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Structure of the Rio Grande rift in southern New Mexico and West Texas based on gravity interpretation

IVAR B. RAMBERG*
FREDERICK A. COOK*
SCOTT B. SMITHSON
Department of Geology, University of Wyoming, Laramie, Wyoming 82071

ABSTRACT

The Rio Grande rift, which is marked by a positive heat-flow anomaly in southern New Mexico, has been the subject of a gravity study based on 4,500 stations which cover a strip across New Mexico. The area consists of a series of basins and intervening ranges formed during Miocene time. This basin-and-range structure is strongly reflected in the Bouguer gravity anomalies, which range from −125 mgal over uplifts to −190 mgal over basins. Lineaments in trends of gravity anomalies are oblique to the predominant north-south trend of the rift and suggest that, in detail, the crust broke upon fractures oblique to the large-scale north-south trend. Thicknesses of Cenozoic sediments, determined from gravity measurements, range from 2 to 3 km in basins. The gravity effect of sediments is removed by stripping, and a broad +30-mgal gravity anomaly is located over the rift. Regional and residual Bouguer gravity anomaly maps have been constructed. The source of the 30-mgal gravity high is interpreted to be a shallow slab of basalt or a deep upwarp of the mantle that results in crustal attenuation. The low-velocity zone may project up toward the base of the crust under the Basin and Range province. Experiments and the observed fault pattern suggest an extensional origin for the Rio Grande rift fracture system.

INTRODUCTION

Southern New Mexico and West Texas — an area marked by a young rift, a thermal anomaly, and a transition in crustal structure — has been the site of a gravity study in order to resolve its crustal structure further. The Miocene to Holocene Rio Grande rift is one of the major north-south tectonic features of North America and forms a series of basins and fault troughs roughly followed by the Rio Grande River. The rift, which is an integral part of the Southern Rocky Mountain tectonic system, extends for at least 950 km from northern Chihuahua in Mexico, through New Mexico, and halfway up into Colorado. Its further extension is uncertain. To the north, the rift may be terminated at the upper Arkansas graben (Chapin, 1971), or it might continue northward through a right-lateral en echelon system of intermontane troughs into Wyoming (Tweto, 1968; Kelley, 1970). To the south, it may continue into the Los Muertos basin of Chihuahua and the generally northwest-trending fold and fault belt of the Texas lineament, or it may be offset by a major zone of strike-slip movement (Eardley, 1962; Chapin, 1971).

The Rio Grande rift separates the Great Plains to the east from the Colorado Plateau and Basin and Range province to the west and includes the highest mountains and deepest intermontane depressions in the country it traverses. The rift zone widens from north to south, where it consists of several parallel basins and intrarift horsts. In this area no well-defined line can be drawn between the Rio Grande rift proper and the wide zone of Basin and Range structure to the west.

Figure 1 shows the part of the rift reported here and the major physiographic elements of southern New Mexico. The outline of the Rio Grande rift follows the definition offered by Chapin (1971). The rift therefore covers a much wider area than that defined by Bryan (1938) and Kelley (1952, 1956) and includes features such as the Mimbres, Jornado del Muerto, and Tularosa basins.

This paper presents a gravity analysis of the southern part of the Rio Grande rift (Fig. 1) based on results from more than 4,500 gravity stations. The area covered extends from the Basin and Range province across the Rio Grande rift into the Great Plains and includes an area of about 480 × 160 km². The anomaly pattern provides the basis for a qualitative analysis of fault directions and origin of graben formation in the study area. Depths of basins have

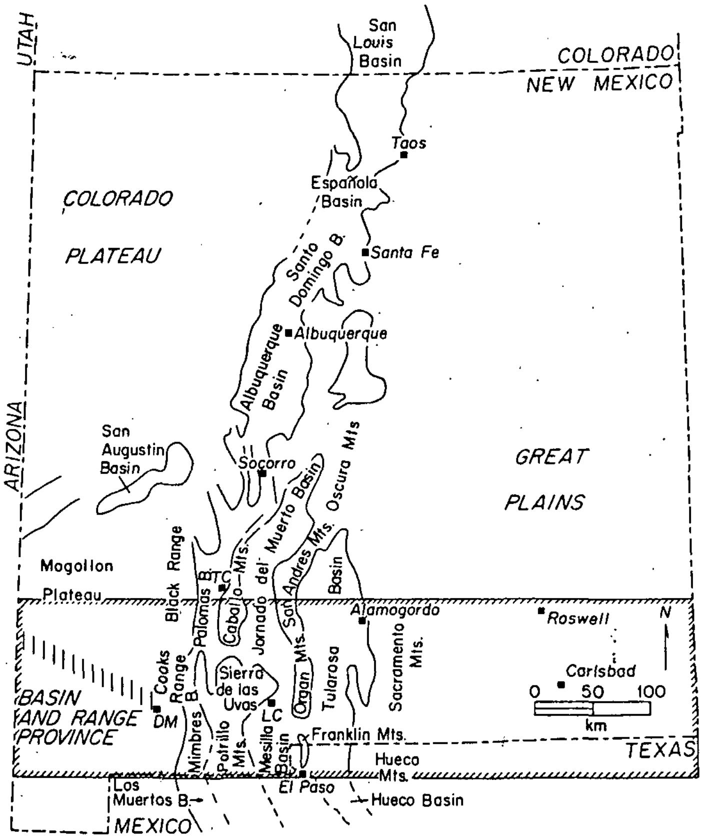

Figure 1. Index map of New Mexico and West Texas. Area of gravity map is outlined.

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* Present addresses: (Ramberg) Institutt for Geologi, Blindern, Oslo 3, Norway. (Cook) Continental Oil Company, Oklahoma City, Oklahoma 73112.

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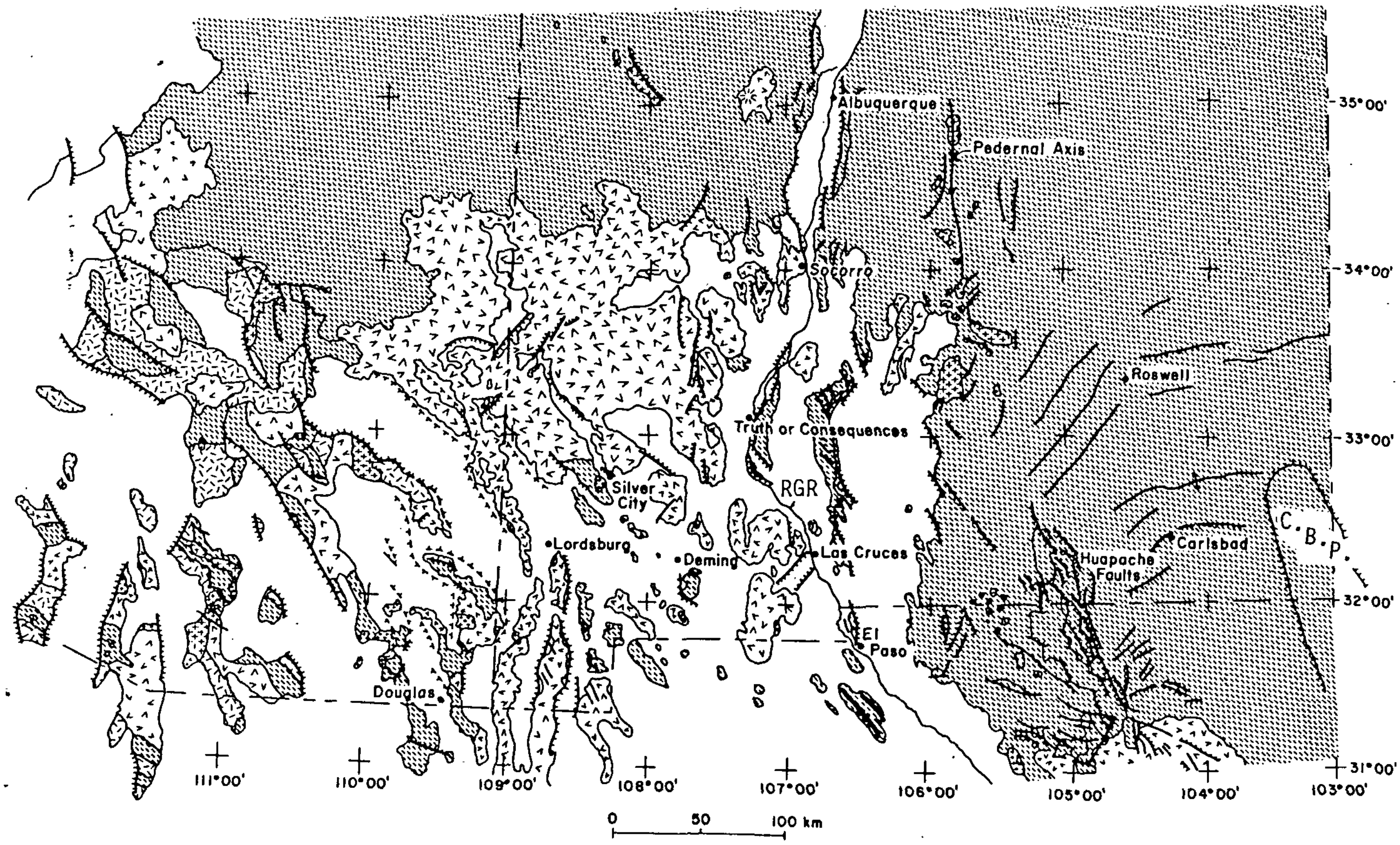


Figure 2. Tectonic map of southern New Mexico. C.B.P. = Central Basin Platform; RGR = Rio Grande rift.

been estimated by means of gravity anomalies and constraints such as surface geology, rock densities, well data, and, where available, seismic profiles. Stripping of surface geology has been applied to obtain information about deeper crustal structures and to compare with other active or ancient continental rifts.

GENERAL GEOLOGY AND GEOPHYSICS

The main structural features of the Ro Grande rift and the surrounding area, taken from the *Tectonic Map of the United States* (Kin, 1969), are presented in Figure 2. The Precambrian basement of southern New Mexico is covered with a sequence of sedimentary rocks ranging from Cambrian to Cretaceous in age. Upper Cenozoic alluvial fill in the individual basins varies within wide ranges; the probable average thicknesses are at least 1.5 to 2 km (Chapin, 1971). Stratigraphic details and tectonic development from various regions within the area investigated have been presented by Dunham (1935), Bryan (1938), Kelley (1952, 1956), Kelley and Silver (1952), Pray (1961), Kottlowski and others (1956), Kottlowski (1960), Dane and Bachman (1965), Kottlowski and LeMone (1969), Chapin (1971), and Harbour (1972).

Rifting in the Rio Grande area was initiated at least 26 m.y. ago (Chapin and Seager, 1975). The rift, which is characterized by extensional tectonism (Kelley, 1952, 1956; Woodward and DuChene, 1975), young basaltic volcanism (Lipman, 1969; Hoffer, 1969; Renault, 1970; Kudo and others, 1971; Chapin and Seager, 1975), and hot-spring activity (Summers, 1968), shows evidence of an increased rate of volcanism (Chapin, 1971). From a more regional point of view, the rift is situated at the zone of transition between the abnormally thin continental crust of the Basin and Range province (averaging slightly more than 30 km) and the Great Plains, with crustal thicknesses in the range of 45 to 55 km (Stewart and Pakiser, 1962; Stuart and others, 1964; Pakiser and Zietz, 1965; Johnson, 1967; Prodehl, 1970). Studies of P_n velocities and travel-time delays led Herrin and Taggart (1962) and Cleary and Hales (1966) to suggest that a pronounced low-velocity layer (P_n velocities of 7.7 to 7.8 km/s) is localized in the upper mantle below the Basin and Range province, and Archambeau and others (1969) concluded that the zone extends from near the base of the crust to depths of 150 to 175 km. Similarly, Julian (1970) has shown that depth to the top of the low-velocity zone increases abruptly from about 30 to 100 km at the Basin and Range–Colorado Plateau transition, the latter province having a markedly thicker crust (<40 km) as compared to the Basin and Range Province to the south and west.

Heat-flow data (Roy and others, 1968, 1971; Decker, 1969; Blackwell, 1969; Warren and others; 1969; Decker and Smithson, 1975; Reiter and others, 1975; Decker and others, 1975) indicate that the upper mantle beneath the Basin and Range province is anomalously hot, but that the Rio Grande rift is characterized by significantly higher surface and reduced flux than the Basin and Range province. The flux gradually decreases eastward to normal values over the Great Plains, the heat-flow transition zone probably being only 50 to 100 km wide. Geomagnetic deep-soundings (Schmucker, 1964, 1970; Porath and Gough, 1971) indicate a shallowing of the isotherms from the Great Plains into the Basin and Range province, which, however, is superimposed on a local upwarp below the Rio Grande rift. Magnetotelluric investigations by

Swift and Madden (1967) largely give similar results but with the upwarp shifted somewhat to the west. All these data are compatible with the idea that the low-velocity layer consists of partially melted material, and they agree with the existence of extensive recent volcanism in the Rio Grande rift. Preliminary gravity studies (Decker and Smithson, 1975; Ramberg and Smithson, 1975) show that the superficial grabens and intrarift horsts of the rift may be associated with the Basin and Range province. The Rio Grange rift not only represents the demarcation line between the Basin and Range province and the Great Plains, but constitutes a characteristic structural province of its own.

ANALYSIS OF GRAVITY DATA

Of the more than 4,500 gravity stations within the study area, approximately 3,000 are stations measured by us. Other sources of gravity data are the Department of Defense, Gravity Library, the U.S. Air Force, and oil companies. All stations were reduced to the same datum level, using El Paso N (established by the U.S. Air Force, $g = 979{,}064.9$ mgal) as the main base station. For vertical control, gravity stations were located on spot elevations (7.5-min. maps, where available) or bench marks. Terrain corrections have not been included; however, sample calculations show that the corrections are generally less than 0.2 mgal for stations in the basins and as much as 4 to 5 mgal in some of the ranges, thereby enhancing the gravity relief between basins and uplifts.

QUALITATIVE INTERPRETATION AND STRUCTURAL TRENDS

The striking feature of the Bouguer anomaly map (Fig. 3) is the relatively high gravity values over uplifts and the low values over basins or grabens. Exceptions are the general lows associated with the uplifted Datil-Mogollon volcanic field and some of the lows and highs over the Great Plains in the Sacramento Mountains and eastward. The typical difference in gravity anomalies between mountain ranges and adjacent alluvial basins is −25 to −35 mgal, although differences of as much as −50 mgal are found, for example, in the Hueco and Tularosa basin. The gravity anomalies confirm basin-and-range structures in southern New Mexico, as has previously been shown for the Rio Grande rift farther to the north (Joesting and others, 1961; Sanford, 1968). The individual anomalies resemble those associated with many sediment-filled grabens of the Basin and Range province in Nevada, Utah, and Arizona (Thompson, 1959; Cook, 1969; Sumner, 1972; and a similar mechanism of formation seems reasonable.

However, the Bouguer anomalies form a more complex pattern than might be expected from the predominantly north-trending physiographic features of the study area; this pattern differs from the commonly occurring unidirectional anomaly pattern present in part of the Basin and Range province (Woollard and Joesting, 1964; Sumner, 1972; West and Sumner, 1973). Inspection of the map (Fig. 3) reveals that the major basins and ranges are subdivided into a number of smaller gravity highs and lows. The gravity expression of the border of the major north-trending features therefore defines a typically broken or zig-zag outline (Ramberg and Smithson, 1975). The individual highs and lows clearly trend in the north-northwest and north-northeast directions, although more westerly and northerly trends do occur.

These trends are better seen from Figure 4 which shows a gravity lineament analysis. The thick, solid lines represent zones of maximum gravity gradients, whereas the dashed lines mark the less prominent zones. A possibly significant difference is seen in the typical Basin and Range province, with its close to orthogonal northwest- and northeast-trending lineament patterns (west of the Florida Mountains), as contrasted to the somewhat more oblique (north-northwest and north-northeast) trending pattern of the central (Rio Grande) area. These linear trends plotted in a rose diagram show maxima for northeast and northwest trends (Fig. 5).

The generally northwest- and northeast-trending lineaments compare to similar trends in (1) the topography of the shaded relief map of New Mexico and the raised relief map of the Las Cruces 2° sheet (Chapin, 1975, personal oral commun.), (2) aeromagnetic maps of the northwestern portion of the area studied, and (3) the predominant fault patterns on detailed maps of the area, such as the Klondyke Hills (Armstrong, 1970) and the Big Burro uplift (Hewitt, 1959; Gillerman, 1970) in the Basin and Range province south of the Mogollon plateau; the Sierra County region (Kelley, 1955); the Caballo Mountains (Kelley and Silver, 1952); the Lake Valley quadrangle (Jicha, 1954); the Fluorite Ridge area (Griswold, 1961); the Tres Hermanas Mountains (Balk, 1961); the San Diego Mountains (Seager and others, 1971); the Franklin Mountains (Harbour, 1972); the Souse Springs quadrangle (Clemons and Seager, 1973); the Bishop Cap–Organ Mountains (Dunham, 1935; Seager, 1973); and the Rincon quadrangle (Seager and Hawley, 1973). Furthermore, where it can be checked, the zones of maximum gravity gradients coincide with mapped faults and flexures. This is perhaps best seen along the eastern slopes of the Franklin–San Andres Mountains and along the western foothills of the Sacramento Mountains where the major structural features are north-northwest–trending right-echelon normal faults (Fig. 2). Other examples are the north-northeast–trending Robledo and Fitzgerald faults (De Hon, 1965) bordering the Mesilla basin southwest of Las Cruces and the more northwest-trending faults flanking the Burro uplifts and intervening basins (Fig. 1).

We therefore suggest that the marked linear gravity trends in the area investigated correlate with major faults, series of step faults, or flexures. This interpretation is in agreement with studies in the Basin and Range province, where steep gravity gradients are commonly considered evidence for graben faults (Stewart, 1971).

Figures 2 to 5 suggest the general interpretation that the larger structural units in the rift are consistently broken up into smaller fault blocks largely trending north-northwest and north-northeast. The individual basins are small and terminated by cross-structures. The inferred gridded fault pattern results in a fragmented appearance of the entire area studied.

Furthermore, the major basins and uplifts form linked en echelon systems of troughs or ridges. This is apparently also the case farther north in the Rio Grande rift, and a right-lateral sense of displacement of the basins has been indicated on the basis of geologic and geophysical evidence (Kelley, 1970; Elston, 1970; Cordell, 1970a).

The predominant northwesterly and northeasterly trends occur in a wide region also outside the study area (for example, Kelley and Clinton, 1960; Wise, 1968; King, 1969; Zietz and others, 1971). Kelley and Clinton (1960), p. 2) concluded that "the dominant regional sets in northeasterly, northwesterly, and easterly directions make it appear that there was some overall deep-seated stress system that was generally responsible for the final features of the fracture system" and "early formed fractures that were favorably oriented with regard to the new stress systems were extended to greater predominance" (p. 97). This and other hypotheses for the formation of the inferred fault pattern in the rift are discussed at the end of this paper.

DENSITY VALUES

Density data for this study were collected from four sources: (1) published data by Mattick (1967) and Sanford (1968), (2) Mobil Oil Company surface samples and density logs, (3) a density profile based on a Continental Oil Company seismic section, and (4) 93 of our own surface-sample measurements.

Mattick (1967) published a gravity survey of the Hueco Basin east of El Paso, Texas, and based much of his density determinations on seismic information. He assigned the following values for

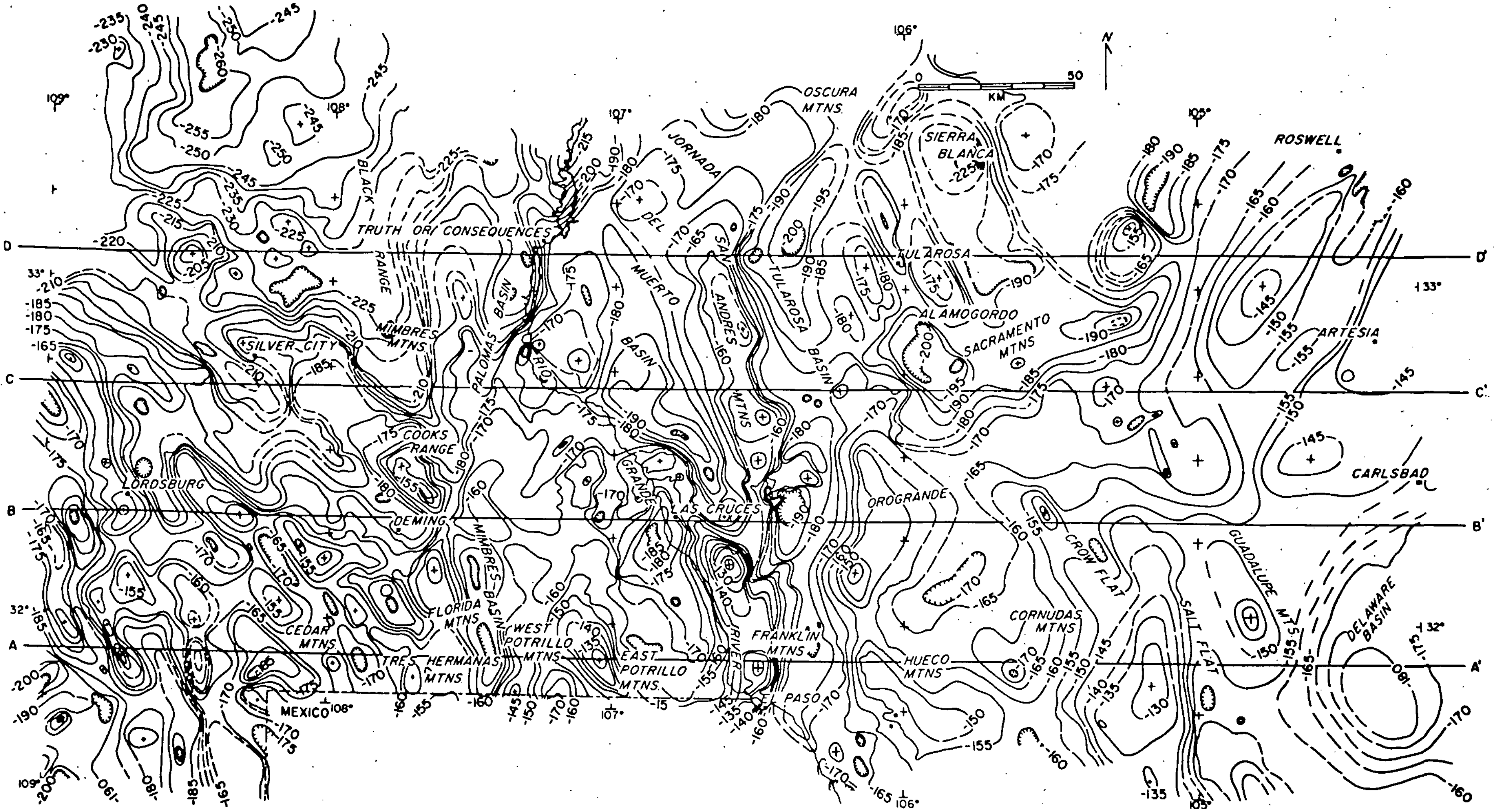


Figure 3. Bouguer gravity anomaly map, south-central New Mexico; contour interval, 5 mgal.

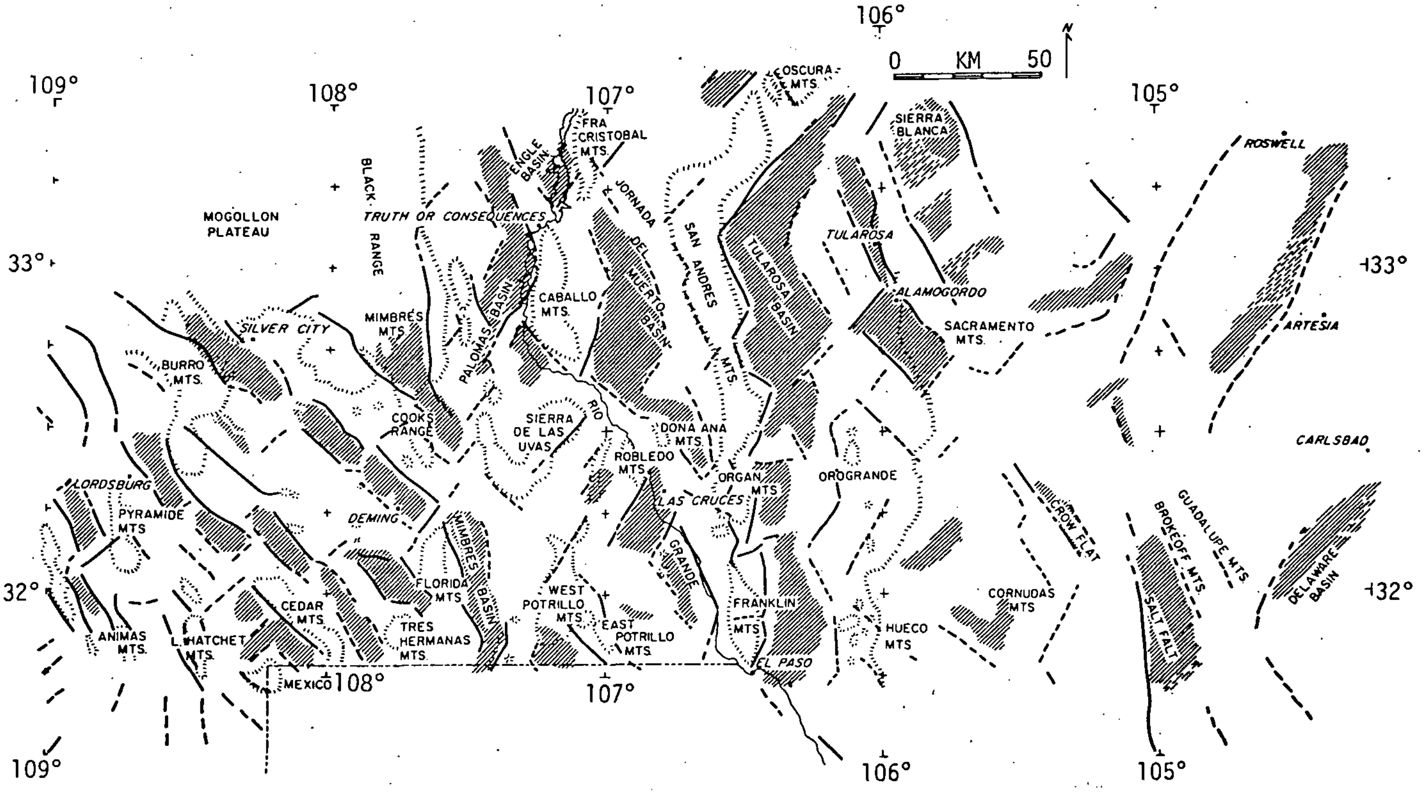


Figure 4. Lineaments in gravity trends found from Bouguer gravity anomaly map (Fig. 3). Mapped faults are also plotted.

density: Paleozoic rocks = 2.55 g/cm^3, Mesozoic and Tertiary rocks = 2.40 g/cm^3, Tertiary bolson deposits = 2.20 g/cm^3, and unconsolidated Quaternary basin fill deposits = 2.15 g/cm^3. Similar values were used by Sanford (1968), although the divisions between each of the density contrasts were slightly different. The average densities used by Sanford were as follows: Paleozoic rocks (Pennsylvanian through Permian) = 2.56 g/cm^3, Mesozoic and Tertiary rocks = 2.37 g/cm^3, and Tertiary Santa Fe Formation = 2.20 g/cm^3.

Density logs of two wells in eastern New Mexico, and values of densities determined from surface samples were donated by Mobil Oil Company. Both the well information [average density = 2.61 g/cm^3 for Montoya (Ordovician) through Cisco (Permian)] and the surface samples (average density = 2.64 g/cm^3 for five Permian formations) suggest that the Paleozoic rocks may require a slightly higher density value in southern New Mexico than those assigned above by Mattick (1967) and Sanford (1968).

Density data for samples collected by University of Wyoming personnel are shown in Table 1. These samples were measured by weighing in air and in water. The results exhibit a very high average (density = 2.62 g/cm^3) for the sedimentary rocks. It is likely that this high value results from an inherent bias present in surface sampling. When collecting surface samples, well-exposed, resistant outcrops were more often chosen, rather than poorly exposed, unconsolidated samples. Resistant rocks tend to have higher density values and should therefore result in a higher average density determination.

Table 2 lists the values obtained for the unconsolidated sediments; these data suggest reducing the average values obtained from the previous surface sampling.

Determining the density values of unconsolidated sediments is much more difficult than for consolidated samples. If the method of weighing in air followed by weighing in water is used, care must be taken to prevent the sample from losing any material. This, of course, is often not possible. In order to circumvent this difficulty, the samples were coated with paraffin, and the volumes were then measured in an air comparison pycnometer. The samples were first cored, weighed, coated with paraffin, and then weighed again. Care was taken to prevent the paraffin from soaking into the pore space, because the bulk density of the sample was desired. Thus, on the basis of the weight and density of the paraffin coat, the volume of the paraffiin could be determined. Finally, measuring in the pyc-

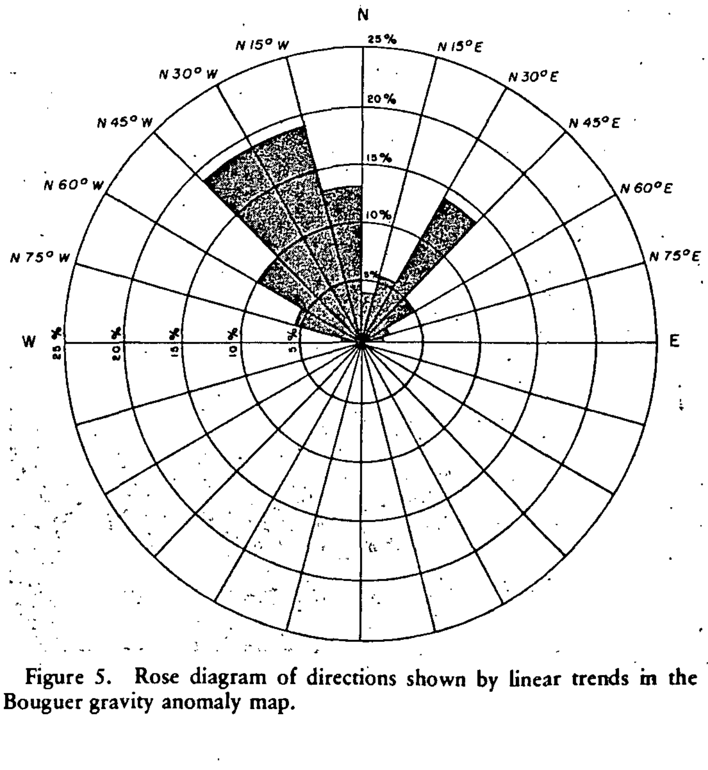


Figure 5. Rose diagram of directions shown by linear trends in the Bouguer gravity anomaly map.

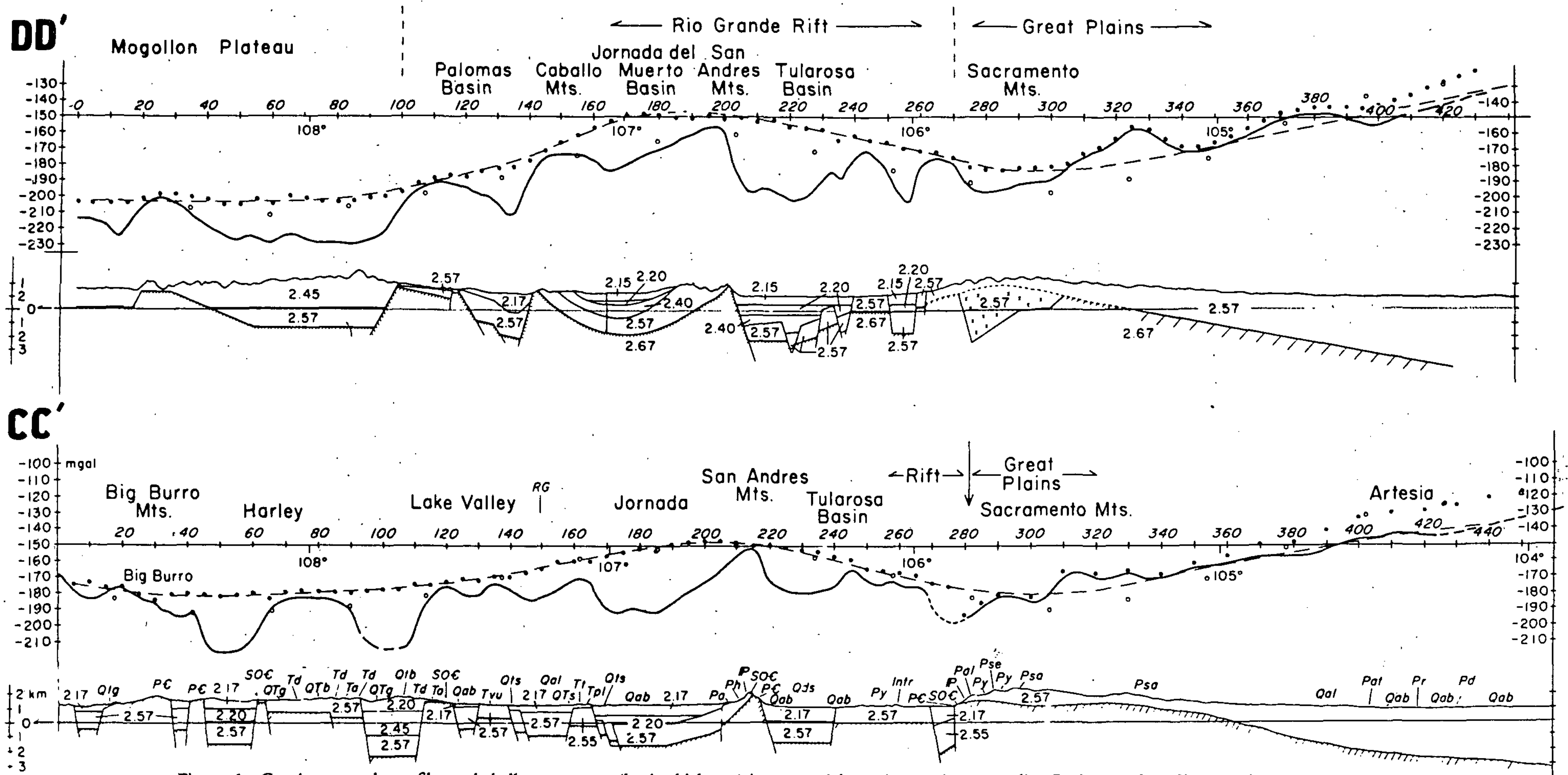


Figure 6. Gravity anomaly profiles and shallow structure (basin thickness) interpreted from the gravity anomalies. Positions of profiles are plotted in Figure 3.

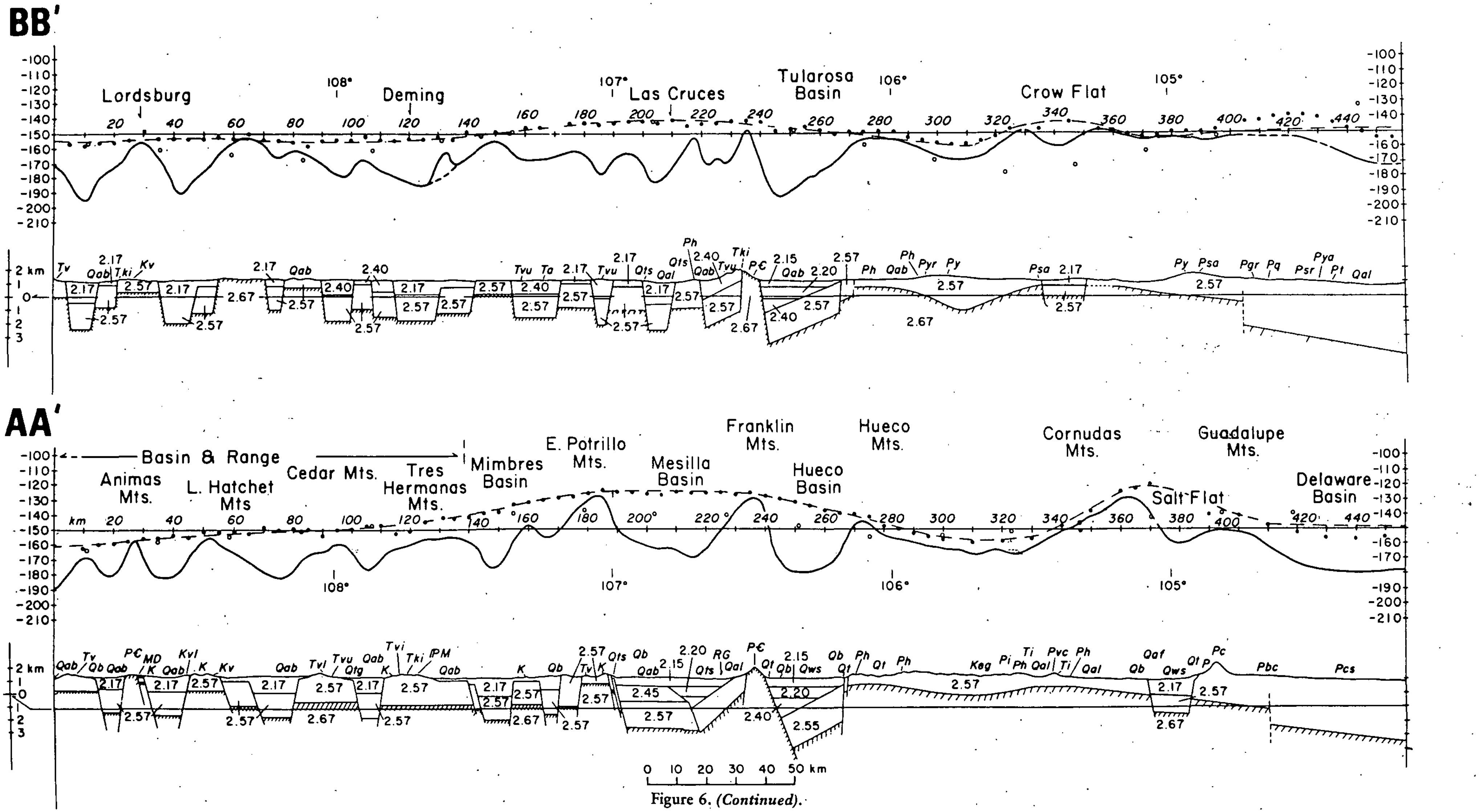


Figure 6. *(Continued)*.

TABLE 1. DENSITY MEASUREMENTS

Rock type	No. of samples	Mean density (g/cm^3)	Range
Precambrian granite	5	2.58	2.55–2.67
Precambrian quartzite	3	2.65	2.65–2.65
Precambrian rhyolite porphyry	6	2.67	2.61–2.71
Ordovician El Paso Limestone	4	2.79	2.77–2.80
Ordovician Montoya Dolomite	2	2.71	2.70–2.72
Silurian Fusselman Dolomite	4	2.78	2.72–2.84
Pennsylvanian Gobbler limestone	7	2.65	2.60–2.67
Pennsylvanian Madera Limestone	3	2.37	2.36–2.37
Pennsylvanian Magdalena Limestone	5	2.48	2.46–2.51
Permian Buisun limestone	7	2.66	2.63–2.70
Permian Hueco Limestone	4	2.69	2.68–2.70
Permian Abo Formation	3	2.51	2.36–2.65
Permian Bone Spring Limestone	2	2.67	2.67–2.68
Permian San Andres Formation	3	2.40	2.07–2.72
Permian Grayburg limestone	1	2.83	2.83
Permian Queen limestone	5	2.73	2.65–2.84
Permian Trivers limestone	1	2.79	2.79
Cretaceous Mesaverde Formation	3	2.61	2.52–2.68
Tertiary Datil Formation	3	2.56	2.49–2.68
Tertiary trachytic intrusive	12	2.48	2.42–2.52
Tertiary Rubio Peak Formation	13	2.43	2.33–2.52
Pleistocene basaltic lava	2	2.44	2.43–2.44

TABLE 2. DENSITY MEASUREMENTS OF POROUS SEDIMENTARY ROCKS

Rock type	Formation name and age	Porosity (%)	Bulk density (g/cm^3)
Shale	Percha, Devonian	20.7	1.88
Sandy shale	Quaternary-Tertiary	23.2	2.00
Limey shale	Quaternary-Tertiary	14.1	2.21
Shale	Mancos, Cretaceous	31.5	1.86
Conglomerate	Thurman, Tertiary	17.6	2.38
Sandy shale	Quaternary-Tertiary	16.7	2.30

nometer allowed calculation of the percentage of pore space in the sample to be made. Hence, the bulk density of the sample could be determined.

The values for sandy shale (Quaternary-Tertiary) are from three rock types in the Tertiary Santa Fe Formation: unconsolidated sand and clay (density = 2.00 g/cm^3), marl (density = 2.21 g/cm^3), and sand and gravel (density = 2.30 g/cm^3). The most prevalent rock types within this formation are the unconsolidated sands and gravels, suggesting that the average density of the Santa Fe Formation is about 2.20 g/cm^3. A seismic profile across the Jornado del Muerto basin was used to construct models of the basin in which density was varied until a good gravity fit was obtained (Cook, 1975). The density values so obtained are as follows: Paleozoic rocks = 2.57 g/cm^3, Mesozoic and Tertiary consolidated and volcanic rocks = 2.40 g/cm^3, unconsolidated Tertiary rocks = 2.20 g/cm^3, and Quaternary basin fill = 2.17 g/cm^3.

DEPTH OF BASINS AND STRIPPING OF SURFACE GEOLOGY

The major features of the Bouguer gravity field are the gravity lows over faulted basins and gravity highs over intervening ranges. These relatively short wavelength features are caused principally by the negative attraction of low-density Cenozoic sediments in the basins. If the effects of sedimentary rocks were removed, we could look at the gravity field as it would be at the surface of unfaulted Precambrian basement and therefore see the effects of deeper features on the gravity field. This process is called "stripping" (Hammer, 1963), and we use it to remove "noise" caused by near-surface structure from the gravity field in order to look at deeper, longer wavelength features that may be related to geothermal anomalies in the area.

Stripping has been carried out along four profiles through the area (Fig. 6). Best values for density, seismic data, and borehole data have all been used for control to determine thicknesses of sedimentary rocks that were stripped. The result is to calculate basin thickness and geometry and then to add the gravity effect of basin models with reversed sign to Bouguer gravity values. This process has the effect of giving a smoothed gravity anomaly that should approximate the gravity field when all sedimentary rocks are removed. Gravity values on the basement in uplifts are used for control of these anomalies. Averaged values of gravity over uplifts give essentially the same picture. Intrabasement density contrasts will affect these basement anomalies, but consideration of large areas should effectively smooth out gravity anomalies from local basement features.

The four profiles (Figs. 3, 6) indicate that the thicknesses of Tertiary basins range from 2 to 4 km. Cenozoic fill in the basins is about 2 km thick. Rather than simple, single downdropped blocks, basins may consist of numerous steplike blocks (Fig. 6). Major basins, based on gravimetric expressions, are the Tularosa, Mesilla, and Palomas basins.

After the gravity effect of sedimentary rocks is calculated, points are plotted to give a smoothed gravity profile that should approximate one found if no sedimentary rocks were present. All four profiles show that the Bouguer gravity field has a marked high of 20 to 30 mgal over the area of the rift. This gravity high generally covers the basins that compose the rift as defined by Chapin (1971). Because of the negative effect of bordering sedimentary basins, gravity anomalies over intervening ranges such as the San Andres Mountains become more positive than observed values. This gravity high also corresponds to the geothermal maximum found by Decker (Decker and Smithson, 1975; Decker and others, 1975). This gravity high is a regional feature that is broad and poorly defined near El Paso and that trends northward at least to central New Mexico as a sharp feature along the rift. The stripped gravity profiles form a basis to construct a regional Bouguer gravity anomaly map (Fig. 7), which clearly shows the gravity high. The regional Bouguer gravity anomalies are subtracted from the simple Bouguer gravity anomalies to give a residual Bouguer gravity anomaly map (Fig. 8); this map primarily shows the negative effect of Cenozoic sedimentary basins.

As an example of deriving sedimentary geometry from gravity anomalies, the Tularosa basin has been modeled by means of a self-adjusting computer program written by Cordell (1970b). Residual gravity anomaly values (Fig. 8) and a constant density contrast of −0.35 g/cm^3 are used. The resulting computer-derived model is shown by means of depth contours (Fig. 9). Any basement-derived gravity anomalies as well as lateral density variations within the sedimentary rocks will cause errors in the model; however, with these exceptions, the model should show relative changes in depths of the basin. The basin ranges in thickness from 2 to 5 km and shows a general maximum thickness of 3 to 4 km. Comparing the three-dimensional model (Fig. 9) with the two-dimensional cross sections (Fig. 6), we see that both models give similar results, except for locally greater depths in three-dimensional models.

THREE-DIMENSIONAL BASEMENT ANOMALIES AND REGIONAL FEATURES

The "regional" or "basement" anomaly map presented in Figure 7 shows the gravity field remaining after removal of the local effects associated with near-surface structures such as basins, intrusive complexes, and so forth. It still contains some irregularities caused by mass anomalies, but its overall configuration reflects more deep seated or large-scale features within the basement complex.

The regional field shows several important features: (1) the rift zone is associated with a broad gravity high trending approxi-

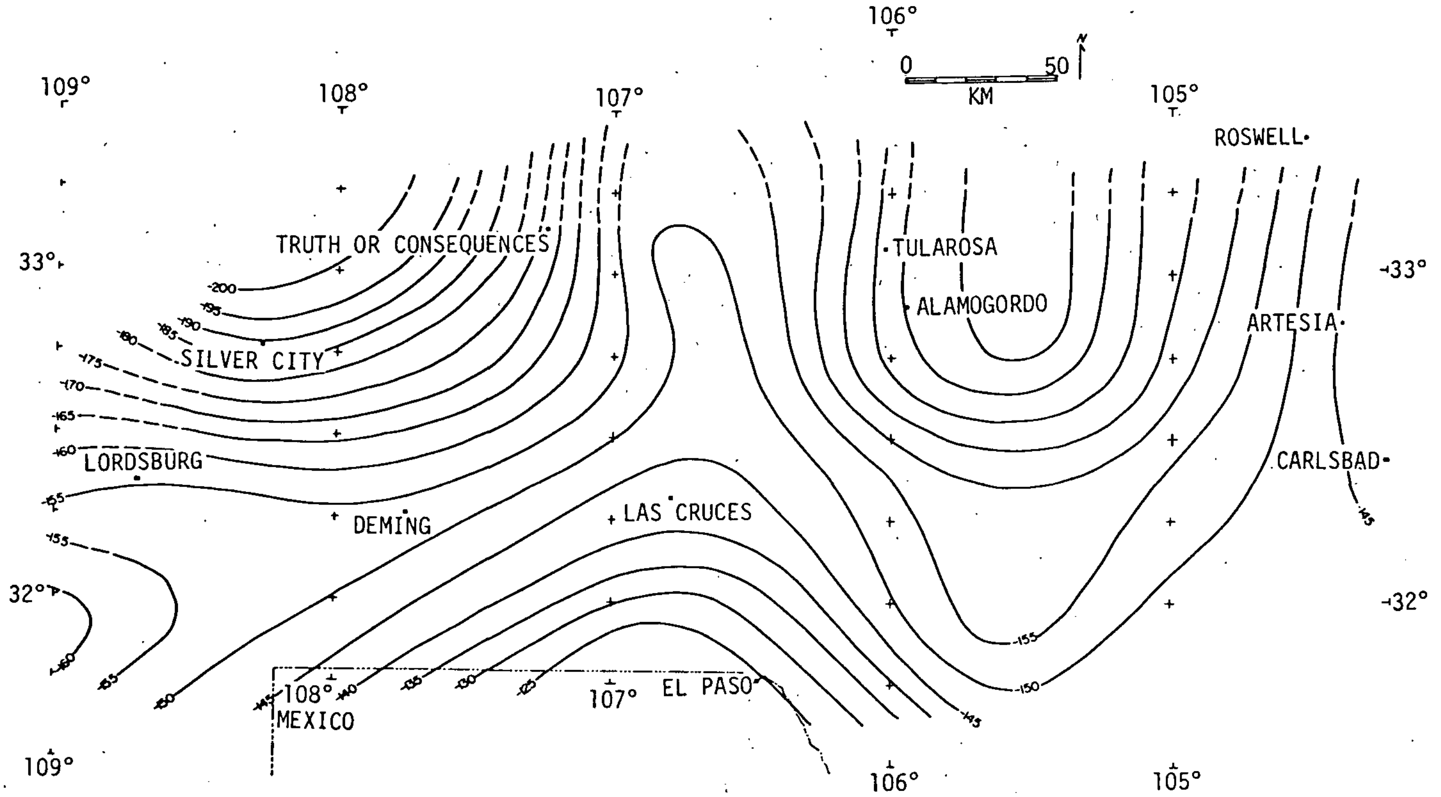


Figure 7. Regional Bouguer gravity anomaly map; contour interval, 5 mgal.

mately north-south; (2) within the study area, the high narrows in a wedgelike fashion from south to north but apparently continues northward along the rift zone outside the map area; (3) in the southernmost part, the high becomes less distinct and merges with the gravity field associated with the adjacent Basin and Range provinces, but it also widens to the east. This high is superimposed on an even wider gravity low extending halfway across the continent from the western part of the Basin and Range province to well inside the Great Plains in the east. Figure 10 illustrates the regional low and how it closely follows "predicted" values calculated from isostatic considerations (Woollard, 1969). It also emphasizes that the regional high is a characteristic feature of the (southern) Rio Grande rift, closely associated with the region of recent volcanism, hot-spring activity, and geomagnetic and electric anomalies.

Figure 11 presents possible lithospheric models based on gravity anomalies for the four profiles A-A′ to D-D′. The two solutions given — (A) subcrustal "rift cushion" or asthenospheric upwarp and (B) shallow mafic intrusion — represent two extremes of a series of hypothetical solutions. For the model calculations, depths to various interfaces and choice of densities were based on available seismic data (Stewart and Pakiser, 1962) and velocity-density relations (Rich, 1960, 1961; Nafe and Drake in Grant and West, 1965).

From gravity anomalies alone, no final conclusion can be drawn, although the gravity gradients indicate that no shallow source is very likely unless it is broad. It seems, however, that the seismic control outside the rift zone and the rise of isotherms indicated by the geomagnetic and electric anomalies (Schmucker, 1964, 1970; Porath and Gough, 1971; Swift and Madden, 1967) favor alternative A. The alkalic basaltic rocks along the rift zone suggest a deep (70 to 150 km) source for these rocks (Lipman, 1969; Green and Ringwood, 1970; Turcotte and Oxburgh, 1969) and demonstrate that vertical flow of mantle-derived material into the crust actually has taken place in the rift zone.

Although a somewhat shallower position of the dense rocks cannot be ruled out, evidence seems compatible with the model of lithospheric thinning as sketched in Figure 11 (solution A). Probably, however, the inferred upwarp is associated with the presence of dense intrusive rocks (dikes) dispersed within the crustal column below the rift, which contribute to the high heat flow and gravity anomaly found at the surface.

STRUCTURAL MODEL OF RIFT

The geological interpretation of the geophysical models presented is summarized in an east-west section across the southern part of the study area and is compared with a similar section across the Basin and Range province to the northwest (Fig. 12).

The low-velocity, low-density zone beneath the Basin and Range province seems well documented (Pakiser and Zietz, 1965; Cleary and Hales, 1966; Archambeau and others, 1969; Julian, 1970; Thompson and Burke, 1974), and the increased thinning in the Rio Grande region is implied in the study reported here. The lower boundary of the low-velocity zone is undetermined but may be gradational into the deeper parts of the upper mantle. The low-velocity zone probably consists of partially melted material (for example, Green and Ringwood, 1967, 1970; Green, 1970, 1971; Archambeau and others, 1969; Roy and others, 1971). While the deeper part of the lithosphere may have given way plastically because of the buoyant rise of upper-mantle material and deep-seated extension, the brittle upper crust accommodated the imposed stress by complex fracturing and graben subsidence.

DISCUSSION

Origin of Fault Pattern and Troughs

The gridded fault pattern and en echelon boundary faults inferred in the Rio Grande rift are features that seem more common in continental rifts than previously recognized. For example, north-northwest en echelon normal faults define the north-trending Ethiopian scarp to the west of the Danakil depression in Afar, and local regions within the depression exhibit regular grid faults and joints (Marinelli and others, 1973). A dominant north-northwest

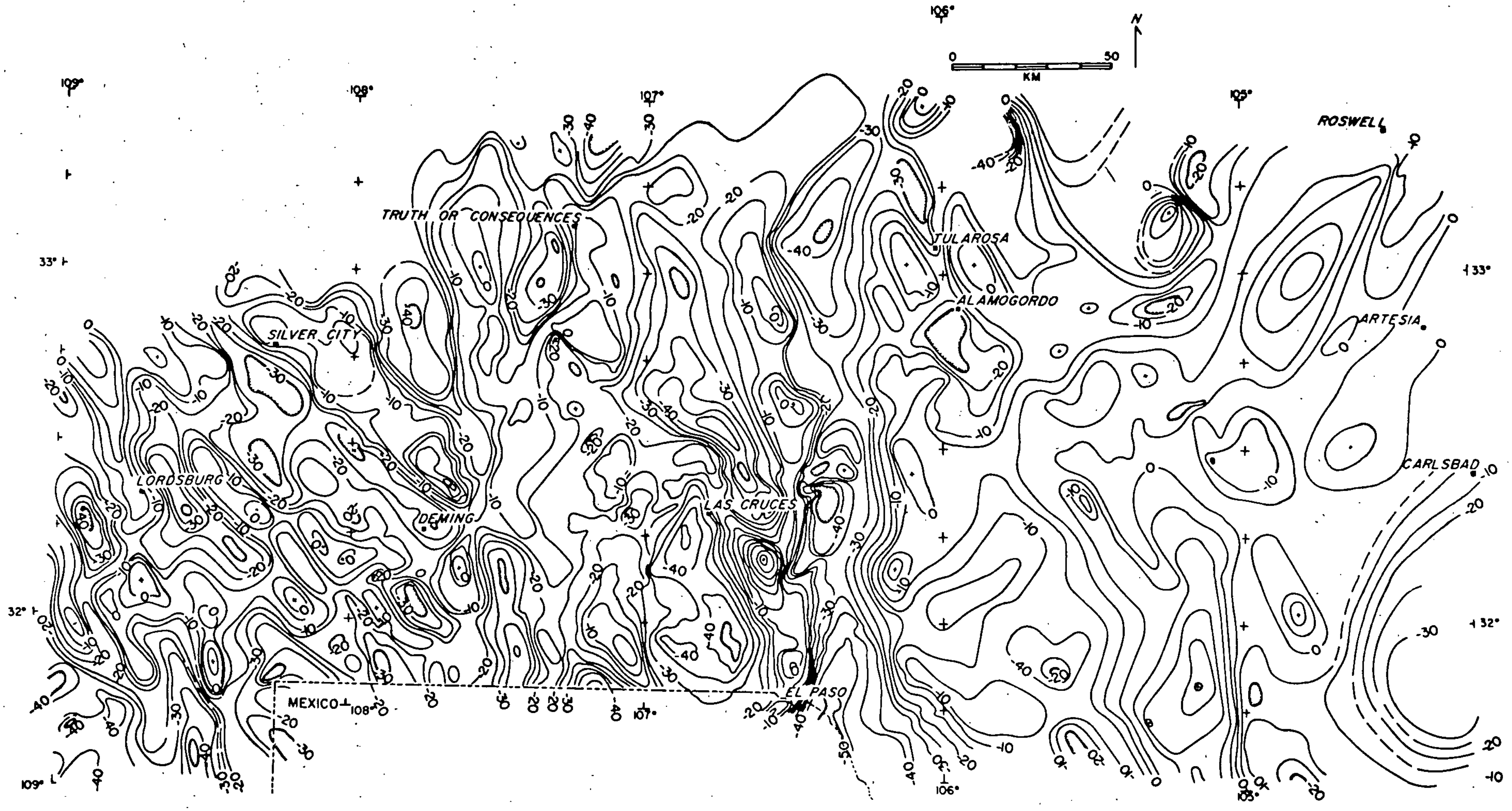


Figure 8. Residual Bouguer gravity anomaly map; contour interval, 5 mgal.

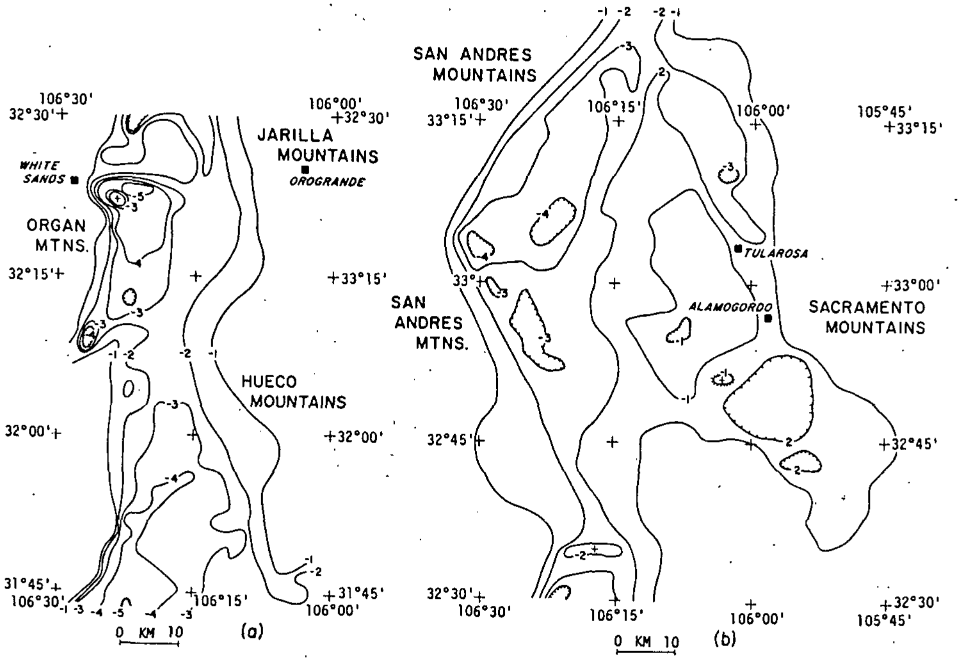


Figure 9. Gravity model of the Tularosa basin. Contours show depth in kilometres to basement based on an overall density contrast of −0.35 g/cm³. Top of (a) is continuous with the bottom of (b).

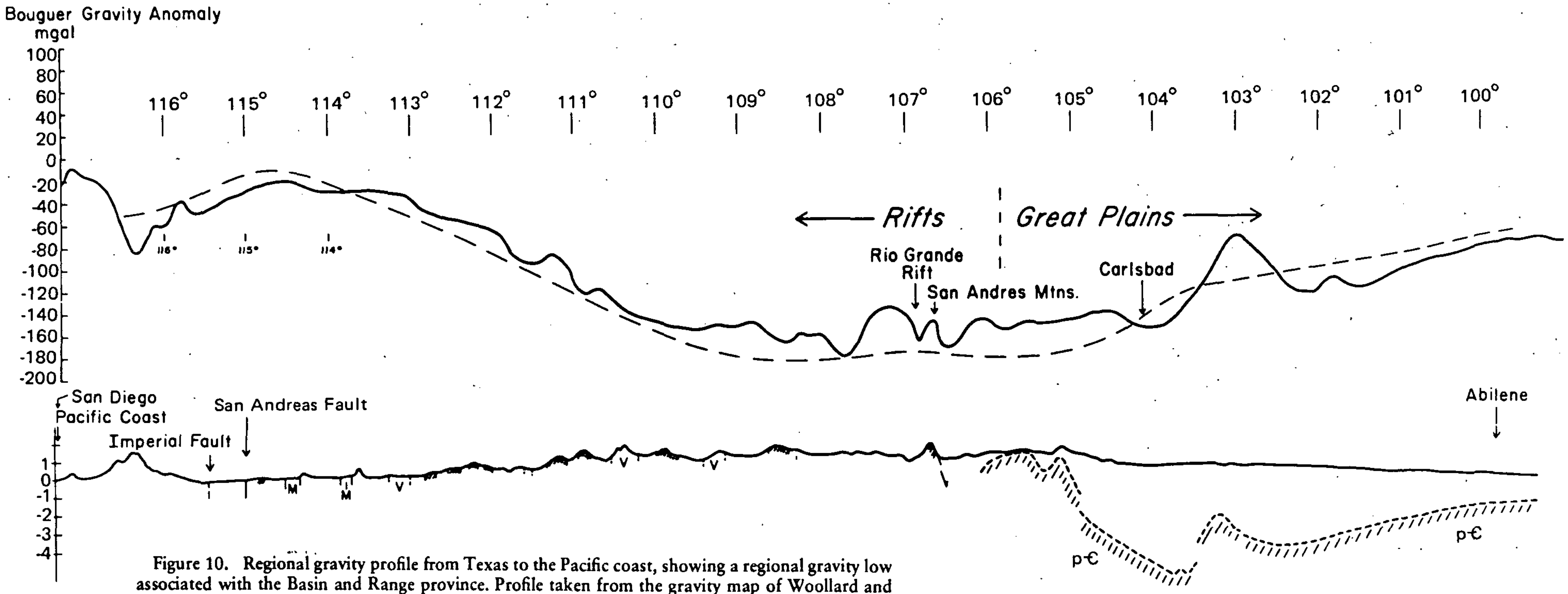
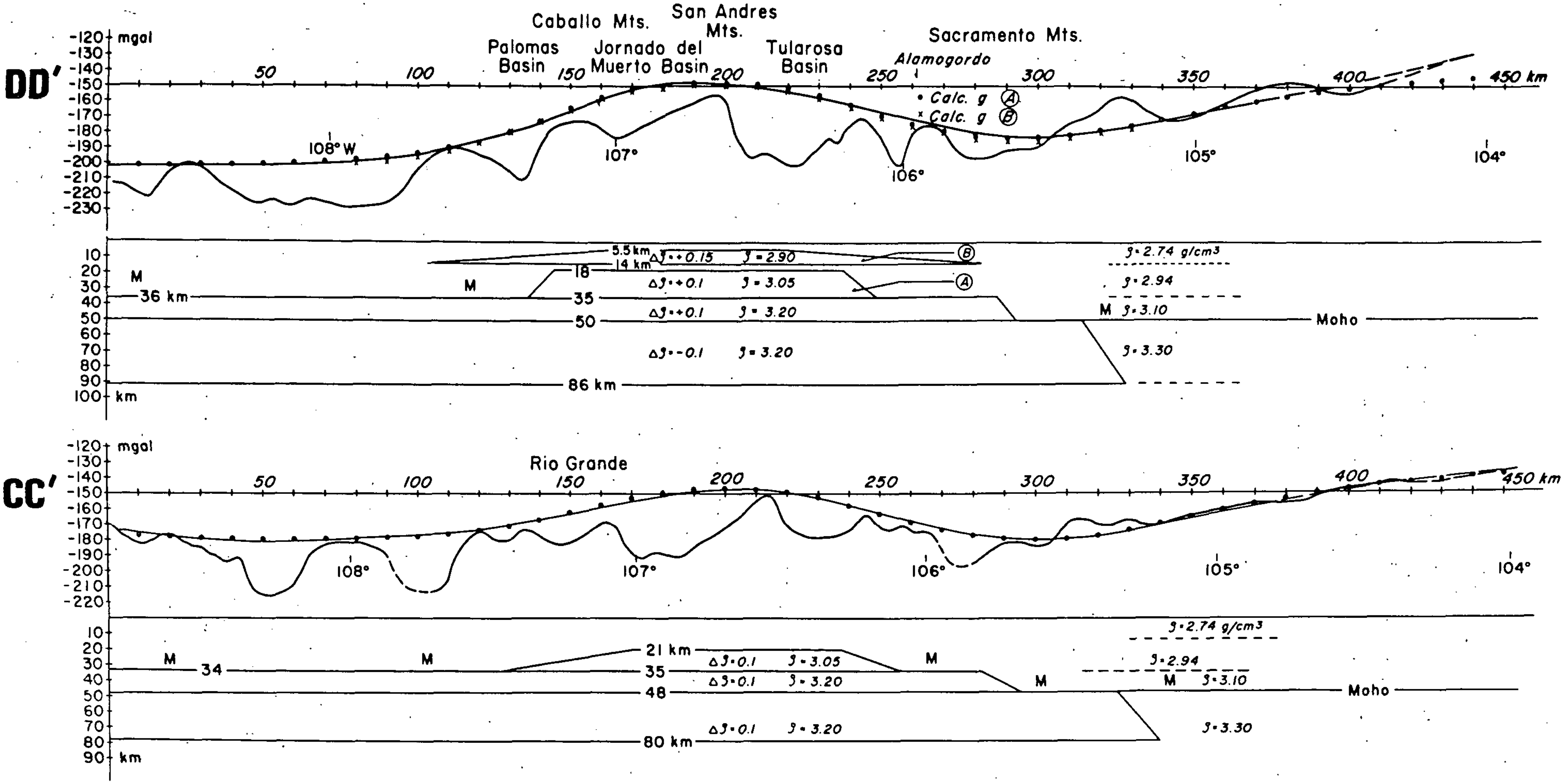


Figure 10. Regional gravity profile from Texas to the Pacific coast, showing a regional gravity low associated with the Basin and Range province. Profile taken from the gravity map of Woollard and Joesting (1964) along lat. 33°N, approximately.

Figure 11. Gravity profiles showing the deep structure of the rift used to explain the position of the gravity anomaly and geothermal high over the rift. Positions of profiles are plotted in Figure 3.



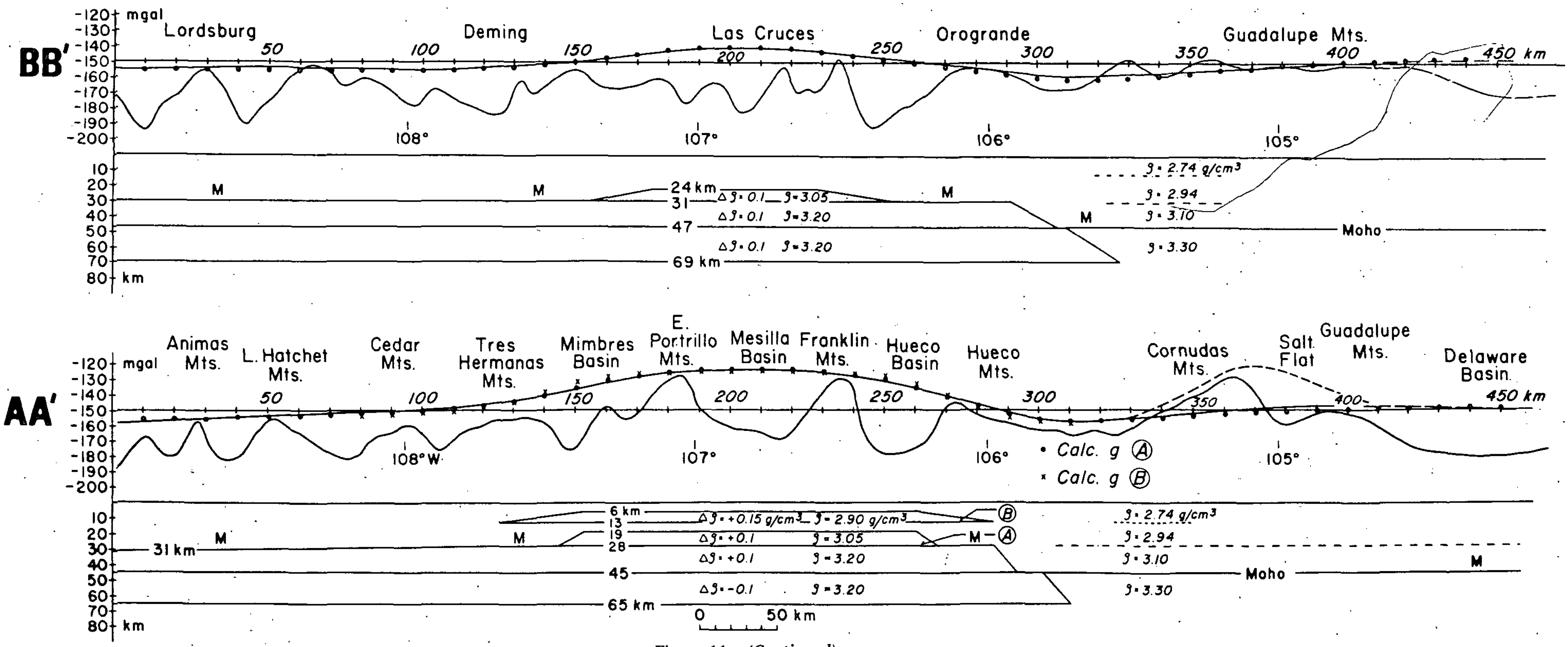


Figure 11. *(Continued)*.

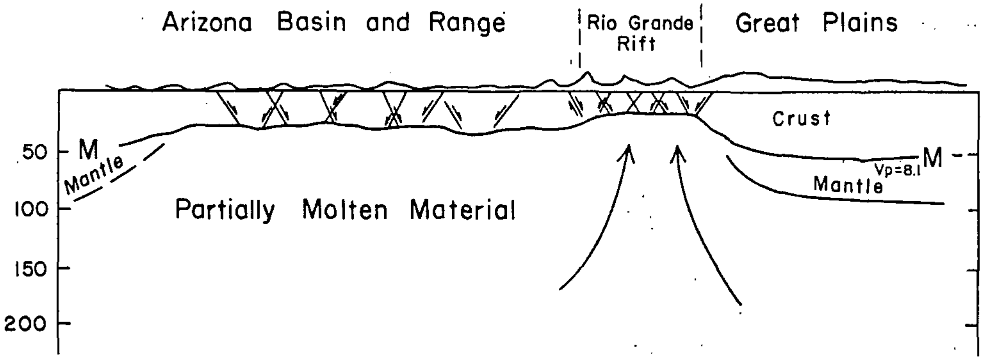


Figure 12. Interpretation of geophysical models of crust and upper mantle similar to the model proposed by Scholtz and others (1971) for the Basin and Range province.

and north-northeast pattern is recognized in wide areas within the Basin and Range province (Donath, 1962; Pease, 1969; Stewart, 1971) as well as within the East African rifts (Baker and others, 1972), the Rhine graben area (Illies, 1974), and the Oslo graben area (Ramberg and Smithson, 1971). Recently, similar morphotectonic features have been described from a graben on the Martian surface (Schafer, 1974). While the angle of intersection between the individual fault sets and the directional trend of the acute bisector with respect to the graben axis may vary from place to place and even within a single rift system, the almost ubiquitous common occurrence of the gridded fault patterns suggest a general explanation.

At least three mechanisms could have caused the fault pattern in the southern Rio Grande: (1) structural control imposed by older basement lineaments; (2) right-lateral shear in analogy with Atwater's (1970) proposal that the Basin and Range province is part of a wide "soft" zone accommodating oblique divergence between the North American and Pacific plates; and (3) extensional tectonics (Hamilton and Myers, 1966; Cook, 1969; Chapin, 1971) resulting from release of compressive stress (Scholtz and others, 1971), or from the formation of a marginal basin by the rise of magma or convection currents above a descending lithospheric plate (Karig, 1971; Thompson and Burke, 1974), or some other cause yet to be found.

The oblique structural pattern may depend upon pre-existing structures in the Rio Grande area. The general northeastern trend represents the principal structural grain of the Central Rockies and the dominant foliation in the Precambrian rocks surrounding the Colorado Plateau, whereas the northwestern trend follows Laramide faults and large Permian-Pennsylvanian uplifts and basins (Kelley, 1955). Many of the mapped faults date back to pre-Cenozoic movements. Within the study area, Pray (1961) concluded the faults in the Sacramento Mountains escarpment have been moved repeatedly since late Pennsylvanian time. Farther south, the northwest-trending lineaments in West Texas and Chihuahua, Mexico, may represent pre-Carboniferous faults (DeFord, 1969). In the Big Burro uplift, late Pliocene or Pleistocene fault zones follow northwest-trending Precambrian diabase dikes emplaced along earlier faults and fractures (Gillerman, 1970). Many smaller faults follow the northeast trend of foliation and Precambrian granitic dikes in the Precambrian basement, and Gillerman and Whitebread (1956) have interpreted this relationship as a reopening in post-Cretaceous time or old Precambrian zones of weakness.

Although the above examples and others may be purely coincidental, no evidence exists to disprove a genetic relationship between pre-existing structural lineaments and the braided fault pattern associated with the young rift. It is therefore possible that the Miocene to Holocene stress was released through early-formed tectonic lineaments that were favorably oriented with respect to potential fault zones in the new stress system. A similar influence of northwest- and northeast-trending basement lineaments upon younger rock formations has been implied on the basis of aeromagnetic anomalies across the northwestern United States (Zietz and others, 1971) and in central and northern parts of the Rio Grande rift (L. Cordel, 1975, oral commun.).

The second possibility, a regional shear zone, may have operated in the Basin and Range province, where, especially in the western part, large strike-slip offsets have been observed along the faults, whereas in the eastern part the sense of movement is largely that of normal faults (Shawe, 1965; Stewart and others, 1968). Such mechanisms have been suggested for the Dead Sea rift and more recently for the Gulf of California–Salton Sea trough (Sumner, 1972; Elders and others, 1972), where graben depressions may have formed as a string of rhombocasins in response to the strike-slip movement.

Applied to the southern Rio Grande region, a similar right-lateral sense of movement, as generally suggested for the western United States (Atwater, 1970), would result in northwest-trending strike-slip or transform faults and in northeast-trending closed basins (Fig. 13). If we assume a series of pre-existing fractures in the area, the north-northwest–and north-northeast–trending fractures might have represented the most favorable directions with regard to the shear system, and the area broke up into a more complex system of rhombocasins with an overall northward trend (Fig. 13).

This hypothesis requires that the north-northeast–trending basins predominate, that the late Cenozoic movement along the north-northwest–trending faults was predominantly right-lateral strike-slip, and that the north-northeast–trending faults were largely normal faults with a possible component of left-lateral strike slip. A field test is complicated by the fact that most boundary faults of the Rio Grande rift are poorly exposed, and very little evidence has been reported with regard to a recent sense of movement along faults in the study area. From the Caballo Mountains, Kelly and Silver (1952) showed that right-lateral and left-lateral movements have occurred in the predicted way, but the timing is uncertain and the opposite sense of movement was also observed along some faults. Farther north, Elston (1970) stated that all observed offsets are right-lateral, whereas Woodward and DuChene (1975) showed that the northeast-trending Sierrita fault has undergone episodic normal slip only. Base on the gravity map (Fig. 4), north-northwest– and north-northeast–trending basins or grabens are equally developed in the study area. Although the shear hypothesis may agree with the regional Cenozoic tectonic development, available geological and geophysical evidence tends to be either negative or inconclusive and thus does not support this hypothesis for the southern Rio Grande rift.

The third possibility, extensional tectonics, has recently received support from a study of fault-plane solutions of earthquakes and in situ stress measurements (Sbar and Sykes, 1973) showing the Rio Grande rift to be an extensional zone with the least compressive principal stress (σ_3) trending approximately west-northwest. Consistent with this, it is reasonable to assume that, superimposed on the regional stress field, the anomalous heat input in the relatively narrow zone of the Rio Grande rift would lead to thermal expansion that would be released by normal faulting in the direction perpendicular to the rift axis, but would result in increased compressional stress along the general (north-south) rift axis.

Simple grabens are depressions bounded by parallel fault-plane traces, and early experiments (H. Cloos, 1936, 1939) implied that the axial collapse resulted from extension and thinning, somewhat similar to the process of necking observed in metal rods. In essentially plane strain experiments, vertical faults form that initially intersect each other at angles close to 90° (H. Cloos, 1928; E. Cloos, 1955; Raleigh and Griggs, 1963). The largely strike-slip faults define traces that form angles of approximately 45^c with the horizontal principal axes of strain. Oertel (1965) carried out a series of clay experiments with general strains (all three principal strain axes different, σ_2 being vertical) and found that four sets of oblique slip faults developed in the clay cakes, forming a symmetric orthorhombic pattern. The four sets occurred in pairs, the faults of each pair having the same strike but being inclined in opposite directions (forming depressions). In most of Oertel's experiments the mutual angle between the strikes of the two pairs was very small, about 15°, but experiments with materials of different rheologic properties or with decreased strain rates both gave less acute angles. Oertel (1965) pointed out that experiments that deviated only slightly from plane strain gave four fault sets with attitudes intermediate between those typical of plane strain and those of general

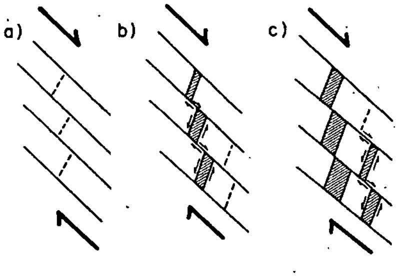


Figure 13. Shear model for formation of the rift.

strain. Although Oertel's (1965) experiments were not primarily designed for a study of regional fault patterns, the results obtained might eventually lead to a better understanding of the laws that govern the formation of the large-scale features, too. It may be significant that, in simple experiments with materials of less well known properties, we found that the acute angle between the fault pairs could attain values of as much as about 50° (Fig. 14), comparable to angles seen in the southern Rio Grande and other rift zones.

The extensional, general strain hypothesis, with the axis of least compressional strain oriented perpendicular to the overall rift axis, explains many of the tectonic features observed in the study area. The apparent difference between the orthorhombic fault pattern in the Rio Grande rift and the almost orthogonal pattern in the adjacent Basin and Range province (Fig. 4) could be due to variations in thermal expansion or to variations in the degree of control by and orientation of the pre-existing fault pattern.

DEEP STRUCTURE OF THE RIFT

Definitive seismic evidence is lacking from the area of the rift itself; however, seismic depths to the Moho outside the rift combined with our gravity data and isostatic constraints (Decker and Smithson, 1975) demonstrate that the density of the upper mantle must decrease underneath the rift and the Basin and Range province to the west. If density did not decrease, the Bouguer gravity anomaly over the rift would increase by several hundred milligals. In line with interpretations from the Basin and Range province in Nevada (Archambeau and others, 1969), this low-density upper mantle is probably hot. A thin (~10 km) lid of normal mantle could be present above low-density mantle and could probably not be resolved by our gravity interpretation. Abnormal, hot upper mantle seems, therefore, most plausible from general geophysical data and serves as an explanation for the geothermal anomalies over the rift and Basin and Range province. The broad positive gravity anomaly over the rift might either come from a wide shallow sheet of basalt intruded into the crust or from a deeper upwarp of mantle at the base of the crust (crustal attenuation). One of these possibilities is required to achieve isostatic compensation for the topographic low of the rift. Although a shallow basalt intrusion is a tempting possibility to explain the geothermal high, the mantle upwarp seems more likely in comparison with other rifts (Girdler, 1964; Ramberg and Smithson, 1971). At approximately the same time that mantle material was rising at the base of the crust, the surface was subsiding to form the rift. A mantle upwarp of 8 km implies a crustal attenuation of 27%. Crustal attenuation may have been accomplished in one of two ways: (1) by extension of the crust as horsts and grabens formed along normal faults (Thompson and Burke, 1974), with possible plastic flow deep in the crust, or (2) by melting at the base of the crust and extrusion caused by proximity to hot upper mantle. The first alternative — extension — suggests a crustal extension of 27% or roughly 1.4 mm/yr if extension is figured from the Miocene at 26 m.y. B.P. The second alternative —melting — might explain felsic and andesitic volcanism during Cenozoic time, but the volume of volcanic rocks is probably not sufficient to account for crustal attenuation. Converting crust to mantle by a phase change at the Moho is a third, less attractive alternative, especially for such an abnormal area as a rift. Crustal attenuation by extension possibly accompanied by some melting and extrusion is the most satisfactory explanation.

Figure 10, a gravity and topographic profile from the Great Plains to the Pacific Coast, shows that the area of the Basin and Range province and the rift is characterized by highly negative Bouguer gravity anomalies. This broad gravity low may be explained by low-density, hot, partially molten upper mantle underlying this entire region. This anomaly can be interpreted as a projection up to the Moho of hot mantle material from the low-velocity zone (Searle, 1970) — in other words, a diapir or asthenolith of mobile, partially molten mantle. On the basis of seismic interpretation, Archambeau and others (1969) have suggested that hot, low-density, low-velocity upper mantle underlies the crust at shallow depth and is separated from the crust by a thin "lid" of more normal upper mantle. Such a "lid" of normal upper mantle would be difficult to resolve by gravity interpretation. Compositions of basalts in the southern Rio Grande rift indicate derivation from the upper mantle at depths greater than 35 km (Kudo and others, 1971). A pillow of partially molten mantle material or an upwarp or diapir of the seismic low-velocity zone would correspond with the broad gravity low under the Basin and Range province, with the high heat flow, and with seismic delays (Archambeau and others, 1969).

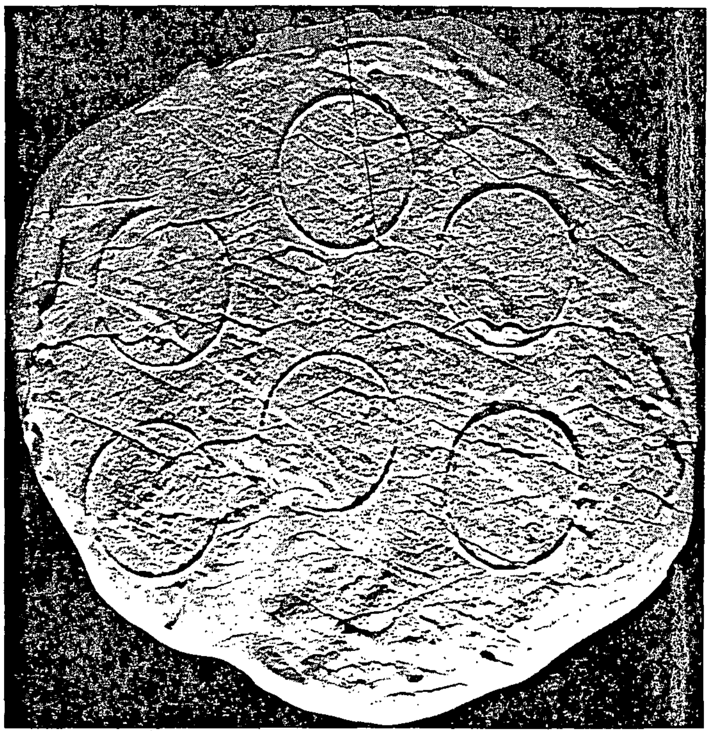


Figure 14. Experiment in plaster of Paris performed under general strain conditions. Fracture pattern resembles system of fractures in the Rio Grande rift. Conditions of experiment allow only qualitative conclusions.

CONCLUSIONS

The main features in the Bouguer gravity anomaly field are the negative anomalies over basins and the positive anomalies over ranges of the basin and Range province. On the basis of gravity data, Cenozoic sediments in the basins range from 2 to 3 km deep. Major sedimentary basins associated with the Rio Grande rift are the Tularosa, Palomas, and Mesilla basins. Gravity-anomaly trends indicate that the individual basins broke up along north-northeast and north-northwest directions oblique to the large-scale north-south direction of the rift probably caused by east-west extension. When the negative gravity effect of basins is removed by "stripping," the Rio Grande rift is associated with a +30-mgal gravity anomaly that coincides with a positive geothermal anomaly found by Decker (Decker and Smithson, 1975). This could be caused by a shallow (~6 km) slablike basaltic intrusion or a deep upwarp of the upper mantle. An upwarp of the upper mantle that results in crustal attenuation is similar to the deep structure of other rifts and is the preferred interpretation.

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