A Review of Historic and Instrumental Earthquake Activity and Studies of Seismic Hazards near Los Alamos, New Mexico
Cover Map: Major faults in the Jemez Mountains region.
A Review of Historic and Instrumental Earthquake Activity and Studies of Seismic Hazards near Los Alamos, New Mexico

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A REVIEW OF HISTORIC AND INSTRUMENTAL EARTHQUAKE ACTIVITY AND STUDIES OF SEISMIC HAZARDS NEAR LOS ALAMOS, NEW MEXICO

by

Leigh S. House and Daniel J. Cash

ABSTRACT

Los Alamos National Laboratory is situated within an active tectonic feature, the Rio Grande rift. Numerous small to moderate magnitude earthquakes have occurred in the Los Alamos area within the past 100 years. The largest was the Cerrillos earthquake of 1918, for which felt reports imply a magnitude of 5 to 6. Several earthquakes of magnitude 3 to 4 have been felt in Los Alamos since the early 1950s. Instrumental information about earthquakes in northern New Mexico has been available for about the past 14 years from the Los Alamos Seismograph Network. An estimate of future earthquake activity extrapolated from seismicity recorded by the network suggests an earthquake of magnitude 4.5 to 5 could occur within 110 km (about 70 miles) of Los Alamos once per 100 years. Recent geologic and seismologic studies from other areas of the United States demonstrate such extrapolations may not be reliable, since earthquakes have occurred that are as much as one to two magnitude units larger than those extrapolated. Additional studies, particularly geologic, are needed to better estimate the magnitude of the largest earthquakes that have affected the Los Alamos area and their recurrence intervals.

Several studies of seismic hazards and seismic risk have been done for the Los Alamos area. The most comprehensive one was completed in 1972 and was intended for design engineering for the TA-55 Plutonium Facility. This study concluded that a peak horizontal acceleration of 0.33 g was appropriate for design of facilities at TA-55 since it was "unlikely to be exceeded." Progress in several areas of earthquake studies in the past 15 years has provided an improved understanding of earthquake occurrence and recurrence, as well as an improved ability to estimate ground response resulting from possible local earthquakes. Because the results of the 1972 study are still being used for seismic design of new facilities at Los Alamos, the seismic hazards and risks for Los Alamos should be reevaluated in order to confirm that the 1972 results are still meaningful and valid. Such a reevaluation is, however, beyond the scope of this report.
INTRODUCTION

Los Alamos National Laboratory is situated near the western edge of the Rio Grande rift, a tectonic feature that extends from southern Colorado through New Mexico into Mexico and has been active for about the past 30 million years (Chapin, 1979). Extension across the rift in the Los Alamos area has been estimated to have occurred at an average (half) rate of 0.1 mm per year for the past 30 million years (Cordell, 1982). Such a rate is fairly small compared with typical sea-floor spreading rates of a few centimeters per year (Minster and Jordan, 1978). Nevertheless, highly damaging earthquakes, such as the 1886 Charleston (South Carolina) earthquake, have occurred in areas of the U.S. in which no simple tectonic cause (such as rifting) can yet be identified (Nuttli et al., 1986). Thus, the earthquake-generating potential of the extension across the Rio Grande rift should not be dismissed simply on the basis of apparently low rates of tectonic displacements. Further, from simple arguments, extension across the rift at a rate of 0.1 mm/year could produce an earthquake of magnitude about 6 every 100 years in the Los Alamos area. Moderate-size earthquakes in the Los Alamos area resulting from volcanic and/or magmatic processes would increase the seismic hazards of the area.

The Los Alamos area has experienced a number of small to moderate earthquakes since the town was established about 45 years ago, four of which were large enough to be felt. The causes of these earthquakes are not known, but presumably earthquake activity results from processes related to extension across the rift, although some may result from volcanic and/or magmatic processes related to the nearby Jemez volcanic field. In historic times, the largest earthquake experienced in the Los Alamos area was the Cerrillos earthquake of 1918 with a magnitude of 5 to 6 and an epicenter believed to have been about 45 km SE of Los Alamos (Sanford, 1976; Olsen, 1979). Elsewhere within the Rio Grande rift, the Socorro area, which is about 200 km south of Los Alamos, has a higher level of current seismicity, and it experienced a swarm of moderate-size earthquakes during 1906 and 1907 that included three as large as magnitude 5 to 6 (Sanford et al., 1979).

It is currently believed earthquakes larger than magnitude 6 may occur in the Los Alamos area, but the time intervals between such occurrences (termed recurrence intervals) may be as long as several 1000 years (Budding and
Purtymun, 1976; see also Machette, 1986). The geologic and seismologic information presently available is not adequate to estimate reliably the sizes or recurrence intervals of the largest earthquakes that may affect the Los Alamos area in the next few decades.

In this report we summarize the information that bears on the evaluation of seismic hazards to the Los Alamos area. First we discuss the available seismologic information, which includes both instrumental data about earthquakes in north-central New Mexico (available for about the past 25 years) and historic information describing earthquakes in north-central New Mexico over about the past 100 years. The seismologic information often used to estimate seismic hazards for Los Alamos is the instrumental information obtained from the Los Alamos Seismograph Network, which has operated since 1973. We describe the information provided by the network and the network's limitations in order to assess the current state of knowledge about seismic hazards to Los Alamos. Next, we summarize the studies that have been done in the Los Alamos area to understand different aspects of the seismic hazards issue. Finally, we critically review the most comprehensive of the seismic hazards studies and identify the areas for which additional studies of some aspects of the seismic hazards issue are particularly important for more reliably assessing the level of seismic hazard that Los Alamos may be exposed to during the next few decades.

This report uses the term "seismic hazards" to refer to the likely sizes, recurrence intervals, and locations of earthquakes that may threaten manmade structures and facilities. We are concerned here mainly with seismologic information related to seismic hazards estimation for the Los Alamos area. The concept of "seismic risk" adds quantitative judgments about the likelihood and amount of damage that may result from earthquakes. Assessing seismic risk is beyond the scope of this report.

We use the term "Los Alamos area" to encompass two different areas around Los Alamos. First, and primarily, we use it to refer to an area of about 6,400 km² that immediately surrounds Los Alamos proper. This is the area located between 35.6° and 36.4° latitude and 105.8° and 106.6° longitude; the community of Los Alamos is located at about 35.9° latitude and 106.3° longitude. Second, we use the term to refer to the larger circular area of about 39,000 km² that extends from Chama, in north-central New Mexico, to just
south of Albuquerque. Sanford (1976) described the earthquake experience in this larger area, which is located within a circle of radius 1° of a great-circle arc from Los Alamos (1° of arc is a distance of 111.1 km). We use "Los Alamos area (111 km)" to refer to the larger area (both areas are indicated on Figure 2).

Because this report uses a number of seismological terms that may not be familiar to all readers, a glossary of the most important terms is included as the Appendix.

HISTORIC AND INSTRUMENTAL EARTHQUAKE INFORMATION

Earthquakes that occurred before the general availability of instrumental (seismograph) data are referred to as "historical" earthquakes. Information about historical earthquakes comes primarily from accounts in newspapers, diaries, and letters, which are referred to as felt reports. Felt reports require careful interpretation because they often describe earthquake effects in imprecise and exaggerated terms. Felt reports from earthquakes in New Mexico are mostly from locations along the course of the Rio Grande River (and hence, within the Rio Grande rift) where most of the State's population has been, and still is, concentrated (Northrop, 1976; 1982).

It is often difficult to reliably determine the epicenters of historical earthquakes; epicenters are usually placed at the location of the greatest earthquake intensity. The magnitudes of such earthquakes are estimated from felt reports, typically using maximum intensity (see Glossary), area within a specific isoseismal, or decrease of intensity with distance. We estimate the magnitudes of historical earthquakes from a relationship between local magnitude, $M_L$ (Richter, 1958), and maximum intensity, $I_o$ (Toppozada, 1975):

$$M_L = 1.85 + 0.49 I_o.$$  

The relationship is imprecise, but it does provide an estimate of the size of a historical earthquake from a sparse set of felt reports, such as are typical from New Mexico earthquakes. Magnitudes estimated from area within isoseismals are more reliable estimates of earthquake size, but require a density of felt reports that is often not obtainable from New Mexico earthquakes.

Instrumental recording of earthquakes in New Mexico began with the installation of a high-magnification seismograph at Albuquerque in 1959. A station of the World-Wide Standard Seismograph Network (WWSSN) was installed in
Albuquerque in 1961. The New Mexico Institute of Mining and Technology installed a seismograph at Socorro in 1962 and has installed and maintained a number of stations in the Socorro area since then.

The Los Alamos Seismograph Network was established by Los Alamos National Laboratory in 1973 to study nuclear test-ban verification, as well as to pursue research on local structure and tectonics and to address the seismic hazards question (Newton et al., 1976). Financial support for network operation has been variable, and it has been difficult to analyze network data beyond the routine process of locating the earthquakes. At one time the Los Alamos Network contained as many as 20 stations located throughout north-central New Mexico. Currently the network contains 10 stations, almost all of which are located in the immediate area of the Laboratory.

Routine analysis of events recorded by the Los Alamos Seismograph Network involves picking arrival times and locating and assigning magnitudes to them. Seismic events that are obviously manmade (i.e., explosions and sonic booms) are not normally analyzed. Earthquake locations are calculated from arrival times at several stations, and magnitudes are determined from the duration of the event, using a relation between magnitude and length of the event "coda" or tail of the waveform (e.g., Newton et al., 1976). Several magnitude scales are currently used by seismologists; magnitudes of events located by the Los Alamos Network are called local magnitudes and designated "ML." Los Alamos National Laboratory has published catalogs containing lists and maps of all earthquakes located in north-central New Mexico by the Los Alamos Network (see list in Wolff et al., 1985). Data have been recorded for nearly 15 years, and more than 2000 earthquakes have been located.

**Historical Earthquakes**

Estimating seismic hazards in Los Alamos requires using historical seismicity information to supplement the relatively short instrumental earthquake record. In particular, two types of historical earthquakes are of interest: those large enough and located close enough to be felt at Los Alamos, and those that are the largest earthquakes known to have occurred in the same tectonic province (Rio Grande rift) as Los Alamos.

The record of earthquakes felt in Los Alamos extends back only about 45 years, since establishment of Los Alamos as a town in the early 1940s. Table I lists felt earthquakes located within 111 km (about 70 miles) of Los Alamos. Felt reports of earthquakes before about 1950 are sparse.
TABLE I. REPORTED EARTHQUAKES IN THE VICINITY\(^1\) OF LOS ALAMOS TO SEPTEMBER 1, 1973
Modified from Newton et al. (1976) and Sanford (1976)

<table>
<thead>
<tr>
<th>Year</th>
<th>Date</th>
<th>Hour of Report (MST)</th>
<th>Locality of Report</th>
<th>Distance from Los Alamos (km)</th>
<th>Maximum Reported Intensity (MM)</th>
<th>Magnitude ((M_L))</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1873</td>
<td>Aug 2</td>
<td>22:00</td>
<td>Santa Fe</td>
<td>40</td>
<td>III(^3)</td>
<td>~3(^4)</td>
<td>Slight shock.</td>
</tr>
<tr>
<td>1893</td>
<td>Jul 12</td>
<td>06:40-06:45</td>
<td>Albuquerque</td>
<td>95</td>
<td>VI(^3)</td>
<td>4</td>
<td>Three shocks.</td>
</tr>
<tr>
<td>1918</td>
<td>May 28</td>
<td>04:30</td>
<td>Cerrillos</td>
<td>55</td>
<td>VIII(^3)</td>
<td>5.5(^6)</td>
<td>Minor damage in Santa Fe, 33 km to the NE.</td>
</tr>
<tr>
<td>1921</td>
<td>Jul 30</td>
<td>22:55</td>
<td>Senorito</td>
<td>55</td>
<td>IV(^3)</td>
<td>3.5(^6)</td>
<td>Very brief shock that shook houses and rattled dishes.</td>
</tr>
<tr>
<td>1930</td>
<td>Mar 23</td>
<td>12:00</td>
<td>Albuquerque</td>
<td>95</td>
<td>IV</td>
<td>3.5</td>
<td>Two distinct shocks. Cracked plaster and broke dishes. Felt area about 18,000 sq. mi.</td>
</tr>
<tr>
<td>1930</td>
<td>Dec 3</td>
<td>14:36</td>
<td>Albuquerque</td>
<td>95</td>
<td>V-VI</td>
<td>4.5</td>
<td>Two shocks.</td>
</tr>
<tr>
<td>1931</td>
<td>Feb 3</td>
<td>16:45</td>
<td>Albuquerque</td>
<td>95</td>
<td>V</td>
<td>4</td>
<td>Hundreds left houses, many in pajamas, and many reported they were thrown from bed.</td>
</tr>
<tr>
<td>1931</td>
<td>Feb 4</td>
<td>21:48</td>
<td>Albuquerque</td>
<td>95</td>
<td>VI</td>
<td>4.5</td>
<td>Two shocks.</td>
</tr>
<tr>
<td>1936</td>
<td>Sep 9</td>
<td>05:55</td>
<td>Albuquerque</td>
<td>95</td>
<td>IV</td>
<td>3.5</td>
<td>4.25 Dishes jarred from shelves. Cracked plaster at one location. Felt within a 16-km radius.</td>
</tr>
<tr>
<td>1947</td>
<td>Nov 6</td>
<td>09:50</td>
<td>San Antonito</td>
<td>85</td>
<td>V-VI</td>
<td>4.5</td>
<td>Felt by all. Slight damage to walls of houses. Doors and dishes rattled. Felt in Española, 25 km from Los Alamos.</td>
</tr>
<tr>
<td>1952</td>
<td>Aug 17</td>
<td>03:45</td>
<td>Los Alamos</td>
<td>0</td>
<td>V</td>
<td>4</td>
<td>Felt at Antonito and 15 miles west of there at Osier, Colorado; also at Chama and Tres Piedras, New Mexico.</td>
</tr>
<tr>
<td>1954</td>
<td>Nov 2</td>
<td>10:00</td>
<td>Albuquerque-Bernalillo</td>
<td>80</td>
<td>IV</td>
<td>3.5</td>
<td>Felt along 32 km of the Rio Grande Valley from Albuquerque to Bernalillo.</td>
</tr>
</tbody>
</table>
### TABLE I. (cont)

<table>
<thead>
<tr>
<th>Year</th>
<th>Date</th>
<th>Hour (MST)</th>
<th>Locality of Report</th>
<th>Distance from Los Alamos (km)</th>
<th>Maximum Reported Intensity (MM)</th>
<th>Magnitude (ML)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1955</td>
<td>Aug 12</td>
<td>09:20</td>
<td>Turquoise Trading Post 25 km SW of Santa Fe</td>
<td>40</td>
<td>V</td>
<td>4</td>
<td>Plaster cracked in wall. At Santa Fe (25 km NE) and Bandelier Nat'l Monument (25 km NW) dishes, windows, etc., rattled.</td>
</tr>
<tr>
<td>1969</td>
<td>Jul 4</td>
<td>07:43</td>
<td>San Juan Pueblo6</td>
<td>35</td>
<td>IV</td>
<td>3.5</td>
<td>Felt most strongly 10 and 20 km N of Española.</td>
</tr>
<tr>
<td>1970</td>
<td>Nov 28</td>
<td>00:40</td>
<td>Albuquerque6</td>
<td>80</td>
<td>V</td>
<td>3.7</td>
<td>Felt in Albuquerque, most strongly in the NW and SW sections of the city.</td>
</tr>
<tr>
<td>1971</td>
<td>Jan 4</td>
<td>00:39</td>
<td>Albuquerque6</td>
<td>80</td>
<td>VI</td>
<td>3.9</td>
<td>Felt most strongly at Corrales (about 20 km NE of Albuquerque).</td>
</tr>
<tr>
<td>1971</td>
<td>Feb 17</td>
<td>(†)</td>
<td>Los Alamos7</td>
<td>0</td>
<td>II</td>
<td></td>
<td>Felt in the Los Alamos area; apparently not felt anywhere else.</td>
</tr>
<tr>
<td>1973</td>
<td>Mar 17</td>
<td>00:43</td>
<td>Abiquiu6</td>
<td>30</td>
<td>V</td>
<td>3.7</td>
<td>Felt in Los Alamos area.</td>
</tr>
</tbody>
</table>

1 Shocks located within 111 km (1° of arc on the surface) of Los Alamos.
2 Information based on catalog compiled by Woollard (1968).
3 Intensities listed here are from the Rossi-Forel (R.F.) scale. For the same seismological effects, the currently used Modified Mercalli (MM) scale gives slightly lower values of intensity.
4 Assigned on the basis of the magnitude-intensity-radius of perceptibility correlations established by Richter (1958).
5 Weak shocks, maximum reported intensity III, in the vicinity of Albuquerque have not been listed.
6 Also located instrumentally by New Mexico stations.
7 Reported in Dames and Moore (1972).
Four earthquakes have been felt by residents of Los Alamos; all were located within 25 km of the town. The first occurred on August 17, 1952, and since the only felt report was from Los Alamos, its epicenter was presumably nearby. This earthquake was of maximum intensity MM V (magnitude about 4) (Coffman and von Hake, 1973). The second event, felt on February 17, 1971, had a maximum intensity of MM 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 date of this felt report may actually be wrong; it 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 Los Alamos residents could have felt such a small shock (ML = 3.4) located that far away. A third earthquake was felt on December 5, 1971, and had a maximum intensity of MM 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 (ML) of 3.3. Minor damage (e.g., 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). The fourth earthquake 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, nearly the same as the December 5, 1971, event. The event was small, with a magnitude (ML) of 3.6 and maximum intensity of MM V. A survey taken by local seismologists found the earthquake was also felt in other nearby communities.

Among the earthquakes that occurred farther away, but still within the Río Grande rift, was the Cerrillos earthquake of May 28, 1918. There are no felt reports of this event from the Los Alamos area, but it is estimated that it would have had the highest intensity at Los Alamos of all the earthquakes in the past 100 years (intensity at Los Alamos was estimated as VI, Dames and Moore, 1972). Its maximum intensity has usually been reported as MM VIII (magnitude of 5-1/2 to 6). Olsen (1979) reinterpreted historical records and concluded the event had a maximum intensity of MM VII and a magnitude of 4-1/2 to 5-1/2. He argued that intensity MM VIII is an exaggerated interpretation of the felt reports. Olsen (1979) placed the epicenter of this event at about
35.5° N, 106.1° W (near Cerrillos and about 45 km south-southeast of Los Alamos) because that was the location of the greatest intensities. The tremor was felt over 31,000 km². Felt reports from the Cerrillos earthquake are sparse, however, and allow interpretations different from Olsen's (1979) both in the size and in the location of the earthquake. If the Cerrillos earthquake is to be used for estimating seismic hazards to Los Alamos, a conservative approach would be to take the larger size for the event and take its epicenter in Los Alamos.

The largest earthquakes that have occurred in New Mexico in historic times were part of a swarm that took place near Socorro from July 1906 to January 1907 (Reid, 1911). Three events have been assigned maximum intensities of MM VIII (Sanford et al., 1979), the largest of which occurred on November 15, 1906, and was felt in Santa Fe and Roswell, New Mexico, and in El Paso, Texas. Damage in the epicentral area included fallen chimneys, damaged walls, and rock falls. This earthquake caused many people to abandon their homes and live in temporary shelters. Fear was probably heightened by the fact that the famous San Francisco (California) earthquake and fire had occurred about three months before the beginning of the 1906-1907 Socorro activity (Sanford, 1963; and as alluded to by local newspaper accounts). The foci of the swarm of earthquakes 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 Socorro earthquakes of 1906-1907 occurred within the Rio Grande rift, which is the same tectonic province that Los Alamos is located in. The methodology used by the Nuclear Regulatory Commission for licensing of commercial nuclear reactors considers the earthquake history of an entire tectonic province to be significant to the evaluation of the seismic hazards of a site within the province, if an adequate site-specific record of earthquake data does not exist (10-CFR-100).

The most recent, damaging earthquake that occurred in New Mexico was located outside the Rio Grande rift proper, but along structures that may be associated with those of the rift. This was the Dulce earthquake of January 23, 1966, which had a magnitude (Mₘ) of 4.5 to 5.1 (ESSA, 1968; Cash, 1971). The earthquake was located within (but near the eastern edge of) the Colorado Plateau geologic province at about 37.0° N, 107.0° W, along the
Gallina-Archuleta Arch (see Figures 1 and 2). It was felt over 42,000 km² and had a maximum intensity of MM 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 a few homes sustained structural damage.

**Instrumental Seismicity of North-Central New Mexico**

Instrumental seismicity information from the Los Alamos Seismograph Network, although available only for the past 15 years, provides earthquake locations that are considerably more accurate than those estimated from felt effects. The accuracy of the instrumental earthquake locations varies, depending on the number and locations of stations that recorded the event and their proximity to the epicenter. The epicenters of events large enough to be recorded at five or more stations, and located within the Los Alamos Seismograph Network, are probably accurate to 5 km or better. Because of this uncertainty it may be difficult to associate individual events with a specific fault. Nevertheless, if events define trends that lie on or near a fault zone and align with it, the association becomes credible. Because of low station density and complex velocity structure, few depths are well determined. Events whose depths have been reliably determined are usually shallower than about 15 km but a few are as deep as 20 km (House, 1987). Because several different techniques have been used to compute event locations, the existing location set is heterogeneous in quality (House, 1987). Errors in locations for individual events may be larger than the 5 km cited above. An effort is currently in progress to systematically relocate the events within the Los Alamos area (House, 1987). Since the relocation study is only partly complete, we will discuss the original location set.

We will summarize here the features of the seismicity distribution that are most pertinent to the seismic hazards question at Los Alamos. For a more complete description, see Cash and Wolff (1984) and Sanford et al. (1979). Figure 1 is a generalized map of the major geologic and tectonic features of north-central New Mexico. Figure 2 is a map of the same area that shows earthquakes located by the Los Alamos network during the period September 1973 through July 1985. An enlarged view of faults and earthquakes in the immediate Los Alamos area is shown in Figure 3.

The Pajarito fault system is probably the most important tectonic feature for estimation of seismic hazards to Los Alamos. The Pajarito fault system
Figure 1. Generalized map of geologic and tectonic features in northern New Mexico. Label PFS identifies location of Pajarito fault system; Los Alamos is located slightly north of the label PFS. Label "S" indicates location of the San Felipe fault zone; "A" indicates location of Albuquerque. Figure after Wolff et al., 1985.
Figure 2. Map of earthquake epicenters determined from the Los Alamos Seismic Network for the time period September 1973 through December 1984. Map is at same scale as Figure 1. Small corners indicate area of Figure 3, referred to as "Los Alamos area" in discussions of seismicity. Dashed circle indicates area within 111 km of Los Alamos, which is area used by Sanford (1976) for discussions of seismic hazards to Los Alamos. Size of epicenter symbols is scaled to magnitude of earthquakes. Figure after Wolff et al., 1985.
Figure 3. Expanded map view of epicenters determined from the Los Alamos Seismic Network between September 1973 and July 1985 and mapped faults in the Los Alamos area. Mapped faults from Smith et al. (1970), Dames and Moore (1972), Dethier and Martin (1984), Gardner (1985), and Gardner and House (1987). PFS identifies the Pajarito fault system; VF identifies the Velarde fault. Triangles are stations used to locate the earthquakes; some stations used are outside the area of the figure. Epicentral symbols are scaled to earthquake magnitudes.
passes within a few miles of several of the Technical Areas of the Laboratory and has offset the 1 million year old Bandelier Tuff by as much as 200 m (Gardner and House, 1987). The Pajarito fault system trends roughly north–south and lies on the east side of the Jemez Mountains, just west of Los Alamos (see Figures 1 and 3). Despite its relatively young age and significant displacement, few, if any, instrumentally recorded earthquakes can be clearly attributed to the Pajarito fault system (see Figure 3). The earthquakes located to the south in Figure 3, near station SPD, are those most closely associable with the Pajarito fault system. The lack of earthquakes clearly attributable to the Pajarito fault system should be taken with caution, however, because the instrumental seismicity shown in Figure 3 encompasses only 12 years, a short time compared with the repeat times of large earthquakes, which may be 100s or 1000s of years (Budding and Furtymun, 1976). In addition, the lack of seismicity clearly associable with the Pajarito fault system does not necessarily indicate a lack of current displacement along the faults. The conclusions of Machette (1986) are particularly pertinent to this point, as he found evidence that earthquakes as large as magnitude 7 have occurred in the Socorro area with recurrence times of several 1000 years. Sanford et al. (1981) also note evidence that seismicity within the central portion of the Rio Grande rift is episodic, and currently anomalously low. A conservative approach to seismic hazards assessment for Los Alamos would be to interpret the lack of current seismicity clearly attributable to the Pajarito fault system as being a temporal effect.

There is a concentration of events northwest of Española near where the Velarde fault projects onto the Pajarito fault zone. This area of seismicity, which lies about 25 km north of Los Alamos, has probably been the site of several earthquakes that were felt throughout the Los Alamos–Española region, including, as noted above, four since Los Alamos was established in the early 1940s. This cluster is located near Lobato Mesa, and Sanford et al. (1979) speculate the seismicity may be related to magma migration within the crust. Reilinger et al. (1979) found, from a repeated leveling survey, the area near the Lobato Mesa earthquake cluster had subsided about 5 cm during a period of about 5 years. Reilinger et al. (1979) speculated the earthquakes and subsidence resulted either from the migration of magma at shallow depths or from normal faulting associated with spreading of the rift.
As can be seen from a comparison of Figures 1 and 2, the area of the Jemez volcanic field is relatively nonseismic. The lack of seismicity may result from high crustal temperatures in and near the Valles and Toledo calderas (Sanford et al., 1979). The high heat flow of the calderas region is well known (Edwards et al., 1976). High temperatures may inhibit the brittle failure that produces earthquakes. Alternatively, stresses within the calderas that might otherwise produce earthquakes may be relieved by slip on the fault zones immediately outside, particularly the north-south-trending zones along the Nacimiento uplift on the west and the Pajarito fault system on the east.

The nonseismic area of the Jemez volcanic field extends southward almost to Albuquerque. This nonseismic area includes the San Felipe fault zone (labeled "S" in Figure 1) that is a zone of north-south-trending normal faults of Pleistocene age or younger, which extends south from the Jemez volcanic field. These faults are particularly visible in the surficial Quaternary-Tertiary basalts of Santa Ana Mesa (Smith et al., 1970).

Although faults in the immediate Los Alamos area do not obviously correlate with earthquake activity, the zone of concentrated epicenters immediately to the west of the Jemez volcanic field (Figure 2) lies along the Nacimiento uplift. The uplift was formed in Laramide time (late Cretaceous to early Paleocene, about 65 Ma) by reverse or high-angle thrust faulting up to the west along the Nacimiento fault. The Nacimiento fault is the probable source of the present-day seismicity. In contrast to their origin as compressional features, the Nacimiento fault structures now are probably undergoing east-west extensional tectonics.

In addition to the naturally occurring microearthquakes shown in Figures 2 and 3, very small microearthquakes (magnitudes range from about -4 to +1) are induced during hydraulic fracturing experiments at the Los Alamos Hot Dry Rock (HDR) geothermal project on the west side of the Jemez Mountains. (This project is located along the east edge of the seismically active region of the Nacimiento uplift.) The induced microearthquakes are not shown in Figure 2. A dense network of nearby seismographs is used to locate the HDR microearthquake activity, which provides information about the fluid systems produced by the hydraulic injections (Fehler et al., 1987).

Seismicity of the Los Alamos Area Over Time

To better understand the time rate of seismicity in the Los Alamos area, it is helpful to consider several different plots of it (Figures 4-6).
Figure 4. Plot of earthquake magnitudes as a function of time for the area within 111 km of Los Alamos from 1918 to 1985. Data from 1918 through 1973 are from Sanford (1976); from 1973 through 1985 from the Los Alamos Seismic Network. Note that the Cerrillos earthquake of 1918, with an estimated magnitude of 5.5, is the largest shown. Note also the large increase in numbers of events detected after 1973 when the Los Alamos Network started operating.
Figures 4 and 5 include earthquakes from the area within 111 km of Los Alamos, and Figure 6 includes earthquakes just from the immediate Los Alamos area plotted in Figure 3. In Figures 4 and 5, earthquakes from the period 1918 to 1973 are from Sanford (1976), and from the period 1973 to 1985 are from the Los Alamos Seismograph Network. Earthquake information plotted in Figure 6 is entirely from the Los Alamos Network.

Figure 4 shows event magnitudes as a function of time from 1918 to 1985. The Cerrillos earthquake of 1918 is the largest earthquake that occurred during this time (approximate magnitude of 5.5). There is a suggestion of a slight decrease in the magnitudes of the largest earthquakes from 1918 to the present, including the time from 1973 to present, which is based on Los Alamos Network data. The major increase in the number of events after 1973 results from events being located by the Los Alamos Network. The seismicity shown in Figure 4 suggests a 15- to 20-year periodicity, with event clusters at about 1930, 1955, and 1971 (just before startup of the network).

From 1918 to 1985, the threshold of complete detection of earthquakes appears to be at a magnitude of about 3 to 3-1/2. We estimated that threshold from a plot of earthquake magnitudes versus number of earthquakes larger than a given magnitude; this is called a "b-value" plot and will be discussed further below. Because magnitude 3 appears to be about the threshold of completeness in the earthquake set, we plot only earthquakes of magnitude 3 and larger in Figure 5. This figure shows two different plots of seismicity for the same time period as that in Figure 4: one trace shows cumulative seismic moment ($M_0$); the other shows cumulative numbers of earthquakes ($\Sigma N$). The cumulative seismic moment is an indication of seismic strain release because, as described in the Appendix, seismic moment is proportional to the product of the fault area and the displacement during an earthquake. In Figure 5, seismic moments were computed from earthquake magnitudes according to an established relation (described in the figure caption) because we do not have enough high-quality seismograms to compute seismic moments directly. The cumulative number of earthquakes shows the time history of seismicity. A comparison of cumulative seismic moment with numbers of earthquakes provides an indication of the relative proportion of larger to smaller earthquakes.

The 15- to 20-year periodicity noted from Figure 4 shows fairly clearly in both traces plotted in Figure 5, with bursts of moment release and numbers of
Figure 5. Plots of cumulative seismic moment \( (M_0) \) and numbers of earthquakes \((\Sigma N)\) from area within 111 km of Los Alamos from 1918 to 1985. Only earthquakes of magnitude 3 and larger are included; magnitude 3 appears to be the threshold of complete detection for the entire time period plotted (see text). Seismic moments were computed from local magnitudes according to the relation of Bakun and Lindh (1977): \( \log_{10}(M_0 \text{ in dyne-cm}) = 1.21 M_L + 17.02 \).

Events in the early 1930s, in the middle to late 1950s, and possibly in the mid 1970s. Note the different sizes of earthquakes that produced the three bursts of moment release. In the 1930s, a small number of earthquakes produced large moment release, while in the early 1970s a large number of earthquakes produced relatively smaller moment release. Overall, from Figure 5, we note a systematic decrease in the size of individual earthquakes from the 1930s to the 1970s. There is a suggestion of a decrease in rate of seismic moment release during the same time. This finding agrees with Sanford's (1976) conclusion that the level of seismicity within 111 km of Los Alamos
Figure 6. Plots of cumulative seismic moment ($M_0$) and numbers of earthquakes ($\Sigma N$) for the immediate Los Alamos area as were included in Figure 3. Seismic moments computed from magnitudes as in Figure 5. Only earthquakes located by the Los Alamos Network are plotted.

was lower in the past 40 years than it was from 1918 to 1930. We emphasize, however, the data of Figure 5 are only suggestive.

Figure 6 shows information similar to that in Figure 5 but in more detail and for the smaller area immediately around Los Alamos, as in Figure 3. All events plotted in Figure 6 are from the Los Alamos Seismograph Network. The cumulative seismic moment plotted in Figure 6 can be reasonably matched by two straight lines, one from about 1974 to 1979, the other, with considerably flatter slope, from 1980 to 1985. From 1974 to 1979 the rate of moment release is about $1.6 \times 10^{20}$ dyne-cm per year or about one earthquake of magnitude 2.6 per year. From 1980 to 1985, the rate of moment release dropped by 80%. By comparison with the cumulative numbers of earthquakes, we see that the abrupt

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decrease of moment release rate after 1979 must have resulted from a decrease in the size of the earthquakes, as the rate of occurrence of earthquakes was about constant from 1974 to about 1981. After 1981, the rate of event occurrence dropped slightly, yet the rate of moment release stayed about constant; thus the size of the earthquakes increased somewhat. Because seismic moment is related to slip, the rate of seismic slip may have decreased in the Los Alamos area since 1979. What significance, if any, to attach to the decrease of seismic moment release and rate of seismicity is not clear, but continued monitoring of seismicity in the Los Alamos area is appropriate, since a decrease of rate of seismicity has sometimes been a precursor to a larger earthquake (Habermann, 1981).

SEISMIC HAZARDS IN LOS ALAMOS

Previous Studies

Previous studies of seismic hazards in Los Alamos were done by Dames and Moore (1972), Slemmons (1975), Budding and Purtymun (1976), Sanford (1976), and Tera Corporation (1984). Of these, the study by Dames and Moore (1972) is the most comprehensive, encompassing geological as well as seismological studies. The studies by Slemmons (1975) and Budding and Purtymun (1976) were primarily concerned with geologic information, while that of Sanford (1976) used primarily seismological information. The Tera Corporation (1984) report draws heavily on the work of Dames and Moore (1972), and the methods used in the Tera study are inadequately documented by the report. For these reasons and because it presents no new field data but rather relies on the material from the Dames and Moore (1972) report, we will not discuss the Tera (1984) report further.

Dames and Moore

The Dames and Moore (1972) study was done for engineering design for the Plutonium Facility at Los Alamos (TA-55). Their work sought to estimate the sizes of "Operating Basis Earthquake" and "Safe Shutdown Earthquake" (OBE and SSE, respectively) and to determine response spectra for the site. The results of this study have also been used as a guide for design of other facilities at Los Alamos. The discussion section will critically review the assumptions and methods used in the section of the report entitled "Seismology," whereas here we shall only summarize that section.
The first problem considered by Dames and Moore (1972) was seismic exposure. From the approximately 100-year catalog of historic earthquakes in New Mexico, Dames and Moore chose a maximum intensity of VIII as representing the largest ground motion that the TA-55 site might experience during the design life of the Plutonium Facility. Intensity VIII is the largest estimated intensity of the 1918 Cerrillos earthquake and is comparable with the estimated maximum intensities of the three largest events of the 1906 Socorro swarm.

After selecting a maximum earthquake intensity for the TA-55 site, Dames and Moore (1972) developed a relation between intensity and peak horizontal acceleration in order to estimate a peak acceleration for the site. They state the "maximum horizontal ground acceleration at the site would probably be on the order of 0.17 g" for an earthquake of intensity VII to VIII at Los Alamos. The Dames and Moore (1972) intensity-peak acceleration relation was based on seven earthquakes located in the western U.S. for which peak accelerations were measured from instrumental records. These earthquakes wrote records with peak horizontal accelerations from 0.08 g to 0.33 g at sites where the earthquake intensity was well documented as VIII. Dames and Moore (1972) chose a peak horizontal acceleration of 0.33 g for the Safe Shutdown earthquake and 0.17 g for the Operating Basis earthquake. A facility should be able to continue operating after experiencing an earthquake the size of the Operating Basis earthquake and should not sustain significant damage to the vital operating and containment structures. The Operating Basis earthquake represents the largest earthquake a facility would probably experience during its design lifetime (often taken as 30 years). The Safe Shutdown earthquake is the largest earthquake a facility could be expected to withstand without sustaining such serious structural damage that it releases radioactive materials. The Safe Shutdown earthquake is the largest earthquake a facility might conceivably experience during its lifetime.

Because no strong ground motion recordings have been made at Los Alamos, Dames and Moore (1972) used strong-motion recordings from earthquakes elsewhere in the U.S., as well as synthetic strong-motion records, to compute the response spectra they proposed for TA-55. Strong-motion recordings are seismograms recorded close to moderate or large earthquakes, where the ground motions resulting from the earthquakes are large. The approach used by Dames and Moore (1972) to compute the response spectra attempted to correct the
strong-motion recordings in order to calculate strong-motion records that would have been recorded at TA-55. They then used the corrected strong-motion recordings to compute several response spectra. The approach to correcting the recordings was first to remove the computed effects of the sedimentary column at the recording site and then to add the computed effects of the sedimentary column at TA-55. Two main assumptions were made: (1) the effects of the geologic structure of the recording site and TA-55 can be adequately accounted for, and (2) the earthquakes themselves are similar in character to those that might affect TA-55. The critical aspect of the geologic structures at the recording sites and TA-55 is how well known are the seismic velocities; uncertainty about these velocities may considerably alter the computed seismograms at TA-55. Moreover, earthquakes from different regions may produce different strong-motion records because of the differing seismic character of the causative fault zones.

The strong-motion records used by Dames and Moore (1972) to compute response spectra were a composite of two strong ground motion recordings of earthquakes along with three synthetic earthquake ground motions. The two earthquake recordings, one each from Montana and California (corrected as described in the previous paragraph), included one of the seven earthquakes used to develop the intensity-peak acceleration relation described previously. The synthetic ground motions were generated to approximate the ground motion characteristics of an earthquake of intensity VII-VIII at the TA-55 site. Response spectra calculated by Dames and Moore (1972) for the TA-55 site are summarized in Figure 7. The figure is a plot of the envelopes of the peaks in the response spectra from the five different seismograms used. This figure is a reproduction of the response spectra chosen for the "Safe Shutdown" earthquake.

Other studies

Slemmons (1975) investigated seismic hazards the Fenton Hill Hot Dry Rock site (located about 40 miles WSW of Los Alamos) might be exposed to and concluded "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 mainly on aerial surveillance and photography, as well as the available seismic record. In addition, he points out the "tectonic flux" (the rate of
Figure 7. Smoothed response spectra computed for TA-55. Figure after Dames and Moore (1972). Computations are for four values of damping and assume a peak horizontal acceleration of 0.33 g, which was considered the Safe Shutdown earthquake. See text for details.
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. Note that the Slemmons (1975) study considered seismic hazards to the Fenton Hill site, and not to Los Alamos itself.

Sanford (1976) investigated the seismicity and seismic risk of the Los Alamos region using only seismologic information and estimates the largest event that will occur in the Los Alamos area in the next 100-year period (the once per 100 year earthquake) may be as large as magnitude 5.5. This estimate is based in part on the instrumental seismicity of the period 1962 to 1972 and in part on reports of historic earthquakes.

Budding and Purtymun (1976) looked at mapped faults in the Los Alamos area. They estimated lengths, offsets, and ages of what they termed "major" faults near Los Alamos. Assuming an individual event would rupture the entire mapped length of the faults, they obtained estimates of maximum earthquake magnitudes from each fault. These estimates averaged 6.7. Budding and Purtymun (1976) used slip during an individual earthquake compared with total slip observed on the faults to estimate an average recurrence interval of about 8,000 years for these maximum magnitude earthquakes. They then extrapolated, using a b-value plot (see below for more discussion), a largest probable earthquake of $M_L = 4.8$ per century within or very close to Los Alamos County.

**Instrumental Data**

Between September 1973 and July 1985, the Los Alamos Network located nearly 1300 microearthquakes within 111 km of Los Alamos. Instrumental seismicity data are often used to extrapolate the frequency of occurrence of larger earthquakes whose recurrence times may be substantially longer than the duration of the instrumental record. The seismicity data are first plotted in what is termed a b-value plot, in which earthquake magnitude, $M$, is plotted against the number of earthquakes that are larger than $M$. Figure 8 is a b-value plot of the nearly 1300 earthquakes located by the Los Alamos Network within 111 km of Los Alamos. B-value plots typically have a range of earthquake magnitude within which the data points define a nearly linear relation between magnitude and the logarithm of the number of events. In Figure 8, this linear range extends from about magnitude 1.5 to magnitude 4.0. Below a certain magnitude, the number of events that can be recorded
decreases, so the number falls below what would have been extrapolated from
the linear portion. That magnitude is generally considered to be the thresh-
old of complete detection of earthquakes; those smaller than the threshold
are not all detected. From the data plotted in Figure 8, we estimate the
threshold of complete detection in the Los Alamos Network data is about
magnitude 1.5.

A plot such as Figure 8 is termed a b-value plot because of the relation
that has been found between the magnitude and frequency of earthquake
occurrence: $\log_10(N) = a - b M$, where $M$ is magnitude and $N$ is the number of
earthquakes larger than $M$. The slope of the straight-line portion of the plot
is the $b$-value in the previous relation. The $b$-value is a measure of the
relative proportion of smaller to larger earthquakes. $b$-values are typically
in the range 0.8 to 1.0; the dashed line in Figure 8 has a slope ($b$-value) of
1.0. The value of "$a$" in the relation above is a constant related to the
relative rate of seismicity of an area. Both the "$a$" and the "$b$" values are
needed to extrapolate the occurrence rate of larger earthquakes. If the
Figure 8 data are normalized to a 1-year period, the "$a$" value is 3.05. We
would then extrapolate the occurrence of one earthquake of magnitude $M_L = 4.0$
about each decade and one of magnitude $M_L = 5.0$ about each century within 111
km of Los Alamos. As discussed below, however, such an extrapolation may
seriously underestimate (by as much as 1 to 2 units) the magnitude of the
hypothesized earthquake.

DISCUSSION

This section focuses on three topics: first, a critical discussion of the
methodology and conclusions of the Dames and Moore (1972) study; second, a
discussion of the problems and uncertainties of extrapolating future
seismicity from recent instrumental seismic data; and last, a discussion of
whether response spectra calculated for a single site are adequate for seismic
design throughout the Laboratory.

Dames and Moore (1972) Study

The study by Dames and Moore (1972), for the Plutonium Facility at TA-55,
is the most comprehensive seismic hazards and risks study yet done for the Los
Alamos area. In addition, the Dames and Moore (1972) findings have been used
as a guide for seismic design of other facilities at Los Alamos. Because the
Figure 8. Plot of earthquake magnitude, $M$, versus number of earthquakes larger than $M$ for earthquakes located by the Los Alamos Network within 111 km of Los Alamos. Earthquakes plotted are from 1974 through July 1985. Numbers of events plotted are not normalized for any possible variations in numbers of stations operating. Seismologists term this type of plot a b-value plot because the numbers of events larger than magnitude $M$ generally follow this relation: $\log_{10}(N) = a - bM$. Straight line plotted has a b-value of 1, which is considered a "normal" b-value. The b-value is an indication of the relative proportion of small to large earthquakes in an earthquake set; the a-value is an indication of the overall level of seismicity of an area.
results of this study have been so important, we discuss the report in some
detail here. We will describe the methods used by Dames and Moore and point
out how their methods and underlying assumptions differ from methods and
assumptions that would be used in a comparable study done today. As Tabor
(1986) notes, the development of new geologic and tectonic concepts over the
past 10 to 20 years has resulted in considerable changes in the way geologic
and tectonic data are evaluated for seismic hazards estimation. In this
discussion we will attempt to understand whether new geologic information and
new methods for interpreting it would significantly alter the conclusions
about levels of ground motion that are in Dames and Moore (1972).

A seismic hazards study currently being done at the Laboratory (Gardner
and House, 1987) seeks to obtain some of the most important geological and
seismological information necessary for a new evaluation of seismic hazards
and risks of the Los Alamos area, but it will not be as comprehensive as the
Dames and Moore (1972) study. A complete seismic risk study would require
considerably more analysis than is planned for the current seismic hazards
study.

One general criticism of the Dames and Moore (1972) report is that
documentation of methods and data used is not always complete enough to
establish the reliability of the conclusions stated. For example, although
they often refer to "probable" and "improbable," these terms are used in a
qualitative way; they defined no quantitative estimates of probability for the
terms. A present-day study comparable with Dames and Moore (1972) would place
greater emphasis on quantifying hazards and risks. The present-day study
would also require more information and interpretation of the seismic history
of Los Alamos and northern New Mexico.

More substantive differences between Dames and Moore results and a study
utilizing presently available information and techniques may be in the estima-
tion of peak ground motions that could be expected at the site and in the
computation of response spectra for the TA-55 site. Of these two topics, the
methods for choosing an appropriate level of peak ground motion are the area
in which the results of Dames and Moore (1972) are weakest and most subject to
change should a similarly comprehensive study be undertaken today. We do not
attempt to determine whether the levels quoted by Dames and Moore (1972) are
appropriate; such determination is beyond the scope of this report. We simply
note that this is a weakness of the Dames and Moore (1972) study.

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Dames and Moore (1972) used the approximately 100 years of earthquake history of New Mexico to estimate a peak intensity of VIII as the greatest earthquake intensity the Plutonium Facility might be subjected to during its design lifetime. Because earthquake intensity is a qualitative measure of earthquake effects, some relation between intensity and actual ground motion had to be used to estimate what ground motion the TA-55 site would experience.

Trifunac and Brady (1975) observe, however, "The physical basis for correlating an earthquake intensity scale with the recorded levels of strong ground motion is dubious indeed. . . . Perhaps one of the most important omissions in the majority of available correlations of peak ground acceleration with earthquake intensity is that insufficient stress is put upon the broad scatter of data points."

Dames and Moore (1972) acknowledged considerable uncertainty in relating intensity and peak ground acceleration. They presented intensity and peak acceleration data from seven earthquakes and used them for estimating a peak horizontal acceleration of 0.17 g for the OBE and 0.33 g for the SSE.

The reasons for the choices made by Dames and Moore (1972) for the OBE and SSE are not well documented, but the peak acceleration of 0.33 g chosen for the SSE is the highest peak acceleration for the seven earthquakes considered. Instrumental measurements of ground acceleration were sparse before the late 1970s, and hence, Dames and Moore (1972) had a limited data set to work with. Nevertheless, they simply chose the largest measured peak horizontal acceleration and did not estimate uncertainty limits for their choices.

A considerable amount of new earthquake data has been recorded and analyzed since the Dames and Moore (1972) study was completed. With the benefit of new insights provided by these data, a new seismic risk study should be able to more quantitatively assess levels of peak accelerations and risks. At the very least, such a study should more accurately quantify the uncertainty in estimates of ground motion parameters. The most important recent findings show that earthquake intensity and peak accelerations are not well correlated (Trifunac and Brady, 1975) and earthquake magnitude and peak accelerations are not well correlated (Hanks and Johnson, 1976). Moreover, two recent moderate-size earthquakes, magnitudes 5 and 6.5, have produced peak accelerations of 0.8 g and greater (Wiechert et al., 1986; Wu, 1987). These
anomalously large peak accelerations may have resulted from directivity (focusing) effects.

In their computation of response spectra for the TA-55 site, Dames and Moore (1972) used strong ground motion recordings from earthquakes located elsewhere in the U.S. (in California and Montana) because there were, and still are, no recordings of strong earthquake ground motions in Los Alamos. Dames and Moore (1972) used a technique for computationally correcting the actual recordings to equivalent recordings at TA-55. The technique relies on an accurate knowledge of the near-surface seismic velocity structures at the recording sites and at TA-55. Dames and Moore (1972) inferred seismic velocities beneath the recording sites and measured velocities in the top few hundred feet beneath TA-55. The resulting recordings corrected to TA-55 will be as uncertain as the seismic velocities are uncertain. Such an approach was the only technique then available to estimate seismic response of a site from which no actual strong ground motion data were available.

Recently, a new technique for synthesizing large earthquake ground motions from one or more small earthquakes (e.g., Joyner and Boore, 1986) has been developed. This approach builds the seismogram for the large earthquake from the seismograms of one or a few small nearby earthquakes that are summed to produce a seismogram equivalent to that from a large earthquake. This is termed an empirical Green's function technique and requires very high quality recordings from small nearby earthquakes to use as Green's functions. A major advantage of this technique compared with that used by Dames and Moore (1972) is that the effects of propagation of seismic waves through the velocity structure at the recording site are contained within the seismogram of the small earthquake and do not have to be computed. We would anticipate that seismograms computed by the empirical Green's function technique would be more closely representative of an actual larger earthquake.

**Extrapolating Future Seismicity from Instrumental Data**

Recent studies of both seismologic and geologic data (Wesnousky et al., 1983; Schwartz and Coppersmith, 1984; Davison and Scholz, 1985) have found that earthquake frequency-magnitude distributions, like that of Figure 8, may be an unreliable way to extrapolate the occurrence and size of future larger earthquakes in an area. It has been shown that the seismicity rate (the "α" value described above, p. 25) is anomalously low during the time between the
largest earthquakes. Extrapolating the size of the eventual earthquake, therefore, underestimates it by as much as one to two magnitude units. The effect has been seen in both seismologic (Davison and Scholz, 1985) and geologic data (Wesnousky et al., 1983; Schwartz and Coppersmith, 1984). Instrumental seismic data of short duration (compared with earthquake recurrence intervals) are particularly likely to produce such an underestimate (Davison and Scholz, 1985). Davison and Scholz (1985) studied earthquakes from the Alaska plate margin and found the underestimation to be strong when data from only an 18-year period and a spatial area only as large as the rupture zone of an individual large earthquake were used. On the other hand, when they considered the entire Alaska plate margin (which is several thousand kilometers in length), they found even the short 18-year instrumental record was adequate to extrapolate the magnitude of the very largest earthquake known to have occurred anywhere along the plate margin. Davison and Scholz (1985) took that fact to indicate that instrumental data should be used from a large area, in which there is a distribution of different-size faults, in order to reliably extrapolate the magnitude of the largest earthquake that will affect the area.

Figure 9 is a schematic illustration of the underestimation effect. In the figure, instrumental earthquake data from a relatively short time period (labeled seismicity data) are compared with geologically obtained information about the occurrences and sizes of the largest earthquakes seen in the geologically recent past (note this is simply a schematic figure that does not contain data from the Los Alamos area). From the seismicity data of Figure 9, we would extrapolate that a once per 100 year earthquake (0.01 per year in the normalized scale of Figure 9) would have a magnitude of about 6.5. From the geologic data, the once per 100 year earthquake would have a magnitude of about 7.5, about 1 magnitude unit higher than that extrapolated from the instrumental seismicity.

If such an effect also occurs in the tectonic setting of the Los Alamos area, an extrapolation from recent instrumental seismicity data of one earthquake of magnitude about 5.0 every 100 years may be too low by one to two magnitude units. Work by Machette (1986) found a level of seismicity preserved in the Holocene geology that far exceeds the instrumental and historical level seen in New Mexico for the past 100 years. Machette's (1986)
Figure 9. Cartoon of a b-value plot in which a single straight line is a poor representation of both instrumental seismicity data and information on earthquakes obtained from geologic studies. In this cartoon, an extrapolation of the seismicity data to estimate the magnitude of the once per 100 years earthquake (cumulative number per year of 0.01) would yield an estimated magnitude of about 6.75. The geologic data show a magnitude of 7-1/2 to 8 for the once per 100 years earthquake in this cartoon. [Figure after Schwartz and Coppersmith (1984); it is not based on data from Los Alamos.]
studies were of the La Jencia fault, which is located in the central portion of the Rio Grande rift, near Socorro. We take Machette's (1986) work as an additional reason to question the reliability of estimates of seismic hazards to Los Alamos that are based solely on levels of current seismicity recorded over the past decade or so in the Los Alamos area; actual hazards may be considerably greater.

Response Spectra

Estimates of the ground response are critical to designing structures that will withstand possible future earthquakes. Response spectra for a single site (such as that generated by Dames and Moore, 1972) may not be appropriate for use in design of structures in other locations at Los Alamos. The near-surface seismic velocities greatly influence the response at the surface (Hays, 1986). Gardner and House (1987) measured seismic velocities at the surface of the Bandelier Tuff in the vicinity of the Laboratory that range from 2,500 to 15,000 ft/sec. Since most Laboratory structures are built on Bandelier Tuff (either on mesa tops or in canyons), the ground response to earthquake excitation may vary widely at different locations around the Laboratory as well. At present, we do not know how large the range of site responses may be and, therefore, cannot evaluate the importance to attach to this possible effect.

CONCLUSIONS AND RECOMMENDATIONS

The instrumental and historical record of earthquakes in New Mexico extends back only about 100 years; during this time, the largest earthquake that occurred within 111 km of Los Alamos was the Cerrillos earthquake of 1918. It had a maximum intensity of VII to VIII, from which we infer a magnitude as large as 5-1/2 to 6. Extrapolating a magnitude for a once per 100 years earthquake from about 11 years of instrumental data recorded in the Los Alamos area yields a size of about magnitude 5. Several recent studies of both geological and seismological information provide persuasive evidence that such extrapolations may be seriously low in their magnitude estimates, and hence, the extrapolations are not reliable for assessment of seismic hazards. Reliably estimating seismic hazards to Los Alamos, therefore, appears to require more information than that currently available.

In particular, we recommend that the following be done:
1. Continued microearthquake monitoring by at least a small local network will be necessary to better reconcile seismic hazards estimated from the relatively short-duration instrumental record with hazards estimated from the longer-duration geologic information that will be acquired from trenching studies at Los Alamos. Although maintaining a seismic network is expensive, it provides information about local seismicity and rates of seismicity that is otherwise unobtainable.

2. New response spectra should be computed for at least one site in the Laboratory using currently available data and techniques. Ideally of course, response spectra should be obtained from strong ground motion recordings from Los Alamos. Since, however, we cannot count on having such recordings available soon, we suggest using a recently developed technique for synthesizing large earthquake records from a superposition of recordings from small local earthquakes (empirical Green's function). This new technique could be used to develop a new response spectrum for at least one site at the Laboratory in order to confirm the appropriateness of the response spectra calculated by Dames and Moore (1972) using earthquake recordings from elsewhere.

3. Finally, additional strong ground motion instruments should be deployed at the Laboratory, particularly in or near facilities that handle radioactive materials and high explosives. These instruments are relatively inexpensive to acquire and maintain. If and when a moderate to large earthquake occurs nearby, recordings from such instruments will be the only impartial information available to evaluate the response of Laboratory structures to the ground motion.

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APPENDIX: Glossary of Seismological Terms

B-Value. An indication of the relative portion of larger to smaller magnitude earthquakes. The magnitude distribution of earthquakes is seen in a plot of magnitude against logarithm of the cumulative number of earthquakes smaller than a given magnitude. Such a plot is commonly called a b-value plot after the relation: log (number of earthquakes smaller than magnitude M) = a - b M. The value of "b" is the slope of a portion of such a plot. Typically, the plot is linear over a range of magnitude; then the number of events smaller than a given magnitude falls below the value expected from the linear portion. This fall-off is indicative of decreased detectability of events, and the magnitude at which the fall-off starts is generally taken as the magnitude threshold for complete detection. The value of "a" in the relation above is a constant indicative of the overall level of seismicity. The relation above is often used to extrapolate the likelihood of experiencing an earthquake of a given size. The discussion section indicates reasons why such extrapolation should be regarded with skepticism.

Epicenter. The surface projection of an earthquake's hypocenter (location in three dimensions).

Event. A seismic event is simply a wave train that is discernible on a seismogram. The term includes manmade phenomena (sonic booms, quarry blasts) as well as earthquakes.

Hypocenter. The location (in three dimensions) of an earthquake's focus, or initiation of rupture. Earthquakes larger than about magnitude 6 have rupture areas that are 10 km or greater in extent. The place within the rupture area at which slip nucleated is referred to as the focus or hypocenter of the earthquake.

Intensity. Earthquake intensity is a subjective measure of the effects of an earthquake at a specific location. Earthquake intensities depend on many factors, including distance from the epicenter, depth of focus of the earthquake, the local geology, and the quality of building construction. In the United States, intensity is reported in terms of the Modified Mercalli (MM) intensity scale of 1931 (Table A-I).

Isoseismal. An isoseismal is a contour of the area of equal earthquake intensity.

Magnitude. An objective measure of an earthquake's size that is obtained from seismograms (instrumental recordings) of an earthquake. Several slightly different magnitude scales are used by the seismological community. The scale most commonly used for nearby earthquakes of moderate size is the "local" magnitude, designated by M L. The local magnitude scale was the first magnitude scale to be defined and is the original "Richter scale." Strictly, M L refers to a magnitude determined from the amplitude of P-waves recorded on a specific type of seismograph or ground-motion recorder. Contemporary use of the term "local magnitude" encompasses earthquake magnitudes determined from other types of seismographs, but which have been calibrated to the local magnitude scale. The magnitude of an
earthquake is simply a measure of the relative size of an earthquake and is not an interpretation of what physically happened within the fault zone during the earthquake. Hence, earthquakes that have the same magnitude may have had different amounts of slip and may have broken different sized areas.

Seismic Moment. Seismic moment ($M_0$) is an instrumental measure of the size of an earthquake. Generally, seismic moment is measured from the long-period (periods of many seconds) portion of the spectrum of an earthquake. In contrast to magnitude, seismic moment has a physical interpretation. The seismic moment of an earthquake is the product of the rigidity of the rock within the source region ($\mu$), times the rupture area ($A$), times the slip during the earthquake ($s$). Thus, $M_0 = \mu As$. Seismic moment is roughly proportional to magnitude; in the absence of seismograms of a quality high enough to determine seismic moment, seismic moment is often estimated from the magnitude of an earthquake. A commonly used relation between magnitude and seismic moment for earthquakes of magnitude about 0 to 6 is $\log_{10}(M_0$ in dyne-cm) = 1.21 $M_L$ + 17.0 (Bakun and Lindh, 1977).

Seismograph. An instrument for measuring and recording ground motion. The ground motion records written by a seismograph are called seismograms.
<table>
<thead>
<tr>
<th>Intensity</th>
<th>Approx. Mag.</th>
<th>Description of Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>2 to 2-1/2</td>
<td>Not felt. Marginal and long-period effects of large earthquakes.</td>
</tr>
<tr>
<td>II</td>
<td>2-1/2 to 3</td>
<td>Felt by persons at rest, on upper floors, or favorably placed.</td>
</tr>
<tr>
<td>III</td>
<td>3 to 3-1/2</td>
<td>Felt indoors. Hanging objects swing. Vibration like passing of light trucks. Duration estimated. May not be recognized as an earthquake.</td>
</tr>
<tr>
<td>IV</td>
<td>3-1/2 to 4</td>
<td>Hanging objects swing. Vibration like passing of heavy trucks; or sensation of a jolt like a heavy ball striking the walls. Standing motor cars rock. Windows, dishes, doors rattle. Glasses clink. Crockery clashes. In the upper range of IV, wooden walls and frames creak.</td>
</tr>
<tr>
<td>V</td>
<td>4 to 4-1/2</td>
<td>Felt outdoors; direction estimated. Sleepers wakened. Liquids disturbed, some spilled. Small unstable objects displaced or upset. Doors swing, close, open. Shutters and pictures move. Pendulum clocks stop, start, change rate.</td>
</tr>
<tr>
<td>VII</td>
<td>5 to 5-1/2</td>
<td>Difficult to stand. Noticed by drivers of motor cars. Hanging objects quiver. Furniture broken. Damage to masonry D, including cracks. Weak chimneys broken at roof line. Plaster, loose bricks, stones, tiles, cornices (also unbraced parapets and architectural ornaments) fall. Some cracks in masonry C. Waves on ponds; water turbid with mud. Small slides and caving along sand or gravel banks. Large bells ring. Concrete irrigation ditches damaged.</td>
</tr>
<tr>
<td>VIII</td>
<td>5-1/2 to 6</td>
<td>Steering of motor cars affected. Damage to masonry C; partial collapse. Some damage to masonry B; none to masonry A. Stucco and some masonry walls fall. Chimneys, factory stacks, monuments, towers,</td>
</tr>
</tbody>
</table>
TABLE A-I. (cont)

elevated tanks twist, fall. Frame houses moved on foundations if not bolted down; loose panel walls thrown out. Decayed piling broken off. Branches broken from trees. Changes in flow or temperature of springs and wells. Cracks in wet ground and on steep slopes.

IX 6 to 6-1/2
General panic. Masonry D destroyed; masonry C heavily damaged, sometimes with complete collapse; masonry B seriously damaged. (General damage to foundations.) Frame structures, if not bolted, shifted off foundations. Frames racked. Serious damage to reservoirs. Underground pipes broken. Conspicuous cracks in ground. In alluviated areas sand and mud ejected, earthquake fountains, sand craters.

X 6-1/2 to 7
Most masonry and frame structures destroyed with their foundations. Some well-built wooden structures and bridges destroyed. Serious damage to dams, dike, embankments. Large landslides. Water thrown on banks of canals, rivers, lakes, etc. Sand and mud shifted horizontally on beaches and flat land. Rails bent slightly.

XI 7 to 7-1/2
Rails bent greatly. Underground pipelines completely out of service.

XII 7-1/2 to 8
Damage nearly total. Large rock masses displaced. Lines of sight and level distorted. Objects thrown into the air.

1 Approximate magnitudes computed assuming the intensity cited is the maximum intensity for the event (I0) and using the relationship: ML = 0.49 I0 + 1.85 (Toppozada, 1975).

MASONRY A, B, C, AND D: (Richter, 1958)

A Good workmanship, mortar, and design; reinforced, especially laterally, and bound together by using steel, concrete, etc.; designed to resist lateral forces.

B Good workmanship and mortar; reinforced, but not designed in detail to resist lateral forces.

C Ordinary workmanship and mortar; no extreme weaknesses like failing to tie in at corners, but neither reinforced nor designed against horizontal forces.

D Weak materials, such as adobe; poor mortar; low standards of workmanship; weak horizontally.
REFERENCES


