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**Fault Activity and Seismicity near
the Los Alamos Scientific Laboratory
Geothermal Test Site, Jemez Mountains,
New Mexico**

by

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FAULT ACTIVITY AND SEISMICITY NEAR THE LOS ALAMOS SCIENTIFIC LABORATORY
GEOTHERMAL TEST SITE, JEMEZ MOUNTAINS, NEW MEXICO

by

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ABSTRACT

The purpose of this study is to develop guidelines for evaluating geothermal sites for earthquake hazards and for the possibility of siting on an active fault. These guidelines were used to minimize these risks for a specific geothermal test site of the Los Alamos Scientific Laboratory (LASL) on the Jemez Plateau, a few miles west of the Valles Caldera, at the center of the Jemez Mountains in north-central New Mexico.

The approach to the problem involves new methods of low-sun-angle aerial photography and photogeology, in combination with conventional geological and seismicity studies. The possibility of future surface faulting or occurrence of strong local earthquakes is analyzed by comparing the structural and seismic setting of the area of investigation with that of the Rio Grande depression and other active zones in the western United States. The evaluation includes identification, delineation and characterization of faults in the region with conventional high-sun-angle aerial photographs, special low-sun-angle aerial photographs taken specifically for this project, Earth Resources Technology Satellite (ERTS) imagery, manned space satellite photography, search of the geological literature, and aerial and ground reconnaissance using both low and high sun angles of illumination at midday, early morning, and late afternoon.

The site area is near the western edge of the Rio Grande depression, the most active seismic zone of New Mexico. The Rio Grande depression is marked in places by geologically youthful fault scarps and in places is known to have significant normal faults.

Topographically the site area is composed of mesas of Quarternary volcanic tuffs and ashes of the Bandelier Rhyolite unit, which dips gently to the southwest with a nearly uniform dip. The upper surface of the mesas have slightly steeper gradients near the source area for the volcanic rocks at the eastern edge of the area. The drainage lines also trend in a southwesterly direction, away from the source of the eruptions, and are of consequent origin. Four streams or valleys have segments that diverge from this general trend: (1) the northern end of the eastern branch of Rio Cebolla, along an arcuate fault mapped by Smith et al. in 1970, about 7 miles (11 km) north of the GT-2 site; (2) a similar trending and concentric zone about 1.6 mile (2.5 km) to the northwest of the Rio Cebolla fault along the upper part of Calaveras Canyon; (3) a small fault along the upper reaches of Virgin Canyon, about 2.5 miles (4 km) southeast of the site; and (4) the Jemez Springs fault, a more important regional fault, about 4.4 miles (7 km) southeast of the site. Although these faults displace the Bandelier Rhyolites of 1.1-million-years age, they all have relatively small displacements (under about 100 ft, or 30 m) and have rates of displacement that are 1 or 2 orders of magnitude smaller than those of the San Andreas fault system, or of major faults of the Basin and Range province of the western United States.

The very low seismic risk is indicated not only by the low level of fault activity, but also by the low level of earthquake activity for New Mexico, the low level of activity in the Rio Grande structural depression (the most important fault zone in New Mexico), the general lack of any earthquakes of Richter magnitudes above 6, and the very sparse distribution of microearthquakes in the Jemez Mountains.

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I. INTRODUCTION

A. Purpose of Study

Standard guidelines have not been developed for evaluating the potential for surface faulting or renewal of earthquake activity at a geothermal installation. This study develops a method of approaching this problem and applies it to a specific site on the Jemez Plateau (Fig. 1).

The preliminary results were used in combination with other data to select the present geothermal exploratory site at GT-2, the Fenton Hill site (Fig. 2).

The results of this study are designed to (1) assist in site selection; (2) aid in project planning and justification; (3) reduce risk of siting near active faults; (4) assess risk of local strong earthquakes; and (5) provide data to be utilized in environmental impact statements.

B. Background for Study

During the early stages of site selection for the Los Alamos Scientific Laboratory's (LASL) geothermal energy experiment, the LASL research staff became convinced that future drilling and test sites should avoid location on or near active faults. This study was initiated during the summer of 1971 and a

preliminary report was submitted on November 14, 1972. The results of this preliminary study were integrated with other LASL staff investigations for the selection of the GT-2 drilling site in a position well away from any active surface faults.

C. Approach for the Fault Study

The evaluation of fault and earthquake activity in the area of investigation was especially difficult since most geological work in New Mexico has not been concerned with fault activity and past seismological data is based on only a few widely scattered and recently installed seismographic stations. Since the region has a low level of seismic activity and the historic record is very short, this study is dependent on correlating structural and seismicity relationships with other better known regions.

The approach used for recognition, characterization and delineation of active faults in the western Jemez Mountains is based on methods developed by the author and Lloyd S. Cluff, Vice President and Principal Engineering Geologist for Woodward-Lundgren and Associates. It is based on a regional investigation designed to achieve two goals: (1) evaluate the potential for surface faulting at the site, and (2) define the level of regional seismicity.

These methods are based on over two dozen studies using combined field, aerial reconnaissance, and

Fig. 1. Index map of major structural features and area of investigation for the geothermal test site in north-central New Mexico (modified from Kelley¹).

Fig. 2. Cultural and drainage features and location of test holes in the area of investigation (from Purtymun²).

photogeological evaluations of areas with active faults. The recognition and characterization of faults has been successfully accomplished in almost every type of terrain, through a wide range of vegetational and climatic zones, and for all types of faults -- strike-slip, normal, and reverse or thrust. The most difficult conditions for distinguishing and characterizing active faults are in heavily forested areas on nearly flat topography, or with reverse or thrust faults in mountainous terrain. The conditions for fault studies in the Jemez Mountains are excellent, since forests are not dense or uniformly distributed and the terrain is uneven and has extensive plateau surfaces that are of a known and geologically youthful age.

The general method for recognition of faults and evaluating fault activity is summarized by Slemmons³ and by Cluff et al.⁴ The optimal study should utilize as many of the following methods and techniques as possible.

1. Geological Methods. The two main types of criteria are geomorphological and stratigraphic. The most useful geomorphological features for recognizing active surface faults have been outlined by Sharp⁵ (see Appendix A). In addition, offsets of the water table, abrupt changes in water chemistry, or development of springs or seepages may assist in delineating faults.

2. Historical Methods. The three types of evidence for faults and the characterization of their activity (or nonactivity) include earthquake activity that can be correlated with a specific fault, evidence of historic surface faulting, and geodetic changes that are localized at a fault.

3. Seismological Methods. Microearthquake studies may delineate faults in three dimensions. For aseismic regions and regions of moderate to low seismicity, the observational period may not be of sufficient duration to identify faults.

For specific sites, conventional aerial photography, normally at midday, reveals faults mainly by their vertical offsets, shown only by stereographic effects, or by tonal changes if different units are exposed on either side of the fault. Fault studies, and particularly active fault studies, are greatly improved by utilization of special low-sun-angle illumination (Slemmons⁶ and Cluff and Slemmons⁷) to enhance fault scarps either by high-lighting or shading areas of different slope.

Based on many detailed studies of surface faults that have experienced historic displacements, investigators have repeatedly observed the historic trace to follow almost exactly the trace of the most recent prehistoric trace. The sense and approximate amount of displacement is generally similar to that of the most recent prehistoric event, and the position of the trace could have been recognized and delineated prior to the historic displacement by geological or geomorphological methods. By using proper combinations of geological, historical, photogeological, and seismological methods, active surface faults can accordingly be characterized as to the nature of future displacements with a high degree of reliability.

The term active fault has no universally accepted definition. The definition used for this report is as follows:

An active fault is a fault that displays sufficient evidence of displacements within the recent geologic past to make it reasonable to assume that new displacements will occur at some time in the future.

Such a fault can be considered as capable.

The above definition embraces the general criterion that has been recognized for over 50 years by workers specializing in the study of active faults. Some workers, mainly engineers, have attempted to restrict the definition of active faults to those with historic displacements, or to a probability defined in terms of the predicted life span of an engineering structure. The philosophy of what constitutes an active fault is well expressed by the definitions given in Appendix B.

D. Sequence for Fault Studies

Normally, the mapping and evaluation of faults on a regional basis should follow a logical sequence.^{3,4} Although a specific application may require modification of the recommended number or sequence of steps, the most effective use of time and the lowest total cost are generally produced with the following series of stages in a regional study.

1. Review of existing knowledge. Search of literature, review of topographic and geologic maps; obtain and review available aerial photography and remote sensing imagery; consultation with authorities on the geology and seismology of the region.

2. Aerial Reconnaissance. Overflight of the area at both low and high altitudes to reveal both

synoptic and detailed features, ideally with optimal sun illumination to enhance the topographic features.

3. Photogeological Study. Study and compile lineament and fault maps from all types of available aerial photography and imagery. Experience has shown that special low-sun-angle aerial photography is by far the most effective method of revealing active faults and should be a standard element of all active fault studies.

4. Field Study. Evaluate all significant lineaments and faults.

5. Synthesis of Results. Preparation of a preliminary report for review; recommend special studies that may be needed (microearthquake surveys, geophysical exploration, geodetic surveys, ground-water studies, exploratory trenching or drilling).

6. Final Report. Should include results from all of the above steps.

In the present study the above recommended series of six steps has been followed.

II. GENERAL GEOLOGICAL SETTING

A. General Comments

The primary purpose of this study is to evaluate the potential for future fault activity at the general site area. Such studies require an adequate knowledge of the stratigraphy, structures, and geomorphology of the region. This study was facilitated because the general geology of the Jemez Plateau and surrounding region has been mapped in detail and has been adequately described.

The geology of the Jemez Plateau has been summarized by Purtymun.² The geological relationships of the Jemez Mountains, including the Jemez Plateau, have been mapped in detail by Smith, Bailey and Ross.^{8,9} Their map is the principal source for the map of active faults of the region (Fig. 3). The regional geology, tectonic setting, and seismic activity are summarized in an unpublished consulting report by Dames and Moore.¹⁰

Purtymun's² synthesis of the geology of the Jemez Plateau included the results of studies by Bailey, Smith, and Ross;¹¹ Doell, Dalrymple, Smith, and Bailey;¹² Fitzsimmons;¹³ Hale, Reiland, and Beverage;¹⁴ Keller;¹⁵ Renich;¹⁶ Ross, Smith, and Bailey;¹⁷ Smith, Bailey, and Ross;^{8,9} and Woods and Northrop.¹⁸ Purtymun also includes data on heatflow in the Fenton Hill area and geologic logs of drill holes at the

site area. The water quality of surface and ground water in the Jemez Plateau area has been evaluated by Purtymun et al.¹⁹

Regional geological relationships are shown in publications by the American Association of Petroleum Geologists,²⁰ Bogart,²¹ and the Rocky Mountain Association of Petroleum Geologists.²² The general tectonic setting for this part of the Rio Grande rift valley and the relationships to adjoining structural provinces have been evaluated by Kelley.^{23,24}

The geophysical and geological interrelationships of the Jemez Mountains are reviewed in a recent publication by West,²⁵ and the summary of literature dealing with regional geophysical studies has been compiled by Cash.²⁶

B. Geography

The area of investigation includes most of the Jemez Plateau, on the western flank of the Jemez or Valles Caldera. The plateau-like terrain (Fig. 4) that characterizes the plateau formed about 1.1 million years ago from a series of violent eruptions from the Valles Caldera which distributed thick blankets of volcanic ash and cinders around the volcanic center. The higher ridge lines have altitudes of between 8000 and 9000 ft (2438 and 2743 m), and the valleys are generally less than 1000 ft (305 m) deep.

C. Stratigraphy

The oldest rocks in the region are Precambrian gneisses and granitic rocks. The regional relationships are outlined in the Atlas of the Rocky Mountain Association of Petroleum Geologists,²² and the detailed petrography of rocks near the site area has been described by Perkins.²⁷ The nearest outcrops of Precambrian rocks are in the Nacimiento Mountains, about 8 miles (13 km) west of GT-2, and Precambrian rocks were encountered in the nearby GT-1 drill hole.

Overlying the basement rocks at the site area are about 2000 ft (593 m) in GT-2 of Paleozoic limestones, shales, arkosic sandstones and siltstones, that vary in age from Permian to Pennsylvanian (see geologic time scale in Appendix C).

Cenozoic rocks of the site area are composed mainly of volcanic units, or sediments derived from volcanic rocks. The regional volcanic relationships and their ages are described by Bailey et al.,¹¹ Doell et al.,¹² Ross et al.,¹⁷ and Smith et al.^{8,9} The unit names and potassium-argon radiometric ages (in

Fig. 3. Faults and volcanic centers in the Valles Caldera region (modified from Smith et al⁹).

Fig. 4. Oblique aerial photograph of the Jemez Plateau site area looking approximately southwest. Photograph was taken in early morning with low-sun-angle illumination to accentuate the topography. The Valles Caldera is in the lower left foreground; one of the ring volcanoes, San Antonio Mountain (elevation: 10,500 ft or 3050 m) is on the left edge of the photograph. The edge of the caldera ring fracture system extends along an arcuate path from the lower right to the left center edge and is followed by the San Antonio Creek branch of the Jemez River. The Jemez Plateau extends southward to the Nacimiento uplift in the middle distance. The white triangle indicates the GT-2 site and the small white dots indicate the position of the Virgin Canyon fault.

millions of years) are given as follows. (Asterisks denote units at or very near the site.)

Volcanic Rocks (Unit Name)	K-Ar Age (m.y.)
*Battleship Rock Member	0.1
*Valle Grande Member	
Intracaldera domes	0.4 to 1.0
*Bandelier Tuff	
Tshirege (Upper) Member	1.1
Otowí (Lower) Member	1.4
El Rechuelos Rhyolite	2.0
*Tschicoma Formation	3.7 to 6.7
Lobato Basalt	7.4
*Paliza Canyon Formation	8.5 to 9.1
Canovas Canyon Rhyolite	8.5 to 9.1

D. Structural Setting

1. General. The site is near the western edge of a long Cenozoic structural trough that extends from southern Colorado southward into northern Mexico (Fig. 5). This zone has been referred to as the Rio Grande depression, the Rio Grande rift zone and the Rio Grande trough. The structure is complex and

consists of a series of downwarped basins or depressions, down-faulted areas, and a flanking series of uplifted north-south trending uplifts and upfaulted blocks. Fossils and a 21-million-year potassium-argon radiometric date suggest that the section of the Rio Grande depression near Santa Fe started its downward deformation about 18 to 21 million years ago.

The Jemez Mountains and the geothermal test site are in a middle section of the Rio Grande depression (Figs. 6 and 7) that is flanked on the west by the north-south-oriented Nacimiento uplift at the eastern edge of the Colorado Plateau, and on the east

Fig. 5. The Rio Grande depression (shown by hatching) in relation to the major geomorphological provinces.

Fig. 6. Relation of the middle Rio Grande depression to the geothermal test site (modified from Kelley¹).

Fig. 7. East-west regional cross-section through the geothermal test site (after West²⁷).

by the Sangre de Cristo uplift. The Nacimiento uplift, about 8 miles (13 km) west of GT-2, is at least in part bounded by high-angle reverse faults. The uplift and fault activity for this block are generally regarded as being confined to the late Mesozoic Laramide Orogeny, over 70 million years before present. No fault offsets of the Bandelier Rhyolite of 1.1-million-years age were noted by Smith et al.,⁹ a relationship that was confirmed by my photogeological and field study.

Three major fault zones cross parts of the Jemez Mountains (Fig. 3): the northeast-trending fault zone at the southwestern part of the range; the north-south-trending San Felipe fault system along the southern axis of the range; and the Pajarito fault system on the eastern slope of the range. All three fault systems offset Cenozoic formations and at least two, the Jemez and the Pajarito faults, offset the 1.1-million-year-old Bandelier Rhyolite. Although only one of these zones, the Jemez fault system, is close to the site, the Jemez and Pajarito fault systems appear to form an en echelon pattern at the Jemez Mountains, where the Rio Grande depression changes from a north-south trend south of the Valles Caldera to a northeasterly trend north of the caldera. The location of the Valles Caldera, just east of the site area, may be controlled by the intersection of the Jemez and San Felipe fracture systems.

The three faults, listed in decreasing order of rate of fault displacements, are: the Pajarito fault system with about 400 ft (132 m) of displacement in the last 1.1 million years; the Jemez Springs branch

of the Jemez fault system with about 100 ft (30 m) of displacement during the past 1.1 million years and no displacements in the last million years; and the San Felipe fault system, which has numerous branches in volcanic rocks of 6-million-years age or more, but no offsets in the 1.1-million-year-old Bandelier Rhyolite.

2. Pajarito Fault System. The Pajarito fault system has been mapped in detail by Smith et al.⁹ and also has been studied in the field and by photogeological methods by Budding and Beers.²⁸ The fault zone is of north-south trend and consists of a series of en echelon and branching high-angle normal faults of variable orientation. Budding and Beers report a maximum offset of the Bandelier Rhyolite of about 400 ft (122 m), and that older Pliocene dacites have displacements of more than 1000 ft (305 m). The length of the fault zone is difficult to assign, since near the Cochiti Pueblo there may be a southerly extension with a reversed sense of displacement with regard to which side of the zone is upfaulted, and north of Los Cerros there are branching segments that have a different orientation. The zone appears at least to extend from near Cochiti Pueblo to Los Cerros, a length of 32 miles (51 km), and may extend further northward to the Rio Chama, for a length of 42 miles (68 km); and it could, conceivably, connect with the La Bajada fault system for an even greater length.

3. Jemez Fault System. The Jemez fault system is defined for this report as a zone of several branching and en echelon faults on the western side of the Jemez Mountains. This zone is close to the area of investigation and to GT-2, and is the only major zone described in later parts of this report. Previous mapping by Smith et al.⁹ was checked and, with the exception of one short fault zone on the northern part of Virgin Canyon, was used for the fault map (Fig. 3). The work of Smith and his colleagues demonstrates that the main branch in this zone is the Jemez Springs fault, which extends northeasterly from the eastern edge of the Nacimiento uplift, near Guadalupe Box, in a N45°E direction toward the southwestern part of the Valles Caldera. A shattered zone of faults of similar orientation may represent an extension of the zone into the central part of the caldera. The total length of the Jemez Springs fault in this zone is at least 18 miles (29 km) and could be

28 miles (45 km) if the intracaldera faults of similar orientation are included. Other faults of similar, but not identical orientation are developed approximately on strike on the northeastern flank of the volcano, but there is no firm basis for connecting these faults to the Jemez fault system. The rate of activity of this zone is much lower than that of the Pajarito fault system, since younger volcanic units (the Banco Bonito Member, and the Battleship Rock Member of 0.1-million-years age) are not offset by the fault. The two faults that are nearest to the geothermal site area are the Virgin Canyon and Jemez Springs faults (Fig. 3).

4. San Felipe Fault System. The San Felipe fault system consists of a swarm of north-south oriented, high-angle normal faults that extend from the Jemez River at least 32 miles (51 km) northward to the edge of the Valles Caldera. The faults are distributed in a broad zone, up to 6 miles (10 km) in width, and offset the older volcanic and sedimentary units of the southern end of the Jemez Mountains and the northern part of the San Ysidro basin.

The Bandelier Rhyolite is not offset by faults of this system, which suggests that this fault zone is either no longer active or that the recurrence interval is extremely long. The Valles Caldera is centered at the junction of this zone of faults and the obliquely-trending faults of the Jemez fault system, which suggests that these two ancient fault systems exerted a control on the positioning of the Valles Caldera of the Jemez Mountains.

5. Rio Cebolla Fault. The Rio Cebolla fault was mapped by Smith et al.⁹ in the northernmost 4 miles (6 km) of the branch of Rio Cebolla trending northeast of Seven Springs Ranger Station. The displacements are small, with the southern block down-faulted. Rio Cebolla trends southwestward on an aligned arcuate trend, and although no fault displacements are visible in the alluvial fill of the valley floor, Smith et al.⁹ projected the trend to the southwest as a factor that may have influenced the present anomalous trend of the Rio. Their inferred fault was projected to a point about 4 miles (6 km) north of GT-2. Our photogeological and field surveys showed no evidence of scarps or recent activity on this segment of the zone, indicating that no significant displacements are present. The arcuate form, that is concentric with a series of other faults centered

about a point inside the Valles Caldera, along San Antonio Creek -- about 2 miles west of Warm Springs -- suggests a volcanic collapse origin for this arcuate zone. It was probably active between 1.1-million-years ago, the time of the Tshirege pyroclastic eruption, and about 0.5-million-years ago, the time of the younger Valle Grande eruptions along the volcanic centers on an inner arcuate zone that includes San Antonio Mountain, Cerro Seco, and Cerro San Luis.

6. Calaveras Canyon Zone. The Calaveras Canyon zone is north and west of the Rio Cebolla fault, and has a similar but larger concentric position at the northwestern edge of the Valles Caldera. Although Smith et al.⁹ did not map a fault in this segment of the branching Rio Cebolla drainage system, the path of the stream appears to be unrelated to the consequent stream development for the western flank of the Jemez Mountain volcanic center. This trend, if projected, could extend southward to Fenton Lake, about 2.5 miles (4 km) west of the GT-2 site. No offset of elevations of the mesas across this zone is measurable. No fault scarps or other structural offsets were observed along this lineament.

III. DETAILED SEARCH FOR ACTIVE SURFACE FAULTS IN THE SITE AREA

The detailed search for all surface faults was conducted as part of the investigational sequence outlined in the introduction of this report. Most of the work was conducted during the spring and summer of 1972. The study involved the following phases.

1. Review of Existing Data. The initial stage of work included a conventional bibliographic search and visits with staff and departmental archives at the University of New Mexico in Albuquerque and the New Mexico Bureau of Mines and Mineral Resources in Socorro.

2. Aerial and Field Reconnaissance. To detect significant faults that might be present on or near the site and provide a preliminary impression of their regional relationships, the area was examined both in the field and by several aerial flights at altitudes of from 1000 to 20,000 ft (305 to 6096 m) above ground level (including fortuitous overflights by commercial airline), and with a range of sun-angles of illumination varying from very early morning to midday, late afternoon and early evening. This aerial reconnaissance provided repetitive synoptic and detailed analysis of both regional and local relationships.

The main aerial study was conducted under excellent atmospheric conditions in mid-March 1972, with LASL geological personnel present on the flights so that the ground relationships and possible site locations could be compared with the regional setting.

Observations during this phase of study were compared with a background of experience accumulated during similar examinations of most of the historic zones of surface faulting in the western conterminous United States and Alaska, and during other field studies in South America and Japan.

3. Normal and Special Aerial Photography. The aerial and field observations showed a significant lineament in Virgin Canyon, near the southern edge of the site. In order to provide adequate aerial photographs of the site and surrounding region, conventional, high-quality, high-sun-angle aerial photography, conducted by personnel at the U. S. Air Force Kirtland Air Base, using their computer programs to execute the photography at proper angles of sun illumination, and utilizing the latest methods of enhancement of topographic features as described in several recent papers (Clark;²⁹ Cluff;³⁰ Cluff, Brogan, and Glass;^{31,32} Cluff, Slemmons, and Waggoner;³³ Slemmons;^{3,6} and Cluff et al.⁴). All photographs were taken to include stereographic coverage, with negatives generally 9 in. by 9 in. or larger and at scales and angles of illumination as follows.

- 1/100,000: Synoptic coverage of the entire region, from the Nacimiento uplift to the Rio Grande River; coverage includes repetitive photography during both early morning and late afternoon, altitude of sun below 30°. U. S. Air Force.
- 1/25,000: Intermediate scale coverage of the entire region, both early morning and late afternoon. U. S. Air Force.
- 1/16,000: Detailed scale coverage of the entire region, midday or high-sun-angle. U. S. Forest Service.

4. Photogeologic Interpretation. Since the topographic expression of faults is often subtle, the procedure used for this study was to examine all aerial photographs at least twice, generally on different days. The second examination was usually conducted with the photographs in an inverted

position to provide a perspective different from that of the first examination. The examination was very carefully conducted for the site area and for an adjoining area of up to about 15 miles (25 km) distance.

5. Field Study. The excellent quality of the aerial photographs of the region along with the limited outcrop exposures and forested nature of the site area made it necessary to focus the field studies on examination of lineaments defined by the photogeological analysis. In order to determine whether there have been fault offsets of the 1.1- to 1.4-million-year-old Bandelier Rhyolite, two work maps were prepared that contoured the elevations of the top and the bottom of the Bandelier Rhyolites. No significant irregularities were observed at any of the lineaments. The limit of resolution for this type of analysis was about 100 ft (30 m) which demonstrated the lack of larger faults in the site area.

The linear nature of several valleys in the area required field checks to determine whether there were any physiographic features or stratigraphic offsets controlled by smaller faults. Only two of the lineaments of this type were verified to be faults, the minor fault in the upper part of Virgin Canyon that had already been recognized during the aerial reconnaissance, and the Jemez Springs fault. The Virgin Canyon fault displaces the Bandelier Tuff, of 1.1-million-years age, by about 50 to 75 ft (15 to 23 m) at the eastern edge of the Jemez Plateau (Fig. 8). This field measurement indicates an average rate of motion of between 0.055 and 0.091 in. (0.0014 and 0.0023 cm) per year, a very low rate compared to major active faults in the western United States. The Jemez Springs fault zone is a major fault that has dip-slip components measured in thousands of feet in the Paleozoic and Precambrian basement rocks near Guadalupe Box. The Tshirege Member of the Bandelier Rhyolite, of 1.1-million-years age, has been offset approximately 100 ft (30 m) at the southern edge of the Jemez Plateau (Fig. 9), which indicates a rate of activity of about 0.11 in. (0.0028 cm) per year, a very low rate. The offsets at the eastern edge of the plateau, near Jemez Springs, are much smaller, indicating a possible decrease in activity to the north along this zone. The fault does not offset the Battleship Rock Member of the Valles Rhyolites;

Fig. 8. Oblique aerial view of the Virgin Canyon fault. Photograph was taken in early morning with low-sun-angle illumination to accentuate the topography. The far (southeastern) side of the canyon is about 50 ft (15 m) higher than the near side. The small white dots indicate the upper segment of Virgin Canyon and the fault trace.

Fig. 9. View of fault offset along the Jemez Springs fault zone near the southern edge of the Jemez Plateau. The offset displaces the Tshirege Member of the Bandelier Tuff along the skyline, with the eastern (right) side downfaulted. View to north from Guadalupe Box.

the 0.48-million-year age for this unit suggests a possible decrease in rate of activity during the last 0.5 million years. The lack of geologically recent activity was confirmed by our field examination of the travertine deposits at Soda Dam, where deposits up to 100 ft (30 m) above the present stream level are not offset by the fault. These travertine deposits are younger than the 0.48-million-year-old Battleship Rock Member, and were estimated by the author at about 0.1- to 0.3-million-years age on the basis of depth of erosion at Soda Dam and at Battleship Rock since the eruption of the Battleship Rock Member.

The GT-2 site is over 3.8 miles (6 km) northwest of the nearest part of the Jemez Springs fault zone and is over 2.5 miles (4 km) northwest of the nearest part of the shorter and relatively minor Virgin Canyon fault. Since both faults trend away from the site, and both faults have low rates of activity, they are very unlikely to be activated by the proposed experiments at the site.

There is a possibility that very minor faulting could have ruptured the Bandelier at points nearer the test site, but that subsequent erosion and deposition has sufficiently modified the terrain so that

the fault scarps are no longer visible. Such displacements would have been visible with the methods used for this study if the total offsets had exceeded about 25 ft (8 m) during the last 0.5 million years or more, and for much smaller offsets during the last few hundred thousand years. Any such faults would be characterized by very low rates of activity and would have to occur early in the 1.1-million-year period of post-Bandelier erosion.

IV. SEISMICITY OF THE SITE AREA

A. General Comments

The potential for future faulting and release of seismic energy at the site is difficult to evaluate because of the relatively low level of activity and because the period of historic records and seismological instrumentation in New Mexico is very brief. The earliest reported earthquake dates back only to the mid-1800's and the first seismographic station was installed in 1960. This brief earthquake record has only a poor correlation with the known fault distribution in the region.

The fault and earthquake hazard can be assessed in two ways -- by earthquake data, and by studies of geologically young faults. The study of seismicity, both regionally and locally, has included the following sources of data: Albee and Smith;³⁴ Algermissen;³⁵ Allen, St. Amand, Richter, and Nordquist;³⁶ Dames and Moore;¹⁰ Eppley;³⁷ Northrop;³⁸ Richter;³⁹ Ryall, Slemmons, and Gedney;⁴⁰ Sanford;⁴¹ Sanford;⁴² Sanford, Budding, Hoffman, Alptekin, Rush, and Topozada;⁴³ Sanford and Cash;⁴⁴ Slemmons, Gimlett, Jones, Greensfelder, and Koenig;⁴⁵ and Slemmons, Jones, and Gimlett.⁴⁶ Studies of regional seismicity and surface faulting interrelationships include: Bonilla;^{47,48} Bonilla and Buchanan;⁴⁹ Budding and Beers;²⁸ Buwalda and St. Amand;⁵⁰ Iacopi;⁵¹ Louderback;⁵² Cluff, Slemmons, and Waggoner;³³ Richter;³⁹ and Slemmons.⁵³

B. Evaluation of Seismicity from Earthquake Data

Several studies permit an approximate evaluation of seismicity of New Mexico and the site. All suggest that, although the Rio Grande rift zone is the most active seismic zone in New Mexico, its activity is very low relative to other parts of the western United States. The historical data suggest that the main zone of seismic activity for the historic period is to the south of the site area, and that this zone

of lower seismic activity has most of its activity well to the east of the site, in the central or eastern parts of the rift valley. No earthquakes have been reported with epicenters at or near the site (Fig. 10 and Table I).

Sanford⁴² reviewed the seismicity of the Los Alamos region based on seismological data. His study included pre-1962 earthquakes, based mainly on noninstrumental data, and post-1962 earthquakes, based on instrumental studies during the 1962-1972 period. His data led him to the conclusion that the recurrence interval for earthquakes of Magnitude 5.5 is about once every 100 years for the part of the Rio Grande depression from Albuquerque to Questa. This indicated that the seismicity of this part of the rift zone is (1) less than the Albuquerque to Socorro segment of the same structure and (2) substantially less than equivalent areas in Southern California. Sanford⁴² recently prepared a special study of the epicentral distribution of microearthquakes and macroearthquakes in the Los Alamos region. His more detailed study of low magnitude earthquakes also shows a sparse distribution of earthquakes near the Jemez Plateau (Fig. 11).

The rate of seismic energy release per unit area, or tectonic flux (Ryall et al.⁴⁰), is about 20 times lower in New Mexico than in the Basin and Range province of California-Nevada-Utah (Fig. 12). Even allowing for a rate of activity for the Rio Grande depression of about double the average for New Mexico, the rate of energy release is approximately an order of magnitude lower than for the California-Nevada region.

Sanford⁴¹ suggested that the number and strength of shocks detected from January 1 to June 30, 1962 indicated a seismicity about one-fiftieth as great as that of southern California. The data for Nevada (Slemmons et al.⁴⁶) when compared with that of Sanford⁴² for New Mexico, also suggest that Nevada is at least 10 times more active. The number of strong earthquakes reported in New Mexico is far smaller than for Nevada, even though New Mexico covers an area that is about 10% larger, and comparisons of numbers of events greater than a given intensity all indicate lower seismicity of New Mexico (Table II). However, the lack of very high M.M. Intensity (over VIII) and high Richter magnitude events (greater than 6) in New Mexico may be related to the too-brief

Fig. 10. Epicentral map for earthquakes that have been felt, or have had Richter magnitudes greater than 4, and significant faults that may be active for New Mexico.

TABLE I

CATALOG OF EARTHQUAKES WITH EPICENTERS IN NEW MEXICO WITH FELT REPORTS, OR RICHTER MAGNITUDES ABOVE 4^a

Date Year-Month-Day	Latitude North	Longitude West	Richter Magnitude	Intensity	Remarks
1868-04-28	34.0	107.0	4.5	V	Socorro. ³⁷
1869-04-18	34.0	107.0	5.5	VII	Socorro. Affected position of water flow from Socorro Springs. Water from springs a rusty color for many weeks. Considerable damage to several houses.
1873-08-02			3.0	III	Santa Fe. ⁴²
1886-07-06	34.0	107.0	4.5	V	Socorro. Rio Grande rift zone. ³⁸
1893-04-08	35.5	106.5	5.5	VII	Belen.
1893-07-12	35.0	106.5	4.5	V	Albuquerque. Three shocks shook every house in city. Clocks stopped. A chandelier swung for 10 minutes. Rio Grande rift zone. ³⁷
1893-09-07	34.5	106.5	5.5	VII	Central New Mexico was subjected to shocks for 3 months during this period, the most severe being on the date here given. Five shocks threw down many adobe buildings at Los Lunas, which were already weakened by previous earthquakes. No lives were lost but many suffered from nausea. Also felt at Sabinal. Rio Grande rift zone. ³⁷
1895-10-07	34.5	106.5	4.5	V	Sabinal and Javales. Articles ³⁷ thrown from shelves. Felt at Albuquerque.
1895-10-31	34.0	107.0	5.0	VI	Socorro.
1897	34.0	107.0	5.0	VI	Waves seen in ground.
1904-01-09	34.0	107.0	4.5	V-VI	
1906-07-12	34.0	107.0	6.0	VIII	Some adobe walls cracked, others thrown down.
1906-07-16	34.0	107.0	6.0	VIII	Train was nearly derailed 10 miles west of Socorro.
1906-11-15	34.0	107.0	6.0	VIII	Frequent rumbling was heard.
1913-07-08	34.0	107.0			
1918-05-28			5.5	VIII	Cerrillos. Minor damage in Santa Fe, 20 miles (33 km) to northeast. ⁴²
1919-01-31	34.0	107.0	4.0	IV-V	
1919-02-01	34.0	107.0	4.5	V	
1921-07-30	36.0	107.0	4.5	IV	Senorito. ⁴²
1924-08-12	36.0	104.5	4.0	V	
1930-03-23	35.0	106.5	4.0	I-V	Albuquerque. Dishes and furniture rattled. Very brief shocks.
1930-10-03	34.5	105.5	4.0	I-V	Duran. Moderate shock. No damage. Rattled windows. Rumbling sound. Rolling motion.
1930-12-03	35.0	106.0	4.5	V-VI	Albuquerque. Two distinct shocks. Vertical movement felt. Cracked plaster.
1931-01-27			3.0	III	

^aThe primary sources for this table are from U. S. Earthquake reports (U. S. Department of Commerce), and Refs. 10, 37, 38, 41, 42, and 43. Estimation of Richter magnitude is based on methods used in Refs. 40 and 46. This method provides a conservative value that is generally higher than values from Sanford, and is consistent with the approach used in preparation of the regional tectonic flux map for the western United States (Fig. 12).

TABLE I (Continued)

CATALOG OF EARTHQUAKES WITH EPICENTERS IN NEW MEXICO WITH FELT REPORTS, OR RICHTER MAGNITUDES ABOVE 4

Date Year-Month-Day	Latitude North	Longitude West	Richter Magnitude	Intensity	Remarks
1931-02-03	35.0	106.0	4.0	V	Albuquerque. ⁴²
1931-02-04	35.0	106.0	5.0	VI	Albuquerque. Some building damage and landslides.
1931-02-12	35.5	105.0	5.0	IV	
1931-04-07					Socorro. Slight shock (4 to 5 seconds).
1934-01-07	34.0	107.0	4.0	V	Slight damage.
1934-02-28			3.5	IV	Bernardo. Small objects moved, cracked plaster, slight damage.
1934-05-07			3.0	III	Magdalena. Moderate shock.
1934-05-06	32.0	108.0	4.0	V	Slight damage to adobe buildings.
1935-01-17			3.0	III	Socorro. Small objects moved.
1935-01-19			3.5	IV	
1935-02-20	34.5	107.0	5.0	VI	Various building damages, walls cracked. Shock accompanied by thunderous roar.
1935-02-30					
1935-12-17	35.0	107.0	4.5	V-VI	Belen. Swarm - 81 shocks (Dec. 12 - Jan. 1).
1935-12-18	35.0	107.0	4.5	VI	Same as above.
1935-12-19					
1936-01-07					Carlsbad. Some property damage.
1936-09-09			4.0	IV-V	Albuquerque.
1936-09-11			3.0	III	Albuquerque.
1937-09-29					Fort Stanton. Slight shock, awakened many.
1938-03-22					Los Lunas. Slight shock.
1938-04-15				Slight	
1938-04-16				Slight	
1938-09-17	33.0	108.5	5.0	VI	Arizona-New Mexico border. Bottles fell from shelves.
1938-09-19	33.0	108.5	4.5	V	
1938-09-29	33.0	108.5	4.5	V	
1938-10-30	33.0	108.5	4.5	V-VI	
1938-11-02					Silver City. Nothing.
1938-11-26	33.0	108.5			Arizona-New Mexico border. Moderate shock.
1938-12-28					Arizona-New Mexico border. Moderate shock.
1941-08-04			4.0		Socorro. Residents awakened. Plates fell. 123 miles (198 km) north - hanging objects swung.
1942-12-27			4.0		Magdalena. Sharp shock felt. Rattled doors and windows.
1947-11-06	34.0	107.0	5.0	VI	San Antonito. Plaster and fireplace cracked at Zamora. South wall of house damaged.
1949-02-02				IV	Carlsbad.
1949-05-23	34.5	105.0	5.0	VI	Objects fell from shelves, building creaked.
1951-06-20	35.5	103.0			
1952-08-03	36.5	105.0	4.5	V	
1952-08-17	35.5	106.0	4.5	V	Los Alamos. Slight damage to walls in home.

TABLE I (Continued)

CATALOG OF EARTHQUAKES WITH EPICENTERS IN NEW MEXICO WITH FELT REPORTS, OR RICHTER MAGNITUDES ABOVE 4

Year-Month-Day	Latitude North	Longitude West	Richter Magnitude	Intensity	Remarks
1952-10-07	37.0	106.0	4.5	V	Colorado-New Mexico border region.
1954-11-02	35.0	106.0	4.0	IV	Albuquerque.
1954-11-03	35.0	106.5	4.0	V	Minor plaster cracks reported.
1955-08-12	30.0	104.5	4.0	V	Santa Fe. Plaster wall cracked in building 15 miles (24 km) SW of Santa Fe. Buildings shaken in Santa Fe.
1956-04-25			4.0	V	
1960-07-22	34.5	107.0	4.5	V	Lajoya. Trophies fell from shelf.
1960-07-23	34.5	107.0	4.0	V	
1960-07-24			4.0		Four miles (6 km) east of Bernardo. Two small windows broken.
1960-09-25	34.0	107.0	3.0	III	
1960-12-19	34.0	107.0	4.0	IV	
1961-01-27	34.0	107.0	4.0	IV	
1961-07-03	34.0	107.0	5.0	VI	Slight damage to plaster at Socorro. Small objects shifted.
1965-02-03	35.5	103.5	4.0	IV	
1965-12-22	34.0	107.0	4.0	IV	
1965-12-29	35.0	106.0	3.0		Windows rattled.
1966-01-21	35.5	103.0	4.0		Many buildings damaged at Dulce (Jan. 22).
1966-01-23	37.0	107.0	5.5	VII	Walls damaged, broken water pipes, people knocked down. Many aftershocks (26 aftershocks >2.7).
1966-05-19	37.0	107.0	4.5		Aftershock of 5.
1966-08-14	32.0		4.5		Windows rattled; similar to sonic boom.
1966-09-17	35.0	104.0	3.5		
1966-10-03		104.0	4.5		
1967-01-16	34.5	107.0	3.5		
1969-01-30	34.0	107.0			Cracks in adobe at Alamillo.
1969-05-12	32.0	106.5	3.5		
1969-07-04	36.0	106.0	4.5	IV	Felt north of Espanola.
1970-01-12	36.0	103.0	3.5		Plaster fell, adobe fell in one area.
1970-11-28	35.0	107.0	3.5	V	Felt in Albuquerque. Shaking, one report of cracked plaster.
1971-01-04	35.0	107.0	4.0	VI	Corrales. Most severe earthquake in New Mexico since 1906. Cracked walls, plaster fell, etc.
1971-12-06	36.0	106.0	3.5		Minor damage in Abiquiu-Los Alamos area. Cracked adobe walls. Barely felt at Los Alamos.

Fig. 11. Map showing location of earthquakes within 69 miles (111 km) of Los Alamos. The triangular symbols are locations of maximum reported intensity for earthquakes occurring prior to 1962. The square symbols are instrumentally determined epicenters for earthquakes occurring after 1962 (from Sanford⁴²).

Fig. 12. Tectonic flux (earthquake energy) map of western United States (modified from Ryall et al.⁴⁰).

TABLE II

COMPARISON OF THE RELATIVE DEGREES OF
SEISMIC ACTIVITY FOR NEVADA AND NEW MEXICO^a

	Nevada	New Mexico
Area of state (in square miles)	109,889	121,445
Highest magnitude earthquake	7.6	6.0
Number of earthquakes above 7 magnitude	4	0
Number of earthquakes from 6.0 to 6.9 magnitude	16	4
Period covered by catalog	1852-1961	1855-1971
Modified Mercalli (M.M.) Intensity IX (or greater)	8	0
M.M. Intensity VIII	8	4
M.M. Intensity VII	34	4
M.M. Intensity VII-IX	50	8
Number of M.M. VII-IX per unit area	75	8

^aThe Nevada data are from Slemmons et al.⁴⁶ The New Mexico data are from Table I.

interval of historic observation. Geologically youthful fault scarps in widely scattered localities in the Rio Grande depression (Dames and Moore¹⁰) suggest that although, through geologic time, earthquakes of Richter magnitudes of 7 or 7.5 are possible but infrequent, the recurrence intervals are very long; and the lack of earthquakes of over 6 magnitude reflects the shortness of the historic period of observation.

C. Evaluation of Seismicity by Geological Methods

The less-rugged topography of New Mexico relative to the Basin and Range province is a strong indication of the lower rates of tectonic activity in the Rio Grande rift valley. A comparison of several profiles along typical Basin and Range ridge lines and valley profiles, to obtain typical hypsometric differences, shows that hypsometric profiles on either side of the singular tensionally faulted zone in New Mexico, the Rio Grande depression, shows a hypsometric relief that is only about one-half that of the Basin and Range region of the western United States. Since there are about 20 closely spaced zones of up-faulted mountain blocks and intervening down-faulted valley blocks, the regional seismicity of Nevada and of the Basin and Range province should be about an order of magnitude greater in energy

Fig. 13. Historic surface faulting in western United States.

release, or of rate of activity on major faults, than that for New Mexico. This conclusion is well supported by the evidence from historic surface faulting in the western United States, which shows that the main belts of activity are well to the west of the Rio Grande depression (Fig. 13). Many active fault zones in California-Nevada have faults that show geomorphic evidence of active faulting that can be measured in terms of hundreds if not thousands of feet of displacement in about 10,000 years. Some ranges of values are as follows.

Fault Zone	Class of Activity	Rate of Deformation (cm per year)
<u>Strike-slip fault zones</u>		
San Andreas fault zone, California	high	1 to 8.5
Denali Fault zone, Alaska	high	0.5 to 2
Bocono fault zone, Venezuela	moderate	—
<u>Normal fault zones</u>		
Donnelly Dome fault zone, Alaska	low	0.026 to 0.06
Lost Cannon Peak fault zone, California	low	0.01
Faults in Bishop Tuff, California	moderate	0.22 to 0.44
Lone Pine alluvial fan, California	high	0.03

<u>Fault Zone (Cont.)</u>	<u>Class of Activity</u>	<u>Rate of Deformation (cm per year)</u>
<u>Faults in the Jemez Mountains Area, New Mexico</u>		
Pajarito fault zone	low	0.008
Jemez Springs fault	low	0.003
Virgin Canyon fault	low	0.0014 to 0.0021

V. CONCLUSIONS

Study of active faults and earthquakes in a variety of tectonic settings in the western United States, in combination with both local and regional studies of the Los Alamos Scientific Laboratory's geothermal test site in the Jemez Plateau, lead to the following conclusions.

1. By combining new methods and technology of studying faults it is possible to recognize, define, and delineate active faults, and to develop guidelines for evaluating geothermal sites for earthquake hazards and the potential for active surface faulting at a given site.

2. Guidelines are proposed for studying geothermal sites that are in regions susceptible to surface faulting or may be affected by future large local earthquakes.

3. The specific geothermal site area on the western flank of the Jemez Mountains was evaluated by the approach recommended in this study, with a combination of new methods of low-sun-angle aerial photography and photogeological interpretation, review of earthquake history, and knowledge of the tectonic setting of the test site. This study showed the site itself to be relatively free of active faults; that dated units of 1.1-million-year age show large areas free from significant displacements on faults; and that regional seismicity is at a low level of activity.

4. The nearest fault to the GT-2 geothermal test site, selected on the basis of preliminary results of this study in combination with other studies, is several kilometers from the nearest active faults -- the Virgin Canyon fault, the Jemez Springs fault, the Rio Cebolla fault and the Calaveras zone (a possible fault zone). These zones trend away from the GT-2 site and are sufficiently distant to have little or no chance of activity that could be affected by operations at the test site.

5. None of the faults in the Jemez Plateau-Los Alamos region have physiographic evidence of displacing late Quaternary deposits. Several, including the three fault zones nearest the GT-2 test site, demonstrate lack of offsets of geologically young deposits. The Jemez Springs fault does not displace the Battleship Rock Member with an age of about 0.1 million years.

6. The general level of activity of the most active fault zones of the region is less than that of the San Andreas fault system, or those of major fault zones of the Basin and Range province of the western United States, by up to several orders of magnitude.

7. With the very deep water table and the lack of local active surface faults at the site, the hazard that the experiment will be disturbed by future surface faulting or by large local earthquakes is very slight.

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APPENDIX A

GEOMORPHOLOGICAL FEATURES ASSOCIATED WITH ACTIVE FAULTS

FAULT SCARPS. Fault scarps are lines of cliffs or steeper than normal slopes that are formed by various combinations of vertical to horizontal displacements of the earth's surface due to faulting. Scarps may vary in height from a fraction of a foot to many thousands of feet. Not all fault scarps are associated with active faults, but generally active faults are marked by segments with fault scarps.

FAULT PATH. Term proposed by Malcolm M. Clark to describe the appearance of recent fault traces in alluvium or soil where there is a zone along the fault that resembles a footpath, but without vertical offsets. The paths may represent differences in grain size or soil texture that lead to a more sparse development of vegetation.

FAULT SCARPLETS. Fault scarps in alluvium may be low in height, and widely distributed in complex systems. Such scarps may be well away from mountain fronts and may develop on piedmont alluvial slopes or basin floors.

FAULT RIFTS. A fault rift (such as the San Andreas rift zone) comprises a linear belt of peculiar topographic features which normally cuts obliquely across the topographic grain of the country and is best appreciated as seen from the air.

FAULT TROUGHS. In size and character fault troughs resemble narrow fault valleys but differ therefrom in not being limited to a single drainage system. Troughs can cross divides or ridges and may include several fault valleys. Fault troughs constitute major features within rift zones.

FAULT-LINE GAPS. Fault-line gaps resemble fault gaps but are formed solely by erosion of resistant ridge-making units laterally offset by earlier faulting.

FAULT-LINE SADDLES. Fault-line saddles are created by more rapid erosion of ridge crests where crossed by faults.

FAULT-TRACE GRABEN. Called gravity graben or subsidence graben by Slemmons (1957). Generally developed by surface extension on normal faults having moderate angles of dip.

CLOSED DEPRESSIONS. Depressions with closure are common, and in many instances a distinctive product of recent faulting. If small and containing water, they are known as sag ponds; otherwise they may be termed fault-sags.

FAULT VALLEYS. Faulting creates linear depressions of various sizes and characteristics. The largest fault valleys in southern California are grabens, of which Owens Valley is certainly an outstanding example.

SIDEHILL RIDGE. (Called KERNBUTTS and KERNCOLS by Sharp, 1954. This term is used by Iacopi, 1964.) These forms were originally defined by Lawson (1904, pp. 331-343) as primary features created by displacement on a fault traversing a hill slope in such a manner that a projecting ridge or buttress, the kernbutt, and an intervening depression or fosse, the kerncol, are formed. The type locality has since been shown to be one of fault-line forms (caused by erosion rather than primary faulting).

FAULT-SLICE RIDGES. These are narrow linear ridges a few feet to a few hundred feet high representing slices of rock squeezed up within a fault zone.

SHUTTERRIDGES. Shutterridges are formed by vertical, lateral, or oblique displacements on faults traversing a ridge-and-canyon topography. The displaced part of a ridge shuts off the adjacent canyon, hence the term.

OFFSET STREAMS. Offset stream channels are a common companion of shutterridges along strike-slip faults, and in places lateral displacements of as much as 1.5 miles (2.4 km) are thus recorded. Offsets of this magnitude must have been produced by repeated small shifts, with the stream reestablishing the continuity of its course during the intervening periods.

TRIANGULAR FACETS. Triangular facets, truncated spurs, and related forms are remnants of a fault scarp dissected by transverse streams.

EN ECHELON FAULTS. A series of parallel or subparallel faults arranged in a pattern such that where one fault ends another begins in a laterally offset position. These faults are generally indicative of a strike-slip component of displacement.

RAMPS. Type of en echelon fault, where there is a combination of sub-equal amounts of strike-slip and vertical-slip components.

DRAINAGE REJUVENATION. Dissection resulting from fault displacement is a secondary product which cannot always be satisfactorily interpreted because of its possible polygenetic origin.

DEPOSITIONAL FORMS. Deposition creates a host of secondary topographic features along fault scarps and to a lesser extent along fault-line scarps. Alluvial cones, fans, and aprons along the bases of fault scarps are common in the Basin and Range province

and attain spectacular development in the desert country, particularly in Owens, Panamint, and Death Valleys. Depositional forms are not usually diagnostic of primary fault features or erosional fault-line features.

APPENDIX B

DEFINITIONS OF ACTIVE FAULTS

WOOD (1915). "Active faults are all faults on which there has been a movement within historic times and also all faults with physiographic evidence of recent surface dislocation."

WILLIS (1923). "It will be seen that two classes of faults are distinguished: Active and Dead... An active fault is one on which a slip is likely to occur. A dead fault is one on which no movement may be expected."

"An active fault is also recognized by minor features of the landscape, 'trace' phenomena, the accidents of its activity, provided the last movement be not too long past."

LOUDERBACK (1950). "Faults are often classified as active or dead faults. Those are considered active which are undergoing movement now or have undergone movements in recent geologic or in historic time and are considered liable to recurrent movements in the future. Dead faults are those which were active in some earlier period of diastrophism but show no sign of having been active in more recent geologic time... Criteria that have been used for arriving at a judgement that a fault is active are geological, historical, and seismological."

ALLEN, ET AL. (1965). "In the absence of strain-accumulation data or historic records of major earthquakes along a given fault, the only satisfactory criterion for activity lies in geological evidence that displacements have taken place along the fault in the recent geologic past.

"Faults that have had sufficiently recent movement to displace the ground surface are usually considered active by geologists simply because the ground surface is a very young and ephemeral feature."

"...if stream offsets and scarps in alluvium are to be used as criteria for activity of faults, then

the term 'active' must apply to events dating well back into the Pleistocene epoch, perhaps as much as 100,000 years."

ALBEE AND SMITH (1966). "...the use of the term 'active fault'...reveals that most geologists use the term 'active fault' in the sense expressed in Webster's (dictionary) definition that active means 'in action, moving.' Although various workers have used various types of criteria for recognizing action, the length of time since last displacement has been considered to be an essential criterion. Whatever the criteria, the use of the term implies a judgement on the part of the geologist that the fault is in action and that it will eventually break again.

"Activity is not just a single state, but varies over a broad spectrum of degrees of activity. For example, some faults are exceedingly 'active.' Use of the term 'active fault' without qualification rings of greater authority than is usually possible in most cases regarding faults and engineering works."

BONILLA (1969). "An active fault can be defined as one that has moved in the recent past and may move in the near future. The 'recent past' as used here includes the current hour and extends back an indefinite time that many geologists would take to include at least the Holocene Epoch (about 10,000 years). The 'near future' as used above includes a length of time on the order of the useful life of engineering structures or the time span considered in long-range plans for the future. The determination of whether a fault is 'active,' as defined above involves geology, geophysics, geodesy, and engineering. Some criteria currently in use are (1) the occurrence of earthquakes that can be related to the fault with reasonable assurance; (2) one or more episodes of surface ruptures (including tectonic creep) or acute

bending in the recent past as defined above; (3) instrumental evidence of elastic and inelastic strain; and (4) structural coupling to another fault (or other tectonic feature such as a monocline) that is active. At present, some active faults may not be identifiable, but the ability to identify them should improve with time."

CLUFF AND BOLT (1969). "Active faults usually are associated with one or more of the following: a historic record of faulting, the occurrence of earthquakes along their courses, evidence of geologically recent movement (the last few thousand years), and slow fault slippage. A fault should be considered active if it has displaced recent alluvium or other recently formed deposits, whose surface effects have not been modified to an appreciable extent by erosion, which has earthquakes located in the near vicinity and whose recurrence of movement is expected,"

WENTWORTH ET AL. (1970). "A fault is active if because of its present tectonic setting, it can undergo movement from time to time in the immediate geologic future. This active state exists independently of the geologist's ability to recognize it."

"...selection of the criteria used to identify active faults for a particular purpose must be influenced by the consequences of fault movement on the engineering structures involved."

ATOMIC ENERGY COMMISSION - PROPOSED AMENDMENT TO 10 CFR PART 100 APPENDIX A (1971). "An 'active fault' is a fault which has exhibited one or more of the following characteristics:

"(1) Movement at or near the ground surface at least once in the 35,000 years or more than once in the past 500,000 years. In the absence of data permitting absolute dating, faults with sufficiently recent movement to leave perceptible evidence of surface faulting, surface warping, or offset of geomorphic features are considered active faults.

"(2) Instrumental well-determined macro-seismicity for a fault located in the continental United States west of the Rocky Mountain Front, or in Alaska, Hawaii, or Puerto Rico.

"(3) A relationship to an active fault according to characteristics (1) or (2) such that movement on one could be reasonably expected to be accompanied by movement on the other."

WESSON (1972). "Faults with a potential for generating damaging earthquakes have been identified by the following criteria - ordered by decreasing certainty of current activity; 1) historic and/or current seismicity or ground breakage, 2) physiographic fault-like features and disturbances in Holocene sedimentary deposits which indicate displacement in the last ten-thousand years, 3) structural geologic evidence for displacement in Quaternary time (last three million years) and 4) geophysical anomalies suggesting displacements in buried bedrock coincident with anomalous distribution of surficial deposits."

ZIONY, ET AL. (1973). "The age of the most recent displacement of faults is commonly the best available criterion for estimating activity of faults in a region because data on recurrence intervals, seismicity, or strain accumulation are not uniformly available."

"Faults of a region can be ranked according to likelihood of future movement on the assumption that those with the most recent displacements probably have relatively short recurrence intervals. Selection of those faults considered to be active and thus requiring more detailed site investigations, must be influenced by the consequences of possible displacement on the engineering works involved. For example, all faults in the region with proved or likely movement during late Quaternary time (past 500,000 years) may be considered active for purposes of siting nuclear power reactors and other structures that require large safety factors, whereas many such faults might not be considered active for less critical land uses."

SHERARD, ET AL. (1974). "An active fault (or a potentially active fault) is defined as one on which there is sufficient evidence of displacement within the recent geologic past to make it reasonable to anticipate that future surface displacements could occur within the lifetime of a dam--about 100 years. It must be emphasized, however, that this definition implies the exercise of judgement by geologists, and that there will be honest differences of opinion among competent geologists specializing in this field as to the likelihood of displacements on a given fault."

APPENDIX C

MAJOR STRATIGRAPHIC AND TIME DIVISIONS

Subdivisions In Use By The U. S. Geological Survey			Age Estimates Commonly Used For Boundaries (In Million Years)	
Era Or Erathem	System Or Period	Series Or Epoch	(a)	(b)
Cenozoic	Quaternary	Holocene		
		Pleistocene	1.5-2	1.8
	Tertiary	Pliocene	ca. 7	5.0
		Miocene	26	22.5
		Oligocene	37-38	37.5
		Eocene	53-54	53.5
		Paleocene	65	65
Mesozoic	Cretaceous	Upper (Late)		
		Lower (Early)	136	
	Jurassic	Upper (Late)		
		Middle (Middle)		
	Triassic	Lower (Early)	190-195	
		Upper (Late)		
Paleozoic	Permian	Middle (Middle)		
		Lower (Early)	225	
	Pennsylvanian	Upper (Late)	280	
		Middle (Middle)		
		Lower (Early)	320	
	Mississippian	Upper (Late)		
		Lower (Early)	345	
	Devonian	Upper (Late)		
		Middle (Middle)		
		Lower (Early)	395	
	Silurian	Upper (Late)		
		Middle (Middle)		
Lower (Early)		430-440		
Ordovician	Upper (Late)			
	Middle (Middle)			
	Lower (Early)	ca. 500		
Cambrian	Upper (Late)			
	Middle (Middle)			
	Lower (Early)	570		
Precambrian	Time Subdivisions Of The Precambrian			
	Precambrian Z--base of Cambrian to 800 m.y.			
	Precambrian Y--800 m.y. to 1600 m.y.			
	Precambrian X--1600 m.y. to 2500 m.y.			
	Precambrian W--older than 2500 m.y.			

^aGeol. Soc. London, "The Phanerozoic Time-Scale, A Symposium," Geol. Soc. London, Quart. Journ. 120, Suppl., 260-262 (1964).

^bW. A. Berggren, "A Cenozoic Time Scale -- Some Implications for Regional Geology and Paleobiogeography," Lethaia 5 No. 2, 195-215 (1972).