SEISMICITY OF THE RIO GRANDE RIFT

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Abstract. Earthquakes have been noted along the Rio Grande rift since 1849. During the period of non-instrumental reporting of earthquakes from 1849 through 1961, nearly all earthquakes occurred along a 150 km section of the rift from Albuquerque to Socorro, the majority in the 75 km of rift from Belen to Socorro. In the latter area, the most notable seismic activity was an intense and prolonged earthquake swarm from 1906-1907 which included three moderately strong shocks (felt areas from 125,000 to 245,000 km²).

Instrumental studies starting in 1962 have revealed a low level of seismicity in the rift during the past 16 years, only an average of two shocks with $M_L \geq 2.4$ each year. During the same period, a comparable level of seismicity was observed in the High Plains and Colorado Plateau, two neighboring physiographic provinces which geologic data indicate are more tectonically stable than the rift. An additional finding of the instrumental studies was large seismic gaps along the rift, e.g. from Socorro to Las Cruces, where no shocks with $M_L \geq 2.4$ have occurred since 1962.

Detailed seismic studies along the rift by New Mexico Institute of Mining and Technology, Los Alamos Scientific Laboratory, and Albuquerque Seismological Laboratory (U.S.G.S.) have shown that areas of concentrated microearthquake activity exist within the rift, notably from Belen to Socorro and 15 km west of Española. Both of these seismic regions may be associated with modern magma bodies at middle to upper crustal levels. An important finding of the LASL studies is an absence of microearthquake activity in a rather large area centered on the Valles caldera, a possible indication of high temperatures at shallow depths in the crust. Composite fault plane solutions for microearthquakes in the rift suggest that both strike-slip and normal faulting, the latter dominant, are currently occurring in the rift. The average direction of the T axis for all solutions is near east-west.

The small number of shocks in the rift, along with their spatial distribution, suggests the rift may not be spreading at this time. Geodetic measurements at one location, Socorro, are in agreement with this tentative conclusion.
Introduction

The Rio Grande rift south of Albuquerque was recognized as a zone of unusually high seismicity in the western U.S. by a number of early investigators (Reid, 1911; Northrop, 1945 and 1947; and Richter, 1959). Identification of the rift as a seismic belt was based totally on reports of felt shocks, some fairly strong, dating from the latter half of the nineteenth century. Perhaps because of the relatively low population of the region and an absence of strong shocks for many years after the turn of the century, instrumental investigation of seismic activity in the rift did not begin until 1960 (Sanford and Holmes, 1961). In 1972 a paper summarizing seismic studies of the rift, conducted primarily by a group at New Mexico Institute of Mining and Technology (NMT), was published (Sanford et al., 1972). Since that date, instrumental data on rift earthquakes have increased dramatically, primarily because of the installation of arrays of seismic stations by groups at the Los Alamos Scientific Laboratory (LASL) and the Albuquerque Seismological Laboratory (ASL) of the U.S. Geological Survey.

This paper is a collaborative effort by NMT, LASL, and ASL to describe what is known of the seismicity of the Rio Grande rift to the present time. The paper summarizes non-instrumental data available prior to 1962, and instrumental data available since that date, including detailed studies of microearthquake activity in three sections of the rift by the groups at NMT, LASL, and ASL.

Geologic and Geophysical Characteristics of the Rio Grande Rift

Comprehensive reviews and interpretations of geological and geophysical studies of the Rio Grande rift have been published by Chapin (1971), Chapin and Seager (1975), and Cordell (1978). Additional details on the geologic and geophysical characteristics of the rift appear in this volume.

Earthquake Activity Prior to 1962

Information on locations and strengths of earthquakes prior to 1962 is based mostly on non-instrumentally determined values of earthquake intensity. Intensity values are assigned on the basis of reactions and observations of people during a shock and the degree of damage to structures. Given many intensity observations, the point of maximum intensity and the area of perceptibility can be established. Both of these factors, particularly the latter, can be roughly related to the earthquake magnitude (Richter, 1958; Slemmons et al., 1965; Wiegel, 1970).

A major weakness in determining the strengths and locations of earthquakes from intensity observations is that the method depends on population density. In sparsely settled areas like much of New Mexico, moderate shocks may go completely unreported or reported at low intensity values which do not indicate the true strengths of the earthquakes. Even in areas of relatively high population density, as along the Rio Grande valley, the point of maximum intensity or area of perceptibility may not be defined because of too few observations.

The reliability of the early reports of earthquakes must also be considered. In the case of Rio Grande rift, some of the intensities for strong earthquakes prior to 1900 are based on reports from local residents tens of years after the shocks (Bagg, 1904). Newspaper accounts of earthquakes have also been used to estimate earthquake intensity. In most cases, this has proven to be a fairly reliable procedure. How-
<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>Day</th>
<th>Location</th>
<th>Maximum Reported Intensity</th>
<th>Maximum Reported Intensity (M. M.)</th>
<th>Area of Perceptibility km²</th>
<th>Calculated Magnitudes</th>
<th>References</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1906</td>
<td>July</td>
<td>12</td>
<td>Socorro</td>
<td>VII-VIII</td>
<td>125,000</td>
<td>4.4, 6.1</td>
<td></td>
<td>Reid (1911), Coffman and von Hake (1973), Sanford (1963)</td>
<td>First strong shock of a swarm that commenced on July 2, 1906 and ended in early 1907. At Socorro, walls of many adobe houses were cracked and some brick chimneys were thrown down.</td>
</tr>
<tr>
<td>1906</td>
<td>July</td>
<td>16</td>
<td>Socorro</td>
<td>VIII</td>
<td>175,000</td>
<td>4.6, 6.3</td>
<td></td>
<td>Reid (1911), Coffman and von Hake (1973), Sanford (1963)</td>
<td>Slightly stronger than the shock of July 12. At Socorro, more cracked walls and toppled chimneys. Many of the people left their houses and lived in tents.</td>
</tr>
<tr>
<td>1906</td>
<td>Nov.</td>
<td>15</td>
<td>Socorro</td>
<td>VIII</td>
<td>245,000</td>
<td>4.9, 6.5</td>
<td></td>
<td>Reid (1911), Coffman and von Hake (1973), Sanford (1963)</td>
<td>Seve rest shock of the swarm. At Socorro, increased damage already done by previous quakes.</td>
</tr>
<tr>
<td>1918</td>
<td>May</td>
<td>28</td>
<td>Cerrillos</td>
<td>VII</td>
<td>31,000</td>
<td>4.1, 5.2</td>
<td></td>
<td>Coffman and von Hake (1973), Northrop (personal communication)</td>
<td>People thrown off their feet, break in earth's surface at edge of town, and plaster fell.</td>
</tr>
</tbody>
</table>
ever, in at least two instances the effects of earthquakes in the Rio Grande rift at Socorro were exaggerated in stories appearing in newspapers at Albuquerque and El Paso (Sanford, 1963; Ashcroft, 1974).

Despite the imperfect nature of the non-instrumental data, they are of considerable value because they are available for a period of time roughly eight times greater than the instrumental data. Summarized below are non-instrumental data which indicate the nature of seismic activity along the Rio Grande rift prior to 1962.

The earliest report of earthquakes anywhere in New Mexico or Colorado is a description of an earthquake swarm in the Rio Grande rift at Socorro by a U.S. Army surgeon (Hammond, 1966). The swarm, which contained 22 felt shocks, commenced on December 11, 1849 and lasted until February 8, 1850. None of the shocks in this swarm was reported felt at distances greater than 25 km. Similar sequences of shocks located away from population centers along the Rio Grande valley could easily have gone unreported before the start of instrumental studies.

For the period 1849 through 1961, Northrop (1961, 1976) cites evidence, primarily from old newspaper files, for over 600 felt earthquakes in New Mexico. About 95 percent of these shocks occurred along a 150 km section of the Rio Grande rift from Albuquerque to Socorro; the majority in the 75 km of rift from Belen to Socorro. The concentration of reported activity in the latter area cannot be attributed to population density. The population from Belen to Albuquerque has always exceeded the population from Belen to Socorro. However, it could be argued that Northrop's data in general are influenced by the distribution of population in the state. Population density is higher in the Albuquerque to Socorro section of the Rio Grande valley than most other sections of the state. In order to eliminate a possible population bias, we have listed in Table 1 all New Mexico earthquakes whose maximum intensity was VII or greater. Because of their large area of perceptibility (from approximately 30,000 km$^2$ to 120,000 km$^2$), shocks of this strength are unlikely to have gone undetected anywhere in the state.

All of the shocks listed in Table 1 had epicenters in the Rio Grande rift, although one (May 28, 1918) is 65 km northeast of the active segment defined by Northrop's data. However, like Northrop's data, the majority of major shocks are at or near Socorro.

Only one shock outside the rift may have had a strength close to those listed in Table 1. This shock, which had a maximum reported intensity of VI-VII, occurred September 17, 1938, in the Gila National Forest during an eight-month earthquake swarm (Neumann, 1940). The quake had an area of perceptibility of 22,000 km$^2$ and an instrumental magnitude of 5.5. Despite this earthquake the evidence appears clear from Table 1 and Northrop's data that the central Rio Grande rift was by far the most active region of New Mexico from 1849 through 1961.

The New Mexico data indicate low activity along the rift south of Socorro and north of Albuquerque. The continuation of the rift into Colorado was also notably lacking in seismic activity during the same period with the exception of a single moderate shock (VI-VII) on the northern end of the Arkansas basin on November 15, 1901 (Simon, 1969; Coffman and vonHake, 1973). The three shocks at Socorro during 1906 (Table 1) are the strongest known earthquakes along the Rio Grande rift in New Mexico and Colorado since the mid-nineteenth century. For this reason, knowledge of the magnitudes of these shocks is important. Several authors have developed empirical relations between the area of perceptibility and magnitude for different physiographic provinces (Slemmons et al., 1965; Wiegel, 1970). The relations for the Rocky Mountain or Basin and Range
<table>
<thead>
<tr>
<th>Date</th>
<th>Duration in Months</th>
<th>Location of Nearest Population Center</th>
<th>Number of Reported Shocks</th>
<th>Maximum Intensity (M.M.) of Strongest Earthquake(s)</th>
<th>Reference</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan. 19, 1904 to March 8, 1904</td>
<td>2</td>
<td>Socorro</td>
<td>34</td>
<td>V</td>
<td>Bagg (1904), Woollard (1968)</td>
<td>Newspaper accounts indicate that shocks on Sept. 10, 1904 at Socorro were not a continuation of this swarm.</td>
</tr>
<tr>
<td>July 2, 1906 to Jan., 1907</td>
<td>7</td>
<td>Socorro</td>
<td>Daily</td>
<td>VIII(2)</td>
<td>Reid (1911)</td>
<td>Distribution of isoseismals suggests hypocenters beneath Socorro Mountain, an intra-graben horst block.</td>
</tr>
<tr>
<td>Dec. 12, 1935 to Dec. 30, 1935</td>
<td>3/4</td>
<td>Belen</td>
<td>&gt;24</td>
<td>V-VI</td>
<td>Neumann (1937), Coffman and von Hake (1973)</td>
<td>At Los Lunas (18 km north of Belen) shocks were much weaker than at Belen. This suggests epicenters near the central part of the rift rather than the margins.</td>
</tr>
</tbody>
</table>
provinces appear to be most applicable for Rio Grande rift earthquakes. The magnitudes using these two relations differ by 1.7 units (Table 1) which suggests considerable uncertainty about the true strengths of these early earthquakes in the Rio Grande rift.

A characteristic of the strong Socorro shocks as well as many other known earthquakes in the rift from Albuquerque to Socorro is that they are associated with earthquake swarms. As has been noted for many years, earthquake swarms are observed in the vicinity of active volcanoes and in regions that have had volcanic activity in geologically recent times (Richter, 1958). The significance of the earthquake swarms in the Rio Grande rift is that they may be related to injection of magma into the crust.

Listed in Table 2 are parameters for known earthquake swarms in the Rio Grande rift during the period 1849 through 1961. By far the strongest and longest earthquake swarm was the 1906-07 swarm at Socorro which appears comparable to the Matsushiro swarm which some believe may have been caused by magmatic intrusion at shallow depth (Stuart and Johnston, 1975). Although the evidence is not absolutely conclusive, the distribution of isoseismals for the 1906-07 swarm suggests hypocenters beneath the Socorro Mountain horst block, a structural feature in the central part of the rift (Chapin and Seager, 1975). Other swarms listed in Table 2 also appear to have originated in the central part of the rift rather than at the margins (see Remarks, Table 2). Recent basalt flows, from north of Albuquerque to south of Socorro, are generally confined to central part of the rift. This observation in conjunction with the location of earthquake swarms may indicate that magma is continuing to be injected into the central part of the rift.

Earthquake Activity After 1961

Prior to 1962, the number of seismographs in New Mexico and bordering states was only adequate to locate a few moderately strong earthquakes in the region. This situation changed in late 1961 and early 1962 when stations at Albuquerque (ALQ) and Las Cruces (LCN), New Mexico, and Payson (TP0), Arizona went into continuous operation. Readings from these stations as well as earlier stations at Tucson (TUC), Arizona, Lubbock (LUB), Texas, and Socorro (SNM), New Mexico, permitted locations of a relatively large number of earthquakes throughout the region.

For the period 1962 through 1972, 211 earthquakes in New Mexico and bordering areas were located by NMT (Sanford et al., 1976a,b). About 30 percent of these shocks were also located by the National Earthquake Information Service (U.S. Geological Survey) and the governmental agencies preceeding it (U.S. Coast and Geodetic Survey and National Oceanic and Atmospheric Administration).

In September, 1973, the number of located shocks in the northern half of New Mexico and southern margin of Colorado jumped sharply when LASL installed an array of continuously recording stations. Another sharp increase in the number of shocks located in central New Mexico occurred in 1976 when the ASL installed a permanent array of stations near Albuquerque. Since 1973, NMT has continued to locate earthquakes but most of these lie in the southern half of New Mexico, west Texas, and northern Mexico.

Regional Seismicity, 1962 through 1972

The earthquake activity in the Rio Grande rift and neighboring physiographic provinces during the period 1962 through 1972 is shown with X symbols in Figure 1. Station bias in this NMT study (Sanford et al.,
Figure 1. Epicenters of earthquakes with $M_L \geq 2.4$ in New Mexico and bordering areas. Earthquake activity throughout the map area during the period 1962 through 1972 is shown with X's. Earthquake activity within or bordering the rift during the period 1973 through 1977 is shown with circles.

1976b) was removed by only plotting epicenters for earthquakes which were as strong or stronger than the minimum magnitude shock ($M_L = 2.4$) that could be detected at the outer margins of the area (approximate borders from $30.0^\circ$N to $38.5^\circ$N and from $101.5^\circ$W to $110.5^\circ$W). Local magnitudes were calculated using the original magnitude scale as defined by Richter (1958) plus an additional distance correction ($-0.0014\Delta$(km)).
and station corrections. Because most earthquakes in the region were too weak and/or too distant to be recorded by Wood-Anderson instruments, maximum SH ground motion was determined at each station (from instrument characteristics) and converted to an equivalent trace amplitude on a Wood-Anderson seismograph. Station corrections were based on average magnitude differences with the station at Albuquerque (ALQ). The magnitudes from ALQ records are known to be smaller than those calculated from other stations (Jordan et al., 1965). Thus the magnitudes for this study may be somewhat smaller than the true magnitudes.

The Rio Grande rift differs structurally from neighboring physiographic provinces shown in Figure 1 in that it has numerous normal faults of Miocene or younger age. Fault scarps offsetting Quaternary geomorphic surfaces have been identified at many locations along the rift (Chapin, 1971; Sanford et al., 1972; Sanford et al., 1974). Some of these fault scarps, notably those along the eastern fronts of the Magdalena and San Andres mountains, have lengths and vertical offsets suggesting association with earthquakes comparable in strength to the Sonoran earthquake of 1887 (Aguilera, 1920). This major earthquake (probable magnitude of about 7.8) produced 80 km of fault scarp (with a maximum displacement of about 8.5 m) extending southward from the United States-Mexico border at about 109°W longitude.

Despite the obvious geologic evidence of recent tectonic movement in the Rio Grande rift, the seismic activity along this structure from 1962 through 1972 was no greater than in neighboring physiographic provinces. For example, the seismic data during the eleven-year period indicate that a magnitude 4.5 shock is the strongest earthquake to expect in a 100 year period/100,000 km² in both the High Plains and Rio Grande Rift/Southern Basin and Range provinces (Sanford et al., 1976b). Not only is the seismic data at variance with the geologic observations but also with reports of felt earthquakes prior to 1962 (Table 1) which clearly indicate a concentration of seismic activity along the Rio Grande rift. A possible explanation for these discrepancies is that activity along the rift is episodic (Richter, 1958) and that during the 1962-1972 period only a general background seismicity for the entire area was observed.

### Rio Grande Rift Seismicity, 1962 through 1977

Table 3 lists origin times, epicenters, and magnitudes of 32 earthquakes occurring within the Rio Grande rift during the period 1962 through 1977. In order to avoid any bias arising from location of seismograph stations, only shocks above the minimum detectable level (M_L = 2.4) used for the NMT 1962-1972 regional study are listed. All magnitudes listed were calculated by NMT whereas many of the origin times and epicenters from 1973 through 1977 were determined by LASL or USGS. On Figure 1, the epicenters for the period 1973-1977 are indicated with circles.

The earthquakes in Table 3 indicate a low level of seismicity in the Rio Grande rift during the 16-year period and no significant long-term upward or downward trend in activity. Perhaps more interesting is the spatial distribution shown in Figure 1. The largest concentrations of activity are centered near Socorro and north of Española. Long segments of the rift, e.g. from south of Socorro to north of Las Cruces, have had no earthquakes with magnitudes greater than 2.4. The number of earthquakes in the northern two-thirds of the Albuquerque basin is small but two of these were among the three strongest earthquakes during the time period.

The epicenters shown in Figure 1 cannot be associated with specific
faults along the Rio Grande rift because probable errors in location exceed the spatial separation of major faults in most cases and minor faults in all cases. Many of the locations given in Table 3 are dependent on readings from stations several hundred kilometers from the epicenter. These readings, in conjunction with a location program that assumes that the crustal structure is the same throughout the region, can lead to rather large systematic shifts in epicenters. For example, the epicenters near Socorro in Figure 1 are to the east and southeast of the activity determined by local arrays (Figures 2 and 5). Other factors contributing to location errors are a poor azimuthal dis-
tribution of stations about the epicenter, and timing and phase identification problems. Absolute errors in location for the shocks listed in Table 3 are probably on the order of 10 to 20 km.

NMT Seismic Studies of the Rio Grande Rift - Socorro Area

As the previous section indicates, the level of seismic activity in the Rio Grande rift is not high relative to other areas in the western U.S., most notably California. Because even weak shocks with local magnitudes on the order of 3 are infrequent, a group at New Mexico Tech initiated studies on the numerous microearthquakes in the Rio Grande rift near Socorro in 1960. A study of these microearthquakes, paralleling the pioneering work of Asada (1957) was published in 1962 (Sanford and Holmes, 1962). Studies on the Socorro microearthquakes have continued since 1962 and a number of papers have been published on the results (Sanford, 1963; Sanford and Long, 1965; Sanford and Singh, 1968; Sanford et al., 1972; Singh and Sanford, 1972; Sanford et al., 1973; Sanford et al., 1977).

The most detailed research on the microearthquakes in Socorro began in May 1975 with the deployment of a moving array of seismic stations consisting of 5 to 6 Sprengnether MEQ 800 portable seismographs operating at a nominal peak magnification of \(1.6 \times 10^6\) (at 40 Hz). Later, additional data for the study was obtained by telemetry of signals from two of the stations in the ASL network (LPM and LAD) and from tape recordings produced by two Sprengnether DR100 portable seismographs. Most of the stations occupied during the study are shown in Figure 2.

Plotted on Figure 2 are the epicenters for 294 microearthquakes located from data gathered during 316 days of recording from May 1975 to January 1978 (Mott, 1976; Shuleski, 1976; Caravella, 1976; Rinehart, 1976; Johnston, 1978; and Fender, 1978). All epicenters shown in Figure 2 are based on P-wave arrival times from 4 or more stations. The computer derived hypocenters are least-square solutions obtained by means of a generalized linear inversion technique. The crustal model used in the location program is a simple half-space with a velocity of 5.8 km/sec. The reasons for adopting a half-space velocity of 5.8 km/sec are given in Rinehart et al. (this volume).

Although lateral variations in crustal velocity are probable, the most significant departures from the half-space model occur in the first several kilometers beneath the surface. The geological conditions beneath the stations shown in Figure 2 range widely, from directly on Precambrian rock at stations WT, FM, LPM, and LAD to location on thick sequences of volcanic rock at stations WM, IC, CM, and SC. For this reason, station corrections ranging in value from -0.28 to +0.20 seconds were applied to arrival times prior to use in the half-space location program. Additional details on station corrections are given in Rinehart et al. (this volume).

The accuracy of epicenters in Figure 2 relative to geologic features is difficult to estimate because the degree of heterogeneity in the upper crust is unknown at this time. However, it is believed that epicenters for earthquakes occurring within the boundaries of an array are nearly always within about 1 km of the true location.

The depth of focus is the least well known spatial parameter for an earthquake. However, these errors tend to be random so that the distribution of depths of focus for all shocks has some physical significance. Shown in Figure 3 with a solid line is the histogram of depths of focus for the 294 epicenters plotted in Figure 2. Hypocenters for all of these shocks were determined by the generalized linear inversion technique. Also plotted in Figure 3 with a dashed line (curve B) is a
Figure 3. Histogram of focal depths of Socorro microearthquakes. Curve A (solid line) is for focal depths determined from P-wave arrivals in a generalized inversion technique; curve B (dashed line) is for focal depths determined from near normal S phase reflections (Rinehart et al., this volume).

The two focal depth distributions shown in Figure 3 are quite similar, but the most reliable focal depths are those derived from the near-normal reflection paths because these depths are least affected by variations in crustal velocity. An important characteristic of curve B is a rapid decrease in the number of earthquakes beyond a depth of 7 km and the absence of any foci with depths greater than 13.5 km. This distribution suggests abnormally high temperatures at depth which inhibits stick-slip movements. The increase in number of earthquakes with increasing depth to a depth of 7 km is probably related to an increase in the strength of crustal rock with depth.

At no time since studies of microearthquakes were initiated at Socorro in 1960 has there been any evidence for earthquakes with depths of focus greater than 13.5 km. Reported mean and maximum depths were 3.7 and 6.3 km in 1962 (Sanford and Holmes, 1962), 5.7 and 13.5 km in 1965 (Sanford and Long, 1965), and 10.3 and 12.9 km in 1973 (Sanford et al., 1973). All data sets used to obtain these values were much smaller and less reliable than the one used in Figure 3.

Magnitudes of the microearthquakes shown in Figure 2 have not been calculated. However, in previous studies (Sanford et al., 1972), magnitudes were determined and the general level of seismic activity in the Socorro area was compared with other regions of the rift.

Shown in Figure 2, in addition to the microearthquake epicenters, are
Figure 4. Map of north-central New Mexico showing epicenters and magnitudes of earthquakes located by local seismic networks between September 1973 and June 1978. Locations of seismic network stations are shown as filled triangles. Focal mechanisms for selected events and areas are included. The base map is simplified from the tectonic map of Woodward et al. (1975). The central valley of the Rio Grande rift is shaded.

the major young and old faults, and the boundaries of the mid-crustal magma body and the Socorro caldera. Also shown in a rectangular inset is a sample of the results of detailed mapping in the Socorro-Polvadera Mountains horst block (Chamberlain, 1978). The complexity of faulting in this area is believed typical of the entire region including the Socorro and La Jencia structural basins.

Nearly all of the microearthquake activity shown in Figure 2 lies well within the margins of the Rio Grande rift. The epicenters are distributed over a 2300 km² area which is centered roughly above the extensive mid-crustal magma body. With the exception of some epicenters in the Jornada del Muerto basin to the east of Socorro, this is the general pattern of seismic activity for the Socorro area obtained by the ASL (Fig. 5).

Within the active area are concentrations of activity, notably west and southwest of station WF and west of station BG. In part, these concentrations of epicenters are the result of having stations favor-
ably positioned for location of shocks in these areas. However, the epicenter map obtained by ASL shows the same concentrations and their network was definitely not favorably positioned for location of shocks in these two areas.

The high concentration of activity to the west and southwest of station WT is interesting because it lies within the margins of the Socorro caldera. Within the caldera, these shocks are diffusely distributed with no obvious association with surface faults. However, this is a region where many important faults could be buried beneath Tertiary fill.

Outside of the caldera, the epicenters are scattered and also show no obvious correlation with known faults. A striking example is the absence of seismic activity along the major young fault bordering the eastern margin of the Magdalena Mountains. Major crustal movements have occurred along this fault in recent geologic time (Sanford et al., 1972).

Three composite focal mechanisms (lower focal sphere) are shown on Figure 2; A is based on 69 earthquakes, all but 2 located within or bordering the Socorro caldera; B is based on 26 shocks located in the southern La Jencia basin west of the structural axis of the basin; and C is based on 7 earthquakes centered 8 km southwest of station EG and east of the structural axis of the Socorro basin. All three focal mechanisms indicate normal faulting with a minor amount of strike-slip movement, and T-axes nearly perpendicular to the dominant direction of mapped normal faults in each area. Although there is considerable variation in the direction of the T-axis, the average position of this axis indicates east-west extension of the upper crust where all foci are located.

A number of observations indicate that the seismic activity in the Socorro area may not be the result of simple east-west extension of the entire crust. Measurements of a geodetic network positioned across the rift in the Socorro area from 1972 to 1976 do not reveal any east-west crustal extension (Prescott, Savage, and Kinoshita, 1970). Analysis of level-line data for the period 1909-1952 indicates surface uplift, as great as 6mm/yr, roughly coincident with the spatial extent of the mid-crustal magma body (Reilinger and Oliver, 1976). The earthquake activity is diffuse and roughly centered on the magma body. Major rift faults away from the boundaries of the magma body are aseismic. Major historical earthquakes as well as 75 percent of the micro-earthquake activity have occurred in swarms. Collectively these observations suggest the earthquake activity in the Socorro area can be explained by extension of the upper crust produced by intrusion of a layer of magma at mid-crustal depths (Sanford et al., 1977; Rinehart et al., this volume). Concentrations of seismic activity, e.g. southwest of station WT, could be the result of injection of small magma bodies into the upper crust (Shuleski, 1976; Caravella, 1976; Johnston, 1978; Fender, 1978; Chapin et al., 1978). These shallower magma bodies could account for the usually high heat flows (as great as 11.7 HFU) observed in the Socorro area (Reiter and Smith, 1977; Sanford, 1977).

LASL Seismic Studies of the Rio Grande Rift from 35°N to 37.5°N

The Los Alamos Scientific Laboratory (LASL) began installation of a network of radio-telemetered, short-period seismograph stations in north-central New Mexico in January 1972. The network expanded to 16 stations by mid 1978 and is supplemented by a telephone line data link with selected stations of the Albuquerque Seismological Laboratory (ASL) operated by the U.S. Geological Survey. The technical details of station locations and instrumental and recorder parameters have been
covered by Newton et al. (1976) and by Cash, McFarland, and Headdy (1978) and will not be further detailed here except to outline some of the procedures used by the LASL group in locating microearthquakes in the study area. Two basic computer programs are used for determining hypocenters: (1) for most routine work, a program (SPHCIR) is used which is a computer adaptation of the graphical arc technique (Newton et al., 1976) and (2) a modified version of HYPO 71 (Lee and Lahr, 1972) utilizing first arrivals only, that is employed for relative locations when station coverage is sufficiently dense. The SPHCIR program makes full use of any readable later arriving phases (S, P*, Sn, Pn, etc.) from a sparse network to assist in determinations of origin times (Wadati method) and epicenters and is particularly convenient for use with the interactive computer graphics terminal. Experience with local blasting sources suggests epicenters are accurate to ±3 km for events recorded by 4 or more stations interior to the network, with accuracies degrading to about ±10 km for events near the periphery of the net and to no better than ±20 km for outside sources. Crustal models employed in hypocenter locations are discussed by Newton et al. (1976). For most of the results reported here we have found it adequate to use a one or two layer over half-space model.

Routine magnitude estimates are made using a duration method (Newton et al., 1976) developed by fitting total durations as measured on vertical component seismograms to local magnitudes (M_L) determined from standard Wood-Anderson instruments at Albuquerque and Socorro. The formula used for magnitude is

\[ M_L(\tau) = 2.8 \log \tau - 3.6 \]  

where \( \tau \) is the measured time, in seconds, from the initial P-wave onset until the coda disappears into the noise background. Because of the relatively low sensitivities of the often distant Wood-Anderson instruments, the duration magnitude estimates for events below \( M_L = 1.5 \) are admittedly extrapolations but are being retained until other systematic studies can be completed to extend the scale downward.

Figure 4, derived from the catalog of Cash, McFarland, and Headdy (1978), summarizes those epicenters located by readings from the LASL network between latitudes 35.0°N to 37.5°N and longitudes 104.4°W to 108.0°W for the period from 1 September 1973 through 31 May 1978. These (approximately 300) events represent a sample somewhat biased in both time and space because both detection thresholds and location accuracies of the network have continually improved as more stations have been added to the network throughout the period. The criterion for inclusion in the data set is that an event must have been detected on at least 3 LASL network stations; in the case of many of the larger events (\( M_L \geq 2.5 \)), supplementary readings from stations in the ASL net and occasionally other more distant WWSSN stations (TUe, GOL, LUB) were employed in the epicentral solutions.

Very few of the microearthquakes have focal depths determined to better than ±5 km since only a few events have occurred at ranges of one or two focal depths of a seismograph station where depth control is optimal. Nevertheless, the focal depth for the more reliably determined hypocenters indicates most of the activity in this study area lies in the upper crustal layer above a depth of -20 km. This depth corresponds approximately to the level at which the P-wave velocity is observed from seismic refraction profiles (Toppozada and Sanford, 1976; Olsen et al., this volume) to increase from 5.8/6.0 km/sec above to a value of -6.4 km/sec below the discontinuity. Evidence from the amplitudes of wide angle reflection phases on refraction record sections implies one or more layers in the lower crust -- at least in the vicinity of the Rio Grande rift -- have low rigidity and should therefore give rise to fewer earthquakes (Olsen et al., this volume).
Details of the Seismicity Distribution

Some significant aspects of the seismicity patterns displayed in Figure 4 are as follows:

1. There is no clear-cut correspondence between mapped epicenters and specific surface faults, although there is a general association of a north-south oriented belt of earthquake activity and the system of faults related to the Nacimiento uplift and Gallina-Archuleta arch. The absence of a close agreement between mapped epicenters and surface faulting should not be surprising in view of the known uncertainties in epicenter locations and the relatively small source dimensions associated with earthquakes of magnitudes less than 4 (Dietrich, 1974).

2. The neighborhood of the 1966 Dulce earthquake (approximately 37°N and 107°W) still exhibits a moderate degree of activity and appears tectonically related to the trends of Gallina-Archuleta arch and the structures on the southwestern borders of the San Juan volcanic field in Colorado.

On the other hand, the present data set shows little evidence of contemporary activity in the vicinity of the 1918 Cerrillos earthquake (approximately 65 km northeast of Albuquerque) on the east flank of the rift just south of Santa Fe.

3. A diffuse distribution of moderate seismicity extends ENE from north of Grants across the volcanic features of Mount Taylor and Chivato Mesa and merges at the southern end of the Nacimiento Mountains with the belt mentioned in item 2. This zone lies to the west of the boundary of the Rio Grande rift as it is usually defined by surface geological criteria (Chapin, 1971), and the relationship of the seismicity to Rio Grande rift tectonics is presently unclear. In fact, the largest earthquakes that occurred in the study area during the 1973-1978 time period were two $M_L > 4$ events at depths near the base of the crust (30-40 km) on January 5, 1976 and May 3, 1977 (focal mechanisms E and D on Figure 4). These shocks are apparently related to the transition between the Mount Taylor volcanic field and the San Juan basin of the Colorado Plateau physiographic province.

4. The most consistently active earthquake zone in the study area is a belt approximately 50 kilometers in length near the western flank of the rift west of Española, New Mexico. Activity in this area consists of moderate events ($M_L = 2$ to 3) that recur at several month intervals. Each of these shocks is usually accompanied by several small aftershocks although a few small swarm-like sequences have been noted. This zone has given rise to moderate ($M_L = 4$) earthquakes that have been felt (intensity IV to V) in the communities of Los Alamos and Española in years prior to the initiation of close instrumental coverage by local seismographic stations. The largest of these felt shocks occurred in 1952, 1969, 1971, and March of 1973 (Sanford, 1976; Newton et al., 1976).

An analysis of geodetic releveling data by Reilinger and York (1979) has revealed a pronounced zone of relative subsidence northwest of Española that appears to be closely associated spatially with this microearthquake belt. The maximum observed subsidence of 4.9 cm (between the 1934 and 1939 surveys) occurred approximately 10 kilometers east of the axis of seismic activity. Apart from direction of movement, the subsidence feature northwest of Española appears similar in several respects to a crustal bulge in the Socorro area (Reilinger and Oliver, 1976) which, on the basis of several lines of evidence (including seismic swarm activity), has been associated with a magma body at mid-crustal depths (Sanford et al., 1977). Reilinger and York (1978) thus hypothesize that the depression feature and the earthquake activ-
ity in this region are consistent with the deflation of a shallow (=10 km) magma body although normal faulting in the crust could also explain the observations. The magma body hypothesis is strengthened by the presence of nearby Tertiary dikes and the proximity to sites of high measured heat flows (~3-5 HFU, Reiter et al., 1975).

(5) One of the more striking features of Figure 4 is the almost complete aseismicity of a large area of the Valles caldera and the northern portion of the Albuquerque basin. Inasmuch as there are several of the more sensitive seismic stations near the center of the area, the detection threshold for very small microquakes (M_L < 1) is especially low so the apparent aseismicity cannot be a result of inadequate monitoring. The low seismicity region is well correlated with a ribbon of high heat flow that generally follows the western margin of the Rio Grande rift (Reiter et al., 1975, 1976; Edwards et al., 1978). The band of high (>2.5 HFU) heat flow values (not plotted in Figure 4) runs northward from near the juncture of the western part of the Albuquerque basin and the Puerco fault zone through the Valles caldera (where values in the range of 3 to 5 HFU have been measured) across the Taos Plateau and on to the vicinity of Raton, New Mexico, and Trinidad, Colorado (Edwards et al., 1978). Similar relatively aseismic zones approximately centered on the Yellowstone (Smith et al., 1974; Eaton et al., 1975) and the Long Valley, California (Steeple and Pitt, 1976) caldera complexes have been noted by other workers. The Yellowstone, Long Valley, and Valles calderas are the only known calderas in the continental United States that are large enough and young enough (<1.1 m.y. old) to possibly still contain residual magma in their chambers (Bailey et al., 1976). In analogy with the Yellowstone and Long Valley data, it appears that the strain release at shallow depths near the Valles caldera may be dominated by stable sliding rather than by brittle fracture. In addition to the purely mechanical phenomena associated with rifting, it would appear that the details of terrestrial heat flow in this section of northern New Mexico and the Rio Grande rift significantly influence the patterns of seismic strain release in the area.

Because of the moderate levels of seismicity in northern New Mexico and southern Colorado and the short time period of detailed microearthquake network coverage, only a few reliable focal mechanisms have been determined for the study area. These are summarized by lower focal sphere diagrams in Figure 4. The predominantly strike slip mechanism A pertains to the January 23, 1966, Dulce earthquake; the solution by Cash (1971) is based principally on Pn readings from stations at regional distances. Cash (1975) has also shown that it is possible to fit the data with a normal fault solution although with considerably less confidence; in either case the direction of the tension axis is WNW-ESE as shown and is very well determined.

Mechanisms D and E (Cash and Jaksha, work in progress, 1978) are solutions for two M_L ~ 4 events occurring deep in the crust that rely mainly on Pn readings. Since these events occurred outside the normally defined boundaries of the Rio Grande rift (as may also be the case for the Dulce earthquake) their relationship (if any) to rift tectonics is unclear. Mechanisms B and C are provisional composite solutions for groups of small earthquakes occurring near the western margin of the rift (Wechsler and Cash, work in progress, 1978). Further data are needed to better define the principal and auxiliary planes but the generally WNW-ESE direction of the tensile axes for these two areas is reasonably well determined and is consistent with other composite solutions for rift events in the vicinity of Albuquerque and Socorro.
Figure 5. Map showing locations of seismic stations and earthquakes near Albuquerque, New Mexico during 1976-1977.
In the fall of 1975, the ASL-USGS installed an eight-station seismic network near Albuquerque. This network expanded to thirteen stations by August of 1977. The technical parameters for this instrumentation are given by Jaksha et al. (1977). Station locations are plotted in Figure 5.

Earthquake hypocenters are obtained from the computer program HYPO 71 (Lee and Lahr, 1972). Accuracy of hypocenters inferred from an analysis of local mining explosions (Jaksha et al., 1978) suggests that events occurring inside the network are located to within 2 km (horizontally) of their true positions. Focal depths are less well determined and are probably accurate to no better than 5 km. Earthquakes occurring outside of the network are thought to be correct to within about 10 km horizontally; focal depths outside the network are estimates only.

The earthquakes located by the ASL near Albuquerque during 1976 and 1977 are shown in Figure 5. The criteria for appearing in Figure 5 are that 3 or more stations observed the event and that it is located less than about 110 km from station ABQ.

The earthquakes are presented as falling into three ranges of magnitude. The magnitudes (Mₗ) are determined from the duration equation developed by Newton et al. (1976) for northern New Mexico. The earthquakes range in magnitude (Mₗ) from -0.2 to 2.9 when calculated by this method. The Mₗ are probably correct to within ± magnitude and should be considered as approximations only.

The hypocenters in this data set range from 1 km to 20 km in focal depth. The average depth of focus for all of the 1977 earthquakes to which a depth was assigned is 6.1 km. There is uncertainty in any depth calculation made from this seismic network because of the large distance between stations. The data suggest, however, that nearly all contemporary seismicity occurs within the upper crust (18.9 km) as defined by Toppozada and Sanford (1976).

Figure 5 shows that the seismicity is not uniformly distributed throughout the study area. The earthquakes during this two-year study period can be grouped into two fairly well contained and one less well defined zones.

Zone 1 lies within the Rio Grande rift and extends from south of Socorro to about Belen. This zone of high seismicity has been noted previously by Sanford et al. (1972) and Northrop (1976). Sanford et al. (1977) propose an inflating magma body beneath a portion of Zone 1 at a depth of about 18 km. Most, but not all, of the seismicity reported here lies above this magma body.

The area bounded by Zone 2 in Figure 5 begins about 30 km northeast of Grants. Sanford et al. (1976a,b) note this zone in a larger context and correlate it with a zone of Miocene and younger volcanics that extend from near Raton to about Silver City. This larger zone is not apparent in this brief data set.

Zone 3 in Figure 5 encompasses a poorly defined region of seismicity to the east of the Rio Grande graben. The data here are sparse and other "zones" could easily be drawn. The study definitely suggests an active area about 20 km east of Estancia but a much longer data sample is required to define the seismicity trends there.

The earthquakes that occurred within the ASL seismic network during 1976-1977 are shown in Figure 6. Several observations are possible from this figure.

(1) The Rio Grande rift from the vicinity of Albuquerque north to about 35.6° latitude was almost aseismic during the time frame of this study.
Figure 6. Map (modified from Woodward et al., 1975) showing relationship of contemporary seismicity to mapped faults.

(2) The seismicity from Albuquerque southward to about 34.2° latitude shows some correlation with mapped, intra-basin fault zones.
(3) The well-defined boundary faults of the rift appear aseismic for the two-year period considered here.
(4) The composite focal mechanisms (lower focal sphere) suggest that both normal and strike-slip faulting are currently occurring along this portion of the rift.

The four composite focal mechanisms constructed from these data agree, when taken together, with regional east-west extension as proposed by Chapin (1971). The composite T axis is oriented 9° north of west.
TABLE 3. Rio Grande Rift Earthquakes with $M_L \geq 2.4$* from 1962 through 1977.

<table>
<thead>
<tr>
<th>Yr.</th>
<th>No.</th>
<th>Day</th>
<th>Origin Time UST</th>
<th>Location Latitude</th>
<th>Longitude</th>
<th>Local Magnitude</th>
</tr>
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<tr>
<td>1962</td>
<td>Sept.</td>
<td>1</td>
<td>16:15:07.9</td>
<td>34.16</td>
<td>106.66</td>
<td>3.0</td>
</tr>
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<td>1963</td>
<td>Feb.</td>
<td>22</td>
<td>07:02:08.1</td>
<td>32.42</td>
<td>106.99</td>
<td>2.5</td>
</tr>
<tr>
<td>1963</td>
<td>Nov.</td>
<td>25</td>
<td>12:52:33.8</td>
<td>36.54</td>
<td>105.37</td>
<td>2.4</td>
</tr>
<tr>
<td>1965</td>
<td>Mar.</td>
<td>9</td>
<td>19:04:48.5</td>
<td>33.87</td>
<td>106.90</td>
<td>2.5</td>
</tr>
<tr>
<td>1965</td>
<td>July</td>
<td>28</td>
<td>04:38:53.4</td>
<td>33.80</td>
<td>106.70</td>
<td>2.6</td>
</tr>
<tr>
<td>1965</td>
<td>Dec.</td>
<td>29</td>
<td>00:50:24.1</td>
<td>35.03</td>
<td>105.78</td>
<td>2.6</td>
</tr>
<tr>
<td>1966</td>
<td>Oct.</td>
<td>6</td>
<td>10:19:08.2</td>
<td>34.04</td>
<td>106.85</td>
<td>2.4</td>
</tr>
<tr>
<td>1968</td>
<td>Mar.</td>
<td>9</td>
<td>21:54:25.7</td>
<td>32.70</td>
<td>106.05</td>
<td>2.9</td>
</tr>
<tr>
<td>1969</td>
<td>Jan.</td>
<td>30</td>
<td>05:17:38.4</td>
<td>34.22</td>
<td>106.75</td>
<td>3.4</td>
</tr>
<tr>
<td>1969</td>
<td>May</td>
<td>12</td>
<td>08:26:18.5</td>
<td>31.95</td>
<td>106.43</td>
<td>3.0</td>
</tr>
<tr>
<td>1969</td>
<td>May</td>
<td>12</td>
<td>08:49:16.3</td>
<td>31.95</td>
<td>106.43</td>
<td>2.6</td>
</tr>
<tr>
<td>1969</td>
<td>July</td>
<td>4</td>
<td>14:43:33.0</td>
<td>36.15</td>
<td>106.13</td>
<td>2.8</td>
</tr>
<tr>
<td>1970</td>
<td>Nov.</td>
<td>28</td>
<td>07:40:11.8</td>
<td>35.10</td>
<td>106.61</td>
<td>3.2</td>
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<tr>
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<td>Nov.</td>
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<td>05:35:20.5</td>
<td>36.25</td>
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<tr>
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<td>35.10</td>
<td>106.60</td>
<td>3.6</td>
</tr>
<tr>
<td>1971</td>
<td>Jan.</td>
<td>6</td>
<td>10:56:31.5</td>
<td>34.15</td>
<td>106.79</td>
<td>2.8</td>
</tr>
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<td>1971</td>
<td>Jan.</td>
<td>27</td>
<td>07:56:28.3</td>
<td>34.06</td>
<td>106.60</td>
<td>2.6</td>
</tr>
<tr>
<td>1971</td>
<td>Feb.</td>
<td>18</td>
<td>11:28:14.3</td>
<td>36.30</td>
<td>105.78</td>
<td>2.8</td>
</tr>
<tr>
<td>1971</td>
<td>Apr.</td>
<td>28</td>
<td>11:36:52.1</td>
<td>36.13</td>
<td>105.96</td>
<td>2.7</td>
</tr>
<tr>
<td>1971</td>
<td>Dec.</td>
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<td>05:18:13.0</td>
<td>36.15</td>
<td>106.11</td>
<td>2.9</td>
</tr>
<tr>
<td>1972</td>
<td>Mar.</td>
<td>28</td>
<td>01:53:33.7</td>
<td>36.17</td>
<td>106.06</td>
<td>2.7</td>
</tr>
<tr>
<td>1972</td>
<td>Mar.</td>
<td>31</td>
<td>20:14:19.8</td>
<td>36.11</td>
<td>106.04</td>
<td>2.4</td>
</tr>
<tr>
<td>1972</td>
<td>Dec.</td>
<td>18</td>
<td>04:07:36.2</td>
<td>35.42</td>
<td>107.16</td>
<td>2.7</td>
</tr>
<tr>
<td>1973</td>
<td>Mar.</td>
<td>17</td>
<td>07:43:06.0</td>
<td>36.14</td>
<td>106.19</td>
<td>2.4</td>
</tr>
<tr>
<td>1973</td>
<td>Sept.</td>
<td>10</td>
<td>20:29:23.7</td>
<td>34.42</td>
<td>106.85</td>
<td>2.4</td>
</tr>
<tr>
<td>1973</td>
<td>Sept.</td>
<td>22</td>
<td>23:38:37.1</td>
<td>34.46</td>
<td>106.95</td>
<td>2.5</td>
</tr>
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<td>1974</td>
<td>Aug.</td>
<td>30</td>
<td>22:57:35.2</td>
<td>34.87</td>
<td>107.06</td>
<td>2.7</td>
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<td>1975</td>
<td>Mar.</td>
<td>7</td>
<td>03:16:13.7</td>
<td>34.55</td>
<td>107.16</td>
<td>2.8</td>
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<tr>
<td>1975</td>
<td>Mar.</td>
<td>7</td>
<td>17:36:08.7</td>
<td>34.55</td>
<td>107.16</td>
<td>2.9</td>
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<tr>
<td>1975</td>
<td>June</td>
<td>26</td>
<td>07:03:43.4</td>
<td>36.95</td>
<td>105.45</td>
<td>2.6</td>
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<tr>
<td>1977</td>
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<td>23:41:58.0</td>
<td>34.03</td>
<td>106.00</td>
<td>2.4</td>
</tr>
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</table>

*Magnitudes calculated by NMT.

Discussion

Existence of significant seismic gaps along the Rio Grande rift as well as a level of seismicity no greater than the Colorado Plateau or the High Plains suggests very little or no crustal spreading in recent years. Geodetic measurements near Socorro are in agreement with this tentative conclusion. Much of the microearthquake activity observed in the rift in recent years is in close association with recent volcanism and possibly with contemporaneous movement of magma in the crust and thus need not signify general extension of the entire crust. Occurrence in swarms and probable locations in the axial regions of the rift also suggest that many of the strong historical earthquakes were closely linked with injection of magma into the crust. On the other hand, geologic evidence indicates clearly that large movements have occurred on major faults along the rift within the past 500,000 years. These large fault movements may be the result of episodic rather than steady-state crustal spreading.
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