Regional geophysical setting of the Rio Grande rift

ABSTRACT

The Rio Grande rift encompasses uplifts of the southern Rocky Mountains and their southern extension as well as axial fault blocks. The rift widens irregularly southward from a narrow horst in Colorado into a broad collapsed fault, characterized by grabens, in southern New Mexico. Whether manifested by horsts or grabens, primarily extensional strain is involved which increases in magnitude southward. Extensional faulting along the rift occurred in Neogene to Quaternary time, but the rift follows an axis of Laramide, Pennsylvanian, and possibly earlier uplifts. Gravity gradients due to the low density of graben fill delineate major faults of the rift system, which show a gridded or en echelon pattern over distances of tens of kilometres. Aeromagnetic data show these faults to be aligned with basement structural grain. Zigzags hundreds of kilometres long in the trend of the rift may also be related to basement grain. Basement trends in the Colorado Plateau to the west seem to differ in direction from those in the High Plains to the east. Seismic data also show that the rift occurs in an area of transition between anomalous crustal and upper mantle structure typical of the Cordilleran and crustal structure typical of the High Plains. Deep seismic data are sparse within the rift, but high heat flow, high elevation, high electrical conductivity, and both residual positive (shallow source) and negative (deep source) gravity anomalies suggest the presence of symmetrical anomalous crustal and upper mantle structure along the axis of the rift. In the Socorro area, where the rift has been studied intensively, available data indicate relatively low compressional velocity, rapid Holocene uplift, and the presence of magma within the crust. In view of geomorphic evidence for widespread Holocene faulting, the seismicity of the rift is surprisingly low.

INTRODUCTION AND GEOLOGICAL BACKGROUND

This paper provides a review of results of geophysical studies in the Rio Grande rift. The rift trends northward across New Mexico and Colorado, the location of its sides and endpoints depending somewhat on one's definition of a rift. Mixed usage of the terms "rift" and "graben" is useful in this regard: a nearly continuous "Rio Grande graben" extends along the axis of the southern Rocky Mountains uplift from Leadville, Colorado, to Santa Fe, New Mexico, and continues southward in New Mexico to Socorro (Fig. 1). The graben is about 25 to 50 km wide. In contradistinction to this, the term "Rio Grande rift" entails genetic concepts that extend the area of consideration to include en echelon and bifurcating uplifts far to the north of Leadville and south of Socorro, and into the Basin and Range country of southern New Mexico, and especially in the Republic of Mexico. As used here, the term "rift" also encompasses flanking uplifted borders and previously uplifted borders that have subsequently been dropped along zones of anthetic faults. The width of the "rift" is several hundred kilometres.

Hammond (1964) subdivided the western United States into four major physiographic types: plains, tablelands, mountains, and mountains-in-plains. These physiographic subdivisions have characteristic geophysical signatures and reflect an evolutionary sequence that is strikingly developed in the Rio Grande rift. Major faults of the rift system are shown with a locality index and physiographic province map in Figure 1. Figure 2 shows generalized elevation contours.

As is apparent in Figures 1 and 2, the rift follows an axis of high mountains. The southern Rocky Mountain system here, as in the earliest geological study of the rift (Lee, 1907), is considered to extend into southernmost New Mexico (Fig. 2). The Colorado Plateau (the large "tablelands" tract near the center of Fig. 1) is rimmed by mountains, and tableland country similar to the plateau extends east of the southern Rocky Mountains. En echelon offsets characterize the rift throughout New Mexico and Colorado. In New Mexico the graben borders are offset, but the axis of the graben is essentially continuous. In Colorado the graben and related fault structure north of Leadville comprise separate elements en echelon in a right-lateral sense.

The most recent episode of uplift and extensional faulting along the rift occurred in Neogene and Quaternary time, although prior episodes of tectonism have occurred along this same trend. Geophysical discontinuities along the axis of the rift suggest inherited Precambrian structural grain. Linear uplift, arkosic sedimentation, and high-angle faulting occurring along the rift in Pennsylvanian-Permian and Late Cretaceous-middle Eocene (Laramide) time, separated by episodes ofplanation during late Mesozoic time (compare Cordell, 1976a, Fig. 4) and again during the late Eocene (Epis and Chapin, 1975). The approximate coincidence of uplifts in time (Chapin and Seager, 1975; Tweto, 1975) is apparent in New Mexico and especially in Colorado, even to the superposition of Holocene and Pennsylvanian alluvial fans along the mountain front (Howard, 1966).

An extensive surface of generally low relief, developed during late Eocene time (Epis and Chapin, 1975; Seager, 1975), provides a structural datum separating the rift from earlier structural regimes. Voluminous andesitic, calc-alkaline magmatism (Elston, 1976) was initiated about 37 m.y. B.P. A chain of these primarily Oligocene andesites occurs within the rift, and it is restricted to the rift, between the Davis Plateau in Texas (300 km south of El Paso; Fig. 1) and North Park in Colorado.

Extensional faulting began 25 to 29 m.y.

LINDRITH CORDELL U.S. Geological Survey, Box 25046, Denver Federal Center, Denver, Colorado 80225
Figure 1. Locality index, major physiographic provinces (modified from Hammond, 1964), and faults of Rio Grande rift. Heavy lines show principal faults of Rio Grande graben, determined primarily from gravity data. Other faults (from Woodward, and others, 1975; Dane and Bachman, 1965; other sources) are shown schematically with lighter lines. Base map showing Utah, Colorado, Arizona, and New Mexico modified from U.S. Geological Survey shaded relief maps, scale 1:500,000. NP = North Park, D = Denver, L = Leadville, SVF = San Juan volcanic field, JVF = Jemez volcanic field, = Mount Taylor, SF = Santa Fe, A = Albuquerque, JL = Jemez lineament (with arrows), S = Socorro, DMVF = Datil-Mogollon volcanic field, LC = Cruces, EP = El Paso, SM = Sacramento Mountains, GM = Guadalupe Mountains.
Figure 2. Generalized elevation, in metres, relative to sea level, of Rio Grande rift. Contour interval is 500 m. Heavy lines show major faults of axial graben, located primarily by gravity data; light lines show schematically other faults of rift and possibly related structure.
ago, according to Chapin and Seager (1975) and Seager (1975), who described the Neogene tectonic development in central and southern New Mexico in terms of initial extension during late Oligocene and early Miocene time, characterized by broad warping and transition from calc-alkaline to "basaltic andesite" volcanism. Uplift, extensive block faulting, and bimodal basalt-rhyolite volcanism ("fundamentally basalt volcanism" in the sense of Christiansen and Lipman, 1972, and Lipman and others, 1972) occurred during late Miocene and Pliocene time. Similarly, Scott (1975) and Taylor (1975) described accelerated uplift during Pliocene time in Colorado.

Tholeiitic basalt occurs along the axis of the rift in southern Colorado and northern New Mexico, according to Lipman (1969) and Lipman and Mennett (1975), who showed that the tholeiite fractionated at shallow depth within an inferred mantle bulge. Kudo and others (1971; Kudo, 1976) have pointed out, however, that in central New Mexico tholeiites also occur west of the axial graben, in the vicinity of Mt. Taylor. Laughlin and others (1972) have also emphasized that a chain of Quaternary basalts trends northeastward from the Mt. Taylor area obliquely across the graben along the Jemez lineament (Fig. 1; Lambert, 1966). This is true, but, as discussed below, these basalts occur within the rift as broadly defined.

The distribution of basalts along the Jemez lineament may reflect the intersection of the rift with a transverse structural discontinuity within the Precambrian basement. Basement structure has been assumed to have played an important role in the Cenozoic development of the rift, but the concept has remained conjectural because of the difficulty of mapping in three dimensions.

GRAVITY DATA

Gravity data facilitate mapping the graben border faults, basement structural grain, and deep-crustal and upper-mantle structure related to Neogene tectonics, although the gravity effects of all of these are superimposed. Gravity gradients related to low-density graben fill delineate major faults of the rift system having displacements of several kilometres each. These faults commonly do not follow the trend of smaller faults mapped at the surface. The use of gravity data in mapping the graben border faults is discussed in detail elsewhere (Cordell, 1970, 1976a). This interpretation, plus reference to gravity maps of Sanford (1968), Kleinkopf and others (1970), Ramberg and Smithson (1975), Cordell and others (1973), and Cordell (1972, 1976a, 1976b), forms the basis for drawing the principal graben border faults as shown in Figures 1 through 7. The faults display a northwest-northeast grid pattern in southern New Mexico (Ramberg and Smithson, 1973). A similar grid pattern is observed in the western part of the graben in New Mexico north of Socorro. Here, however, the eastern margin of the graben comprises north-trending en echelon faults.

Gravity data can also be used to estimate structural relief across the graben faults, although the estimates are subject to errors in assigned densities and other factors (Joesting and others, 1961). Estimated structural relief is typically 2 to 3 km and, exceptionally, as much as 5 km. Larger structural relief reported for the San Luis basin in southern Colorado may be in error, due to suspected error in elevation control (W. F. Isherwood and G. R. Keller, 1976, oral commun.).

Apart from the shallow-source gravity anomalies caused by low-density sedimentary rocks, two broad, deep-source anomalies are observed. A residual broad positive gravity anomaly attributed to the penetration of mantle material into the crust occurs along the rift axis (Cordell, 1976a). A very broad negative anomaly is associated with the regional uplift. These show up best on profiles and will be discussed in connection with Figures 9 through 15.

A Bouguer gravity anomaly map of the Four Corners states is shown in Figure 3. Sparse seismic data (Fig. 5) indicate regional variation in seismic velocity of the upper mantle, suggesting that the broad features in the gravity map are related to density variation within the upper mantle as well as variation in crustal thickness. The broad topographic and gravity features (Figs. 2, 3) coincide, reflecting rapid buoyant response (Bridwell, 1976) to regional density changes in the crust or mantle related to Neogene tectonics. Like the uplifts, the associated broad gravity lows are Neogene in age.

Gravity anomalies associated with essentially static intracrustal density variation include those associated with the lithology of the sedimentary cover, such as the graben fill anomaly; Paleogene batholiths in southwestern Colorado, southwestern New Mexico, and perhaps elsewhere (Plouff and Pakiser, 1972; Steven, 1975; Elston and others, 1973, 1976); and intrabasement density variation in eastern New Mexico and elsewhere. The long northeast-trending gravity gradient crossing northeastern Arizona and the extreme northwest corner of New Mexico (Fig. 3), not apparent either in the topography (Fig. 2) or in the structure of the sedimentary cover, is associated with an aeromagnetic lineament and probably delineates a northeast-trending Precambrian discontinuity. A parallel northeast-trending gravity gradient may be present in New Mexico, intersecting the rift obliquely between Santa Fe and Socorro, but this trend, if it exists at all, is obscured by gravity trends related directly to the rift.

AEROMAGNETIC DATA

Aeromagnetic coverage of Colorado is available at a flight-line spacing of 1.6 to 8.0 km (Zietz and Kirby, 1972), and coverage of Arizona is available at a flight-line spacing of 5 km (Sauck and Summer, 1970). In New Mexico, aeromagnetic surveys were flown at 1.6-km flight-line spacing, although coverage does not yet extend far east nor west of the rift; all the available data are shown in Figure 4. The New Mexico aeromagnetic data are available as U.S. Geological Survey Open-File maps at a scale of 1:125,000 and a contour interval of 20y. Generalized trends are shown at a contour interval of 100 y in Figure 4.

Rocks of the sedimentary cover are effectively nonmagnetic. Except over areas of extensive volcanic or shallow intrusive rocks, the magnetic anomaly gradients delineate structural or lithologic boundaries in the Precambrian basement. In a preliminary analysis, I have shown that aeromagnetic gradients and inferred basement structures are aligned with graben border faults in central New Mexico (Cordell, 1976a). The alignment can be seen in various places in Figure 4. On the basis of the observed parallelism of graben faults with magnetic anomaly trends, it seems likely that inherited Precambrian basement grain has influenced, in a passive way, the trend of Cenozoic graben faults at a scale of tens of kilometres.

Principal regional trends in the magnetic anomaly gradients which are thought to be representative of basement structural grain are indicated on the gravity map (Fig. 3) by dotted lines. In this preliminary identification, the selection of trends and the evaluation of the effects of volcanic cover and basement relief are subjective. Together with trends in the graben border faults, which are in part basement controlled, the aeromagnetic trends seem to indicate a change in basement grain across the rift. Trends are more or less north-south, northeast, or random in the High Plains east of the rift. To the west the trends are strongly northwest or northeast, and the rift seems
An aeromagnetic gradient (Sauck and Sumner, 1970) is associated with the pronounced northeast-trending gravity gradient in northeastern Arizona, and both are attributed to a source in the Precambrian basement. A parallel magnetic gradient to the west, however, is not associated with any obvious gravity trend. A major northeast-trending age-province boundary also occurs across eastern Arizona and northwestern New Mexico (L. T. Silver, unpub. data). At the latitude of Albuquerque, tholeiitic basalt occurs west of the axial graben along the northeast-trending Jemez lineament (Fig. 1). From this general area southward, the rift widens and changes character.

Figure 3. Bouguer gravity anomaly contours and trends of aeromagnetic gradients (dotted lines) thought to be related to structure in Precambrian basement. Base map showing generalized trends of rift faults is from Figure 1. Gravity map is generalized from map prepared by Defense Mapping Agency, Aerospace Center, St. Louis Air Force Station, St. Louis, Missouri, for publication with U.S. National Atlas.
Gravity and aeromagnetic data considered together suggest that the Colorado Plateau is characterized and delimited by elements of conjugate northwest-northeast basement grain. Lack of parallelism with trends in the craton east of the plateau could indicate that the plateau was appended onto the craton during Precambrian time, forming a basement suture along the site of the future rift. Such a feature could account for the observed angulation and en echelon pattern of the rift as well as the recurrence of tectonism along these trends. At present, evidence for a suture is circumstantial. Completion of the aeromagnetic coverage in eastern and northwestern New Mexico should establish whether parallelism exists in the basement grain east and west of the rift. Preliminary interpretation of the deep seismic reflection data (Oliver and Kaufman, 1976; Kaufman and others, 1977) suggests a fundamental crustal discontinuity within the rift, as discussed below.

**SEISMIC DATA AND SEISMICITY**

Noninstrumental historical records since 1849 indicate a concentration of seismicity along the rift which probably can be attributed only in part to concentration of population in the Rio Grande Valley (Sanford and others, 1972; Northrop, 1976). In discussing more recent instrumental data, Sanford and others (1972, 1976), Olsen and others (1976), and Smith and Sbar (1974) described belts of seismicity along the Rio Grande graben, the northeast-trending Jemez lineament, and the arcuate fault zone across northern New Mexico, southwestern Colorado, and eastern Utah (Fig. 1). All of these are included within the rift as broadly defined here. The highest level of seismicity occurs within the rift between Socorro and Albuquerque. It should be noted, however, that the seismicity of the rift, at least as determined instrumentally since 1960, is much lower than that of the intermountain seismic belt (compare Smith and Sbar, 1974, Fig. 2) and the East African (Fairhead and Girdler, 1971; Wohlenberg, 1975), Baikal (Solonenko, 1968), and perhaps other Neogene-Quaternary rifts.

The comparatively low level of anomalous seismicity associated with the Rio Grande rift seemingly is not an artifact of insufficient data. Noting the abundance of Holocene fault scarps in the Socorro area, Sanford and others (1972) estimated long-
term seismicity using King and Knopoff's (1968) equation relating fault length, offset, and associated earthquake magnitude. They concluded that the historical record showing relatively modest seismicity along the rift is probably representative of longer term trends, although their analysis of paleoseismicity was admittedly subject to considerable uncertainty. More recently, soil studies (Machette, 1976) and geologic mapping in progress by Machette, G. O. Bachman, C. E. Chapin, and others (1977, oral commun.) have brought to light more large fault scarps, some of which can be dated. Because of the importance, in terms

Figure 5. Seismic data, showing depth in kilometres below sea level to M discontinuity and, in parentheses, compressional wave velocity of upper mantle in kilometres per second. Stars denote shot points. Arrows at stars indicate reversed profiles; arrows at dots indicate nonreversed profiles. Location of first vibroseis profile in New Mexico by Consortium on Continental Reflection Profiling (Oliver and Kaufman, 1976) is shown by label COCORP. Recently (Kaufman and others, 1977), these profiles have been extended across western border of graben. Dashed lines show parts of western border of Colorado Plateau. Sources: a, Hill and Pakiser (1967); b, Ryall and Stuart (1963); c, Keller and others (1975) and Braile and others (1974); d, Roller (1965); e, L. Pakiser (1977, personal commun.); f, Jackson and Pakiser (1965); g, Jackson and others (1963); h, Warren (1969); i, Toppozada and Sanford (1976) and Toppozada (1974); j, crustal "low-rigidity" zone of Sanford and others (1973); k, Stewart and Pakiser (1962).
of tectonics and seismic risk, of determining the long-term seismicity of the rift, it would be worthwhile to update the paleoseismicity analysis.

During the early 1960s several long seismic refraction lines in the western United States (Pakiser, 1963) were obtained by the U.S. Geological Survey; these data have established important distinctions among the tectonic provinces (Fig. 5). In Figure 5, depth to the M discontinuity is relative to sea-level datum and rounded off to whole kilometres. In round numbers, the crust is about 30 km thick in the Basin and Range province, 40 km thick in the Colorado Plateau, and 50 km thick in the western Great Plains. Low seismic velocities in the upper mantle (P_n < 8.0) are observed in the Basin and Range province and the Colorado Plateau.

Closest to the Rio Grande rift are the following refraction lines: (1) in the Colorado Plateau, Hanksville-Chinle (Roller, 1965) and Gasbuggy (Toppozada and Sanford, 1976; compare Warren and Jackson, 1968); (2) in the southern Rocky Mountains, Climax (Jackson and Pakiser, 1965) and unpublished data of C. Prodehl and L. C. Pakiser; and (3) in the High Plains, Lamar (Jackson and others, 1963) and Gnome (Stewart and Pakiser, 1962). Taken at face value, these indicate asymmetric crustal and upper-mantle structure across the rift between the High Plains and the Colorado Plateau. It is emphasized, however, that except for the Gasbuggy interpretation (i in Fig. 5), there are no refraction data over the rift itself.

Interpretation of natural teleseismic events is essentially in agreement with the results from explosion seismology. Phinney (1964) identified by means of spectral analysis of long-period P waves intracrustal and M discontinuities at Albuquerque, although his range of depths to Moho (35 to 40 km) and range of P_n velocity (7.4 to 8.4 kms) are too large to resolve essential questions about deep structure within the rift. Bucher and Smith (1971) obtained depths to Moho of 32 km in the eastern Basin and Range province and 39 km in the western Colorado Plateau. They did not indicate an upper-mantle lid in the plateau (compare Archambeau and others, 1969), and they showed the low-velocity zone in the upper mantle to be about 80 km thick in both provinces. Layering within the upper mantle in the vicinity of the Rio Grande rift has not been described by induced-energy seismic studies, although Jackson and Pakiser (1963), Warren (1969), Decker and others (1975), Bridwell (1976), and others have suggested configurations of the low-velocity zone determined from gravity data and isostatic considerations.

Most of the earlier seismic studies identified a Conrad or other discontinuities within the crust (not shown in Fig. 5). Prodehl (1970) reinterpreted these and other data in the western United States according to a specialized inversion procedure and suggested a low-velocity zone within the crust rather than a Conrad discontinuity. Prodehl also depicted the M discontinuity to be a zone 3 to 5 km thick in the Basin and Range and as much as 10 km thick in the Colorado Plateau. The crustal low-velocity zones may be related to zones of low rigidity having possible tectonic significance in areas of extensional faulting (Shurbet and Cebull, 1971; compare Landisman and others, 1971).

Detailed seismic refraction data are available at the Basin and Range–Colorado Plateau boundary along the Wasatch front in Utah and in central Arizona (Figs. 1, 5). Although these areas are distant from the Rio Grande rift, their tectonic styles are similar, and it is worthwhile to consider the Utah and Arizona data in the light of a possible analogy with the rift. Keller and others (1975, 1976a) showed a mantle bulge (M 24 km below sea level) and extremely low seismic compressional velocity (P_n = 7.4 to 7.5 km/s) along the Wasatch front in Utah. A crustal profile across the western border of the plateau at the Wasatch front, determined by projecting the seismic refraction models (Fig. 5) along strike onto a profile along the lat 40°N parallel, is shown in Figure 6. Porath (1971) measured high electrical conductivity and inferred high temperature within the upper mantle along this same trend (as discussed below). Detailed refraction studies in Arizona by Warren (1969) show Basin and Range crust to be anomalously thin on the southwest edge of the Colorado Plateau as well (Fig. 5).

Detailed refraction data are not available for the Rio Grande rift; however, preliminary results of a study of surface-wave dispersion data (Keller and others, 1976b; G. R. Keller, 1977, oral commun.) indicate that the average crustal thickness within the rift is about 35 km. Anomalously low seismic velocities (Toppozada and Sanford, 1976) and other similarities between the rift and the Wasatch front, as discussed below, suggest that Figure 6, with the M discontinuity shifted down about 10 km, may provide a predictive model for the rift.

Within the Rio Grande graben, recent seismic and other investigations are focused on the possible occurrence of magma at shallow depth in the Socorro area. Sanford and Long (1965) and Sanford and others (1977) identified on microearthquake seismograms S-phase to P-phase and S-phase to P-phase reflections from a discontinuity within the crust. The ratio of the observed amplitudes of these phases, corrected for angles of incidence, were compared with theoretical ratios for several types of discontinuities. The best match was obtained for a discontinuity having solid rock underlain by material of very low rigidity. By inference, this material could be considered to

![Figure 6. Interpretive profile along lat 40°N across mantle bulge and low-velocity anomaly in both lower crust and upper mantle west of Wasatch front in Utah. Based on refraction data of Keller and others (1975) and other refraction studies shown in Figure 5 projected onto profile line. Numbers show compressional-wave velocities in crust and upper mantle; dashed line shows projected position of M discontinuity.](image-url)
molten. Compressional velocities indicate that this interface is not the M discontinuity. The zone of low rigidity is estimated to be about 18 km deep at Socorro. It is identifiable as far as 60 km north of Socorro, where it reaches a depth of about 30 km. The latter depth is tentative because wide-angle reflections were used, and these depend critically on an accurate knowledge of S-phase velocity (A. R. Sanford, 1976, oral commun).

Repeat leveling data of Reilinger and Oliver (1976) indicate relative uplift of the Socorro area in the vicinity of Sanford and others' (1977) proposed shallow magma body. They reported 20 cm of vertical uplift in 40 yr, indicating an exceptionally high average relative velocity of 0.5 cm/yr.

A network of deep seismic reflection "vibroseis" profiles (165 km) has been used to determine crustal thickness. These data indicate a depth to the Moho of approximately 30 km, with the crustal thickness varying from 30 to 40 km. This information is essential for understanding the geophysical setting of the Rio Grande Rift.

Figure 7. Heat flow. Data in New Mexico and Colorado are from Reiter and others (1975), published with permission of M. Reiter and Geological Society of America. Data in Arizona and Utah are from Diment and others (1975). Solid circle = >2.5 hfu; large dot = 2.0 to 2.5 hfu; small dot = 1.5 to 2.0 hfu; open circle = <1.5 hfu.
completed recently in the Socorro area by the Consortium on Continental Reflection Profiling (COCORP). Preliminary results (Oliver and Kaufman, 1976; Kaufman and others, 1977) indicate reflections from as deep as 50 to 60 km, a zone of sparse reflections near the graben border, and differences in record character at the east border suggestive of a major lateral discontinuity. A strong reflection above an anomalously homogeneous zone, observed over large areas within the graben, correlates well with the inferred magma body of Sanford and others (1973, 1977).

HEAT FLOW, ELECTRICAL CONDUCTIVITY, AND DEEP TEMPERATURE STRUCTURE

Temperature within the lower crust and upper mantle is particularly difficult to measure. Near-surface heat flow would seem to provide the most direct information on temperature at depth, although the heat-flow data are subject to relatively

Figure 8. Electrical conductivity zonation, probably within upper mantle, determined from geomagnetic variation studies. Dots show locations of recording arrays. Profile along lat 38°N is shown in Figure 9. Conductivity map after Gough (1974) and published with his permission and that of *Journal of Geoelectricity and Geomagnetism*.

Figure 9. Elevation profile and conductivity model (Porath, 1971, copyrighted by American Geophysical Union and published with permission) at lat 38°N. Vertical exaggeration of elevation profile is about 150:1. Dashed line in lower part of figure shows top of a zone of anomalously high electrical conductivity. Although conductivity model is not unique, it does indicate high electrical conductivity and inferred high temperature (probably within upper mantle) beneath Rio Grande rift and Wasatch-Hurricane front. Heavy dashed line in top part of figure shows accordance of nonvolcanic summits with broad features of elevation profile.
Generally high conductivity is associated with the Basin and Range province. Belts of very high conductivity follow the southern Rocky Mountains-Rio Grande rift and Wasatch-Hurricane front along the east edge of the Great Basin. Station spacing (about 100 km) is too wide to determine source depths. The Wasatch front and Rocky Mountain anomalies seem to die out at about lat 43°N.

A conductivity distribution in the upper 160 km compatible with the data (after Porath, 1971) is shown along lat 38°N in Figure 9 (lower part). The solution is not unique, and a conductivity interface could be shifted downward to considerable depth. Porath (1971) and Gough (1974) discussed independent temporal, geoelectrical, and tectonic considerations indicating that the highly conductive sources occur in the upper mantle, as shown. They suggested that the seismic and conductivity data, therefore, be considered together to reflect partial melting within the low-velocity zone in the upper mantle. Very shallow-source effects related to zones of hydrothermal alteration could make a significant contribution locally to the conductivity anomalies; this has not been taken into account (W. D. Stanley, unpub. data). It is unlikely, however, that the regional data could be satisfied by means of reasonable conductivity anomalies within the upper crust or the sedimentary cover alone. It seems more likely that a zone of high electrical conductivity, and, by inference, anomalously high temperature, having considerable width and depth extent exists within the lower crust and upper mantle under both the Rio Grande rift and the Wasatch front.

Figure 10. Gravity and elevation profiles along lat 37°N (Colorado-New Mexico border). Dashed segment of gravity profile shows, schematically, residual broad positive anomaly upon which gravity low associated with graben fill is superimposed.
TOPOGRAPHIC AND GRAVITY PROFILES ACROSS THE RIFT

Elevation provides a crude structural datum, and its broader components represent a systematic response to integrated density and rheological effects in the crust and upper mantle. East-west profiles across the Rio Grande rift at intervals of 1° of latitude (about 115 km) are shown in Figures 9 through 15. In Figure 9 the profile at lat 38°N is extended westward across the Great Basin to the Sierran front so that the Great Basin and the Rio Grande rift can be compared.

All ramifications of the Atwater (1970) hypothesis require large Cenozoic extension within the North American Cordillera. Hundreds of kilometres of extension were established beforehand by Hamilton and Myers in 1966. Hamilton (1969) described a system in which everything west of the southern Rocky Mountain front moved under inertial body forces northwestward relative to the craton. In this system rifts, such as the Rio Grande, represent secondary effects formed where coherent blocks, such as the High Plains and the Colorado Plateau, “pulled apart.”

Alternatively, mechanisms such as back-arc spreading (Scholz and others, 1971) involve vertically directed magmatic forces, rather than horizontal body forces, as a first cause. Eaton and others (1976) showed the Great Basin to be bilaterally symmetrical about a north-trending axis (Fig. 9) and suggested that the causal mechanism is rooted to this axis at depth. Their suggestion of symmetric “spreading” east and west from the center of the Great Basin raises a question as to which direction the Colorado Plateau was “pulled.”

In the profile across the Great Basin and Rio Grande rifts shown in Figure 9, neither erosion nor constructional volcanic features obscure the general accordancy of summits along the simple double bulge shown by the dashed line. Eaton and others (1976) axis of symmetry within the Great Basin trends roughly normal to the profile at about long 115° to 116°W. From this perspective it becomes difficult to visualize the Rio Grande rift as a “pull apart” foundered in the wake of the westward-drifting Colorado Plateau. Rather, the plateau looks like a “pushed aside,” lying between two great rifts. The Rio Grande and the Great Basin are parallel, consanguineous, yet separate structures showing different stages of the extensional process developed over about the same time span. At this latitude the Rio Grande gra-

ben (compare Fig. 2) is a narrow cleft in the vault of the southern Rocky Mountains uplift. The vault in the Great Basin seemingly has collapsed. In terms of the four major physiographic subdivisions discussed in connection with Figure 1, the plains subdivision represents the stable craton; the mountains with flanking dissected tablelands represent incipient rifting as seen in the Rocky Mountains in the northern part of the Rio Grande rift and at the edges of the Great Basin; and the mountains-in-plains subdivision represents the climax state as seen within the Great Basin itself.

Interestingly, the mountains, rather than the mountains-in-plains, are the more anomalous geophysically. Geophysical data are most complete along the Hurricane-Wasatch front, where we observe, relative to both the Great Basin on the west and the Colorado Plateau on the east, the following characteristics: anomalously low seismic velocities in the crust and upper mantle (Fig. 6), uplift, high seismicity, relatively high heat flow, high electrical conductivity, and an anomalously thin crust. Conductivity data of Schmucker (1970) and preliminary results from studies now in progress (W. Isherwood, 1976, oral commun.) indicate similarly very anomalous conditions along the Sierran front. Thus, the principal geophysical and topographic anomalies of the Great Basin occur at its edges. If the Basin and Range (mountains-in-plains) physiography grew outward from a once-narrower and geophysically anomalous axial uplift, such as is now seen in the southern Rocky Mountains, the anomalous conditions at the center may have been relieved, in part, by collapse and extension of the vault itself.

Reference to “collapse” is misleading because of the extreme vertical exaggeration on the profile. Although both horizontal

Figure 11. Gravity and elevation profiles along lat 36°N (Jemez Mountains).
and vertical movement contributed to the mountains-in-plains physiography, and horizontal movement is the greater by an order of magnitude, there is no structural evidence showing which occurred first. Paleoclimatic and pollen data of Axelrod (1975) and Axelrod and Bailey (1976) indicate about 1,200 m of epeiric uplift of the Rio Grande rift after 15 m.y. B.P. — that is, after the initiation of extensional faulting, conceivably before the culmination of extensional faulting during Pliocene time, but probably contemporaneous with it. Other pollen data seem to indicate Oligocene uplift in southern New Mexico, although in this case they attribute high-altitude flora to constructional volcanic topography rather than to uplift.

Figure 9 does not establish that the southern Rocky Mountains—Rio Grande rift and the Great Basin represent different stages in the rift process. This idea is based on the observation that the Rio Grande rift progresses southward from mountains into mountains-in-plains, which is illustrated with a series of profiles in Figures 10 through 15. The progression may be more in the domain of intensity than in time, as there is at present no evidence of progression along the rift.

The profile along the Colorado—New Mexico state border at lat 37°N (Fig. 10) is essentially free of constructional volcanic topography and characterizes the southern Rocky Mountain section of the rift more truly than Figure 9. The principal mass flux is upward, comprising a horst 100 to 150 km wide having at least 3 km of structural relief (on the Precambrian basement) superimposed on a sinusoidal bulge several hundreds of kilometres wide. Part of the structural relief on the Precambrian basement is Laramide in age (Woodward, 1976). Topographic relief, by contrast, was developed on the late Eocene peneplane and indicates roughly the minimum amount of post-Laramide, primarily Neogene, uplift. Structural relief in the narrow Rio Grande graben, lying near the center of the axial valley, is also about 3 to 4 km on its eastern side. If the faults dip uniformly 63°, the component of horizontal extension would be equal to the sum of the structural relief of all the horsts and grabens, say, about 6 to 8 km. This represents a minimum amount of extension, because some of the fault blocks are covered and the fault planes probably flatten with depth (Moore, 1960; Woodward and DuChene, 1975; Woodward, 1977). Thus, in the southernmost Colorado section of the rift, horizontal extension is...
greater, but probably not an order of magnitude greater, than vertical uplift. A similar 140-km-wide basement-cored horst containing an axial graben is also observed in the lat 36°N profile (Fig. 11).

First stages in major extension and collapse of the uplifted vault are apparent in Figure 12. The western shoulder of the rift occurs as far west as long 108°W along the northeast-trending Jemez lineament (Fig. 1). The Rio Puerco antithetic fault zone probably represents a 100-km-wide zone of late Neogene extension. Mesozoic rocks are not eroded in the Rio Puerco zone nor within the graben at Albuquerque (Black and Hiss, 1974), as they would be had the area been uplifted. To judge from regional tectonic and magmatic patterns, however, the Rio Puerco zone is obviously part of the rift. (Evidence for a possible Laramide ancestry is discussed by Slack, 1975.) Mesozoic rocks may have been preserved in this area because accelerated horizontal extension didn't allow much vertical uplift to develop.

North of lat 35°N (Fig. 12), the rift crosses a suspected northeast-trending discontinuity in the Precambrian basement (Jemez lineament) or perhaps a series of parallel northeast-trending discontinuities. It is in this general area that the rift changes trend and character and horizontal extension increases significantly (Fig. 12). Profiles at lat 34° 33° and 32°N are shown in Figures 13 through 15. West of about long 108°W the profiles cross the structural grain at small angles (Fig. 2) and are probably misleading. The eastern border of the rift, however, is fairly well depicted by the profiles. The eastern border extends along the Sacramento-Guadalupe Mountains (Fig. 1), across Trans-Pecos Texas, and into the Republic of Mexico. The location of the western and southern borders is arbitrary. Figures 13 through 15 show a general progression into the "mountains-in-plains" physiography typical of the Great Basin (compare Figs. 9 and 15). Even though the exact number of horsts and grabens is not known, it is likely that by lat 32°N (Fig. 15), horizontal extension is more than an order of magnitude greater than uplift.

The topographic profiles show the rift zone to be essentially either a horst or a broad uplift, which from Colorado southward sags in the center as it increases in width. Bouguer gravity profiles (Figs. 10 through 15) show a reciprocal but essentially similar north-to-south progression.

Neglecting the narrow gravity low associated with graben fill, one observes a residual positive gravity anomaly over the axial graben (dashed line in Figs. 10 through 12), and a broad residual negative anomaly over the regional uplift. Amplitudes of both residual anomalies would be significantly increased if near-surface density variations were taken into account (compare Decker and others, 1975).

Gravity profiles across the Rio Grande rift resemble profiles across the Gregory rift in Kenya (Searle, 1970), which Girdler (1975; Girdler and others, 1969) interpreted in terms of thinning of the lithosphere over an asthenospheric bulge. Similarly, from gravity analysis with seismic and heat flow constraints, Bridwell (1976) suggested a 60-km-thick "inclusion" of asthenosphere beneath the Rio Grande rift in northern New Mexico, and Decker and Smithson (1975) suggested thinning of the crust by 75% to 100% over a 30- to 60-km-thick silt of "low-density mantle." To the extent that within interpretational latitude the low-density mantle extends nearly to the base of the lithosphere, these two interpretations for the Rio Grande rift are somewhat the same. They have in common with each other and with Girdler and others' (1969) model for Kenya a very great thickness of inferred low-density, asthenosphere-like upper mantle. In part, the resulting very great thickness of anomalous upper mantle is built into these analyses because only steady-state, conductive heat transfer is considered. More recently, Decker and Smithson (1977) have considered transient heat sources (analogous to convective, magmatic heat transport) leading to a significantly thinner anomalous zone.

Figure 14. Gravity and elevation profiles along lat. 33°N (Jornada syncline).
The broad gravity low may be related to the shape of the low-velocity zone in the upper mantle, but it may be more critically related to density changes due to thermal expansion and mass transport within the upper mantle (see Fig. 6) and to both inherent and intrusion-related lateral density variation within the crust. High heat flow and high electrical conductivity indicate that the low-velocity zone is hot, but its shape, internal density structure, and convective motion are unknown. One can guess at the density and invert the gravity data in terms of the shape of the low-velocity zone, but as more seismic and electrical data become available it might become possible to constrain the shape and invert the gravity data in terms of the density distribution within the low-velocity zone.

The residual positive gravity anomaly associated with the axial graben is apparent in Figures 10 and 11 in the vicinity of long 106'W and is very obvious in Figure 12. I have attempted to illustrate the anomaly by interpolating the gravity field over the abrupt local gravity low associated with low-density graben fill, as shown by dashed lines in Figures 10, 11, and 12. An axial positive gravity anomaly within a broad gravity low is also characteristic of the Gregory rift and other continental rifts. Model studies (Searle, 1970; Girdler, 1975; Cordell, 1976a; Bridwell, 1976) indicate the source of the axial positive anomaly to be narrow and steep sided. This shape seems inconsistent with freeboard topography on a buoyantly supported asthenosphere. It seems more likely that the axial positive gravity anomaly indicates mantle material decoupled from the underlying anomalous upper mantle and intruded by dynamic means into the crust.

**DISCUSSION**

The southern Rocky Mountain uplift (the Neogene-Quaternary uplift) and the Rio Grande graben cannot be considered separately. They are parts of a system of uplift, magmatism, and extension that makes up the Rio Grande rift. Among the continental rifts, a unique feature of the Rio Grande rift is its vergence, providing from south to north a sort of down-structure view of the rift process initiated as mountains and culminating as mountains-in-plains.

The geophysical data show that heat and mass have been added to the system, as is the case with spreading ridges. On the other hand, the relatively low level of seismicity would indicate that the rift is not very active at present. The low seismicity may not be representative of long-term trends, however, to judge from the evidence provided by seismology and electrical conductivity data for existing major deep structure. Detailed seismic data are sparse within the rift itself, except in the Socorro area. The rift seems to occur in the general area of a lateral transition in crustal and upper-mantle structure between the High Plains and the Colorado Plateau. As Figure 9 suggests, however, the plateau may have no particularly characteristic crustal structure in its own right, the more significant Neogene structure possibly being symmetric to the axis of the rift.

Zigzags in the fault blocks on the order of tens of kilometres, as well as zigzags in the trend of the rift itself on the order of hundreds of kilometres, are aligned with basement structural grain, as traced under sedimentary cover by means of the aeromagnetic data. Inherited structural grain has undoubtedly influenced both the rift and earlier uplifts along this same trend. Whether the rift has sought out a fundamental basement suture or has simply taken advantage of ubiquitous basement cracks is uncertain.

The tectonic work has been accomplished by some combination of the effects of heat, density, chemical phase change, and mass transport, all of which are interrelated. Similarly, the geophysical data — gravity, heat flow, seismic velocity, electrical conductivity, and elevation — are functionally interrelated. The system is overdetermined and, in principle, could be solved uniquely. To do so realistically would require more constraints on the geometry of deep structure within the rift itself; that is, physical-property information derived from potential-field data is reasonably complete, but sounding-type geophysical data that could provide constraints on shape and depth of critical interfaces are needed. When that information becomes available, the study of the rift will enter an exciting new phase in which the geophysical and petrological data and the geological history can be quantitatively combined.

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