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Seismicity of the Los Alamos Area Based on Geologic Data

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SEISMICITY OF THE LOS ALAMOS AREA

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ABSTRACT

The seismicity of the Los Alamos area was determined by geologic data from four major faults that offset the Bandelier Tuff. The Bandelier Tuff was deposited as an ashflow about 1.1 million yr ago. From geologic data, fault length, displacement, and age of the Bandelier Tuff, it was concluded that the Los Alamos area may experience one shock of a maximum magnitude 5 during a period of 100 yr.

I. INTRODUCTION

This study was undertaken in order to evaluate the effect of faulting in the vicinity of Los Alamos, New Mexico, and to derive from the faults an estimate of the seismicity of the area. A knowledge of the length and maximum displacement allows an estimate of the maximum magnitude of earthquakes that could have been generated along these faults. From the geological history, it is possible to make an estimate of the periodicity of fault movement, and thus of the seismicity of the area. The study was requested and supported by Environmental Studies Group (H-8) of the Los Alamos Scientific Laboratory, and was completed on January 1, 1973. For a similar study of the seismicity of the Los Alamos region based on seismological data, see Los Alamos Scientific Laboratory report LA-6416-MS by Allan R. Sanford.

Information for this study was obtained from a number of sources:

1. Existing geologic maps and reports, particularly references by Kelley,[1] Ross et al.,[2] Bogart,[3] Griggs,[4] Bailey et al.,[5] and Smith et al.[6]

2. Aerial photographs of the Los Alamos region, consisting of black and white photographs and color infrared photographs. One set of black and white photographs, taken in November 1969, shows snow cover on north facing slopes and is of poor quality, particularly along the edges of the photographs. Due to differences in ground elevation, the scale of these photographs varies from place to place, but at a ground elevation of 1700 m the scale is approximately 1:30 000.

Two sets of photographs were taken at low sun angle, one early in the morning, and one late in the afternoon. The advantage of low sun angle photographs is the enhanced possibility of recognizing fault scarps, particularly those which have a northerly trend. An additional set of photographs was produced during the summer of 1972 in color infrared. On these photographs, different wavelengths on the infrared portion of the electromagnetic spectrum show in different colors. The scale of these photographs is approximately 1:23 000.

3. A number of faults, recognized on the aerial photographs, were inspected in the field. During the field work, it became apparent that some fractures which had been identified as faults on the photographs were fractures without appreciable offset and, therefore, should be classified as joints. The field work also established the recurrent nature of many faults. Estimates of displacement along individual faults were measured in the field and entered on the tectonic map (Fig. 1).

Most faults in the Los Alamos area have steep dips and will intersect the surface in the form of a straight or nearly straight line. Therefore, all more or less straight features on the aerial photographs may represent faults. Such straight, linear features are often referred to as "lineaments."

One of the advantages of the use of aerial photographs in structural studies is that high-angle faults can be readily recognized. Many lineaments that are inconspicuous from the ground can be seen on aerial photographs. However, all linear features on aerial photographs were carefully examined and field checked, as all lineaments do not represent faults.

Lineaments in the Los Alamos area are expressed by alignments of vegetation, straight segments of stream courses, alignments of topographic features, rectilinear depressions, displacement of uniformly sloping surfaces, or a combination of these features.[7] It was necessary to examine all lineaments on the aerial photographs to find supporting evidence for faults as interpreted on existing geologic maps.

II. GEOLOGY

Exposed rocks in the Los Alamos area under consideration are all of Cenozoic age, and include volcanic rocks and clastic sediments of great diversity. Rocks of pre-Bandelier age are the Puye Formation, basalts of Cerros del Rio, and the Tschicoma Formation. The Bandelier Tuff, made up of the lower Otowi member and the upper Tshirege member, is most extensive in the vicinity of Los Alamos. Rocks younger than the Bandelier Tuff are mainly restricted in occurrence to the Jemez caldera.

Rocks of the Santa Fe Group include in ascending order the Tesuque Formation, the Tschicoma Formation, and the Puye Formation. Rocks of the Tesuque Formation are composed of well-cemented siltstones and sandstones and are found in the valley of the Rio Grande. The Tschicoma Formation underlies the Bandelier Tuff over a large area, and represents the older volcanic rocks of latitic and andesitic composition of the Jemez Mountains volcanic field. Farther east, the Tschicoma Formation thins rapidly and interfingers with the Puye Formation. This unit, which underlies the Bandelier Tuff in the lower reaches of Guaje Canyon, is in part derived from the rocks of the Tschicoma Formation. A lower unit of the Puye Formation carries abundant fragments of quartzite and granite whereas boulders of latitic composition predominate in the upper part of the unit.

A Pleistocene sequence of rhyolite ash flows and ash falls, named the Bandelier Tuff, is most extensive in the vicinity of Los Alamos. The Bandelier Tuff is usually subdivided into two members.[5] The lower, or Otowi Member, has been dated as 1.4 million yr old.[8] It contains abundant lithic fragments, which are much less numerous in the upper or Tshirege Member. The lowermost ash fall unit of the Tshirege Member

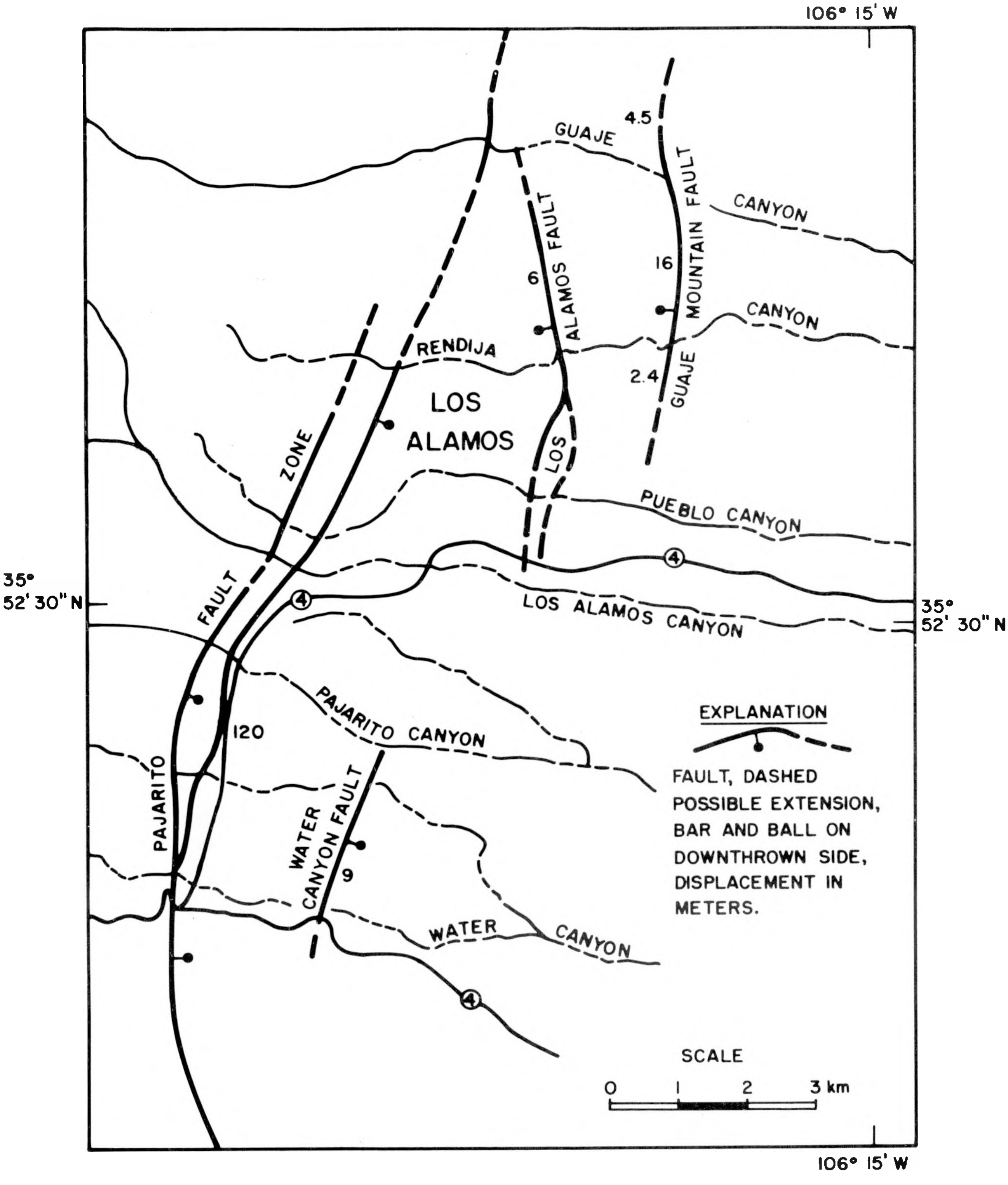

Fig. 1. Tectonic map of the vicinity of Los Alamos showing distribution and extent of normal faults.

has been dated radiometrically as 1.1 million yr old.[8] The Otowi Member had its source in the more northerly Valle Toldeo, whereas the Tshirege Member was derived from the Valles Caldera in the Jemez Mountains west of the Los Alamos area.[2] Los Alamos is located on the Pajarito Plateau which forms an apron around the eastern flanks of the Jemez Mountains. The Jemez Mountains are a marginal feature of the Rio Grande rift zone which extends from central Colorado to near El Paso, Texas. The rift is a zone of coalescing structural basins of different width, length, and structural orientation. The Pajarito Plateau is a part of the Espanola structural basin which extends from the Embudo channel northeast of the town of Espanola in a south-southwest direction to the vicinity of Santa Domingo where the rift zone widens into the Albuquerque-Belen basin. The western marginal uplifts of the Espanola basin are the Nacimiento-San Pedro Mountains; the eastern margin is formed by the Sangre de Cristo uplift. The formation of the Rio Grande rift zone and accompanying uplifts started in the Middle Miocene (about 20 million yr ago) and therefore predates the volcanism of the Jemez Mountains.

basin is well-defined and consists of a number of steep, en echelon, north trending faults, near the longitude of Santa Fe.[9] The western boundary of the structural basin is largely obscured by the volcanic sequence of the Jemez Mountains. The margin of the basin is well displayed 6 km west of Abiquiu along the Chama River, where the Abiquiu Tuff of the Santa Fe Group of the basin is in fault contact with Mesozoic rocks of the adjoining uplift. The fault zone disappears to the south under Pliocene and younger volcanic rocks, which do not show visible offsets. Southwest of the Jemez Mountains, the Jemez fault is a possible continuation of the western margin of the Rio Grande rift. The faulting west of Abiquiu and the Jemez fault may represent a continuous marginal zone of weakness along the west edge of the rift, which has been partly covered by the late Pliocene and Pleistocene volcanic rocks of the Jemez sequence. The extension of this fault border beneath the volcanics appears to pass very close to the centers of volcanic activity, the Toledo and Valles Calderas, and it is therefore possible that the volcanism utilized this zone of weakness as a channel way for the magma to reach the surface.

III. MAJOR FAULTS AND THEIR CHARACTERISTICS

The extent and characteristics of faults were studied in the area between 35°45' and 36° N lat, and between 106° and 106°30' W longitude. Faulting in this area involved displacement of members of the Bandelier Tuff in the western part of the area, and units of the Santa Fe Group in the east.

The major fault is the Pajarito fault which extends in a northerly direction west of Los Alamos. Its displacement, based on elevation differences of units of the Bandelier Tuff, is 120 m with the east side downthrown (Fig. 1).

A second fault extends north from Los Alamos (Los Alamos fault). South of Pueblo Canyon, the structure shows as a lineament on the aerial photographs but field inspection shows little evidence for faulting in the Bandelier Tuff. Along the S wall of Pueblo Canyon, members of the Bandelier Tuff form a monoclinal flexure with the steeper part of the structure dipping to the W. Across the canyon, on the north wall, faulting is evident in the tuff with a maximum displacement of 13 m down to the west. This displacement is distributed among a number of parallel, nearly vertical fault slices.

One km north of Rendija Canyon the displacement of the fault is only 6 m (Fig. 1). The vertical displacement increases to about 18 m in an additional kilometer and then decreases. In the north wall of Gauje Canyon, the fault does not appear to offset units of the Bandelier Tuff and dies out at this point.

The Guaje Mountain fault parallels the Los Alamos fault to the east at a distance of from 2 to 2.5 km. This fault also has its downthrown side to the west. Guaje Mountain which lies east of the fault is made up of densely welded latite of the Tschicoma Formation and rises 45 to 60 m above the surrounding Bandelier Tuff. Although these relationships would seem to indicate a considerable throw on the Guaje Mountain fault, displacement of Bandelier Tuff units in the north wall of Guaje Canyon amount to only about 4.5 m (Fig. 1).

A fault paralleling the Pajarito fault to the east at a distance of about 2 km is here referred to as the Water Canyon fault.[10] The fault has a maximum vertical displacement of about 9 km (Fig. 11). The fault is downthrown to the east along the north wall of Water Canyon.

The observations on the four major faults in the vicinity of Los Alamos can be summarized as follows.

1. All faults are generally north trending with a downthrown side either to the east or west.

2. The angle of dip of the faults is very steep to vertical. Displacements are essentially vertical and as a result the faults can be easily identified on aerial photographs.

3. The amount of vertical displacement or throw may change markedly along the trace of the faults. Values of displacement obtained on older units (pre-Bandelier Tuff) exceed throws measured on Bandelier Tuff or those derived from offset of geomorphic surfaces.

The above information indicates that faulting in the Los Alamos area in many cases predates the deposition of the Bandelier Tuff. The ash falls and ash flows of the Bandelier Tuff were deposited on an uneven surface of rocks of the Tschicoma Foundation. The topographic highs on this surface may have been the result of fault movements or may be due to differential erosion of the latite prior to Bandelier time. Eruption of the Bandelier Tuff buried the uneven surface, but differential compaction of the tuff above and adjacent to the topographic highs resulted in the development of monoclinal flexures in the tuff blanket, and possibly contributed to faulting. Evidence for this process may be observed along the Los Alamos fault in Pueblo Canyon and along the Guaje Mountain fault west of Guaje Mountain.

IV. SEISMICITY BASED ON GEOLOGIC DATA

The four major faults in the vicinity of Los Alamos have been listed in Table I. Their lengths vary from 4.6 to 12 km and their maximum displacements (stratigraphic throw) range from 6 to 120 m. The observed data of length and displacement can be used

TABLE I

PARAMETERS OF FAULTS

IN THE VICINITY OF LOS ALAMOS

Name of Fault	L in Centimeters	D in Centimeters	N	M_L
Pajarito fault	1.2×10^6	1.2×10^4	100	6.8
Los Alamos fault	8.4×10^5	6.0×10^2	7	6.6
Guaje Mountain fault	6.4×10^5	1.6×10^3	25	6.5
Water Canyon fault	2.4×10^5	9.0×10^2	38	5.9

L and D are, respectively, total length of the fault trace and total displacement of the fault in centimeters. N is the number of seismic events of local magnitude M_L that have taken place along each fault.

to calculate the maximum magnitude of earthquakes that may have occurred along the faults in the manner outlined by Sanford et al.[7]

From the study of lengths and displacements of fault scarps associated with historic earthquakes, it has been determined that the average ratio of displacement (D) to length (L) of a single seismic event is of the order of 10^{-4}.[11] Inasmuch as the faults in the Los Alamos area have D:L ratios larger than 10^{-4}, it is necessary to assume that maximum displacement is due to the cumulative effect of several earthquakes originating along the same fault plane. The number (N) of seismic events of maximum magnitude that can occur along each fault has been calculated (Table I).

The following expression has been used to calculate magnitude of earthquakes originating along each fault.

$$M_L = 0.45 \log_{10} LD^2 + 2.23. \qquad (1)$$

This is an empirical formula where L and D are, respectively, length and displacement of the fault expressed in centimeters; M_L is the local magnitude of the earthquake.[12] Calculated magnitudes vary from 5.9 to 6.8 (Table I). A total of 132 seismic events of average magnitude 6.7 may have occurred along the three faults which according to their length and displacement are able to produce shocks of magnitude 6 or larger. As displacement was measured on members of the Bandelier Tuff, the faulting must be younger than Bandelier time or younger than 1.1 million yr. A total of 132 earthquakes of magnitude 6.7 may thus have taken place along the three faults during the last 1.1 million yr.

The seismicity of the Los Alamos area can thus be expressed as one magnitude 6.7 earthquake occurring on an average of 1 100 000:132 = 8 333 yr.

In many seismically active regions of the world, a systematic relation exists between the number of shocks and their magnitudes. The number of shocks of a particular magnitude is about 8 to 10 times larger than the number of shocks of one higher magnitude.[13] This relationship may be formalized as

$$\log_{10} \Sigma N = a - b M_L \qquad (2)$$

in which N is the number of shocks of magnitude M_L or greater. In many seismic areas of the world, b is close to 1.0, and it will be assumed that this value also holds for the Los Alamos area. In a structurally similar region near Socorro, Sanford and Singh found b = 1.0 from microearthquake data collected over a 30-month period.[14]

The significance of a in the above formula can be understood by the following argument. Suppose that over a period of 10 yrs a region experiences one maximum magnitude shock of magnitude 5. For this 10-yr period N = 1, and M_L = 5, or

$$\log_{10} 1 = o = a - 5, \text{ or } a = 5 \qquad (3)$$

again assuming that b = 1. The physical significance of a is therefore the single maximum shock that may occur in the area in the period of time considered, here taken as 10 yr.

Now consider a 100-yr period in the same area during which 10 shocks of magnitude 5 will occur. Over this longer period, N = 10 and

$$\log_{10} 10 = 1 = a - 5, \text{ or } a = 6. \qquad (4)$$

Over the 100-yr period we may expect one magnitude 6 shock to occur. Therefore, an increase in magnitude by 1 (= $\log_{10} 10$) will decrease the number of shocks by a factor of 10. Still considering the same example, a shock of magnitude 7 may occur once every 1 000 yr.

In the Los Alamos area we had established that one magnitude 6.7 shock may occur once in 8 333 yr, or a = 6.7, and

$$\log_{10} \Sigma N = 6.7 - M_L . \qquad (5)$$

In order to relate this to a 100-yr period, we must add to a = 6.7 the $\log_{10} \frac{100}{8\ 333}$ = -1.9 and the expression becomes

$$\log_{10} \Sigma N = 4.8 - M_L . \qquad (6)$$

Thus, in a 100-yr period, the maximum magnitude shock (N = 1) that may be expected to take place, has a magnitude of 4.8.

In this calculation it has been assumed that fault movement occurs only during seismic activity or that creep along the fault has been of negligible importance.

Former studies of the seismicity of New Mexico have shown that earthquakes with magnitudes larger than 5.5 are relatively rare events in New Mexico.[7] The seismicity of the Los Alamos region, here estimated to be one magnitude 5 earthquake per 100 yr, compares with an estimated maximum magnitude shock of 6 during the same time interval in the Albuquerque-Socorro section of the Rio Grande rift zone.

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