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A GEOPHYSICAL ANALYSIS OF CRUSTAL STRUCTURE IN THE RUIDOSO AREA

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Abstract—A variety of geophysical data has been analyzed in the Ruidoso area in order to determine the deep structure of the area. From a crustal structure point of view, the crustal thinning associated with the Rio Grande rift extends well into the physiographic Great Plains. On a more local scale, a large gravity high in the Ruidoso area appears to outline a Pennsylvanian uplift.

INTRODUCTION

The Ruidoso area is located on the northeastern shoulder of the southern segment of the Rio Grande rift (Fig. 1). The central and northern segments of the rift are composed of a nearly end-to-end series of grabens trending in a north-northeasterly direction from about Socorro, NM, into Colorado (Tweto, 1979; Kelley, 1979). However, south of Socorro, the structural character of the rift changes to a series of three or four parallel grabens. The total width of these basins is roughly 2.5 times that of the northern and central segments (Chapin, 1979).

Fig. 2 shows the major structural features of the Ruidoso area. The intra-rift basins of the region include the Albuquerque, Jornada del Muerto and Tularosa Basins. The clear, well-defined faults on the eastern edge of the Albuquerque Basin become buried farther south, near Socorro, under the sediments of the Jornada del Muerto Basin. The eastern rift boundary jumps eastward at this point to the bounding fault between the Tularosa Basin and the Sacramento uplift. East of the Sacramento Mountains, the major structural trend is the gentle eastward dip of the western Pecos Valley. This region, named the Pecos slope (Kelley and Thompson, 1964), is modified by a large number of faults and fold belts (Kelley, 1971). To the southeast lie the thick Permian deposits of the Delaware Basin.

A number of geophysical surveys, including seismic-refraction profiles (Toppozada and Sanford, 1976; Olsen et al., 1979; Cook et al., 1979: Daggett, 1982; Sinno et al., 1986), surface-wave dispersion measurements (Keller et al., 1979; Sinno and Keller, 1986), heat-flow analyses (Decker and Smithson, 1975; Reiter et al., 1975, Swanberg, 1979; Daggett, 1982; Reiter et al., 1986) and gravity surveys (Cordell et al., 1982; Ramberg et al., 1978; Cordell, 1978; Daggett et al., 1986), have been conducted within the study area in an effort to delineate and define the Rio Grande rift. Many of these studies, and others, are summarized by Cordell (1978) and Keller et al. (1990). These studies show that the rift has a thinner crust, lower upper-mantle compressional seismic velocities and higher heat flow than the surrounding provinces (with the possible exception of the Basin and Range), and has a distinctive gravity signature extending its entire length. This gravity signature suggests a wide zone (several hundred kilometers) of lithospheric thinning and a narrow zone of crustal thinning approximately centered on the rift valleys. While these studies have added tremendously to the knowledge of the crustal structure and tectonic history within the rift, few workers have examined the transition zones to the east or west.

The primary thrust of this work is to examine the transition zone between the Rio Grande rift (RGR) and the Great Plains province (GPP) to the east. Stewart and Pakiser (1962) monitored the GNOME nuclear explosion in southeastern New Mexico with a widely spaced seismic array trending due north along the eastern side of the Pecos Valley. Their work showed that the GPP crust under eastern New Mexico is over 50 km thick, with a Pn velocity of 8.2 km/s. This contrasts with the work of Sinno et al. (1986) just to the west of our study area, which shows the southern rift crust to be about 30 km thick, with a Pn velocity of 7.7 km/s. The region between these two surveys is about 300 km wide and includes the Ruidoso area.

For this study, a long-offset seismic profile across east-central New Mexico was recorded using nuclear explosions from the Nevada Test Site (NTS). The locations of the seismic stations are marked on Fig. 1. The large nuclear explosions at NTS provide excellent seismic sources and the resultant long offsets (>1000 km) make it possible to examine the structure of the transition region to depths below the low-velocity zone in the upper mantle. The investigation targeted these depths because it is presumed that the RGR-GPP transition extends into the deep lithosphere and asthenosphere. A gravity model along the same profile was used to help corroborate the seismic results. In addition, gravity and magnetic maps were generated for the area and analyzed for their geologic implications.

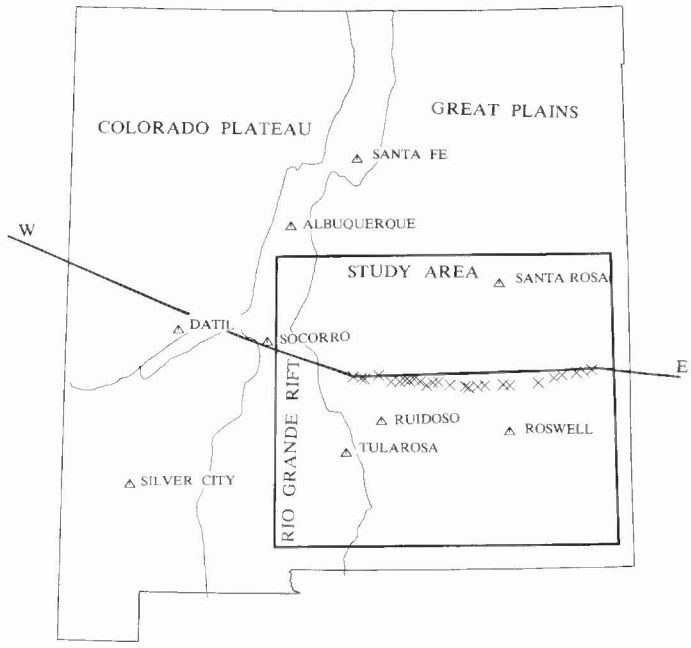


FIGURE 1. Location of the study area. The solid line traces the gravity profile. Seismic stations are marked with an X. The short-receiver offset at the westernmost station is 1027 km; the offset at the easternmost station is 1248 km. The sources for the seismic survey were in southern Nevada and therefore do not appear on this map. The origin of the gravity profile is coincident with the shots but only the easternmost portion is presented here.

SEISMIC SURVEY

Since 1985, a seismic array has been set up periodically across central New Mexico to monitor large nuclear explosions at the Nevada Test Site. The array trends nearly east-west along latitude 33.7°N, between about 106°W and 103°W longitude, yielding station offsets between 1000 km and 1250 km with an average station spacing of 7 km. At its western extreme, the array ties with the intra-rift refraction profile of Sinno et al. (1986), and its eastern end crosses the refraction profile of Stewart and Pakiser (1962). These long-offset data were gathered into two separate seismic sections (named NTS2 and NTS4), both of which displayed strong refracted arrivals from the uppermost mantle (Pn) and from under the lithosphere/asthenosphere boundary (P1; Fig. 3). A two-

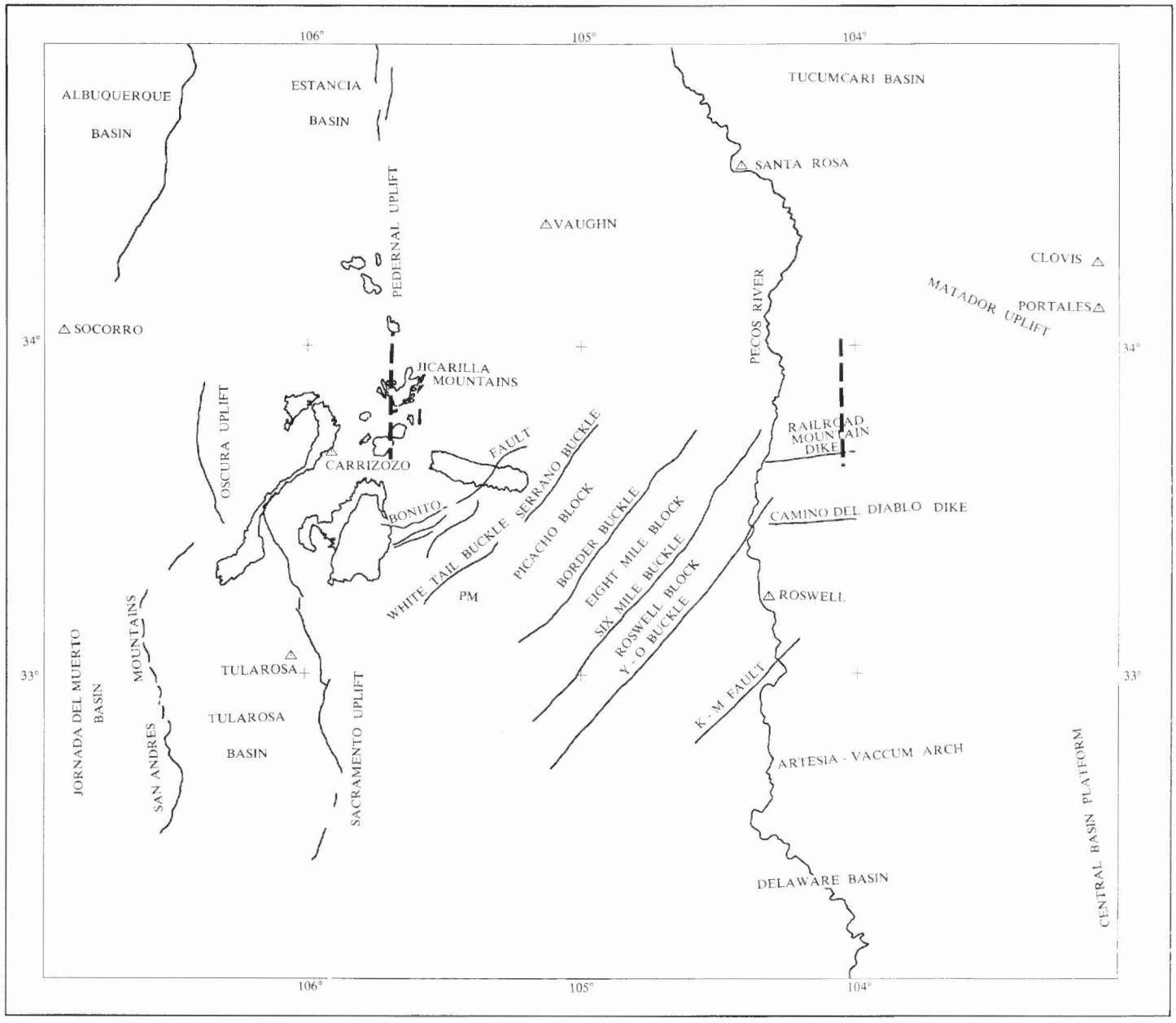


FIGURE 2. Major geologic features within the study area. The outlines of these features also appear in Fig. 7. The dotted lines outline the lithospheric transition zone between the Rio Grande rift and the Great Plains, as defined by the slope of the Mohorovicic discontinuity in our seismic model.

dimensional ray-tracing algorithm, modified to compensate for earth curvature, was used with the data to model the deep structures under the Rio Grande rift and its transition regions to the east and west.

The seismic waves recorded during the survey traveled through or under several geologic provinces within the western United States. Several previous results in this area were synthesized to create a starting model. The crustal structure was taken from Taylor (1983; Basin and Range), Warren (1969; Colorado Plateau), Schneider (1990; Datil-Mogollon volcanic field), Sinno et al. (1986; Rio Grande rift) and Stewart and Pakiser (1962; Great Plains). The deep structure was taken from Burdick and Helmberger (1978). It is important to note that the limited aperture of this survey provides little or no resolution over many of these regions due to the very narrow band of take-off angles spanned by the packet of energy that reached the seismic array. This is not perceived as a problem because the seismic "rays" within this packet do not diverge appreciably until after their respective turning points, thus minimizing the impact of Basin and Range and Colorado Plateau structures, and accentuating the effect of structures under the Rio Grande rift and Great Plains, which are the focus of this investigation.

Fig. 4 is a drawing of the final model derived from this study. Fig. 3 shows the modeled arrival branches superimposed on the seismic sections. The match between modeled and observed arrivals is very good in all areas except for the P1 arrivals between R = 1070 km and R = 1130 km. Further analysis of the record sections and synthetic sections generated over a similar one-dimensional model of the area indicates that several arrival branches from the upper asthenosphere are coincident within the aperture of this survey. At least two arrivals appear to be present in our sections at about 12 s. Further analysis with two-dimensional synthetic modeling is necessary to completely resolve this problem.

East of the Colorado Plateau, the depth to the Moho is steady at 32 km from R (lateral distance in our model space) = 841 km to R = 1050 km (105.7°W), and then drops steadily at an angle of about 7.6° until R = 1190 km (104.1°W), where it reaches a depth of 51 km. The depths

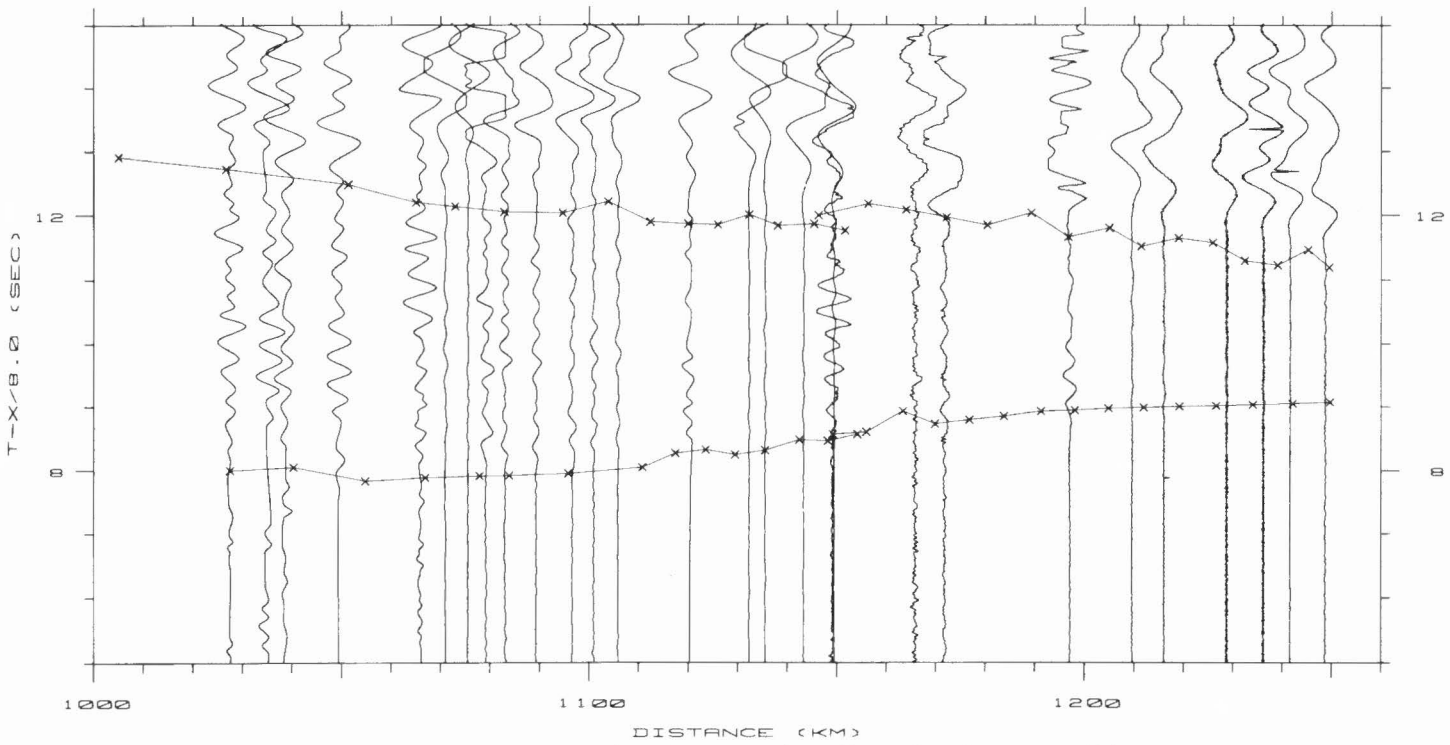


FIGURE 3. Modeled arrival branches overlying the observed seismic sections. All stations with an offset of less than 1149 km recorded shot NTS2. All stations with larger offsets recorded NTS4. The station at R = 1149 km was occupied for both shots. Shotpoint NTS4 is located 7.5 km closer to the array than shotpoint NTS2.

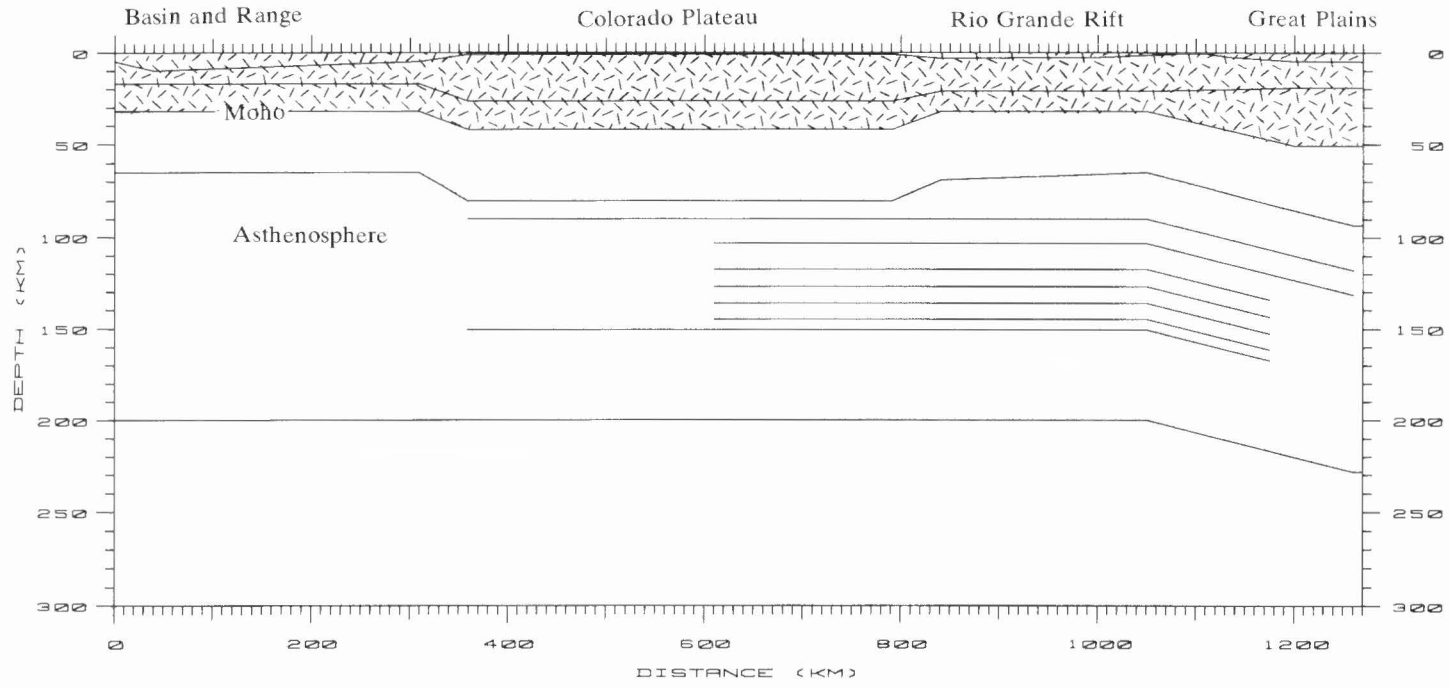


FIGURE 4. Final seismic model plotted as a "flat" earth. The stippled pattern highlights the crust. The layer immediately below the crust represents the lithospheric upper mantle and is underlain by the low-velocity zone on the uppermost asthenosphere. This survey was able to resolve the crustal regions beneath the Rio Grande rift and the deeper structure under the Colorado Plateau/Rio Grande rift transition.

of 32 km and 51 km were taken from Sinno et al. (1986) and Stewart and Pakiser (1962), respectively, but the geometry of this interface between these two tie points was determined during this study.

The next interface, at D = 65 km in the west, represents the base of the lithosphere and the top of the low velocity zone (LVZ) of the upper asthenosphere. As previously mentioned, the starting model of the asthenospheric region across most of the model was taken from Burdick and Helmberger (1978). For this reason, the initial model contained no asthenospheric discontinuities and the velocity gradient was varied according to their model T7. The only asthenospheric interfaces drawn in Fig. 4 are those that deviate from the initial model. In the east, the same dip of 7.6° was used on the asthenosphere boundary, which began

to drop from 65 km at R = 1050 km to about 93 km at R = 1260 km. The resolution on the details of this interface in the transition, however, is limited.

The P-wave velocity beneath the crust within the rift is 7.7 km/sec at the Moho and increases very slightly to about 7.72 km/sec at the base of the lithosphere (D = 65 km). At the lithosphere/asthenosphere boundary, the velocity drops to 7.65 km/sec, then slowly decreases at a rate similar to the T7 model to a local minimum of 7.6 km/sec at D = 90 km. From that depth downward, the geometry of the modeled interfaces is taken directly from the T7 model, with the velocities modified to fit the new data. Our model begins to match the T7 model at a depth of 150 km but the deeper parts of this region were not sampled by the seismic energy.

To test the validity of the seismic results, a gravity profile coinciding with the seismic array was constructed and modeled using a 2.5D forward-modeling algorithm (Cady, 1980; profile marked in Fig. 1). The shallow details of the model are discussed in the next section, but of note here is the agreement between the gravity and seismic results at depth (Fig. 5). In the gravity model, the crust is thinnest (32 km) in the eastern part of the rift in the vicinity of the northern Tularosa Basin. From there the crust thickens gradually to the west, reaching a thickness of 40 km under the Colorado Plateau. To the east, the crust thickens more quickly to 50 km under the Great Plains. From approximately R = 1050 km eastward, the shape of the Mohorovicic discontinuity in the seismic and gravity models presented here is identical.

Superimposed on the geologic data in Fig. 2 are two north-south-trending dashed lines, one at 105.7°W and the other at 104.1°W longitude. These lines define the limits of the lithospheric transition zone between the rift and the Great Plains as defined by these data. Comparing this location to the surface structural features leads to two conclusions: (1) the Tularosa Basin is definitely a part of the Cenozoic extensional regime responsible for the rift, and (2) the anomalous subsurface structure of the rift extends beneath surface features traditionally associated with the western Great Plains.

GRAVITY AND MAGNETIC MAPS

Gravity- and magnetic-anomaly maps of the study area were also generated. A uniform grid of complete Bouguer values was created using nearly 10,000 gravity readings from the University of Texas at El Paso gravity database. A second-order polynomial was fitted to these data in order to remove the large-scale regional trend from the map (Suleiman and Keller, 1985). The residual gravity field was then contoured and is presented in Fig. 6. The magnetic map (Fig. 7) is derived from the New Mexico magnetic database compiled by Cordell (1983). Superimposed on both maps are the structural features from Fig. 2.

Many of the well-known basins within the area are easily identified on the gravity map. The gravity low in the northwest corner of the map outlines the southern portion of the intrarift Albuquerque Basin and is bordered by a gravity high delineating the Los Pinos–Manzano uplift on the east. The smaller gravity low to the east of that uplift coincides with the Estancia Basin (Kelley, 1972). The series of gravity highs and lows west of the Oscura uplift suggests a complex basement structure beneath the northernmost Jornada del Muerto Basin.

The Tularosa Basin lies between the San Andres and the Sacramento uplifts in the southwestern portion of the maps. A gravity high in the center of the basin, bordered to the east and west by gravity lows, suggests that the floor of the basin is broken into two sub-basins by a horst block or similar structural high.

The gravity low northeast of the Oscura uplift correlates with the Claunch sag, a Laramide-age basin that seems to coincide with a mid-Permian evaporite basin (Kelley and Thompson, 1964). The sag forms a rough connection between the Estancia Basin to the north and the Tularosa Basin to the south, and is bounded on the west by a mild structural (and gravity) high known as Chupadera Mesa (Kelley and

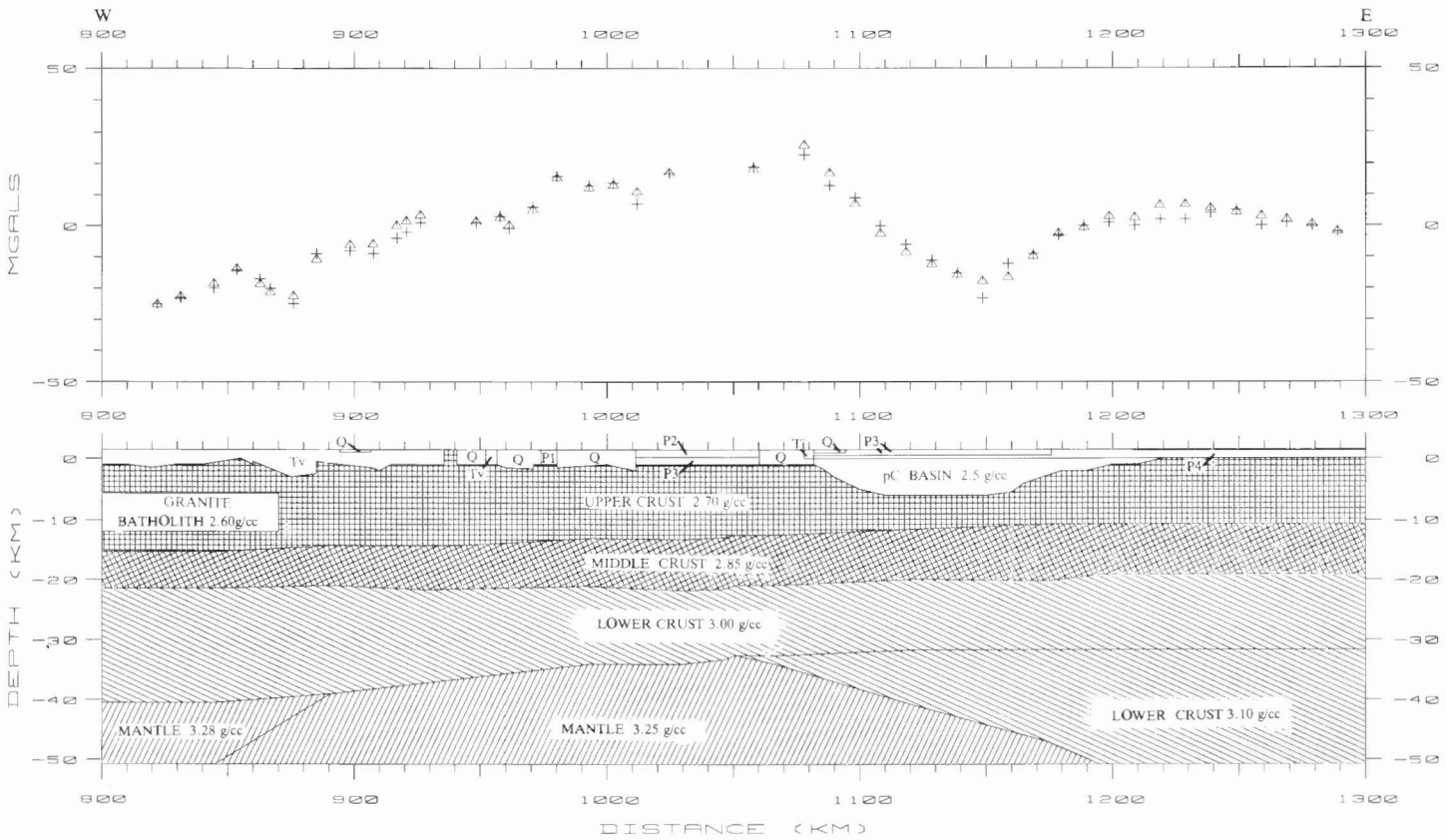


FIGURE 5. Gravity profile across New Mexico. See Fig. 2 for the exact location of the profile. The eastern half coincides with the seismic array. The densities near the surface are Tv (Tertiary volcanics) = 2.45 gm/cc; Q (Quaternary fill) = 2.35 gm/cc; P1 (Paleozoic rocks) = 2.5 gm/cc; P2 and P3 (Paleozoic rocks) = 2.35 gm/cc; P4 (Paleozoic rocks) = 2.58 gm/cc; Ti (Tertiary intrusives) = 2.65 gm/cc.

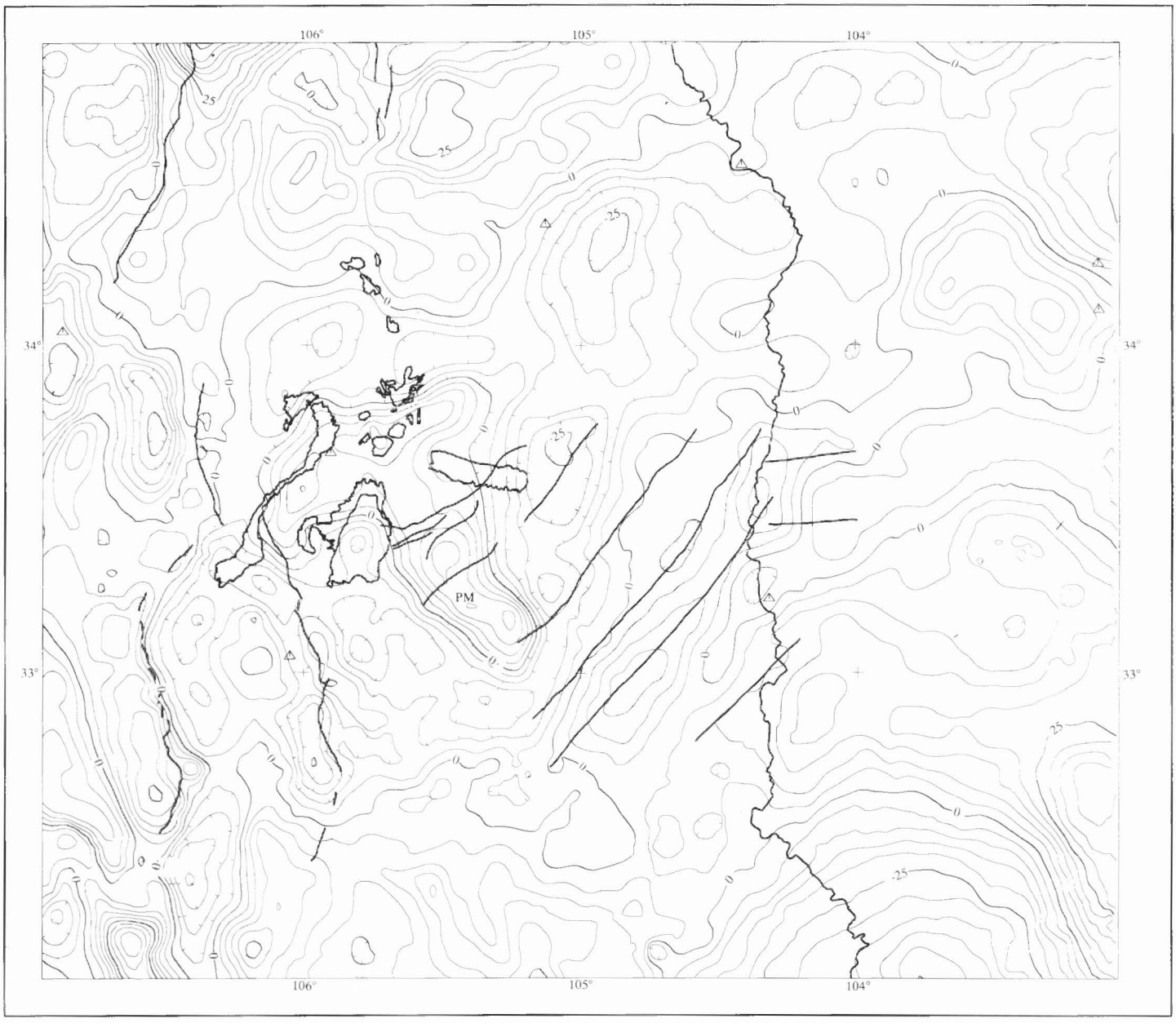


FIGURE 6. Residual gravity map of the study area obtained by removing a second order polynomial from Bouguer anomaly values: contour interval = 5 mgals, Bouguer reduction density = 2.67 gm/cc, sea level datum.

Thompson, 1964). The lowlands of the Estancia Basin, Claunch sag and Tularosa Basin form a somewhat continuous regional depression to the west of the late Paleozoic Pedernal uplift (Kelley and Thompson, 1964).

Moving to the southeast corner of the map, the thick Permian deposits within the Delaware Basin create the lowest gravity values on the map. Northeast of this basin, the northernmost extent of the Central Basin Platform creates values that are nearly the highest on the map. The gravity high near the northeast corner of the map corresponds approximately to the Matador uplift, an east-west-trending structural high. The Tucumcari Basin shows up as a mild gravity low.

A linear gravity low can be traced across the map extending southwest from the Tucumcari Basin. West of the Gallinas intrusions, this low bends to the south and continues for about 150 km, then turns abruptly to the northwest and terminates near the Sierra Blanca intrusion. Suleiman and Keller (1985) noted that the northern parts of this trend may be related to the Tucumcari Basin or may outline a previously unknown basin masked in drill-hole data by an igneous intrusion or a thrust sheet. The gravity profile generated as part of this study transects this feature at about 33.7°N latitude and our modeling indicates that the anomaly could be due to a Proterozoic basin that is up to 8 km deep (Fig. 5).

The southern portions of this gravity low outline the most prominent gravity feature in the Ruidoso area, a long, northwest-trending, T-shaped, 20–25 mgal gravity high. This anomaly appears to be overprinted on the southwest by the gravity low generated by the sediments within the Sierra Blanca Basin. Kelley and Thompson (1964) described this basin as a late Laramide feature unconformably overlain by the Paleogene Sierra Blanca Volcanics. It is generally aligned with the previously mentioned series of lowlands that bound the ancient Pedernal uplift.

With the exception of the Delaware Basin, the Central Basin Platform, and possibly the Tularosa Basin, most of the features described above can also be located on the magnetic map (Fig. 7). The Tucumcari Basin and the possible Proterozoic basin mentioned above have partic-

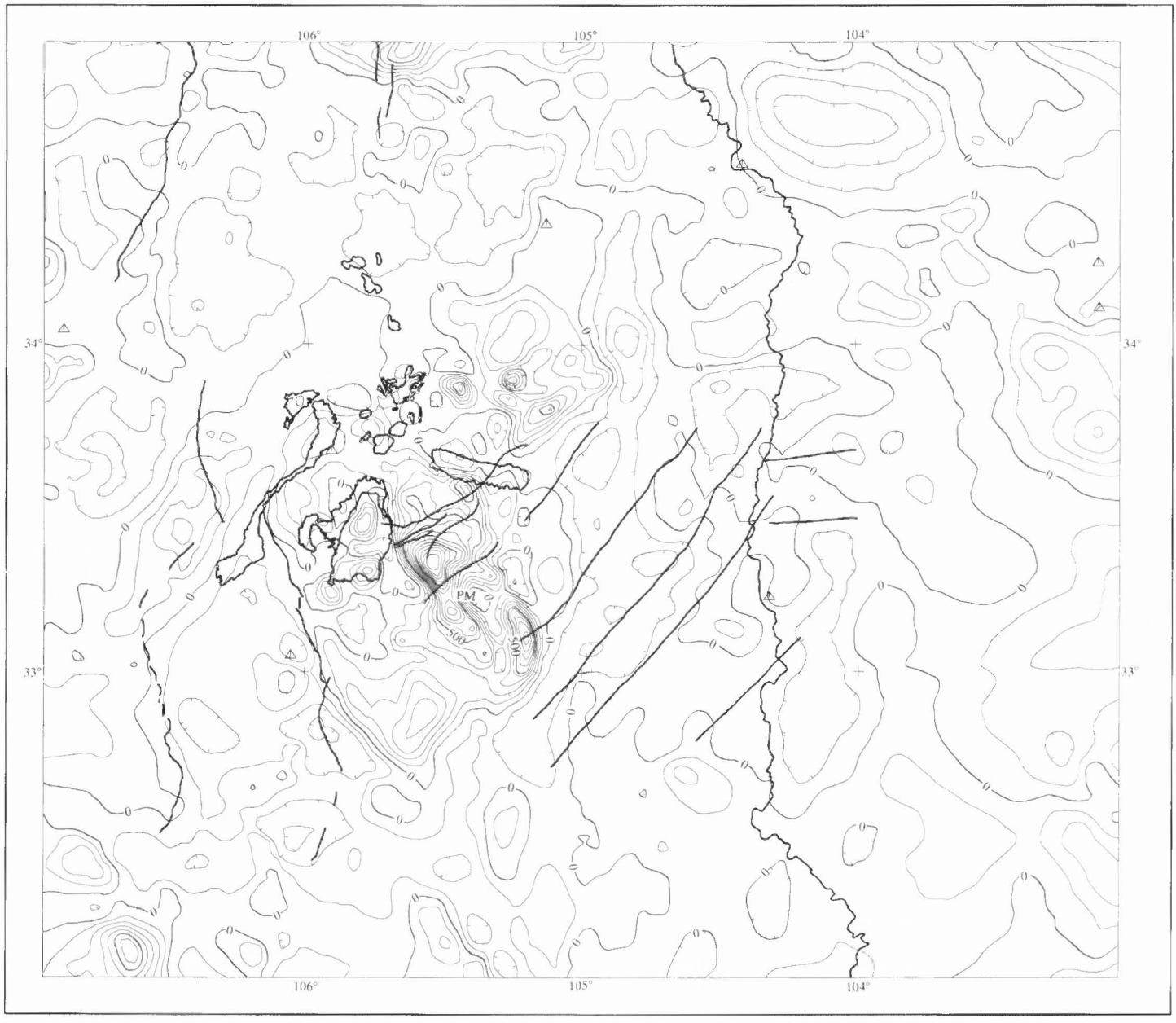


FIGURE 7. Magnetic intensity map of the study area. Contour interval = 50 gammas.

ularly strong magnetic signatures. The most prominent anomaly on the map appears to be associated with the same source that created the T-shaped gravity high.

The source of these two potential-field anomalies appears to transect the Laramide-age Mescalero arch, as described by Kelley and Thompson (1964), and the axis of the late Paleozoic Pedernal uplift (Kelley, 1971). Kelley (1971) noted that the Precambrian igneous exposures at Pajarito Mountain (noted in the figures as PM) are at the crest of the southeast portion of this gravity anomaly. The sharp angle at which these anomalies cut across other structures in the region, the lack of correlative surface features of similar scale, the exposures of intermediate-composition Precambrian igneous rocks near the crest, and the large areal extent of the anomalies suggest that the source body is a major crustal feature.

In the nearby Permian Basin, similar gravity anomalies were interpreted to be associated with large mafic intrusions (Keller et al., 1980). This interpretation was confirmed by a recent drill hole in which approximately 5 km of 1.1-Ga-old mafic intrusive rocks were encountered (Keller et al., 1989). By analogy, we suggest that the T-shaped gravity anomaly in the Ruidoso area is also due to a late Proterozoic mafic intrusion.

Gravity anomalies, seismic data and geologic data show that mafic intrusions form cores of several ancestral Rocky Mountain (Pennsylvanian) uplifts, such as the Central Basin Platform, Wichita uplift, Sierra Grande uplift, and Uncompahgre uplift (e.g., Keller et al., 1980; Suleiman and Keller, 1985). We feel it is possible that the interpreted mafic intrusion in the Ruidoso area was also at the core of a Pennsylvanian uplift. This feature would represent a structural apex on the Pedernal landmass.

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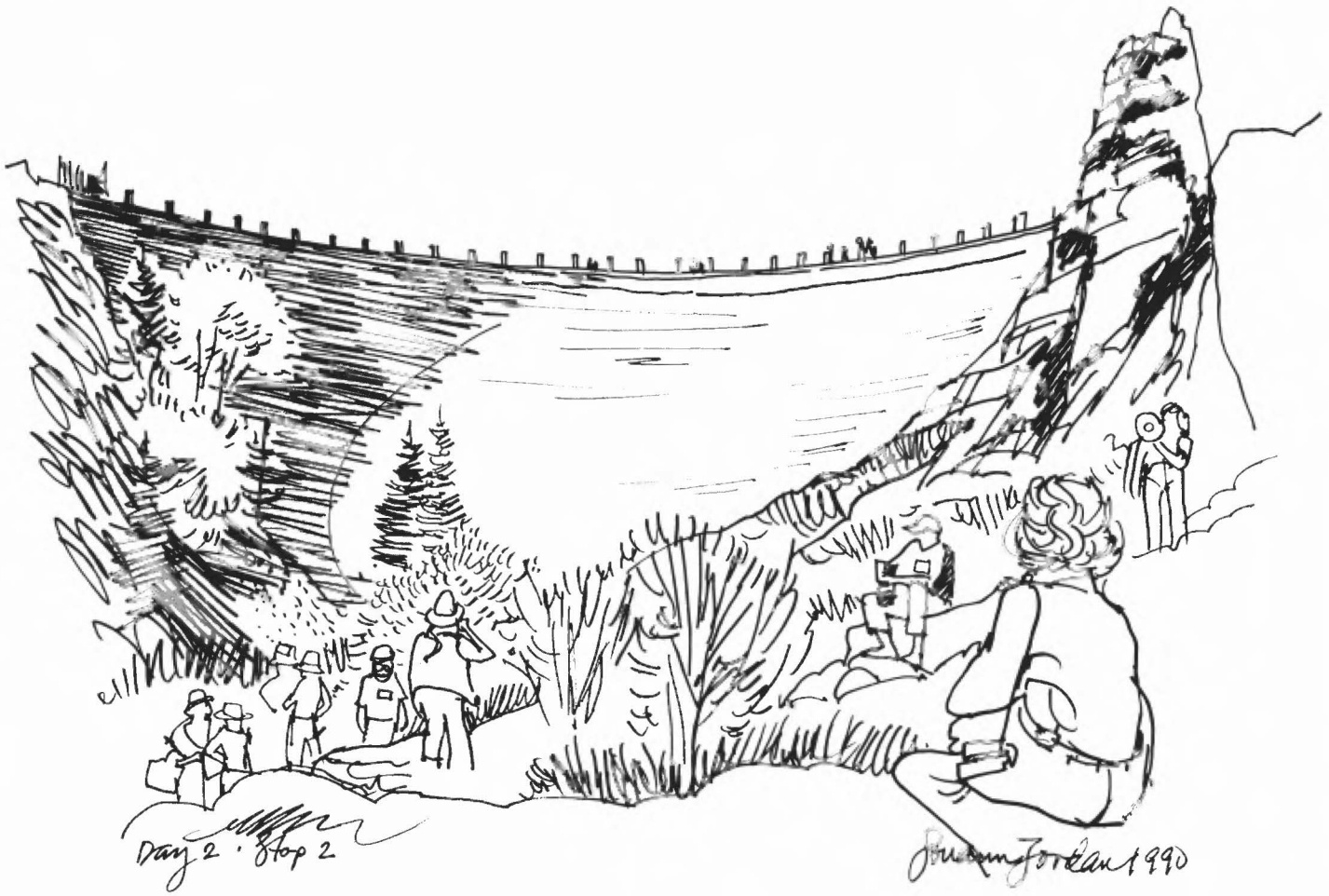
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Below Eagle Nest dam on the Cimarron River. The large dam and reservoir are owned by the CS Cattle Co. of Cimarron. The dam, completed in 1918, abuts into Precambrian gneiss. Day 2, Stop 2 of the 1990 NMGS Fall Field Conference. Illustration by Louann Jordan of Santa Fe, 1990.