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THE SEISMICITY OF NORTH-CENTRAL NEW MEXICO WITH PARTICULAR REFERENCE TO THE CERRILLOS EARTHQUAKE OF MAY 28, 1918

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INTRODUCTION

Earthquakes within the State of New Mexico have been known since 1849 when a swarm near Socorro was described in a diary by a U.S. Army surgeon (Hammond, 1966). Prior to this date, the relative absence of written records among the small and widely scattered settlements of the Indian and Spanish cultures means that even fairly substantial earthquakes (i.e., magnitudes perhaps slightly in excess of 6) would have gone unreported. For the period from 1849 until 1960, the record of seismic activity within the state is dependent largely on felt effects which were published principally in the local newspapers of the day. Northrop (1961, 1976) has compiled many of the data from old newspaper files which indicate over 600 felt earthquakes in the state. The majority of these occurred along the Rio Grande valley, the most densely populated region. Since most of the state outside the agricultural lands of the Rio Grande valley was populated very sparsely, this undoubtedly has led to a bias in the reporting of felt shocks and to perhaps an overemphasis of the seismicity of the Rio Grande rift relative to neighboring physiographic provinces. However, these felt data do indicate correctly that the section of the rift from Belen to Socorro had the highest rate of earthquake occurrence, as has been confirmed by modern instrumental studies (Sanford and others, 1979a).

Shortly after the turn of the 20th century, various universities, government agencies and other organizations (most notably the Jesuit Seismological Association) began installation of seismograph stations at widely scattered locations throughout North America. The earliest instruments were quite primitive by modern standards, and since they were designed primarily to register long-period waves from very large, distant earthquakes (teleseisms), they had very low sensitivity to strong local and regional shocks. The closest of these stations to New Mexico, at Denver and at Tucson, began operation about 1909. Because of the distance and relative insensitivity of seismograph stations in nearby states, only marginal instrumental data on a few of the larger New Mexico earthquakes are available for the period 1910-1960.

The first permanent seismograph station in New Mexico was installed at Socorro (SNM) in 1960 near the campus of New Mexico Institute of Mining and Technology (NMIMT). This high-gain, short-period instrument permitted the initiation of studies of the seismic activity in the vicinity of Socorro (Sanford, 1963). Various organizations began operating high-quality, modern stations in 1961-1962 at Albuquerque (ALQ) and Las Cruces (LCN), New Mexico, and at Tucson (TUC) and Payson (TFO), Arizona. Readings from these stations combined with the SNM data then permitted the location of many earthquake epicenters throughout the state. This distribution and density of seismograph stations achieved essentially complete coverage of all earthquakes within New Mexico stronger than the detection threshold of Richter magnitude 2.4 (Sanford and others, 1976a,b). The magnitude scale used in this work was an adaptation of the "local" (MO scale originally developed by Richter (1958) for use in southern California. Detailed mapping of even smaller shocks for the north-central part of the state was initiated when the Los Alamos Scientific Laboratory (LASL) installed a network of continuously recording high-gain stations beginning in 1973. A similar network in the vicinity of Albuquerque begun in 1976 by the USGS Albuquerque Seismological Laboratory (ASL) has permitted the extension of these detailed studies for the entire section of the Rio Grande rift from the Colorado-New Mexico border to Socorro.

The instrumental data on earthquake epicenters throughout the state since 1962 have been summarized by Sanford and others (1976a, 1976b, 1979b), who showed that the greatest concentrations of continuing activity are centered near Socorro and northwest of Espanola. Reviews of the details of seismic activity, specifically for the Rio Grande rift, including the historic felt reports as well as instrumental data, are given by Sanford and others (1972, 1979a). Sanford and coworkers also have conducted specialized and detailed studies of the microearthquake activity in the vicinity of Socorro and the association of this seismicity with a probable magma body at midcrustal depths (Rinehart and others, 1979; Sanford and others, 1977).

Interest in the assessment of possible geologic and seismic hazards in the north-central section of New Mexico has increased rapidly in recent years. Not only is this region the site of a developing major urban area including the state's two largest cities of Albuquerque and Santa Fe, but the area contains, or is in close proximity to, significant potential resources of geothermal energy and ground water in addition to known major production areas of coal, uranium, oil and gas.

One of the principal goals in the installation of the LASL seismic network north of Albuquerque was to obtain better information on the long-term seismic risk to this section of the state and to correlate the seismic patterns with the contemporary tectonic activity. Because of the history of development of seismographic stations, a less detailed picture of seismicity over a shorter time period is available for the region between Albuquerque and the Colorado-New Mexico border than for the Albuquerque-Socorro segment. This is also the situation for the historic felt earthquake data, a consequence of both a lower population density and probably a lower rate of earthquake occurrence in the 1849-1979 time period. The evaluation of earthquake risk in a particular geographic area

relies on three complementary techniques: (1) the determination of the centers and rates of present day activity by instrumental means, (2) a compilation of earthquake information over the somewhat longer periods covered by historic records, and (3) an assessment of probable sizes and recurrence intervals of larger earthquakes over geologic time scales by geological techniques involving measurements and dating of offsets on fault scarps (Allen, 1975). Because of the highly episodic nature of earthquake activity, all three techniques are necessary in order to arrive at a valid estimate of the earthquake potential of a region. The instrumental studies are capable of defining patterns of usually small magnitude and more frequent events, but data are usually available for only a few years; the historic information is a valuable adjunct since it is often available for tens to hundreds of years, and serves to define better the occurrence rate of the infrequent but higher magnitude shocks which have most of the potential for creating damage. For north-central New Mexico, these three types of earthquake risk studies have been undertaken only during the past few years; summaries of some of the early results, mainly in the vicinity of Los Alamos, are contained in reports by Budding and Purtymun (1976) (geological techniques), Newton and others (1976) (all techniques), Sanford (1976) (mainly historic felt reports), and Sanford and others (1979a) (instrumental results).

The objective of this paper is to examine the relationship between the instrumental studies of microearthquakes carried out by LASL since 1973 and the Cerrillos earthquake of 28 May 1918, which may have been the largest earthquake in the area that is known from the historical record. In addition to its importance in helping define the seismicity of north-central New Mexico, the Cerrillos shock is of interest to the student of New Mexico earthquakes for several reasons: (1) it usually is listed among the five largest known historic earthquakes in the state but is somewhat isolated from the Socorro region where most of the other large shocks occurred; (2) to my knowledge, it is the only New Mexico earthquake where major ground breakage is alleged to have occurred; and (3) its size and location suggest its potential importance in understanding the tectonics of the Rio Grande rift (Sanford and others, 1979a).

Many of the facts regarding the Cerrillos earthquake have been known to investigators of New Mexico earthquakes for a number of years, but the details are contained in widely scattered publications. In addition, I know of no previous attempts to locate possible eyewitnesses among still living individuals or to evaluate potential data that may exist on the recordings of the few early seismograph stations of the western United States. For these reasons, I believe it is of some value to review here the circumstances of the Cerrillos earthquake and try to relate it to modern work on the seismicity of the region.

PHYSIOGRAPHIC AND TECTONIC SETTING

The base map of Figure 1, adapted from Baltz (1978), outlines the major tectonic elements of north-central New Mexico. The dominant structural feature is the Rio Grande rift which bisects the area north-to-south. The rift lies between two prongs of the Southern Rocky Mountains which separate the Great Plains physiographic province on the east and the Colorado Plateau to the west. The salient of the Rocky Mountains that extends southward from Colorado into central New Mexico has the greatest uplifts generally along the eastern margin of the rift. The Rio Grande rift consists of a series of elongate basins with uplifted margins arranged in a right stepping echelon pattern. Most of the deep basins (San Luis, Santo Domingo and Albuquerque basins) in this section of the rift overlie a basement of asymmetric, east-tilted blocks with the greatest fault displacements occurring along the eastern margins; the Espanola basin is more nearly a synclinal sag (Baltz, 1978) whose western boundary faults are masked largely by the Jemez volcanic pile.

Gravity data (Cordell, 1976, 1979) suggest a structural relief of more than 2 km across the rift margins, but modeling across the steep gravity gradients also suggests either a complex series of stair-step faults at depth or a lateral inhomogeneity in sediment density near the basin margins (Cordell, 1979).

The study area is transected SW to NE by a series of volcanic centers (Mt. Taylor, Jemez, Taos and Capulin volcanic fields) which has been termed the Jemez lineament, and which Chapin and others (1978) have suggested is one of several transcurrent shear zones controlled by deeply penetrating flaws in the lithosphere that tend to leak magma and influence deformation in the near-surface rocks.

This discussion is intended only as a brief sketch of the major features of the area. For details on geology, tectonics, geophysics and evolution, the comprehensive reviews (and references therein) by Baltz (1978), Chapin (1971, 1979) and Cordell (1978) should be consulted.

SEISMICITY FROM INSTRUMENTAL STUDIES 1973-1978

Figure 2 is an overlay plot of the microearthquake epicenters located within the study area for the period from 1 September 1973 through 30 November 1978. The data are derived from the catalog of Cash and others (1979), and represent readings principally from the LASL seismic network with supplementary readings from both SNM and the ASL network, especially after 1976. The distribution of continuously recording seismograph stations as of spring 1979 is portrayed in Figure 3. The concentration of stations along and immediately to the west of the Rio Grande rift is evident. This distribution probably leads to a bias against the detection and location of the smaller magnitude earthquakes (M_L <1.5) when they occur more than 20-50 km from the densest part of the network; this bias may be partly responsible for the impression of diminishing seismicity near the NW, NE and SE corners of Figure 2. The distribution of smaller events also is affected somewhat by detection threshold effects in 1973-1975 before about half of the LASL network had been installed (Cash and others, 1979); the major features of the distribution as determined by the larger shocks are, however, well established. Magnitudes shown in Figure 2 are based on a coda-length (duration) measurement technique that probably will require minor adjustments to properly match the Richter M_L scale for events above 5. Accurate focal depths have been determined for only a few of the earthquakes shown in Figure 2; these reliably known values plus other evidence indicate that most of the seismic activity in the area occurs in the upper crustal layer above a depth of about 20 km (Cash and others, 1979; Sanford and others, 1979a).

The above authors have discussed the microearthquake pattern of this area for the time period prior to June 1978. Here, only the highlights of the activity pertinent to the present discussion will be given.

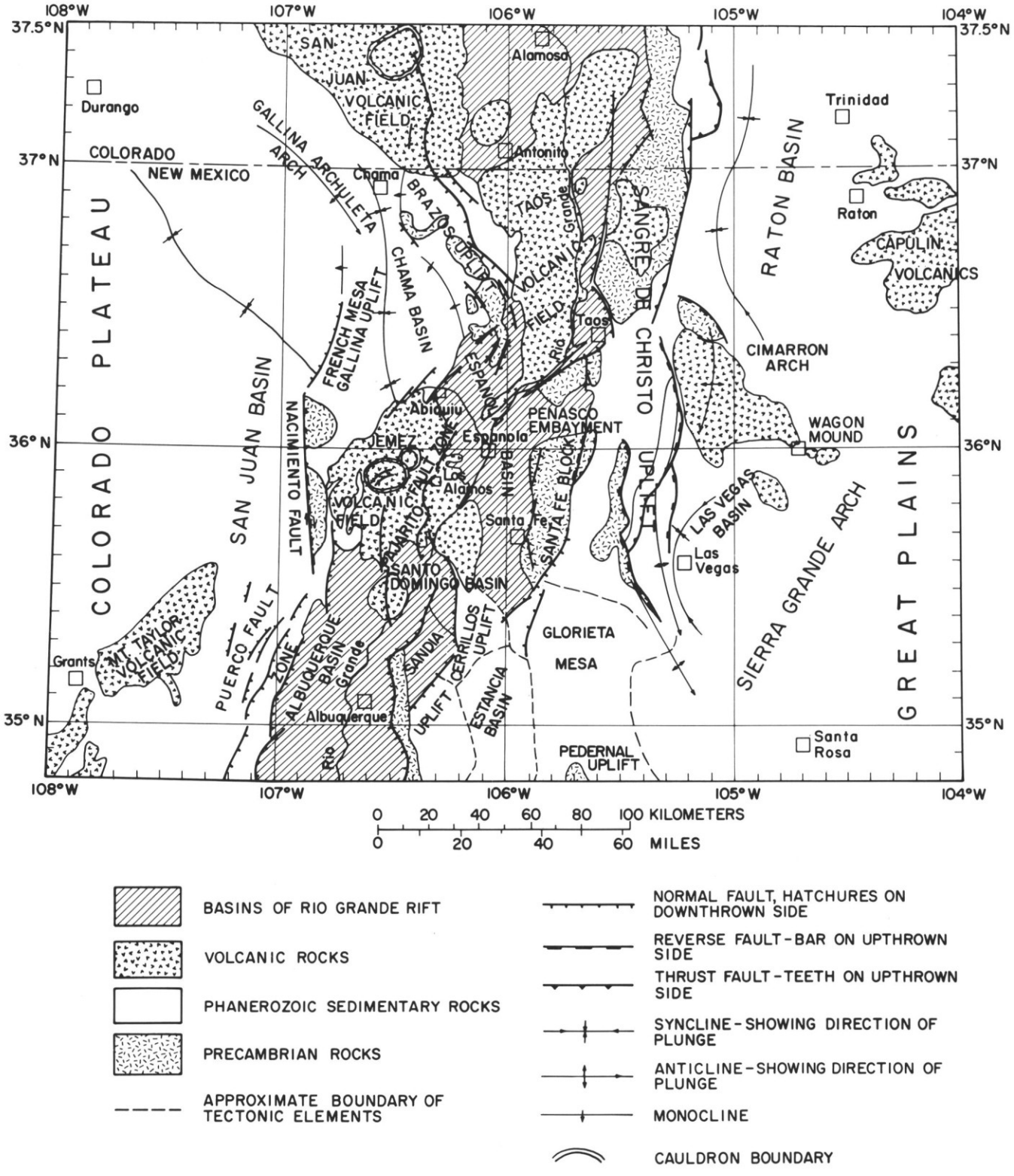


Figure 1. Generalized tectonic map of north-central New Mexico. Adapted from Baltz (1978), and Woodward and others (1975).

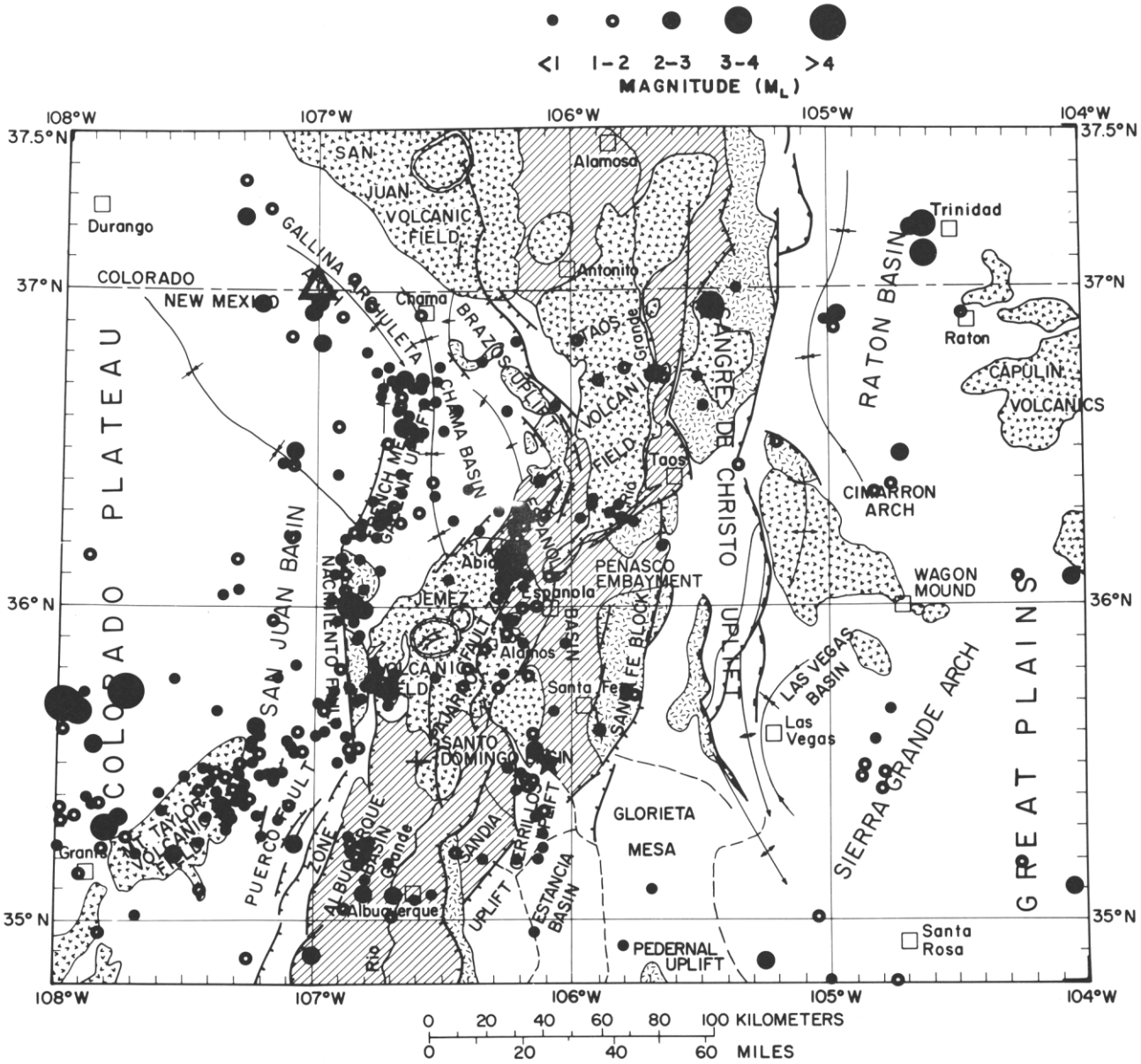


Figure 2. Map of north-central New Mexico showing epicenters and approximate magnitudes of earthquakes located by local seismic networks between September 1973 and December 1978. The approximate epicenter of the 1918 Cerrillos earthquake is shown by a star at 35.5° N, 106.1° W. An open triangle (37.0° N, 107.0° W) indicates the epicenter of the 1966 Dulce earthquake.

(1) The first impression from Figure 2 is that the largest percentage of microearthquakes during this 5-year period follows the SW-NE trend of the Cenozoic volcanics (Jemez lineament). This apparent association with the Cenozoic volcanics over even a wider part of the state has been noted previously by Sanford and others (1976a,b). A second arcuate belt of activity follows the northerly trend of the system of faults and uplifts of the Nacimiento fault-Gallina uplift-Archuleta arch system into southwestern Colorado where the detection sensitivity for the LASL network declines significantly. There is no obvious association of epicenters with the major surface features of the Rio Grande rift during this period.

(2) A striking feature of Figure 2 is the almost complete absence of even small earthquakes in large approximately circular areas centered on the Jemez volcanic field and about 60 km to the south, at the northern end of the Albuquerque basin. These areas are well covered down to very low ('\0 to 1) magnitude levels by several nearby seismograph stations, so that the feature is not a result of inadequate monitoring. Olsen and others (1976), and Sanford and others (1979a) have proposed that the apparent quiescence can be explained by high temperatures at shallow depths in the crust, which allow strain release by plastic deformation rather than by brittle failure. This western flank of the rift is a high heat-flow area (Reiter and others, 1979). Similar aseismic features are centered on the Yellowstone and Long Valley (California) calderas.

(3) There is no clear association of epicenters with specific surface faulting, partly because the probable errors in epicenter location are too large (at least ±5 km) to permit an unequivocal association with surface faults. The most consistently active earthquake zone is a N-S cluster (about 50 km long) between Espanola and Abiquiu (centered at about 36.1°

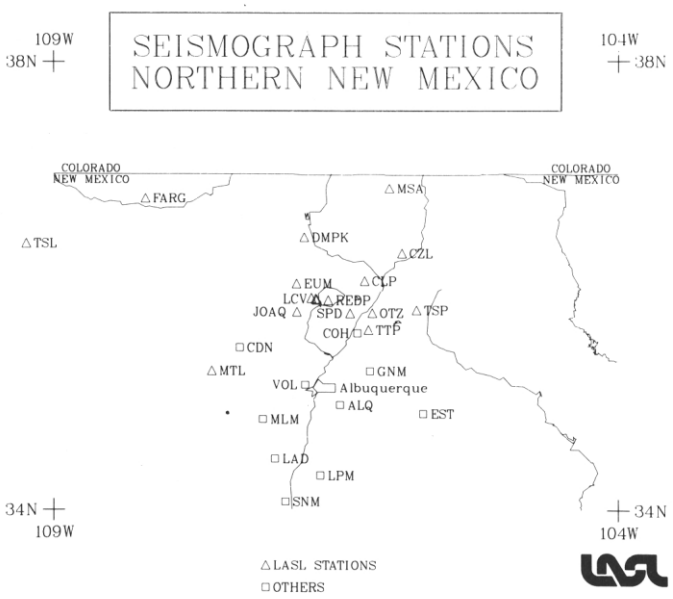


Figure 3. Index map showing locations of permanent seismograph stations in northern New Mexico as of April 1979.

N, 106.2° W on Figure 2) near the intersection of the western boundary of the Rio Grande rift and the Jemez lineament. Swarm-like activity has been known here since at least 1952. In the fall of 1978, two small swarms occurred for several months near the Albuquerque Volcanoes (35.2° N, 106.8° W) and west of Jemez Springs (35.7° N, 106.7° W).

(4) The neighborhood of the magnitude *5.5,* January 22, 1976, Dulce earthquake (open triangle in Figure 2 near 37° N, 107° W) still shows a moderate level of activity although the time period (several months to a year) for aftershock activity from a main shock of this magnitude has been exceeded. The probable epicenter for the 1918 Cerrillos earthquake (star near 35.5° N, 106.1° W of Figure 2) is situated at the edge of only a minor and poorly defined region of activity.

THE MAY 28, 1918 CERRILLOS EARTHQUAKE

Principal Facts

The Cerrillos earthquake occurred at 1130 GMT (5:30 a.m. mountain daylight time or 4:30 a.m. MST) on Tuesday, May 28, 1918. The latest revised edition of the *Earthquake History of the United States* (Coffman and von Hake, 1973) lists the event as an "intermediate to minor earthquake," maximum intensity VII-VIII, a felt area of 7,500 square miles ('N.'19,400 km^2) and centered at 35.5° N latitude and 106.6° W longitude. As will be seen from the data discussed below, the longitude value of 106.6° W places the epicenter about 0.5° ('N.'45 km) too far to the west to be consistent with maximum felt effects near Cerrillos. This is undoubtedly a clerical error, which crept into the tabulations in an early edition of the *History* (von Hake, personal commun., 1979). Tabulations by most other workers (e.g., Sanford, 1976; Sanford and others, 1979b; Woollard, 1968) list more nearly correct values of 106.0° or 106.1° W. Accordingly, the position of the 1918 earthquake is denoted by the star on Figure 2 at 35.5° N, 106.1° W.

It is interesting to note that the erroneous longitude value would have placed the 1918 earthquake in the center of the large aseismic area in the northern Albuquerque basin that has been delineated by instrumental studies since 1973. Although the felt reports discussed below clearly show this is not the case, it nevertheless leads one to wonder over what time scales (years, centuries or longer) such a seismic anomaly can exist. One of the alternative explanations for the aseismic region could be that it is a "seismic gap" where the faults are presently locked and where stress is building up until a threshold value for releasing large but infrequent earthquakes is reached. Such occurrences (especially near subducting plate boundaries in oceanic trench regions) are well known from recent seismological researches. Although the limited evidence in the Jemez and Albuquerque basin regions is as yet far from conclusive, I believe the more likely hypothesis is the one advanced earlier: that high temperatures in the upper crust allow continuous stress release by plastic deformation rather than by intermittent large earthquakes. The analogous seismic patterns near Yellowstone and Long Valley argue strongly for this interpretation. However, the question of the geologic time scales for changes in such thermo-relaxation phenomena is still of considerable interest and importance for geologic hazard assessment.

From early in the century until 1924, the U.S. Weather Bureau was the federal agency charged with collection and tabulation of reports on U.S. earthquakes. Both felt reports and abbreviated summaries of instrumental data were tabulated in the *Monthly Weather Review* (MWR) journal. The felt reports for the 1918 earthquake as given in the May 1918 MWR are reproduced here as Table 1. It was customary in 1918 to report effects on people and structures in the epicentral areas on the Rossi-Forel (RE) intensity scale. The Rossi-Forel scale is similar in many respects to the presently used Modified Mercalli (MM) scale, which was revised and standardized in 1931 (Richter, 1958). RF intensities are approximately 1/2 intensity unit greater than MM for the same effects; the differences are mainly of importance in attempting to compare peak intensities of older earthquakes with the correlations (of peak accelerations, magnitudes, etc.) that usually have been made with the MM scale. The RF values originally reported in 1918 are used here with an attempt below to correct to equivalent MM values before making magnitude estimates.

The intensity values of Table 1 are plotted in map form in Figure 4 and approximate isoseismal contours are drawn in. A similar map, based on the same data, was constructed several years ago by Northrop (personal commun., 1979). Although the data are sparse, a fairly consistent set of contours emerges. The largest ambiguity is the datum point for Montoya, NM (a station on the AT&SF railway) which appears to be either overestimated or spurious. On the other hand, an extension of the "feeble shock" (RE II) region to the east may be a manifestation of a much more efficient transmission (i.e., less attenuation) of seismic vibrations through the crustal structure of the Great Plains than is the case for the more attenuating paths within the Rio Grande rift. Large differences in total felt area for earthquakes in the eastern U.S. versus western U.S. (especially California) are well documented (Nuttli and Zollweg, 1974). The best known comparisons are the vastly different felt areas for the 1812-New Madrid and the 1906-San Francisco earthquakes (Nuttli, 1973). For the purposes of this discussion, I have discounted the Montoya report, and thence derive an average radius of perceptability (defined as MM in-

*Table 1. Summary of Noninstrumental Reports for the Cerrillos Earthquake of 28 May 1918**

Station	Approximate Latitude	Approximate Longitude	Intensity Rossi-Forel.	Number of Shocks	Duration	Sounds	Remarks	Observer
Albuquerque	35 06	106 39	3	1	Few	None.	Slight trembling.	Albuquerque Even. Herald
Cerillos. . .	35 27	106 07	10	. . . . .	. . . . .	. . . . .	Many plastered ceilings and chimneys fell. People on street thrown off their feet. Heavy break in surface of earth at edge of town. No one badly injured.	Albuquerque Even. Herald
Espanola. . .	36 00	106 05	3-5	1	02	Faint.	Like distant thunder. Rapid rocking and trembling. People awakened.	Mrs. E. F. McBride
Estancia. . .	34 49	106 04	2	1	1 00	None.	Rapid twisting.	J. L. Stubblefield
Lamy.	35 29	105 53	7-8	. . . . .	12	. . . . .	Rapid twisting about six times. Frame house swayed back and forth and walls creaked in the corners of rooms.	T. W. Hanna
Las Vegas. .	35 35	105 14	2	1	Few. . . .	None.	. . . . .	Las Vegas Daily Optic
Montoya. . .	35 06	104 04	2	2	10	None.	Abrupt trembling.	E. S. Micksch
Moriarty. .	34 59	106 03	5	1-3	05	Rumbling.	Like distant thunder. Abrupt trembling.	H. M. Bigger
Pena Blanca	35 35	106 21	5-7	1	. . . . .	. . . . .	. . . . .	Samuel H. Sayee
Porvenir . .	35 43	105 25	2	1	Few. . . .	None.	. . . . .	R. E. Springfels
Santa Fe . .	35 41	105 57	4-7	1	03	Rumbling.	Abrupt rocking SW-NE. Shook down plaster. Doors and windows rattled.	Charles E. Linney
Stanley. . .	35 07	106 00	5-8	1	. . . . .	Rumbling.	Abrupt bump and rocking E-W. Doors rattled, piano sounded, some adobe walls cracked.	Henry Winans
Valmora. . .	35 47	104 59	2	1	Few. . . .	None.	. . . . .	Alice Brown
Waldo. . . .	35 28	106 10	5-8	1	Few. . . .	. . . . .	Awakened people.	Albuquerque Even. Herald

*[Reproduced from the US Weather Bureau's Monthly Weather Review (MWR) for May 1918, page 243]

tensity 1.5 according to Richter (1958) or the boundary of the RF II isoseismal) of 100 km. This leads to a total felt area of about 31,000 km^2.

Several additional facts about the 1918 shock are worth mentioning:

(1) The time of the shock is perhaps known within ± 5 minutes. *The Santa Fe New Mexican* for May 28 quotes Mr. John Daniels, a clerk at the Montezuma Hotel, as saying:

> it occurred exactly at 5:30, for I had to call a guest at that hour and was on my way downstairs ..."

The Albuquerque Morning Journal quotes an observed time of 5:33 a.m. in Albuquerque.

(2) Oldtimers could remember only two previous occasions when earthquakes were felt in Santa Fe: "in 1874 and in 1906." The 1874 reference probably refers to the August 1, 1873 (4:30 p.m.) earthquake centered near Galisteo (?), for which there seems to be a six-hour discrepancy in time between the (1873) newspaper report and the tabulation of Woollard (1968). The 1906 reference is undoubtedly to one or more of the three large Socorro events of that year (beginning in July, 1906), although most of the quoted residents seem rather to associate it in their minds with the famous San Francisco earthquake (in April, 1906). Apart from perhaps the description of some of the effects at Cerrillos (see below), there seems to be little obvious exaggeration or sensationalism in the newspaper articles as there often are for very large earthquakes and as was the case for the 1906 Socorro shocks (Ashcroft, 1974).

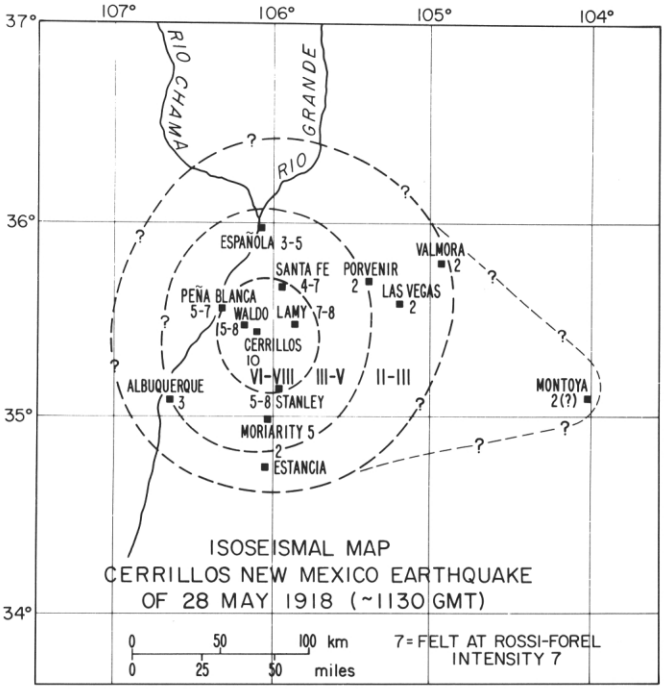


Figure 4. Sketch map showing reported Rossi-Forel intensity estimates and approximate isoseismal contours for the 28 May 1918 earthquake.

(3) A brief article in *The Santa Fe New Mexican* for Friday, June 1, refers to a visit to Santa Fe by "Prof. Fayette A. Jones, well known mineralogist, geologist, former president of the state school of mines (Socorro) and a mining engineer...." Jones is quoted as saying "a small slip on a fault caused Tuesday's earthquake." No record can be found of Prof. Jones' paying a visit to the Cerrillos area to inspect the crack in the ground or other damage there. This is regrettable as fresh, first-hand observations by a trained geologist would be very useful in the present task of evaluating the size of the 1918 shock. Jones had been at Encino on the day of the earthquake and stated that the effects there were strong enough to "send people flying from their beds...." When taken literally, the reference to people "flying from their beds" would suggest an intensity at Encino as great as RF VI, which is more typical of the Santa Fe reports! The MWR did not list any report from Encino and its location (34.6° N, 105.5° W—about 50 km ESE of Estancia) near the boundary of the outer isoseismal in Figure 4 would indicate that there is considerable exaggeration in the report. However, the possibility remains that the Encino intensity was indeed somewhat greater than the barely marginal RF II which lends credence to the reality of the "Montoya salient." Thus, this evidence suggests that the 31,000 km^2 felt area adopted here may be on the low side.

(4) Many of the felt reports in Table 1 and in newspaper reports set forth the impressions of the witnesses as to the direction of shaking or that "the quake moved from southwest to northeast." Prior to 1915, John C. Branner, one-time president of the Seismological Society of America, attempted to evaluate personal (i.e., noninstrumental) impressions of direction of vibration (Branner, 1915). He concluded that although direction of vibration was one of the items listed in defining the Rossi-Forel scale (RF III), personal impressions could not be correlated with instrumental data and that such criteria should be dropped from the RF definitions. Modern usage of the MM scale does not recognize as significant the apparent direction of vibration when estimated by observers indoors.

Effects at Cerrillos

The shaking effects at Cerrillos deserve a careful consideration because most estimates of the ultimate strength of the shock rely almost exclusively on these observations. The descriptions of effects contained in the newspaper reports and summarized in Table 1 for the nearby communities of Waldo, Pena Blanca, and to some extent, at Stanley and at Lamy are so brief as to make them difficult to evaluate, beyond noting that they are consistent with the definitions in the MM V to VII range (the MM and RF scales are nearly identical in this range). At Cerrillos, the assigned intensity value of RF X in Table 1 apparently is influenced heavily by the reported "heavy crack" in the ground; the other phenomena, such as the falling of some plaster and chimneys, broken windows, cracks in the adobe buildings, and difficulty in people standing are more typical of MM VII (lower ranges of RF VIII) effects. Nason and Espinosa (1977) pointed out that continuing experience has shown major difficulties with the position of geologic ground failures relative to building damage on the MM and RE scales. Building damage is primarily a consequence of shaking (i.e., acceleration), whereas ground failures due to liquefaction, slumping, faulting and landslides are long-period effects more nearly related to displacements and are critically dependent on the exact nature of the soil, saturation, water table depth, etc. Based on instances (e.g., the Guatemala earthquake of 1976) where earth failures occurred at comparatively low intensities, Nason and Espinosa (1977) recommend reevaluation of the ground breakage criteria to make them more representative of the degree of shaking for a given intensity value. I believe that the probable location of the ground crack at Cerrillos (see below) indicates that it was in soft, sandy material close to the Galisteo River, and therefore, represented a relatively minor, secondary effect which should be given low weight in assigning an intensity value for the 1918 earthquake. Accordingly, I have adopted an intensity of MM VII (or possibly low MM VIII) for Cerrillos which agrees with the interpretation of several other investigators (e.g., Coffman and von Hake, 1973; Northrop, personal commun., 1979; Sanford, 1976).

In order to clarify the location and nature of the 1918 ground breakage, I made an effort to locate and interview present residents of Cerrillos who might remember the earthquake and its results. This venture met with only limited success. Four people were found who were school children living at Cerrillos in 1918. Three of these could not recall the earthquake at all either from personal experience or from having heard family or friends talk of it. The fourth, Mrs. Emma Simoni Montoya, whose father owned the store and boarding house across the street from the Tiffany Restaurant and Saloon, remembered being awakened by the shock in her bedroom on the second story of the store. The Simoni store sustained several cracks in the walls at the rear of the building, and Mr. Simoni repaired the damage by connecting bolts and plates in the outer walls by a steel cable running through the building and then plastering over the cracks. She remembered the crack in the ground as running approximately in an east-west direction and crossing the street in the vicinity of the present church about one and a half blocks ('\50 meters) southwest of the store. This places the crack approximately midway between the store and the bank of the Galisteo River. She could not recall any details of the length or width of the opening in the ground. From the location and the nature of the sandy, alluvial soil in the vicinity, it would appear that the ground breakage likely was caused by compaction and settling of the soil at relatively shallow depths in the terrace upon which the town is built north of the river.

In reply to a question as to what the people who were "thrown off their feet" by the shock were doing out on the street at 5:30 a.m., Mrs. Montoya and another resident, Mr. Verne Byrne, stated that many people were up early to begin work in the mines in the area. Although the heyday of the mining boom in the Cerrillos district had passed about the turn of the century (Simmons, 1974), mining was still the principal occupation of most of the residents, with several active lead-zinc mines just north of Cerrillos and the Ortiz Mountains 10 km to the south. The coal workings at Madrid (3 km south) also were operating at the time.

Instrumental Data

In addition to the noninstrumental reports reproduced here as Table 1, the *Monthly Weather Review (MWR)* for May 1918 contains a section for instrumental data. One of the seismograph stations tabulated in the May 1918 MWR was the station at Sacred Heart College (now Regis College) in Denver, Colorado, which noted wavelets visible on both seismograph components at 1610 and about 1800 GMT. Although these signa-

tures were unlikely to have originated with the Cerrillos shock that occurred at 1130 GMT, this reference prompted the author to see if the old seismograms from Denver, and possibly other stations, could be located and measured to give further data on the Cerrillos earthquake.

In 1918, there were only 6 operating seismograph observatories within 1500 kilometers of Santa Fe. These consisted of: 3 stations at Denver, Colorado (485 km), Santa Clara, California (1430 km), and St. Louis, Missouri (1450 km) operated by the Jesuit Seismological Service (Macel wane, 1950); 2 stations at Berkeley (1466 km) and Mt. Hamilton (Lick Observatory) (1407 km) operated by the University of California; and one station operated by the U.S. Coast and Geodetic Survey at Tucson, Arizona (567 km). The nearest station in Mexico was Tacubaya (near Mexico City at 1908 km); unfortunately, the high-quality, 1200-kilogram Wiechert instruments were not installed at Chihuahua until 1927. The instruments at all the Jesuit installations were two-component Wiechert astatic inverted pendulums of 80 kg mass, 6-second natural period and writing traces on smoked paper which were magnified 80-fold from the true horizontal ground displacements. The Tucson instrument was a Bosch-Omori undamped horizontal pendulum of 20-second period giving a nominal magnification of 10. The California observatories used a variety of similar instruments, but I have not examined the 1918 California records because of the negative results obtained from the closer stations at Denver and Tucson.

A search of the archives of the Tucson, Denver and St. Louis seismological observatories yielded only the seismogram from Tucson for the day of 28 May 1918. For both Denver and St. Louis, it apparently was decided some years ago to clean out and discard seismograms for those days that "did not contain earthquakes," not realizing that even marginal recordings could in some cases provide useful information on detection ranges and magnitudes for past earthquakes. However, all stations had retained records for 23 May 1918 when a large earthquake occurred in the Gulf of Mexico. A comparison of the measurable 23 May records with an estimate of the small background amplitude excursions (which were quite similar from day to day) for the missing 28 May records would at least allow an estimate of the upper limit to the magnitude of the Cerrillos quake.

The existing 28 May Tucson record does not show any obvious "wiggles" at the time of day of the Cerrillos earthquake. Since the Tucson Bosch-Omori instrument was relatively insensitive even to the long-period (20 sec) waves characteristic of distant large earthquakes (teleseisms) which it was designed to record, it hardly would respond at all to the higher frequencies of even very strong local and regional earthquakes. This was a common difficulty with the early and more recent amateur pendulum instruments (Richter, 1958, p. 336). Absence of damping in the Bosch-Omori also makes reliable amplitude measurements very difficult (Davison, 1921; Heck, 1936). For these reasons, plus the fact that the stylus of the Tucson instrument was off the paper resulting in a six-minute gap during the 23 May earthquake, the Tucson records could not be used to set a magnitude limit on the Cerrillos earthquake.

Magnitude readings for an earthquake observed at different observatories are made by measuring amplitudes of several seismic phases from the seismograph records, applying a correction for the distance (and sometimes the direction) between the earthquake and the seismograph, and converting these to a logarithmic scale. Magnitude is thus a quantitative measure of the energy of the earthquake source whereas the intensity values depend on the distance from the epicenter, focal depth, nature of the transmission path and other factors in addition to the energy. The several different magnitude scales in use (local Richter, body wave, surface wave, etc.) often are confusing to the nonspecialist. In essence, all magnitude scales are derived empirically and are complicated by the fact that several varieties of earthquake waves (phases) leave the earthquake source and travel by various paths through the Earth's crust and mantle to the seismograph. The character of the seismogram changes with distance, with certain phases becoming prominent and measurable only over limited distance ranges. The average relationships between magnitudes measured on the different scales are known (Bath, 1973; Richter, 1958), and for purposes of comparison, the values derived from different phases can be converted to equivalent magnitude values on a single chosen scale. Here, I have converted all magnitudes to an equivalent on the M_L or local scale of Richter (1958), which strictly is applicable only within about 600 km of the source, although, for example, the measured phase on the seismogram in question may have been a surface wave at considerably greater distance.

Because the calibration characteristics of the early seismographs often were not well specified and could have been changed significantly by a variety of factors (e.g., friction in the recording linkage, pier and foundation construction, damping adjustments, etc.), it is helpful to have observations of a common known event to reassure the observer before attempting evaluation of amplitude measurements for quakes of unknown magnitudes. Thus, the May 23, 1918 (11:57:30 GMT) earthquake in the Gulf of California (near 27° N, 111° W) is very useful in checking the operating characteristics of the Denver and St. Louis Wiechert seismographs for May 1918. This earthquake was assigned a surface wave magnitude value of 6.8 by Gutenberg and Richter (1954, table 17, event #340), who averaged readings from many stations around the world. The measured amplitudes and the derived magnitudes for the Denver and St. Louis 80 kg Wiecherts are summarized in Table 2a for surface waves (the most prominent phase on both records) and in Table 2b for body waves. The three magnitude scales in common use (the surface wave magnitude Ms, the "unified" or body wave scale, m, and the local scale M_L) all nearly coincide in numerical value for the range 6.5 to 7.0 so that no scale corrections are necessary. Even though the surface wave values may be affected by azimuthally dependent radiation-pattern effects and the body waves (in this case, the P phase) on the seismogram were near the limit for accurate measurement, the derived values in Table 2 usually fall with ± 0.5 magnitude unit of the Gutenberg and Richter assigned value. These are representative of the scatter of individual determinations of station magnitude.

Since the records from both St. Louis and Denver for 28 May 1918 apparently were not retained, any phases from the Cerrillos event can be assumed to have been less than or equal to the small oscillations that occur more or less continuously on the seismograms of other days. This threshold level was found to be approximately 1 mm on the seismograms; anything coherent on both components of greater amplitude than this probably would have been noticed and the records thus retained. Table 3 summarizes the results of assuming these

Table 2. Magnitude Estimates

80 kg Wiechert Seismographs at Denver and St. Louis

Gulf of California Earthquake of 23 May 1918 (11:57:30 GMT)
M_s = 6.8 (Gutenberg and Richter, 1954)

TABLE 2a - SURFACE WAVE MAGNITUDE - calculated from Moscow-Prague formula of 1962 (Båth, 1973, p.114): $M_s = \log_{10} (a/T) + 1.66 \log_{10} \Delta^\circ + 3.3$.

Station	Distance, Δ (degrees)	Component	Measured Double (Peak-to-Peak) Amplitude on Seismogram (mm)	Observed Period T (seconds)	Calculated Magnitude (M_s)
Denver	13.7	N-S	72	∿ 10	6.8
		E-W	84	∿ 10	6.9
					6.85 Avg.
St. Louis	20.9	N-S	9	∿ 10	5.9
		E-W	34	∿ 10	6.8
					6.35 Avg.

Table 2b - BODY WAVE MAGNITUDE - calculated from Gutenberg & Richter (1956b): $m = \log_{10} (A/T) + Q (\Delta,h)$

Station	Distance, Δ (degrees)	Component	Measured Double (Peak-to-Peak) Amplitude on Seismogram (mm)	Observed Period T (seconds)	Calculated Magnitude (m)
Denver	13.7	N-S	∿ 0.5	∿ 3	6.9
		E-W	∿ 0.5	∿ 3	6.9
St. Louis	20.9	N-S	∿ 0.5	∿ 3	6.4
		E-W	∿ 1.0	∿ 3	6.7

upper-limit signals and deriving the equivalent magnitude values above which the Cerrillos earthquake should have been observable at these stations. As expected, the nonobservability of any phases at Denver places a greater restriction on the magnitude than is the case for St. Louis. The surface-wave estimate depends somewhat on the period assumed for surface waves; even if these were as short as 6 seconds, as is often the case for moderate earthquakes observed with modern instruments, this only increases the limit by + 0.3. The numbers in Table 3b are derived by assuming that the largest amplitudes would be the same phases that are observed out to about 600 km by a Wood-Anderson seismograph, the instrument upon which the M_L scale is based. These upper-limit crustal-phase values are significantly in excess of the corresponding values for surface-wave observations and serve as a reminder of the considerable insensitivity of early instruments to even moderately strong regional shocks.

Although the results of the study of the 1918 seismograms are somewhat less definitive than was hoped, I conclude that instrumental evidence suggests that the Cerrillos earthquake had an equivalent M_L magnitude in the range of 4.5 to 5.0.

DISCUSSION AND CONCLUSIONS

When the experience with soil failures observed at moderate intensity levels in several recent earthquakes is considered, the ground crack observed at the 1918 Cerrillos earthquake becomes relatively unimportant in assigning a peak intensity value to the 1918 earthquake. Although the peak intensity of MM VII compared with a total felt area of 31,000 km² is somewhat higher than the norm for California earthquakes, it is within the spread of the data and perhaps may be the consequence of a very shallow (less than 5 km) focal depth. The pronounced effects in the town of Cerrillos probably mean that the epicenter was within a few km and the town, in

Table 3. Upper-Limit Magnitude Estimates for the 1918 Cerrillos Earthquake

Derived from Denver and St. Louis Wiechert Seismograms

Station	Distance (degrees/ kilometers)	A. SURFACE WAVES: Limiting Amplitude (mm)	Assumed Period (sec)	M_s	M_L (equivalent)	B. CRUSTAL WAVES: Limiting Amplitude (mm)	M_L
Denver	4.36° 485 km	< 1	∿ 10	< 4.5	< 4.8	< 1	< 5.9
St. Louis	13.0° 1450 km	< 1	∿ 10	< 5.2	< 5.5	< 1	(< 7.3)*

*Based on an extrapolation of Richter's (1958) log Ao distance correction.

effect, suffered a "direct hit" from an intermediate-sized earthquake.

The intensity and felt area can be used to estimate the magnitude of the Cerrillos shock. The relationships between seismic intensities and earthquake magnitude have been studied and documented by many investigators. The relationships between maximum reported intensity and/or felt area versus magnitude are best known for earthquakes in California and western Nevada where data for nearly a century are available. Richter (1958) reviewed the empirical data on peak intensity versus magnitude and radius of perceptibility versus magnitude for southern California earthquakes. Slemmons and others (1965) derived a relation between magnitude and total felt area for a larger data set of California and western Nevada shocks. Toppozada (1975) also studied the California/western Nevada data and presented several relations between magnitude and the areas included within isoseismal contours at various intensity levels. Barosh (1969) summarized seismic intensity scales and magnitude relationships, including Soviet results. Nuttli and Zollweg (1974) provided magnitude-versus-felt-area relationships for earthquakes in the central United States, and Housner (1970) listed separate magnitude-intensity equations for earthquakes in the eastern U.S., Rocky Mountains and western U.S.

Very few data are available on which to base an empirical relationship between magnitude and peak intensity or felt area for New Mexico earthquakes. The different crustal structures in different parts of the state (Great Plains province, Colorado Plateau, Rio Grande rift, and Basin and Range province) imply that separate and perhaps quite different relationships should be used for each major tectonic province. A few available intensity data suggest that, for earthquakes occurring within the Rio Grande rift, the relationships developed for California and western Nevada give reasonable and consistent results when compared with instrumental magnitudes. Table 4 lists the magnitude estimates of the 1918 Cerrillos shock as derived from the various intensity relationships developed by several researchers for western U.S. earthquakes. All of these magnitude estimates are based on the values adopted here of maximum intensity MM VII, total felt area of 31,000 km², and a radius of perceptibility of 100 km². In applying Toppozada's formulae for areas including the intensity V and VI isoseismals to the Cerrillos event, there is some ambiguity as to the exact boundaries of these isoseismals, as can be seen from Figure 4.

Table 4. Estimates of Local Magnitude, M_L, of the 1918 Cerrillos Earthquake Based on Intensity and Felt-Area Data

INVESTIGATOR	TECHNIQUE AND RELATED VARIABLES	M_L
Gutenberg & Richter (1956) Also Barosh (1969)	Magnitude vs. Radius of Perceptibility	4.6
Slemmons et al. (1965)	Total Felt Area	5.3
Housner (1970)	Total Felt Area-Western U.S.	4.5
Toppozada (1975)	Peak Intensity	5.3
Toppozada (1975)	Total Felt Area	5.0
Toppozada (1975)	Area Within Intensity = 6 Isoseismal ($\sim$ 2800 km^2)	5.5
Toppozada (1975)	Area Within Intensity = 5 Isoseismal	4.6

The inner contour shown in Figure 4 equally well could be interpreted as the boundary enclosing intensity V or the boundary enclosing intensity VI. Upper and lower limits on the magnitude can be derived by assuming that this contour (radius 'N. 30 km, area's 2800 km^2) is, respectively, the intensity VI and the intensity V boundary.

The intensity evidence summarized in Table 4 indicates that the Cerrillos shock had a magnitude between 4.5 and 5.5, with the preference for a value slightly greater than 5.0. The M_L 4.8 upper limit derived from the instrumental analysis is in very good agreement considering the uncertainties in both techniques. Corresponding quantities for the 1966 Dulce earthquake were reported by Cash (1971) as: maximum reported intensity VII, total felt area 42,000 km^2, m_b 4.9 and M_L 5.2. Since the felt area of the Cerrillos earthquake may be somewhat underestimated because of low population density in 1918, the two shocks were apparently very similar as was proposed previously by Sanford (1976).

This review of the available information on the Cerrillos earthquake suggests that no unusual or unique mechanism is needed to fit the 1918 earthquake into the seismicity pattern and rates observed presently in north-central New Mexico.

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