surface gradient near the fault. The Q_1 surface within 0.5 km of the fault has a surface gradient of 45 m/km, approximately three times its gradient away from the fault. Projection of the lower-gradient portion of the Q_1 surface to the fault zone places the surface at an elevation approximately 50 m higher than that obtained by a similar projection of the portion with the steeper gradient. Thus, the block southeast of the Embudo fault zone has been downdropped by 50 m since 350 Ka (a rate of about 0.02 cm/yr). The base of the Puye Formation, which is subparallel to the Q_1 surface elsewhere, is also steeply tilted (61 m/km) at this same locality. Hence, recurrent downdropping of the block southeast of the Embudo fault zone has occurred since 2 Ma (constraint on upper age of Puye Formation; Manley, 1979; Gardner et al., 1986).

A fault that trends northeast, within the Embudo fault zone, is exposed in an arroyo (NW1/4,Sec13,T21N,R7E) just north of the graded road. The fault cuts a colluvial channel fill, displacing the base ∿0.2 m. The channel is cut into the Q_2 surface (350 to 240 Ka), and the colluvial fill possesses no appreciable carbonate accumulation. Hence, the channel is younger than the Q_2 surface, and the time of faulting is substantially more recent than Q_2 development.

At the western end of a paleochannel of Arroyo de la Presa (Sec12,T21N, R7E), a Lobato Basalt flow dips gently north and abruptly terminates against beds of the Chamita Formation (Santa Fe Group), which dip steeply southeast. Several low-angle faults within the Lobato outcrop are offset (∿10 cm) by several high-angle faults with dips to the north. Above the Lobato flow is a coarse volcanic-clast-rich gravel, which fills the broad paleochannel. The volcanic boulder gravel that fills the bottom of the channel thickens to 10 m at its southern edge. The gravel is overlain by a sandy unit that thickens to the south across the paleochannel to a maximum of 2 m. The sandy unit extends farther south than the gravel bed, although it decreases in thickness. The trends of the paleochannel, upper Arroyo de la Presa, the gravel terminus, and the basalt terminus are all parallel to the trend of the adjacent Embudo fault. The paleochannel fill is cut by two modern arroyos. The major arroyo (1) has a linear trend (N60-65°E) on line with the basalt and gravel terminus, (2) is on strike with the Embudo fault zone, (3) is cut across the topographic slope rather than down the slope, (4) is not cut at the low part of the paleochannel surface, which occurs 30 m to the north, and (5) lies at the base of a small scarp (∿0.5 m high), which forms the north wall of the modern channel. The topographic surface behind the scarp, if projected south across the channel, would be over 1 m higher than the present surface. Thus, the modern arroyo appears to be cut along the trace of a fault of the Embudo fault zone, and movement on this fault must postdate development of the paleochannel surface. Varnish cation ratios (see for example, Harrington, 1986a, 1986b) from boulders on this surface indicate an age for this portion of the surface of 42 Ka. Vertical displacement on the fault in excess of 0.5 m has occurred with the south side down since 42 Ka. As movement on the Embudo fault zone usually has a large strike-slip component, net slip must have been considerably more than 0.5 m. Minimum rate of motion for the fault is thus 0.001 cm/yr.

The fault zone southwest of Hernandez consists of a series of north- to northwest-trending faults that occur within 4 km of the Embudo fault zone. One of these faults, exposed in the south wall of the arroyo (above) cut along the Embudo fault zone, strikes N40°W with a 60°N dip on the fault plane. This fault has slickensides that rake 80°N, indicating motion east side down on the fault with a dip-slip component. An undated tephra bed has been downdropped ~1.5 m on the eastern block. The fault plane can be traced to within 0.3 m of the surface and may extend even higher. Soil profiles across the fault are markedly different. On the upthrown block the soil profile has a 0.3-m A horizon; the calcic B horizon extends down to 2.0 m with Stage II development. The soil profile on the downthrown block has an A horizon thickness similar to that across the fault, but the calcic B horizon extends only to 1.0 m depth with Stage I development.

Sediment on the downthrown block is 6 m thick. Beds within the lower part of the sediment, in particular thin gravel layers, are bent and stretched along the fault plane, thinning and terminating ~3.0 m below ground surface. Upper beds curve and become asymptotic as the fault is approached. The deformation of the lower beds and the difference in orientation compared with the upper beds suggest movement on the fault following deposition of the lower beds and before deposition of the upper beds. Therefore, at least three periods of motion have occurred along the fault based on displacement of the tephra bed, sediment deformation, and disruption of the soil profiles across the fault. The fault truncates the volcanic boulder gravel and appears to break the topographic surface (42 Ka) of the paleochannel. Minimum displacement along the fault yields an average rate of 0.2 cm/yr with last motion no earlier than Holocene and possibly about 2,000 years ago (minimum time to accumulate Stage I carbonate in the soil).

There are no piercing points that can be used to determine the net slip on the Pajarito fault zone, but by considering several pieces of data a reasonable estimate can be made. A 10.6-Ma dike is offset nearly 0.5 km in a right lateral sense by a major basin-bounding northwest- to north-trending east-side-down fault of the Lobato Mesa zone (Dethier and Martin, 1984; Dethier and Aldrich, unpub. data). Slickensides and grooves on the fault plane rake 15°S and 35°S, respectively. If these orientations are taken to reflect the range in net slip values, then the net slip on the fault since 10.6 Ma is somewhere between 490 and 520 m. The smaller slip (slickensides) rake angle probably reflects the counterclockwise rotation of the intrarift blocks (cf. Muehlberger, 1979; Aldrich, 1986), and the larger slip (grooves) rake angle the E-W extension that is occurring simultaneously with the block rotations. If we assume that the fault has been moving from the time the dike was emplaced, it has a minimum average movement rate of 0.005 cm/year. This fault juxtaposes the Ojo Caliente Sandstone and Chama-El Rito members of the Tesuque Formation (both of the Santa Fe Group) and has a vertical throw in the range of 112 to 228 m (based on the slip indicator and displacement of the offset dike), which is consistent with the observed stratigraphic separation. Estimates of rates of movement based on Dethier and Martin's (1984) reported offset of Bandelier Tuff (15 m) yield minimum average rates of about 0.002 cm/yr over the last 1 million years.

Along the Pajarito fault, on the Santa Clara Indian Reservation, a high erosional surface on the Puye Formation immediately north of Santa Clara Canyon and west of the fault is at or near the stratigraphic top of the Puye Formation that formed in the eastern Jemez Mountains during the Pliocene. This surface is approximately 120 m higher than the top of the Puye east of the fault. The fault, then, has a minimum throw of 120 m at this location, which has developed since the Puye fan ceased forming around 2 Ma (Manley, 1979; Gardner et al., 1986). Although the slickensides of the synthetic fault 2.5 km south of Santa Clara Canyon are horizontal, the net slip on the Pajarito fault zone must have had some dip-slip component to drop the east side some 120 m since the late Pliocene. The slickensides, therefore, do not represent the average net-slip orientation. When we assume that the average net-slip rake is approximately the same as that of the western-basin-bounding fault of the Lobato Mesa zone (15°-35°S), then the net slip on the Pajarito fault in the past 2 Ma has been somewhere between about 220 m and 500 m, and the movement rate has been in the range of 0.01 to 0.025 cm/year.

CHAPTER III:

SEISMOLOGICAL STUDIES

III-A: BACKGROUND

Most comprehensive of the previous studies of seismic hazards in Los Alamos were those done by Dames and Moore (1972) and Tera (1984). The Dames and Moore (1972) study was done for design of the Plutonium Facility (TA-55), while the Tera (1984) study was commissioned by the Department of Energy through Lawrence Livermore National Laboratory. Of the two, the Dames and Moore (1972) study is more comprehensive. In addition, a number of other seismic hazards-related studies of the Los Alamos area have been done (e.g., Slemmons, 1975; Budding and Purtymun, 1976; Sanford, 1976; and Savage et al., 1977). The discussion that follows focuses on the Dames and Moore (1972) and Tera (1984) studies; the others cited are summarized in the Appendix "Previous Studies."

Dames and Moore. The Dames and Moore (1972) report, "Report of geologic, foundation, hydrologic, and seismic investigation: plutonium processing facility, Los Alamos Scientific Laboratory, Los Alamos, New Mexico," discusses the work done to establish design criteria for the Plutonium Facility (TA-55). The seismic investigations were of seismicity and of seismic response at the site. The seismicity investigations were based on the available historic and instrumental seismicity. Estimating the seismic response of the site was done by calculations applied to real and synthetic strong earthquake ground motions.

The intent of the Dames and Moore (1972) study was to establish a level for the Operating Basis and Safe Shutdown Earthquakes. Although the amount of instrumental seismicity information from northern New Mexico was small in 1972, the investigators compiled what was available from various sources, and hence, the Dames and Moore (1972) report represents a fairly comprehensive source of information about earthquakes near Los Alamos up to 1972. The result of the seismicity investigations is that Dames and Moore (1972) argue that "it is unlikely that earthquake ground motion greater than Intensity VI has been experienced at the proposed site [Los Alamos] since the date of the first reported New Mexico earthquake in 1849." Note, however, that the term "unlikely" is not quantified, so there is no probability associated with it. Dames and Moore (1972) take Intensity VIII as the highest seismic intensity that the Plutonium Processing Facility will experience during its design lifetime. Note that Intensity VIII is the maximum experienced during the Socorro earthquake swarm of 1906.

The next step that Dames and Moore (1972) took was to correlate a peak horizontal ground acceleration of 0.33 g with the maximum Intensity value of VIII. Correlations between earthquake Intensity and peak ground acceleration are poor (Trifunac and Brady, 1975), yet such correlations are generally used by the earthquake engineering community. The Intensity-peak acceleration relation from Trifunac and Brady (1975) shows a peak ground acceleration for Intensity VIII of 0.26 g, but the data are scattered (standard deviation of 0.08 to 0.10 g); hence, the value chosen by Dames and Moore (1972) may not be as conservative as it might appear. Dames and Moore (1972) take a peak acceleration of 0.33 g for the Safe Shutdown Earthquake and about half that value (0.17 g) for the Operating Basis Earthquake.

Response spectra presented by Dames and Moore (1972) are taken from recordings of two earthquakes as well as three computer-synthesized earthquakes that were modified for presumed responses at both the recording and the TA-55 sites. To estimate the material properties beneath the TA-55 site, Dames and Moore (1972) took corings from the top 180 ft and assumed properties to presumed basement at 7000 ft. Because of the widely varying seismic velocities (Table III) and thickness of the Bandelier Tuff, particularly within the area of the Laboratory (Dransfield and Gardner, 1985), the response spectra computed for TA-55 may be unreliable for other sites.

Tera. The Tera Corporation (1984) report, "Seismic hazard analysis for the Bendix, Los Alamos, Mound, Pantex, Rocky Flats, Sandia-Albuquerque, Sandia-Livermore, and Pinellas sites," is a revision of a report originally issued in 1981. For purposes of this discussion, only the section on Los Alamos is considered. This study purports to be a "detailed seismic hazard analysis" of the Los Alamos DOE site. The principal result of the study is a probabilistic determination that the Los Alamos area would experience a peak horizontal ground acceleration of 0.08 g with a return period of 100 years and 0.22 g with a return period of 1,000 years. Much of this report is based on the work originally reported in Dames and Moore (1972).

The documentation in the Tera (1984) report is inadequate to determine the credibility of the results. The recent (historic) seismicity is used as input to the probabilistic model. The probabilistic model itself is not documented nor even summarized in this report. Although "sensitivity analysis" is mentioned several times in the report, nowhere is there any quantitative discussion of what was varied and what the outcomes were. Although terms such as "best estimate" and "weighted average" are used, there is no mention of how the estimate is "best" or how the individual items were "weighted." The response spectral curves shown in Figure 3-11 of Tera (1984) are simply taken from the Dames and Moore (1972) study and scaled to 1 g peak acceleration.

III-B: HISTORICAL EARTHQUAKES

Evaluating seismic hazards in Los Alamos from seismologic data requires using historical seismicity to extend the time duration of the instrumental earthquake record. In particular, two types of historical earthquakes are of interest: those large enough and close enough to be felt at Los Alamos, and those that are the largest earthquakes known to have occurred in the Rio Grande rift.

The record of earthquakes felt in Los Alamos extends back only about 45 years, since the Laboratory's beginnings in the early 1940s. Table IV lists all felt earthquakes that were located within about 100 km of Los Alamos. Felt reports of earthquakes before about 1950 are very sparse. Four earthquakes have been felt by residents of Los Alamos; all were located within 25 km of Los Alamos. The first occurred on August 17, 1952, and since the only felt reports were from Los Alamos, its epicenter was presumably nearby. This earthquake was of maximum Intensity V (magnitude about 4) (Coffman and von Hake, 1973). The second event, felt on February 17, 1971, had a maximum Intensity of II and was barely perceptible (Dames and Moore, 1972). This event was too weak to be located by the sparse seismograph coverage of that time (the nearest was at Albuquerque). It apparently was felt only in Los Alamos, and hence, it must have been located nearby. The time of this earthquake may be wrong; the felt report might have been from an earthquake that occurred early the next morning and was located about 70 km east-northeast of Los Alamos, although it seems unlikely that Los Alamos residents could have felt such a small shock (M_L = 3.4) located that far away.

A third earthquake was felt on December 5, 1971, and had a maximum Intensity of V. It was located instrumentally at 36.1°N, 106.3°W (Sanford, 1976), about 25 km north of Los Alamos, and was assigned a magnitude (M_L) of 3.3. Minor damage (for example, slight cracks in adobe walls) and audible rumblings were experienced in the epicentral region. Three other tremors were reported within an hour of the main shock (Sanford, 1976).

TABLE IV: REPORTED EARTHQUAKES IN THE VICINITY[a] OF LOS ALAMOS TO SEPTEMBER 1, 1973

Year	Date	Hour (MST)	Locality of Report	Distance From Los Alamos (km)	Maximum Reported Intensity (MMI)	Magnitude (M_L)	Remarks
1873[b]	8/2	22:00	Santa Fe	40	III?[c]	3[d]	Slight shock.
1893[b]	7/12	6:40-6:45	Albuquerque	95	VI[c]	4[d]	Three shocks.
1918[b]	5/28	4:30	Cerrillos	55	VIII[c]	5-1/2[d]	Minor damage in Santa Fe, 33 km to the NE.
1921[b]	7/30	22:55	Senorito	55	IV[c]	3-1/2[d]	
1930	3/23	12:00	Albuquerque[e]	95	IV	3-1/2	Very brief shock that shook houses and rattled dishes.
1930	12/3	14:36	Albuquerque	95	V-VI	4-1/2	Two distinct shocks. Cracked plaster and broke dishes. Felt in area about 18,000 sq. mi.
1931	2/3	16:45	Albuquerque	95	V	4	
1931	2/4	21:48	Albuquerque	95	VI	4-1/2	Hundreds left houses, many in pajamas, and many reported they were thrown from bed.
1936	9/9	5:55	Albuquerque	95	IV	3-1/2	Two shocks.
1947	11/6	9:50	San Antonito	85	V-VI	4-1/4	Dishes jarred from shelves. Cracked plaster at one location. Felt within a 16-km radius.
1952	8/17	3:45	Los Alamos	0	V	4	Felt by all. Slight damage to walls of houses. Doors and dishes rattled. Felt in Española, 25 km from Los Alamos.
1952	10/7	2:20	San Juan Mtns., Carson National Forest	110	V	4	Felt at Antonito and 15 miles west of there at Osier, Colorado; also at Chama and Tres Piedras, New Mexico.
1954	11/2	10:00	Albuquerque-Bernalillo	80	IV	3-1/2	Felt along 32 km of the Rio Grande Valley from Albuquerque to Bernalillo.
1954	11/3	13:39	Albuquerque-Bernalillo	80	V	4	Felt most strongly at Bernalillo. Windows, doors rattled. Loose objects shifted.
1955	8/12	9:20	Turquoise Trading Post, 25 km SW of Santa Fe	40	V	4	Plaster cracked in wall. At Santa Fe (25 km NE) and Bandelier Nat'l. Monument (25 km SW) dishes, windows, etc., rattled.
1956	4/25	20:30	Sandia Mountains	90	V	4	Sharp jolt. Awakened many and frightened few in Tijeras Canyon. Loose objects rattled. Maximum extent of felt area 28 km.
1969	7/4	7:43	San Juan Pueblo[f]	35	IV	3.5	Felt most strongly 10 and 20 km N of Española.
1970	11/28	0:40	Albuquerque[f]	80	V	3.7	Felt in Albuquerque, most strongly in the NW and SW sections of the city.
1971	1/4	0:39	Albuquerque[f]	80	VI	3.9	Felt most strongly at Corrales (about 20 km NE of Albuquerque).
1971	2/17	(?)	Los Alamos[g]	0	II		Felt in the Los Alamos area; apparently not felt anywhere else.
1971	12/5	22:18	NE Jemez Mtns.[f]	25	V	3.3	Minor damage in the Abiquiu-Los Alamos area.
1973	3/17	0:43	Abiquiu[f]	30	V	3.7	Felt in Los Alamos area.

[a] Shocks located within 111 km (1° of arc on the surface) of Los Alamos.

[b] Information based on catalog compiled by Wollard (1968).

[c] Intensities listed here are from the Rossi-Forel (R.F.) scale. For the same seismological effects, the currently used Modified Mercalli (MMI) scale gives slightly lower values of intensity.

[d] Assigned on the basis of the magnitude-intensity-radius of perceptibility correlations established by Richter (1958).

[e] Weak shocks, maximum reported Intensity III, in the vicinity of Albuquerque have not been listed.

[f] Also located instrumentally by New Mexico stations.

[g] Reported in Dames and Moore (1972).

The fourth earthquake felt in Los Alamos occurred on March 17, 1973, and was reported by NOAA/USGS (1975) as "felt in the Los Alamos area." The earthquake was shallow (depth of a few kilometers) and its epicenter was at 36.1°N, 106.2°W, in nearly the same area as the December 5, 1971, event. The event was small, with a magnitude (M_L) of 3.6 and maximum Intensity of V. A survey taken by local seismologists found that the earthquake was felt in other nearby communities, especially those closer to the epicenter than Los Alamos.

Among the earthquakes that occurred farther away, but still within the Rio Grande rift, was the Cerrillos earthquake of May 28, 1918. There is no known documentation of the effects of this event in the immediate Los Alamos area, but it may have had the greatest intensities in Los Alamos of all the earthquakes known in the past 100 years. Its maximum Intensity has usually been reported as VIII (magnitude of 5.5 to 6). Olsen (1979) reinterpreted historical records and concluded that the event had a maximum Intensity of VII and a magnitude of 4.5 to 5.5. He argues that a maximum Intensity of VIII is an exaggerated interpretation of the felt reports. Olsen (1979) placed the epicenter of this event at about 35.5°N, 105.1°W (near Cerrillos and about 45 km south-southeast of Los Alamos) because the greatest intensities were reported from Cerrillos. The tremor was felt over an area of 31,000 km^2. We note, however, that felt reports from the Cerrillos earthquake are sparse and allow interpretations different from Olsen's (1979) both in earthquake size and in location. Hence, if the Cerrillos earthquake is used for estimating seismic hazards at Los Alamos, the larger size should be taken, and its epicenter should be taken to have been closer to Los Alamos.

A more recent, damaging earthquake, the Dulce earthquake of January 22, 1966, occurred within the Colorado Plateau physiographic province (that is, outside the Rio Grande rift) along a possible extension of structures associated with those of the western margin of the Rio Grande rift. The Dulce earthquake had a magnitude (M_L) of 4.5 to 5.1 (ESSA, 1968; Cash, 1971). The earthquake was located at about 37.0°N, 107.0°W, and was felt over an area of 42,000 km^2 with a maximum Intensity of VII (Cash, 1971; Herrmann et al., 1980). The earthquake was very shallow, perhaps less than 3 km deep. Damage from the Dulce event was moderate, although many homes sustained structural damage.

The largest earthquakes to occur in New Mexico in historic times were part of a swarm that was located near Socorro in 1906. Many events were felt, almost daily, in a swarm that lasted from July 1906 until January 1907 (Reid, 1911). Two events have been assigned maximum Intensities of VIII (Sanford et al., 1981), one of which occurred on November 15, 1906, and was felt in Santa Fe, Roswell, and El Paso. Damage in the epicentral area included fallen chimneys, damaged walls (the corner of one building collapsed), and rock falls. Many people abandoned their homes for tents and temporary wooden shelters. Fear may have been heightened by the fact that the famous San Francisco earthquake and fire had occurred about three months before the beginning of the 1906-1907 Socorro activity (Sanford, 1963). The foci of the swarm are thought to have been under Socorro Mountain, a few kilometers west of Socorro. Although their epicenters were a considerable distance (approximately 200 km) from Los Alamos, the earthquakes occurred within the Rio Grande rift. In the standard procedure of 10 CFR 100-A, the seismicity of one part of a geological feature is significant to the evaluation of the seismic hazards of any other part.

III-C: RESPONSE SPECTRA

We were asked by the Laboratory to revise the Dames and Moore (1972) response spectra using seismograms recorded at Los Alamos. Because currently there are no recordings at Los Alamos of the moderate-size earthquakes that are of interest to engineers, obtaining response spectra for Los Alamos still involves a certain amount of data manipulation. One of the original intents of the seismological effort was to exploit the fact that a nuclear explosion, Gasbuggy, from the Plowshare peaceful nuclear explosion series, had been recorded at Los Alamos at the LAMPF site (Mickey et al., 1968). The Gasbuggy explosion was located about 40 km south-southwest of the epicenter of the 1966 Dulce earthquake. The epicenter of the Dulce earthquake was about 140 km north-northwest of Los Alamos. Since the source signatures of nuclear explosions and earthquakes are dissimilar, the Los Alamos recording of Gasbuggy could not be used directly for computing meaningful earthquake response spectra. Instead, a way of correcting the Los Alamos recording of Gasbuggy was needed. Both the Gasbuggy explosion and the Dulce earthquake were recorded at Albuquerque, at the World-Wide Standard Seismograph Network (WWSSN) station there. Because of the proximity of the two seismic sources, the seismic ray paths to both Los Alamos and Albuquerque are nearly identical for the two events. Hence, the difference in the seismograms from .the two events at Albuquerque would largely be the result of the difference in the sources. The source difference then could be applied to the Gasbuggy seismogram from Los Alamos, and an "equivalent" seismogram from the Dulce earthquake could be obtained. This equivalent seismogram could then be used to compute response spectra for the Los Alamos site. Unfortunately, two problems developed, both related to availability of original seismograms. First, the Los Alamos recordings of the Gasbuggy explosion could not be located. Second, the requisite Albuquerque seismograms from the Dulce earthquake also could not be located (broadband seismograms were needed to make the technique work). Therefore, in our current work, a different approach is being taken to obtain response spectra. This approach will use recordings of small local earthquakes to synthesize the seismograms due to a larger event.

III-D: NETWORK MONITORING

During the period of the initial studies, 1984 to 1985, the existing northern New Mexico network was maintained and recorded on a "status quo" basis, without major effort to expand or maintain stations. For calendar year 1984, events were timed and located, and an earthquake catalog was issued, along the lines of the previous earthquake catalogs (Wolff et al., 1985). During 1985, the number of stations operating declined so much that routine locations of local events were not systematically possible, so they were no longer attempted, except for significant events (Cash, pers. comm., 1986). The reasons for the declining number of stations were twofold. First, the existing stations were not able to be kept operational, and second, data communication by the New Mexico state microwave system was turned off because of its great expense. Data from the more distant stations were transmitted via the New Mexico state microwave system back to the recording facilities at DP-Site (TA-21) at the Laboratory. Total expenses of the data links became prohibitive with the available funding.

A total of 102 events were located from 1984. Figure 10 is a plot of the events located during 1984; for comparison, Figure 11 shows the events located from 1973 to 1984. Activity during 1984 did, in general, continue to define the areas that were already seen as seismically active before 1984. A few events were located away from the zones of prominent activity, such as the two in the San Juan Basin (between 36° and 37° latitude, and between 107° and 108° longitude) and the three events located to the southeast of Santa Fe.

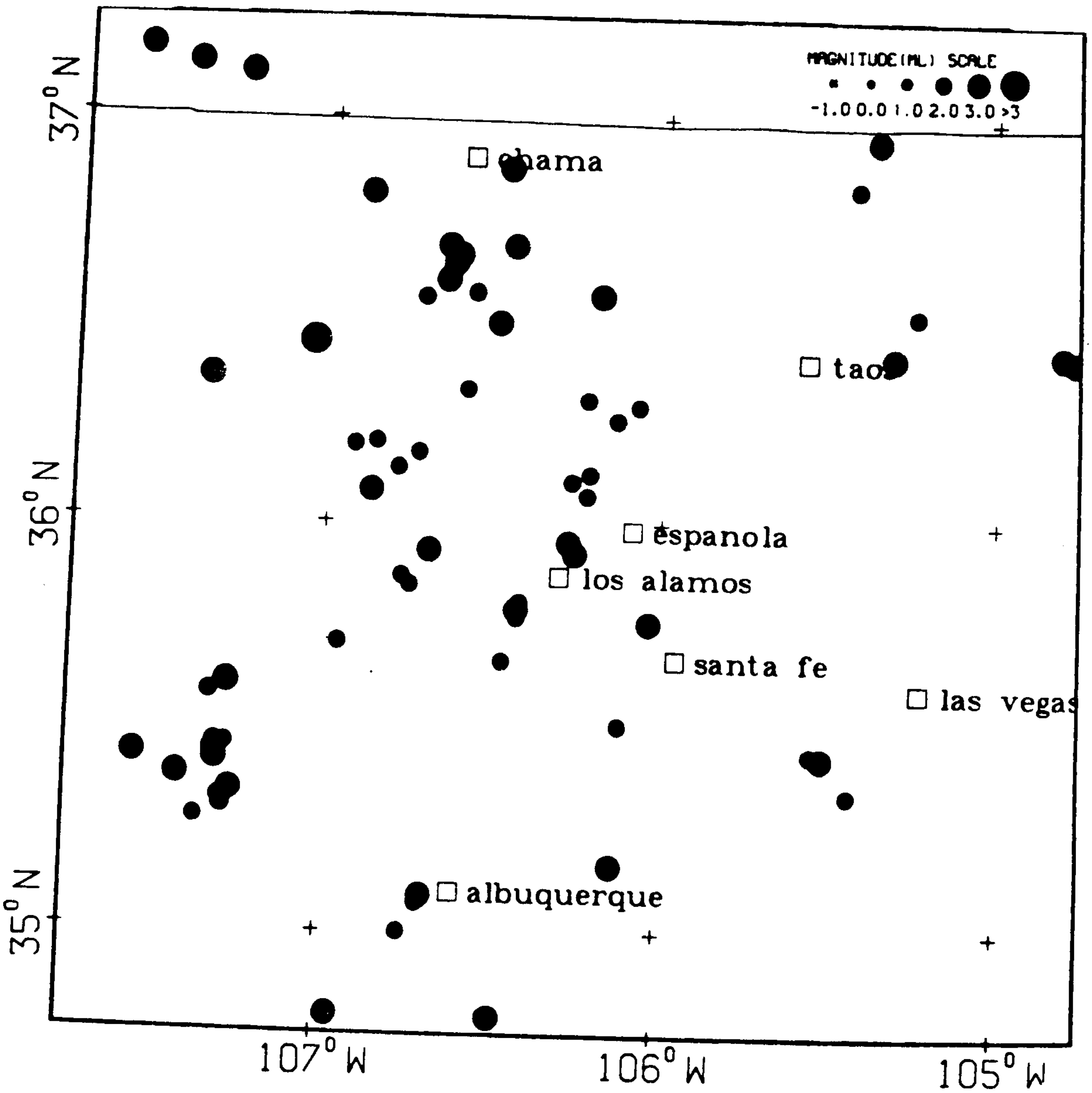


Figure 10: Earthquakes in north-central New Mexico located by the Los Alamos Seismic Network in 1984.

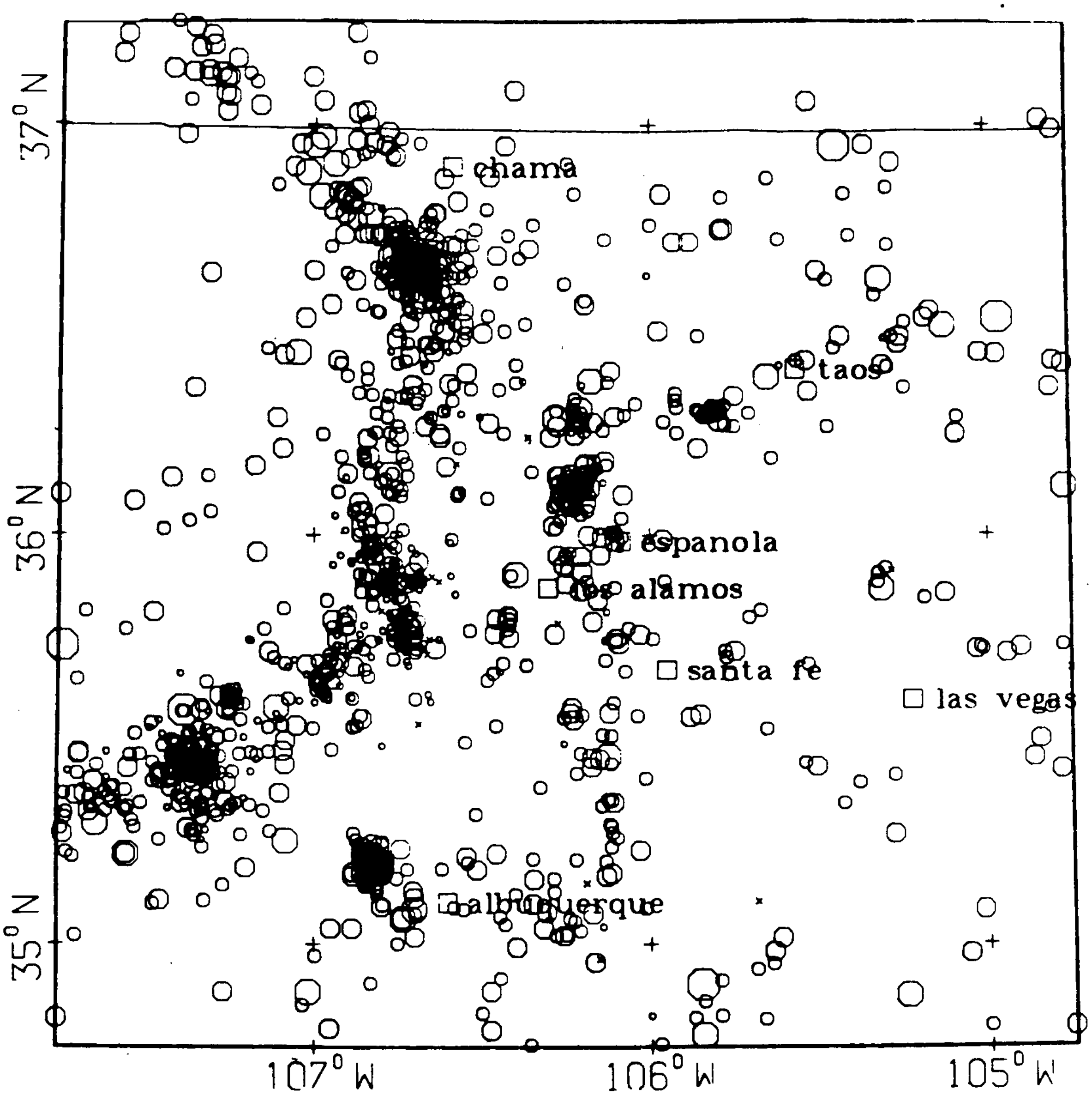


Figure 11: Cumulative plot of all earthquakes located by the Los Alamos Seismic Network from September 1973 to December 1984. Note the band of seismicity extending south of Chama; this band coincides with the Nacimiento uplift. Cluster of seismicity northwest of Española lies near the intersection of the Pajarito and Embudo fault zones. Between the seismicity of the Los Alamos and Nacimiento areas is a seismically quiet area, which is the Valles caldera. The lack of seismicity there has been attributed to elevated temperatures associated with the recent volcanism of the caldera.

CHAPTER IV:
DISCUSSION OF PRELIMINARY HAZARD MAPS

Seven maps, all at the same scale of 1:62,500, are included with this report. Most of these maps must be considered preliminary and should be updated as more relevant data become available. A brief discussion of the maps, their limitations, if any, and their intended utility follows.

IV-A: GEOLOGIC MAP

Five 15-minute U.S. Geological Survey topographic sheets serve as the base for the geologic mapping of the Pajarito fault system. Particular emphasis in the mapping is placed on the regional context and continuity of the main structural elements of the fault system. Because of limitations of level of effort, we have not mapped portions of the Pajarito Plateau removed from the fault zones; hence, some small faults may not be shown, and much of the geology of these areas is taken from Griggs (1964). Much of the geology of the southern segment of the fault system has been modified from Gardner (1985), and a few areas in the central segment are modified from Smith et al. (1970). Much of the geology of the southern San Juan Pueblo quadrangle has been modified from Dethier and Manley (1985). Detailed discussions of stratigraphic relations may be found in Dethier and Manley (1985) and Gardner et al. (1986). MAP IV-A also serves as a base for overlay of the other preliminary seismic hazards maps.

IV-B: STRUCTURE CONTOUR MAP OF THE PRE-BANDELIER TUFF SURFACE

This map is taken from Dransfield and Gardner (1985), wherein one may find discussions. Comparison of this map to the geologic map reveals continuations of surface structures into the pre-Bandelier Tuff subsurface. Furthermore, the structure contour map shows that the Guaje Mountain and Rendija Canyon faults, together with the other down-to-the-west faults beneath the Pajarito Plateau, contribute to the asymmetry of the Española Basin with the deepest part, the intrarift Velarde Graben, along the western boundary. Perhaps most significantly, the structure contour map shows that the Guaje Mountain and Rendija Canyon fault zones persist in the pre-Bandelier Tuff subsurface beneath the Laboratory. In that portions of these faults show evidence of young movements (Chapter II), their subsurface continuations beneath the Laboratory must be considered as having relatively high potential for surface rupture (see Chapter I, Approach, and MAP IV-D).

IV-C: PALEOGEOLOGY OF THE PRE-BANDELIER TUFF SURFACE

This map, based on MAP IV-B and well log information, is also taken from Dransfield and Gardner (1985). The map shows that three main geologic units, each with its own characteristic paleogeomorphic expression on MAP IV-B, underlie the Bandelier Tuff of the Pajarito Plateau. The three main lithologies beneath the Bandelier Tuff and the Laboratory are dacite, old alluvium (Puye Formation), and basalt, all of which apparently interfinger beneath the central portions of the Laboratory. These different subsurface geologic units, together with properties of overlying Bandelier Tuff and distance from an earthquake source, will cause potentially large differences in seismic response of a given site within the Laboratory. Hence, one response spectrum for the entire Laboratory is probably unrealistic.

IV-D: ZONES OF RELATIVE POTENTIAL FOR SEISMIC SURFACE RUPTURE

This map is a preliminary relative delineation of areas within the Laboratory with respect to potential for seismic surface rupture. It must be stressed that these zones are relative only to each other within the area of the Laboratory; comparisons of the relative potential for surface rupture with other seismically active areas, such as California, are neither intended nor applicable. Areas we judge to bear highest potential for seismic surface rupture include active fault traces, their continuations in the pre-Bandelier Tuff subsurface, and areas with potential for cross rupture between narrowly spaced active faults. Zones with probably lower potential for seismic surface rupture include areas with faults that do not break the Bandelier Tuff, but that bear potential for reactivation because of structural and geometric relations to active faults, and areas in which pre-Bandelier Tuff topography has apparent fault control. The width of zones with highest potential for seismic surface rupture is the result of application of the <u>minimum</u> fault zone control width of 10 CFR 100-A.

IV-E: PRELIMINARY MAP OF POTENTIALLY HAZARDOUS MASS WASTING DURING AN EARTHQUAKE

This map simply delineates areas where topography (slope) and the competence of the geologic materials indicate a potential for hazardous mass wasting by rockfall, debris flow, and/or landslide. The shaded zones on this map are areas that warrant further stability analysis. Consideration of additional factors, such as fracture density and degree of water saturation, would greatly refine this hazard map.

IV-F: CULTURAL OVERLAY MAP

This map shows main roads and Laboratory technical areas taken from recent 7.5-minute topographic maps. The scale has been reduced from 1:24,000 to 1:62,500 so that this map may be used as an overlay with the other preliminary hazards maps.

IV-G: MAP OF GEOMORPHIC SURFACES, SOUTHERN SAN JUAN PUEBLO QUADRANGLE

Because of the abundant geomorphic information on young fault movements in the southern San Juan Pueblo quadrangle, and because such information is difficult to convey on conventional geologic maps, we include this map of Quaternary geomorphic surfaces. The only faults shown are those that affect the Quaternary surfaces. The ages of the surfaces generally are the times of surface stabilization. These ages have been determined with the rock varnish cation ratio technique (Harrington, 1986a, 1986b) and radiometric techniques.

CHAPTER V: CONCLUSIONS

1. The Pajarito fault system is a major element of the regional Rio Grande rift system. Estimates of the total linear extent of the fault system are difficult to make because faults of the system connect with other regional structures that show no clear terminations. In this study we have mapped more than 100 km of major, interrelated fault traces.

2. The Pajarito fault system has experienced recurrent movements over a long period of time (greater than 16 million years), and most significant movements have occurred within the last 1.1 million years. Microseismic activity may be associated with portions of the fault system. Available evidence indicates that major movements have occurred within the last 500,000 years and as recently as 350,000 years ago, 240,000 years ago, 42,000 years ago, possibly <10,000 years ago, and 2,000 years ago (Table II). Clearly the fault system is capable in the sense of 10 CFR 100-A.

3. We have identified three localities which provide data that may be interpreted so as to yield amount of vertical displacement per earthquake event. Estimates based on these data must be considered tentative and will be refined as new and better constraints become available. Using empirical relations of magnitude to displacement (Figure 25 of Slemmons, 1977), we deduce from these observed or inferred displacements the following: an earthquake of magnitude 7.8 occurred on the Pajarito fault (Bland Canyon) sometime within the last 500,000(?) years; an earthquake of magnitude 6.8 occurred on a splay of the Embudo fault (Arroyo de la Presa) within the last 42,000 years; and an earthquake of magnitude 6.5 occurred on the Embudo fault (Arroyo de la Presa) within the last 240,000 years (Table II).

4. The style of deformation in the Pajarito fault system transforms from dominantly normal faulting in the southern segment, to apparently oblique normal to right lateral slip in the central segment, to dominantly right lateral slip in the northern segment.

5. Using 12 years of microseismic data recorded by the Los Alamos Seismic Network, a simple earthquake frequency-magnitude relation would imply a "once per hundred years" earthquake of magnitude 4.5 in the Los Alamos area. However, such results must be considered in the context of results by Schwartz and Coppersmith (1984) and Davison and Scholz (1985). Both of these studies, the former based on geologic and seismic information, the latter based on long-term seismologic information, found that the magnitudes of the characteristic earthquakes extrapolated from short-term earthquake data, such as that

of the Los Alamos Seismic Network, were underestimated by one to two magnitude units. In addition, Sanford (1976) noted that current levels of seismicity in the northern Rio Grande rift are abnormally low. Hence, the estimate of the "once per hundred year" earthquake of magnitude 4.5, based on the Los Alamos Seismic Network data, is most likely a substantial underestimate.

6. At present we cannot make a realistic estimate of recurrence interval for the characteristic earthquake and cannot, therefore, estimate probabilities so as to address the question of seismic risk at Los Alamos. However, commonly in seismic hazards studies the assumption that average minimum rates of movements (discussed in Chapter II) can be taken to represent strain rates is made to generate crude estimates of size and recurrence of earthquakes (for example, Figure 2 of Slemmons, 1977). These estimates, shown in Table II, are so variable and the relations on which they are based are so dubious that we question the significance of the estimates.

7. In light of the variable seismic properties of the Bandelier Tuff (Table III), the variable thickness of Bandelier Tuff on the Pajarito Plateau (MAP IV-A and MAP IV-B), and the variable subsurface geology of the Pajarito Plateau (MAP IV-C), one response spectrum for the entire Laboratory may be unrealistic.

8. Previous recommendations for ground accelerations based on earthquakes of Intensity VII to VIII (Dames and Moore, 1972; Tera, 1984) may be too low, because ideal correlations of magnitude estimates, discussed in Conclusion 3, above, to the Modified Mercalli Intensity scale give MMI VIII to X (Table I).

9. Preliminary seismic hazards maps, most of which need to be revised with further detailed studies, significantly imply the Laboratory and Los Alamos County will be isolated by road in the event of a large earthquake due to induced mass wasting and/or surface rupture.

APPENDIX:

PREVIOUS STUDIES

In this appendix we present a list of previous studies most relevant to seismic hazards at Los Alamos National Laboratory. For the most important of these works we provide critical discussion. For the reports that offer relevant pieces of data we have reproduced the author's abstract. Reports regarding structural and/or seismic background specific to the Los Alamos area are simply listed for reference. It should be noted that we have not listed general references to the Rio Grande rift region. The works of Dransfield and Gardner (1985), Wachs et al. (in prep.), House and Cash (in prep.), and various earthquake catalogs are not listed herein because relevant data from these studies have been incorporated into the body of this report.

Aldrich, M. J., Jr., 1986, Tectonics of the Jemez lineament in the Jemez Mountains and Rio Grande rift: J. Geophys. Res., v. 91, p. 1753-1762.
Author's abstract: "The Jemez lineament is a NE trending crustal flaw that controlled volcanism and tectonism in the Jemez Mountains and the Rio Grande rift zone. The fault system associated with the lineament in the rift zone includes, from west to east, the Jemez fault zone southwest of the Valles-Toledo caldera complex, a series of NE trending faults on the resurgent dome in the Valles caldera, a structural discontinuity with a high fracture intensity in the NE Jemez Mountains, and the Embudo fault zone in the Española Basin. The active western boundary faulting of the Española Basin may have been restricted to the south side of the lineament since the mid-Miocene. The faulting apparently began on the Sierrita fault on the east side of the Nacimiento Mountains in the late Oligocene and stepped eastward in the early Miocene to the Cañada de Cochiti fault zone. At the end of the Miocene (about 5 Ma) the active boundary faulting again stepped eastward to the Pajarito fault zone on the east side of the Jemez Mountains. The north end of the Pajarito fault terminates against the Jemez lineament at a point where it changes from a structural discontinuity (zone of high fracture intensity) on the west to the Embudo fault zone on the east. Major transcurrent movement occurred on the Embudo fault zone during the Pliocene and has continued at a much slower rate since then. The relative sense of displacement changes from right slip on the western part of the fault zone to left slip on the east. The kinematics of this faulting probably reflect [sic] the combined effects of faster spreading in the Española Basin than the area north of the lineament (Abiquiu embayment and San Luis Basin), the right step in the rift that juxtaposes the San Luis Basin against the Picuris Mountains, and counter-clockwise rotation of various crustal blocks within the rift zone. No strike-slip displacements have occurred on the lineament in the central and eastern Jemez Mountains since at least the mid-Miocene, although movements on the still active Jemez fault zone, in the western Jemez Mountains, may have a significant strike-slip component. Basaltic volcanism was occurring in the Jemez Mountains at four discrete vent areas on the lineament between about 15 Ma and 10 Ma and possibly as late as 7 Ma, indicating that it was being extended during that time."

Aldrich, M. J., Jr., and Harrington, C. D., 1984, Pliocene to Recent deformation in the northeast Jemez Mountains, New Mexico: Geol. Soc. Am. abstracts w/programs, v. 16, no. 4, p. 213. Authors' abstract: "The northeast Jemez Mountains is [sic] a seismically active area characterized by a major northeast-trending (N.60°E.) fault zone and north-trending normal faults. The fault zone, which lies on and parallel to the Jemez lineament, consists of an en echelon series of left-stepping, northeast-trending faults connected by shorter north to north-northwest-trending faults. Between about five and two million years ago, several kilometers of right oblique slip occurred along the northeast-trending fault zone resulting in rotation of Santa Fe beds and flows of Lobato basalt into the vertical or near vertical along much of the fault zone west of Chili, New Mexico. In most places the steeply inclined beds dip south; however, at one locality they are overturned and dip north at 75°. The deformational style indicates that significant compressional stresses were associated with the faulting. This fault zone is part of a transform fault system separating two basins (San Luis and Española) of the Rio Grande Rift.

"Erosional and constructional surfaces that have developed on the Santa Fe Group, Puye (~2.1 - 3.0 m.y.B.P.), and Bandelier (1.1 - 1.4 m.y.B.P.) formations record recent motions on the north-trending faults in several locations. Field evidence, including offsets of young Quaternary (<1.0 m.y. old) - Holocene(?) gravel deposits and soil profiles indicate that these faults in the northeast Jemez Mountains have been active throughout Quaternary and Recent time. Slickenside orientations show that movements on the north-trending faults have been predominatly dip slip."

Aubele, J. C., 1978, Geology of the Cerros del Rio volcanic field, Santa Fe, Sandoval, and Los Alamos counties, New Mexico: Univ. New Mexico, M.S. thesis, 136 p.

Aubele, J. C., 1978, Geology of the Cerros del Rio volcanic field: New Mexico Bureau of Mines and Mineral Resources Circular 163, p. 198-201.

Axelrod, D. I., and Bailey, H. P., 1976, Tertiary vegetation, climate, and altitude of the Rio Grande depression, New Mexico-Colorado: Paleobiology, v. 2, p. 235-254.

Bachman, G. O., and Mehnert, H. H., 1978, New K-Ar dates and the Late Pliocene to Holocene geomorphic history of the central Rio Grande Rift: Geol. Soc. Am. Bull., v. 89, p. 283-292.

Baltz, E. H., Abrahams, J. H., Jr., and Purtymun, W. D., 1963, Preliminary report on the geology and hydrology of Mortandad Canyon near Los Alamos, New Mexico, with reference to disposal of liquid low-level radioactive waste: U.S. Geological Survey (Albuquerque, NM), open-file report, 105 p. w/13 plates.

Bridwell, R. J., Homuth, E. F., and Potzick, C., 1979, Preliminary predictions of Cenozoic, Mesozoic, and Paleozoic stratigraphy of EGH-LA-1 (Sigma Mesa, Los Alamos County, New Mexico): Los Alamos Scientific Laboratory, unpub. report, 18 p.

Browne, C. I., 1982 (response to request for review of reports for the "Natural Phenomena Hazards Guideline Model Development Project," [see Tera, 1981, 1984, below] submitted to H. E. Valencia, Area Manager, Los Alamos Area, U.S. Dept. of Energy), Los Alamos National Laboratory, written commun., May 5, 1982, #ADTS-82-131, 12 p.

Budding, A. J., 1978, Subsurface geology of the Pajarito Plateau: interpretation of gravity data: New Mexico Bureau of Mines and Mineral Resources Circular 163, p. 196-198.

Budding, A. J., 1978, Gravity survey of the Pajarito Plateau, Los Alamos and Santa Fe counties, New Mexico: Los Alamos Scientific Laboratory report LA-7419-MS.

Budding, A. J., and Purtymun, W. D., 1976, Seismicity of the Los Alamos area based on geologic data: Los Alamos Scientific Laboratory report LA-6278-MS. In this report geological structures in the Los Alamos area are used to estimate lengths, offsets, and ages of what are termed "major" faults near Los Alamos. The authors assumed that an individual seismic event would rupture the entire mapped length of the faults and that all slip is released seismically. We note, however, that all faults in the area, particularly the Pajarito fault zone, are much longer than their assumed length of surface rupture, and further that most major faults interconnect (see MAP IV-A). The authors obtained estimates of maximum earthquake magnitude which averaged 6.7. They then estimated an average recurrence interval of about 8,000 years for these maximum magnitude earthquakes. The recurrence interval was derived from using the 1.1 million year age of the Bandelier Tuff and the number of maximum magnitude earthquakes needed to account for the offsets they observed. They then extrapolated, on a frequency-magnitude diagram, using a b-value of 1.0, a largest probable earthquake of M_L = 4.8 per century within or very close to Los Alamos County. This approach is appropriate for estimating a rate of strain release or a rate of seismic energy release, but is not appropriate for estimating probable earthquakes with regard to seismic hazard or seismic risk. It is not the time average over 1,000s of years that is pertinent to hazards and risk but rather the exposure and likelihood of occurrence in a specific time period.

Cash, D. J., 1982 (internal memo regarding review of two seismic risk documents from Tera Corporation, submitted to Allen Stoker, H-8; summarized in Browne, 1982, above), Los Alamos National Laboratory, written commun., 6 p.

Cash, D. J., 1983, Seismicity near S-site, Los Alamos National Laboratory: unpub. report, 20 p.

Cooper, J. B., Purtymun, W. D., and John, E. C., 1965, Records of water-supply wells Guaje Canyon 6, Pajarito Mesa 1, and Pajarito Mesa 2, Los Alamos, New Mexico: U.S. Geological Survey (Albuquerque, NM), Basic Data Report, 90 p. w/original well logs.

Cordell, L., 1979, Gravimetric expression of graben faulting in Santa Fe County and the Española Basin, New Mexico: New Mexico Geological Society Guidebook, Santa Fe Country, 30th field conference, p. 59-64.

Dames and Moore, 1972, Report of geologic, foundation, hydrologic, and seismic investigation: Plutonium Processing Facility, Los Alamos Scientific Laboratory, Los Alamos, NM: Dames and Moore consulting report, job number 0651-120-02, Los Angeles, CA. This study was done for site engineering for the Plutonium Facility at Los Alamos (TA-55). It notes the sparseness of information about historic seismicity in New Mexico and summarizes the known earthquakes that would influence seismic design. It is a comprehensive source for citations of historic northern New Mexico earthquakes, although it presents only information regarding time, intensity, and general location.

The report notes the sparseness of instrumental coverage for the state of New Mexico as a whole, and for northern New Mexico in particular. Central and southern New Mexico have been better studied, in part because of the occurrence of a swarm of events in 1906-1907 in the Socorro area. The Socorro swarm included three events with Intensities as high as VIII (Modified Mercalli Intensity scale).

The report notes that "...sufficient [earthquake] data has [sic] not yet been collected. It will be necessary to collect such data in the coming years to serve as a basis for performing a meaningful analysis." Although the report notes that the largest earthquakes reported in the rift have been from the Socorro area, it also notes "there is no indication that the tectonic structure to the north near Los Alamos is any different." Nevertheless, the report asserts that "It is unlikely that earthquake ground motion greater than Intensity VI has been experienced at the proposed site [Los Alamos] since the date of the first reported New Mexico earthquake in 1849."

The report presents a series of "recurrence curves" (Plate S-3) that do not show the data points from which the lines were drawn. It notes that "while an average interval between events may be calculated, no mathematical probability of occurrence should be directly derived from it ...it should be recognized that this record may be too incomplete for statistical significance." Without further discussion, Intensity VIII is taken as the maximum earthquake intensity that Los Alamos will experience.

In the Engineering Seismology section the peak acceleration is correlated with the Intensity VIII. Trifunac and Brady (1975) state that the correlations between maximum earthquake Intensity and peak acceleration show scatter of one order of magnitude or more. Trifunac and Brady (1975) derive a relation that yields a peak acceleration of 0.26 g for an earthquake of maximum Intensity VIII, but in their data set (a total of four earthquakes), the standard deviation is relatively large, 0.08 to 0.10 g. Dames and Moore (1972) chose an accelerogram from the 1940 Imperial Valley, California, earthquake that was written at El Centro to determine a peak acceleration value for the Safe Shutdown Earthquake. The Intensity reported for the Imperial Valley earthquake at El Centro was VIII, and the peak acceleration written was 0.33 g. Dames and Moore then state that "We have had occasion to inspect and verify the 1940 damage and have compared it with other events at both higher and lower levels to confirm the 0.33 g-Intensity VIII correlation." No data are presented, so the adequacy of the Dames and Moore conclusions cannot be independently judged.

The El Centro record from the 1940 Imperial Valley earthquake was written at a distance of 10 km from the epicenter. Hanks and Johnson (1976) provide a quantitative analysis of peak acceleration as a function of earthquake magnitude. They show that many earthquakes of magnitudes smaller than 7.1 produced accelerations greater than 0.35 g at comparable distances. Hence, the significance of the peak acceleration chosen by Dames and Moore (1972) is not clear.

In the Dames and Moore report, the section entitled Design Earthquake Values, the choice of peak acceleration for the Operating Basis Earthquake is discussed. The report states, "It is probable that the maximum level of ground motion experienced in the past century at the site has been no more than Intensity VI. However, the occurrence of an earthquake similar to the 1918 Cerrillos event at Los Alamos, with a site Intensity of VII to VIII, is not improbable. For this condition, the maximum horizontal ground acceleration at the site would probably be on the order of 0.17 g. This is the level of ground motion which we recommend for the Operating Basis Earthquake." Where the 0.17 g comes from and what the probability is for such ground motion are not documented.

Dames and Moore (1972) devised response spectra for the TA-55 site. Documentation of their methodology is inadequate. While they claimed to have modeled the upper 7000 ft of the material beneath the site, they actually measured velocities from only the upper 180 ft and assumed velocities for the next 6820 ft. The overall conclusion was that, at frequencies above about 2 Hz, the site response attenuated "bedrock" motion, but at frequencies below about 2 Hz, the site amplified "bedrock" motion. Because of the sparse documentation of the methods used, it is difficult to evaluate the significance of these assertions.

Dethier, D. P., and Manley, K., 1985, Geologic map of the Chili quadrangle, Rio Arriba County, New Mexico, Scale 1:24,000: U.S. Geological Survey, Map MF-1814.

Gardner, J. N., 1985, Tectonic and petrologic evolution of the Keres Group: implications for the development of the Jemez Volcanic Field: Univ. of California, Davis, Ph.D. dissertation, 293 p.

Gardner, J. N., and Goff, F., 1984, Potassium-argon dates from the Jemez Volcanic Field: implications for tectonic activity in the north-central Rio Grande Rift: New Mexico Geological Society Guidebook 35, pp. 75-81.
Gardner and Goff discuss the tectonic activity of the Española Basin of the Rio Grande rift in the context of the volcanic evolution of the Jemez volcanic field. Of particular significance to seismic hazards studies at Los Alamos they note: the deep intrarift graben beneath the Pajarito Plateau, revealed in various geophysical studies, is bounded on the west by the Pajarito fault system; the Pajarito fault system has been active since about 4 Ma and is the presently active western deformational boundary of the basin; and various estimates of rates of movement and amounts of extension by Golombek and coworkers (see below) are unrealistically low because the Golombek models fail to include significant relevant information on fault zones.

Goff, F. E., and Gardner, J. N., 1980, Geologic map of the Sulphur Springs area, Valles caldera geothermal system, New Mexico: Los Alamos Scientific Laboratory report LA-8634-MAP.

Goff, F., and Grigsby, C. O., 1982, Valles caldera geothermal systems, New Mexico, U.S.A.: J. Hydrol., v. 56, p. 119-136.

Goff, F., and Kron, A., 1980, In-progress geologic map of Cañon de San Diego, Jemez Springs, New Mexico, and lithologic log of Jemez Springs geothermal well: Los Alamos Scientific Laboratory report LA-8276-MAP.

Goff, F., 1982, Subsurface structure of Valles caldera: a resurgent cauldron in northern New Mexico: Geol. Soc. Am. Abst. w/programs, v. 15, no. 5, p. 381.

Golombek, M. P., 1981, Structural analysis of the Pajarito fault zone in the Española Basin of the Rio Grande Rift, New Mexico: Ph.D. dissertation, Univ. Massachusetts, 129 p.

Golombek, M. P., 1983, Geology, structure, and tectonics of the Pajarito fault zone in the Española Basin of the Rio Grande Rift, New Mexico: Geol. Soc. Am. Bull., v. 94, p. 192-205. (See discussion of Gardner and Goff, 1984). Author's abstract: "The Pajarito fault zone forms the western border of the Velarde graben, the presently active, central subbasin of the Española basin section of the Rio Grande rift in north-central New Mexico. The fault zone is a north-northeast-trending zone of predominantly down-to-the-east faults that cut Miocene to Pliocene volcanic rocks along the eastern flank of the Jemez Mountains. Where the fault zone cuts the 1.1-m.y.-old Tshirege Member of the Bandelier Tuff, it has produced a steep, 50- to 100-m-high fault scarp. The total displacement across the fault zone during its 5-m.y. history is between 200 and 600 m. Rates of displacement for the time periods 0-5, 0-1.1, and 1.1-5 m.y. ago range from 0.02 to 0.136 mm/yr.

"Abrupt facies changes between older volcanics and volcaniclastic sediments of the Jemez Mountains appear to have controlled the local position, trend, and character of the Pajarito fault zone. The fault zone bows and/or steps eastward where two large volcanic complexes are present but is found farther west in between and at either end of the volcanic complexes. One complex was sufficiently massive to interfere with the development of the Velarde graben.

"Slickensides on mesoscopic faults in the Tshirege Member of the Bandelier Tuff indicate that the Pajarito fault zone has undergone extension in two directions during the past 1.1 m.y., approximately parallel and perpendicular to the local trend of the fault zone. These directions indicate that the Pajarito fault zone has reoriented the regional minimum and intermediate stress directions to perpendicular and parallel, respectively, to the local trend of the fault zone, and that both minimum and intermediate stress directions are tensional.

"A tectonic history for the Pajarito fault zone area of the Española basin begins with relatively stable accumulation of prerift and synrift sediments from Eocene to Oligocene time. Sedimentation concomitant with faulting, unrelated to the Pajarito fault zone, filled deep central depressions within the Española basin. This faulting ceased prior to the end of the filling of the basin, around 10 m.y. ago in the local area. Jemez Mountain volcanism began about this time, before movement along the western-margin border faults of the Española basin caused west-tilting of old volcanics and sediments, about 7.5 m.y. ago. Volcanism continued under relatively stable conditions until 5 m.y. ago. At this time, the Pajarito fault zone and Velarde graben formed. Faulting has continued to the present, localized along this central subbasin."

Golombek, M. P., McGill, G. E., and Brown, L., 1983, Tectonic and geologic evolution of the Española Basin, Rio Grande Rift: structure, rate of extension, and relation to the state of stress in the western U.S.: Tectonophysics, v. 94, p. 483-507.

Griggs, R. L., 1964, Geology and ground water resources of the Los Alamos area, New Mexico: U.S. Geological Survey Water Supply Paper 1753. This report provides the best available geologic map of Los Alamos County. Griggs identified the major structures and rock units of the area and noted evidence for recurrent movements on the Pajarito fault zone since at least Pliocene times.

Harrington, C. D., and Aldrich, M. J., Jr., 1984, Development and deformation of Quaternary surfaces in the northeast Jemez Mountains, New Mexico: Geol. Soc. Am. Abstracts w/programs, v. 16, no. 4, p. 224. Authors' abstract: "Quaternary erosional and deformational events in the northeastern Jemez Mountains have yielded a topography consisting of a complex sequence of stepped, erosional surface segments. Tectonic-geomorphic studies show that three erosional surfaces developed across the northeastern flank of the mountains during Quaternary time. The uppermost surface (Q_1) truncates the Bandelier Formation (1.1 - 1.4 m.y.B.P.) and is graded to the northeast. It is capped primarily by pediment gravels and colluvial deposits. The Q_2 and lowermost Q_3 surfaces are graded eastward into the Española Basin. Capping deposits on these surfaces largely consist of pediment gravels, alluvial fan deposits, and alluvial-valley fills. Each surface has been dissected by streams whose valley floors were then graded to the next lower surface. In addition to the three erosional surfaces, undeformed Holocene(?) alluvial terraces are present in most of the larger arroyos.

"The erosional surfaces within this area have been displaced by movement along faults. The north-trending faults, some recently active, have broken the surfaces into a complex arrangement of steps which are generally down to the east. A northeast-trending fault zone that has undergone significant oblique-slip displacement broke the surfaces parallel to their slopes and raised the terrain to the north. Most displacement along this zone occurred prior to formation of the Q_1 surface; however, small movements have occurred since the surface formed.

"Ongoing studies, utilizing several Quaternary dating techniques are expected to result in more accurate dating of fault motions and Quaternary surface development within the northeastern Jemez Mountains."

Harrington, C. D., and Aldrich, M. J., Jr., 1984, Development and deformation of Quaternary surfaces on the northeastern flank of the Jemez Mountains: New Mexico Geological Society Guidebook 35, p. 235-239. This paper documents three erosional surfaces that developed along the western margin of the Española Basin during the Quaternary. Deformation of these surfaces records recurrent motion along the Santa Clara fault zone and adjacent north-trending faults. One north-northwest-trending fault has displaced a basalt boulder gravel formed on the youngest of these surfaces (22,000 ± 3,000 years old), a minimum distance of 10 m.

John, E. C., Enyart, E., and Purtymun, W. D., 1966, Record of wells, test holes, springs, and surface-water stations in the Los Alamos area, New Mexico: U.S. Geological Survey (Albuquerque, New Mexico), open-file report, 139 p.

Keller, M. D. (ed.), 1968, Geologic studies and material properties investigations of Mesita de Los Alamos, Los Alamos Scientific Laboratory report LA-3728. Contributors to this report asserted that the Pajarito fault offsets the El Cajete pumice, which they assumed to be 50,000 years old, because the pumice occurs on the downthrown side of the fault. They attributed its absence on the upthrown side to removal by erosion. Then, using a maximum offset of the El Cajete of 500 ft, and assuming that each displacement by the Pajarito averaged 10 ft, they calculated that one increment of displacement has occurred every 1000 years. However, there is no definitive evidence that the El Cajete pumice is offset by the Pajarito fault.

The report concluded from (1) the presence of tent rocks, many of which are capped by boulders, (2) the existence of old, undamaged adobe structures, (3) the lack of Spanish and Mexican records of earthquakes, and (4) the lack of significant seismicity recorded during this study (nine days) that the likelihood of severe seismic damage in the Los Alamos area was remote. No quantitative estimate of seismic risk was given.

The lines of evidence on which these conclusions are based are tenuous. Earthquake damage to adobe structures and, for that matter, tent rocks will be dependent on distance from the earthquake, the nature of the intervening geology, the size of the earthquake, and the geology at the specific site. Furthermore, adobe structures are virtually under continuous repair, and we do not know how quickly tent rocks can form. A lack of historic records of earthquakes in New Mexico may be as much a result of sparse population and disorganized record keeping as a lack of earthquakes. Finally, nine days of seismic monitoring is inadequate for extrapolating levels of future seismicity.

Kelley, V. C., 1978, Geology of the Española Basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Geologic Map 48. This is the best general map of the geology of the Española Basin, including the more regional structural relations of the Pajarito fault zone. It also includes a generalized tectonic map of the central Rio Grande rift. Kelley does not specifically address Quaternary or Holocene faulting.

Kelley, V. C., 1979, Tectonics, middle Rio Grande rift, New Mexico: in Riecker, R. E., ed., Rio Grande Rift: Tectonics and Magmatism, Am. Geophys. Union, Washington, D.C., spec. pub. p. 57-70.

Kelley, V. C., Woodward, L. A., Kudo, A. M., and Callender, J. F., 1976, Guidebook to Albuquerque Basin of the Rio Grande Rift, New Mexico: New Mexico Bureau of Mines and Mineral Resources Circular 153, 31 p.

Lewis, L. M., 1980, A gravity study of north-central New Mexico: Univ. of Texas, El Paso, M.S. thesis, 78 p.

Los Alamos National Laboratory, 1985 Emergency Response Plan. On page X-4 of the Laboratory's Emergency Response Plan there appears the following: "EARTHQUAKE: Earthquakes are rare in the Los Alamos area; however, a major fault lies some 35 miles to the east of the Laboratory. Records indicate that this area has been relatively free of major earthquakes, and although the Rio Grande fault has generated earthquakes, they have been well south of the Laboratory."

Machette, M. N., and Personius, S. F., 1984, Map of Quaternary and Pliocene faults in the eastern part of the Aztec 1°x2° quadrangle and the western part of the Raton 1°x2° quadrangle, northern New Mexico: U.S. Geological Survey Map MF-1465-B. This map shows faults in north-central New Mexico along which movement has occurred during the last 5 million years. Several faults of this age occur in the Española-Abiquiu area. They show 12 localities with Pleistocene and 1 locality with Holocene movements along the eastern Embudo fault zone.

Manley, K., 1976, The Late Cenozoic history of the Española Basin, New Mexico: Univ. of Colorado, Ph.D. dissertation, 171 p.

Manley, K., 1978, Cenozoic geology of Española Basin: New Mexico Bureau of Mines and Mineral Resources Circular 163, p. 201-210.

Manley, K., 1979, Stratigraphy and structure of the Española Basin, Rio Grande Rift, New Mexico: in Rio Grande Rift: Tectonics and Magmatism, R. E. Riecker, ed., Am. Geophys. Union Spec. Pub., p. 71-86.

Mickey, W. V., 1968 (memo regarding seismograms from LASAL [sic]-LAMPF, submitted to M. D. Keller, ENG-9), U.S. Department of Commerce, Environmental Science Services Administration, written commun., ref. C233, Feb. 19, 1968, 3 p.

Newton, C. A., Cash, D. J., Olsen, K. H., and Homuth, E. F., 1976, LASL seismic programs in the vicinity of Los Alamos, New Mexico: Los Alamos Scientific Laboratory report LA-6406-MS.

Nyhan, J. W., Hacker, L. W., Calhoun, T. E., and Young, D. L., 1978, Soil survey of Los Alamos County, New Mexico: Los Alamos Scientific Laboratory report LA-6779-MS.

Pellette, P. R., Endebrock, E. G., Giles, P. M., and Shaw, R. H., 1977, Seismic qualification of equipment for the TA-55 Plutonium Processing Facility: Los Alamos Scientific Laboratory report LA-6787-MS. Working from the "Design Basis Earthquake" (DBE) and the "Operating Basis Earthquake" (OBE) as determined from the Dames and Moore (1972) study, this report discusses the procedures used to verify that critical equipment intended for installation at the Plutonium Facility would withstand the chosen ground motions. Individual items of operating equipment (generator, pumps, motors, fans, etc.) were tested on shake tables.

Purtymun, W. D., 1984, Hydrologic characteristics of the main aquifer in the Los Alamos area: development of ground water supplies: Los Alamos National Laboratory report LA-9957-MS.

Purtymun, W. D., 1967, Record of water-supply well PM-3, Los Alamos, New Mexico: U.S. Geological Survey (Santa Fe, NM), open-file report, 22 pages w/original well logs.

Purtymun, W. D., Becker, N. M., and Maes, M., 1983, Water supply at Los Alamos during 1981: Los Alamos National Laboratory report LA-9734-PR, 46 p.

Purtymun, W. D., Becker, N. M., and Maes, M., 1984, Water supply at Los Alamos during 1982, Los Alamos National Laboratory report LA-9896-PR, 46 p.

Purtymun, W. D., and Cooper, J. B., 1969, Development of ground-water supplies on the Pajarito Plateau, Los Alamos County, New Mexico: U.S. Geological Survey Prof. Paper 650-B, p. B149-B153.

Purtymun, W. D., and Jordan, H. S., 1973, Seismic program of the Los Alamos Scientific Laboratory: Los Alamos Scientific Laboratory report LA-5386-MS. The motivation for and anticipated scope of earthquake and explosion seismology at Los Alamos are briefly summarized. Seismologic work was an offshoot of the weapons program carried out in Group J-9. Motivation for seismologic studies was (1) environmental monitoring, (2) studies associated with the geothermal program, (3) studies of underground explosions and their effects, and (4) strong-motion studies.

Reynolds, C. B. (no date), Experimental shallow seismic reflection survey, Los Alamos area, New Mexico, unpublished consulting report, C. B. Reynolds, Registered Geophysicist and Certified Professional Geologist, California, 16 p.

Rodean, H. C., 1970, Explosion-produced ground motion: Technical summary with respect to seismic hazards, <u>in</u> Symposium on Engineering with Nuclear Explosives, Conf. Proceedings, Am. Nuclear Soc. and U.S. Atomic Energy Comm., CONF-700101, p. 1024-1050.

Sanford, A. R., 1976, Seismicity of the Los Alamos region based on seismological data: Los Alamos Scientific Laboratory report LA-6416-MS. Sanford investigated the seismicity and seismic risk of the Los Alamos region using entirely seismologic information. From 10 years of instrumentally monitored seismicity (1962 to 1972), Sanford estimates that the largest event that will occur in the Los Alamos area in the next hundred year period (the "once per hundred year earthquake") will be of magnitude 4.8. On the other hand, he notes that, compared with the preceding 50 years, seismic activity during the period 1962 to 1972 was abnormally low. Without information regarding recurrence intervals of earthquakes, the once per hundred years' earthquake should not be taken to be smaller than what has been observed in the past 100 years. Hence, a reasonable estimate for the once per hundred years' earthquake must be at least 5.0 to 5.5, based on the 1918 Cerrillos earthquake (see Chapter III, Seismological Studies).

Savage, W. U., Ely, R. W., and Tocher, D., 1977, Review of the Los Alamos seismic monitoring program in relation to the Hot Dry Rock geothermal project: Woodward-Clyde consulting report L47-85930-1. 28 p. This report is a thorough and critical review of the seismic monitoring efforts undertaken particularly for the Hot Dry Rock project at Fenton Hill; it also reviews the seismic monitoring done for Los Alamos in general. Among the conclusions that are also pertinent to seismic hazards studies of Los Alamos are the following:
1) "In general, the degree of detail and documentation of geologic mapping in the vicinity of the Valles Caldera is insufficient to support a state-of-the-art seismic hazard assessment ... The same is true of [the lack of detailed] studies conducted for faults near LASL ..."

2) "Because Fenton Hill and LASL are located within an active, first order tectonic feature (the Rio Grande Rift) and adjacent to a major Quaternary volcanic center (the Valles Caldera), we feel that prudence requires a thorough evaluation of geologic hazards in the surrounding area. Because of the national importance of the HDRG [Hot Dry Rock Geothermal] research at LASL, the political consequences of failure to have done this may be severe in the event of a significant earthquake or volcanic eruption."

3) "In a siting study prepared by Dames and Moore (1972), seismic risk for the plutonium enrichment facility at LASL was estimated. However, the risk estimation methodology has been incompletely presented and implemented."

The most fundamental recommendations from this report that are relevant to evaluating seismic hazards in Los Alamos are in the areas of geologic studies:

1) "Integration and synthesis of existing geologic, seismologic, and geophysical data, with the objective of identifying locations for future detailed study, as well as areas of insufficient data."

2) "Detailed study of the faults identified ... as having experienced displacements in the last 100,000 years. This program should include trenching, large scale (1:24,000) geologic mapping along fault traces, stratigraphic study of late Quaternary deposits, and remote sensing to help determine the earthquake recurrence interval on these faults."

Slemmons, D. B., 1975, Fault activity and seismicity near the Los Alamos Scientific Laboratory geothermal test site, Jemez Mountains, New Mexico: Los Alamos Scientific Laboratory report LA-5911-MS. Slemmons investigated the seismic hazards that the Fenton Hill Hot Dry Rock site (located about 40 miles WSW of Los Alamos) might be exposed to and concluded that "the hazard that the experiment [site] will be disturbed by future surface faulting or by large local earthquakes is very slight." His study was based on geologic field work, in particular aerial surveillance and photography, as well as the available seismic record. In addition, he asserts that the current "tectonic flux" (the rate of seismic energy release per unit area) in the Rio Grande Rift is about a factor of 10 less than in the Basin and Range province of California-Nevada-Utah. We note the significance of current tectonic flux with respect to recurrence of large earthquakes is ambiguous. Note also that this study considered seismic hazards to the Fenton Hill site, and not to Los Alamos itself.

Smith, R. L., Bailey, R. A., and Ross, C. S., 1970, Geologic map of the Jemez Mountains, New Mexico: US Geological Survey Misc. Geol. Investigations Map I-571. This is the best general map of the geology of the Jemez Mountains. Area includes the Pajarito fault zone. Much of this information was compiled by Kelley (1978).

Tera Corporation, 1981 Seismic hazard analysis for the Bendix, Los Alamos, Mound, Pantex, Rocky Flats, Sandia-Albuquerque, Sandia-Livermore, and Pinellas sites; Tera, 1984, Seismic hazard analysis for Los Alamos Scientific Laboratory and Sandia Laboratories, New Mexico, unpub. consulting report #B-81-63, Tera Corporation, Berkeley, CA. (Revised 1984, consulting report #B-82-261, 38 p.) (Only the section pertinent to Los Alamos is considered.) This study purports to be a "detailed seismic hazard analysis" of the Los Alamos DOE site (among others). The principal result of the study is a probabilistic determination that the Los Alamos area would experience a horizontal peak ground acceleration of 0.08 g with a return period of 100 years and of 0.22 g with a return period of 1,000 years. In addition, the study presents response spectra, normalized to 1 g. Response spectral shapes were taken from Dames and Moore (1972).

The documentation in the Tera report is inadequate to determine the credibility of the results. The recent (historic) seismicity is used as input to the probabilistic modeling, but the probabilistic model itself is not documented nor even summarized in this report. Although "sensitivity analysis" is mentioned several times in the report, nowhere is there any quantitative discussion of what was varied and what the outcome was. Although terms such as "best estimate" and "weighted average" are used, there is no mention of how the estimate is "best" or how the individual items were "weighted."

Fundamental to the approach employed by Tera are data regarding ages, recurrence intervals, and sizes of earthquakes associated with the faults near the site under evaluation, as well as information on the regional historical and instrumentally measured seismicity. In that Tera generated no new data and considered only a few years of regional seismicity beyond that included in Dames and Moore (1972), much of the data necessary for a credible probabilistic model does not yet exist. Hence, the Tera probabilistic seismic risk analysis adds nothing to previous studies and brings us no closer to being able to address the question of seismic risk at Los Alamos.

Williams, L. M., 1979, Gravity study of the Los Alamos area, New Mexico: Los Alamos Scientific Laboratory report LA-8154-MS.

Williston, McNeil, and Associates, 1979, A time domain survey of the Los Alamos region, New Mexico: Los Alamos Scientific Laboratory report LA-7657-MS.

REFERENCES

Aldrich, M. J., 1986, Tectonics of the Jemez Lineament in the Jemez Mountains and Rio Grande rift: J. Geophys. Res. 91(B2), 1753-1762.

Aldrich, M. J., and Laughlin, A. W., 1982, Orientation of least-principal horizontal stress: Arizona, New Mexico, and the Trans-Pecos area of west Texas (stress data and references): Los Alamos National Laboratory report LA-9158-MAP.

Arabasz, W. J., Smith, R. B., and Richins, W. D., 1979, Earthquake studies in Utah, 1950 to 1978: University of Utah Spec. Pub., 552 p.

Atwater, T., 1970, Implications of plate tectonics for the Cenozoic tectonic evolution of Western North America: Geol. Soc. Am. Bull. 81, 3513-3535.

Baldridge, W. S., Damon, P. E., Shafiqullah, M., and Bridwell, R. J., 1980, Evolution of the central Rio Grande rift: New potassium-argon ages: Earth Planet. Sci. Lett. 51, 309-321.

Brown, L. L., and Golombek, M. P., 1986, Block rotations in the Rio Grande rift, New Mexico: Tectonics 5, 423-438.

Budding A. J., 1978, Gravity survey of the Pajarito Plateau, Los Alamos and Santa Fe counties, New Mexico: Los Alamos Scientific Laboratory report LA-7419-MS.

Budding, A. J., and Purtymun, W. D., 1976, Seismicity of the Los Alamos area based on geologic data: Los Alamos Scientific Laboratory report LA-6278-MS.

Cash, D. J., 1971, The Dulce, New Mexico, earthquake of January 23, 1966: Location, focal mechanism, magnitude, and source parameters: dissertation, New Mexico Institute of Mining and Technology, Socorro,

Cash, D. J., and Wolff, J. J., 1984, Seismicity of the Rio Grande rift in northern New Mexico, 1973-1983: New Mexico Geol. Soc. Guidebook 24-28.

Chapin, C. E., 1979, Evolution of the Rio Grande rift: A summary: in Rio Grande Rift: Tectonics and Magmatism, R. E. Riecker, ed., Am. Geophys. Union (Washington, D.C.) Spec. Pub., p. 1-6.

Chapin, C. E., and Seager, W. R., 1975, Evolution of the Rio Grande rift in the Socorro and Las Cruces areas: New Mexico Geol. Soc. Guidebook 297-322.

Christiansen, R. L., and Lipman, P. W., 1972, Cenozoic volcanism and tectonic evolution of the western United States. II. Late Cenozoic: Royal Soc. London Philos. Trans. 271, 249-284.

Coffman, J. L., and von Hake, C. A., (eds.), 1973, Earthquake history of the United States: U.S. Dept. of Commerce (Washington, D. C.), Publication 41-1, 208 p.

Crowe, B. M., 1978, Cenozoic volcanic geology and probable age of inception of basin-range faulting in the southeasternmost Chocolate Mountains, California: Geol. Soc. Am. Bull. 89, 251-264.

Dalrymple, G. B., Cox, A., Doell, R. R., and Gromme, C. S., 1967, Pliocene geomagnetic polarity epochs: Earth Planet. Sci. Lett. 2, 163-173.

Dames and Moore, 1972, Report of geologic, foundation, hydrologic, and seismic investigation: Plutonium processing facility, Los Alamos Scientific Laboratory, Los Alamos, NM: Dames and Moore (Los Angeles, CA) consulting report, job number 0651-120-02.

Davison, F. C., and Scholz, C. H., 1985, Frequency-movement distribution of earthquakes in the Aleutian Arc: A test of the characteristic earthquake model: Bull. Seismol. Soc. Am. 75, 1349-1361.

Dethier, D. P., and Harrington, C. D., 1986, Late Quaternary erosion history of the western Española Basin, New Mexico: Geol. Soc. Am., Abstr. with Programs 18(5), 351.

Dethier, D. P., and Manley, K., 1985, Geologic map of the Chile Quadrangle, Rio Arriba County, New Mexico: U.S. Geol. Surv., Misc. Field Studies Map, MF-1814, scale 1:24,000.

Dethier, D. P., and Martin, B. A., 1984, Geology and structure along part of the northeast Jemez Mountains, New Mexico: New Mexico Geol. Soc. Guidebook 35, 145-150.

Doell, R. R., Dalrymple, G. B., Smith, R. L., and Bailey, R. A., 1968, Paleomagnetism, potassium-argon ages, and geology of rhyolites and associated rocks of the Valles caldera: Mem. Geol. Soc. Am. 116, 211-248.

Dransfield, B. J., and Gardner, J. N., 1985, Subsurface geology of the Pajarito Plateau, Española Basin, New Mexico: Los Alamos National Laboratory report LA-10455-MS, 15 p.

DuBois, S. M., and Smith, A. W., 1980, The 1887 earthquake in San Bernardino Valley, Sonora: Arizona Bureau of Geology and Mineral Technology, University of Arizona, Special paper 3, 112 p.

ESSA, 1968, United States earthquakes 1966, U.S. Dept. of Commerce, Earth Sciences Services Admin. (Washington, D.C.), 110 p.

Gardner, J. N., 1985, Tectonic and petrologic evolution of the Keres Group: Implications for the development of the Jemez volcanic field, New Mexico: Ph.D. dissertation, University of California, Davis, 293 p.

Gardner, J. N., and Goff, F., 1984, Potassium-argon dates from the Jemez volcanic field: Implications for tectonic activity in the north-central Rio Grande rift: New Mexico Geol. Soc. Guidebook 35, 75-81.

Gardner, J. N., Goff, F., Garcia, S., and Hagan, R. C., 1986, Stratigraphic relations and lithologic variations in the Jemez volcanic field, New Mexico: J. Geophys. Res. 91(B2), 1763-1778.

Goff, F., and Grigsby, C. O., 1982, Valles caldera geothermal systems, New Mexico, U.S.A.: J. Hydrol. 56, 119-136.

Goff, F., and Kron, A., 1980, In-progress geologic map of Cañon de San Diego, Jemez Springs, New Mexico, and lithologic log of Jemez Springs geothermal well: Los Alamos Scientific Laboratory report LA-8276-MAP.

Golombek, M. P., 1981, Structural analysis of the Pajarito fault zone in the Española Basin of the Rio Grande rift, New Mexico: Ph.D. dissertation, University of Massachusetts, 129 p.

Griggs, R. L., 1964, Geology and ground water resources of the Los Alamos area, New Mexico: U.S. Geol. Surv. Water Supply paper 1753, 107 p.

Hanks, T. C., and Johnson, D. A., 1976, Geophysical assessment of peak accelerations: Bull. Seismol. Soc. Am. 66, 959-968.

Harrington, C. D., 1986a, The use of rock varnish as a Quaternary dating method within the central Rio Grande rift, New Mexico and the Nevada Test Site: Geol. Soc. Am., Abstr. w/Programs 18(5), 360.

Harrington, C. D., 1986b, Rock varnish dating: A new tool in the assessment of fault hazard potential: EOS, Trans. Am. Geophys. Union 67(44), 1211.

Harrington, C. D., and Aldrich, M. J., 1984, Development and deformation of Quaternary surfaces on the northeastern flank of the Jemez Mountains: New Mexico Geol. Soc. Guidebook 35, 235-239.

Herrmann, R. B., Dewey, J. W., and Park, S. K., 1980, The Dulce, New Mexico, earthquake of 23 January, 1966: Bull. Seismol. Soc. Am. 70, 2171-2183.

House, L. S., and Cash, D. J. (in prep.), A review of historic and instrumental earthquake activity and studies of seismic hazards near Los Alamos: Los Alamos National Laboratory report.

Housner, G. W., 1970, Strong ground motion: in Earthquake Engineering, R. L. Wiegel, ed., Prentice-Hall Pub. (Englewood Cliffs, NY), 75-91.

Izett, G., Obradovich, J., Naeser, C., and Cebula, G., 1980, K-Ar and fission track zircon ages of Cerro Toledo Rhyolite tephra units in the Jemez Mountains, New Mexico: U.S. Geol. Soc. Prof. Paper 1199, 37-41.

Keller, M. D. (ed.), 1968, Geologic studies and material properties investigations of Mesita de Los Alamos: Los Alamos Scientific Laboratory report LA-3728.

Kelley, V. C., 1978, Geology of the Española Basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Geologic Map 48.

Machette, M. N., 1986, History of Quaternary offset and paleoseismicity along the La Jencia fault, central Rio Grande rift, New Mexico: Bull. Seismol. Soc. Am. 76, 259-272.

Machette, M. N., and Personius, S. F., 1984, Map of Quaternary and Pliocene faults in the eastern part of the Aztec 1 x 2 degree quadrangle and the western part of the Raton 1 x 2 degree quadrangle, northern New Mexico: U.S. Geological Survey, Misc. Field Studies Map MF-1465-B.

Manley, K., 1979, Stratigraphy and structure of the Española Basin, Rio Grande rift, New Mexico: in Rio Grande Rift: Tectonics and Magmatism, R. E. Riecker, ed., Am. Geophys. Union (Washington, D. C.), Spec. Pub., 71-86.

Manley K., 1984, First-day road log from Taos to Embudo, Dixon, Peñasco, Vadito, Tres Ritos, Holman Hill, and back to Taos via U.S. Hill and Talpa: New Mexico Geol. Soc. Guidebook 35, 303-319.

Marvin, R. F., and Dobson, S. W., 1979, Radiometric ages: Compilation B., U.S. Geological Survey: Isochron West 26, 2-32.

McKee, E. H., Nobel, D. C., and Silberman, M. L., 1970, Middle Miocene hiatus in volcanic activity in the Great Basin area of the western United States: Earth Planet. Sci. Lett. 8, 93-96.

Mickey, W. V., Devine, J. F., and Meyer, A. V. C., 1968, Project Gasbuggy: Response of the Mesita de Los Alamos to the Gasbuggy experiment and induced vibrations: U.S. Dept. of Commerce, Earth Sciences Services Admin., and U.S. Coast and Geodetic Survey (Rockville, MD).

Muehlberger, W. R., 1978, Frontal fault zone of northern Picuris Range: in Guidebook to Rio Grande rift in New Mexico and Colorado, J. W. Hawley, ed., New Mexico Bureau of Mines and Mineral Resources, Circular 163, 44-46.

Muehlberger, W. R., 1979, The Embudo fault between Pilar and Arroyo Hondo, New Mexico: An active intracontinental transform fault: New Mexico Geol. Soc. Guidebook 30, 77-82.

NOAA/USGS, 1975, United States earthquakes, 1973: U.S. Dept. of Commerce, National Oceanic and Atmospheric Admin., and U.S. Geological Survey (Washington, D.C.).

Olsen, K. H., 1979, The seismicity of north-central New Mexico with particular reference to the Cerrillos earthquake of May 28, 1918: New Mexico Geol. Soc. Guidebook 30, 65-75.

Personius, S. F., and Machette, M. N., 1984, Quaternary and Pliocene faulting in the Taos Plateau region, northern New Mexico: New Mexico Geol. Soc. Guidebook 35, 83-90.

Reid, H. F., 1911, Remarkable earthquakes in central New Mexico in 1906 and 1907: Bull. Seismol. Soc. Am. 1, 10-16.

Richter, C. F., 1958, Elementary Seismology: Freeman Pub. (New York, NY).

Sanford, A. R., 1963, Seismic activity near Socorro: New Mexico Geol. Soc. Guidebook 14, 146-151.

Sanford, A. R., 1976, Seismicity of the Los Alamos region based on seismological data: Los Alamos Scientific Laboratory report LA-6416-MS.

Sanford, A. R., Olsen, K. H., and Jaksha, L. H., 1981, Earthquakes in New Mexico, 1849-1977: New Mexico Bureau of Mines and Mineral Resources Circular 171, 20 p.

Savage, W. U., Ely, R. W., and Tocher, D., 1977, Review of the Los Alamos seismic monitoring program in relation to the Hot Dry Rock geothermal project: Woodward-Clyde Consultants (San Francisco, CA), consulting report L47-85930, 28 p.

Schwartz, D. P., and Coppersmith, K. H., 1984, Fault behavior and characteristic earthquakes: Examples from the Wasatch and San Andreas Fault Zones: J. Geophys. Res. 89(B7), 5681-5698.

Schwartz, D. P., Coppersmith, K. H., and Swan, F. H., 1981, Characteristic earthquakes on intraplate normal faults: Earthquake Notes 52, 71.

Seager, W. R., and Morgan, P., 1979, Rio Grande Rift in southern New Mexico, West Texas, and Northern Chihuahua: in Rio Grande Rift: Tectonics and Magmatism, R. E. Riecker, ed., Am. Geophys. Union (Washington, D.C.) Special Pub., 87-106.

Slemmons, D. B., 1975, Fault activity and seismicity near the Los Alamos Scientific Laboratory geothermal test site, Jemez Mountains, New Mexico: Los Alamos Scientific Laboratory report LA-5911-MS.

Slemmons, D. B., 1977, State-of-the-art for assessing earthquake hazards in the United States: Report 6, Faults and earthquake magnitude: U.S. Army, Corps of Engineers, Waterways Experiment Station, Misc. Paper S-73-I, 129 p. w/appendix.

Smith, R. B., and Bruhn, R. L., 1984, Intraplate extensional tectonics of the eastern Basin and Range: Inferences on structural style from seismic reflection data, regional tectonics, and thermal-mechanical models of brittle-ductile deformation: J. Geophys. Res. 89(B7), 5733-5762.

Smith, R. L., Bailey, R. A., and Ross, C. S., 1970, Geologic map of the Jemez Mountains, New Mexico: U.S. Geol. Surv. Misc. Geol. Invest. Map. I-571.

Stein, R. S., and Bucknam, R. C., 1985, Basin and Range viewed from Borah Peak: EOS, Trans. Am. Geophys. Union 66, 603.

Tera Corporation, 1984, Seismic hazard analysis for the Bendix, Los Alamos, Mound, Pantex, Rocky Flats, Sandia-Albuquerque, Sandia-Livermore, and Pinellas sites; Tera Corp. (Berkeley, CA), consulting report B-82-261.

Tillson, D. D., 1984, ESS Division earthquake risk assessment program: D. D. Tillson, Inc., consulting report C-3100, 9 p.

Trifunac, M. D., and Brady, A. G., 1975, On the correlation of seismic intensity scales with the peaks of recorded strong ground motion: Bull. Seismol. Soc. Am. 65, 139-162.

Wachs, D., Harrington, C. D., Gardner, J. N., and Maassen, L. W., (in prep.), Evidence of young fault movements on the Pajarito fault system in the area of Los Alamos, New Mexico: Los Alamos National Laboratory report.

Wallace, R. E., 1984, Patterns and timing of Late Quaternary faulting in the Great Basin province and relation to some regional tectonic features: J. Geophys. Res. 89(B7), 5763-5769.

Wolff, J. J., Cash, D. J., Olsen, K. H., and Stewart, J. N., 1985, Earthquake catalog for northern New Mexico, 1984: Los Alamos National Laboratory report LA-10598-PR.

Wollard, G. P., 1968, A catalogue of earthquakes in the United States prior to 1925: Hawaii Institute of Geophysics, University of Hawaii, Data Report No. 10.

Zoback, M. L., and Zoback, M., 1980, State of stress in the conterminous United States: J. Geophys. Res. 85, 6113-6156.

POCKET CONTENTS

Geologic Map IV-A, 6 sheets

Map IV-B, Structure Contour Map of the Pre-Bandelier Tuff Surface, Pajarito Plateau

Map IV-C, Paleogeology of the Pre-Bandelier Tuff Surface, Pajarito Plateau

Map IV-D, Zones of Relative Potential for Seismic Surface Rupture

Map IV-E, Preliminary Map of Potentially Hazardous Mass Wasting During an Earthquake (Shaded) (Includes Rockfall, Debris Flow, and Landslide)

Map IV-F, Cultural Overlay Map

Map IV-G, Geomorphic Surfaces, Southern San Juan Pueblo Quadrangle

Printed in the United States of America
Available from
National Technical Information Service
US Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

Microfiche (A01)

Page Range	NTIS Price Code	Page Range	NTIS Price Code	Page Range	NTIS Price Code	Page Range	NTIS Price Code
001-025	A02	151-175	A08	301-325	A14	451-475	A20
026-050	A03	176-200	A09	326-350	A15	476-500	A21
051-075	A04	201-225	A10	351-375	A16	501-525	A22
076-100	A05	226-250	A11	376-400	A17	526-550	A23
101-125	A06	251-275	A12	401-425	A18	551-575	A24
126-150	A07	276-300	A13	426-450	A19	576-600	A25
						601-up*	A99

*Contact NTIS for a price quote.