Discussion of new gravity maps for the Albuquerque Basin area

V. J. S. Grauch, Cindy L. Gillepsie, and G. R. Keller

1999, pp. 119-124. https://doi.org/10.56577/FFC-50.119

in:

Albuquerque Geology, Pazzaglia, F. J.; Lucas, S. G.; [eds.], New Mexico Geological Society 50 th Annual Fall Field Conference Guidebook, 448 p. https://doi.org/10.56577/FFC-50

This page is intentionally left blank to maintain order of facing pages.

DISCUSSION OF NEW GRAVITY MAPS FOR THE ALBUQUERQUE BASIN AREA

V. J. S. GRAUCH[1], CINDY L. GILLESPIE[2], and G. R. KELLER[2]

[1]U.S. Geological Survey, MS 964, Federal Center, Denver, CO 80225; [2]The University of Texas at El Paso, Department of Geological Sciences and Pan American Center for Earth and Environmental Studies, El Paso, TX 79968

Abstract—Gravity data recently acquired to fill in a large gap in data coverage in the southwestern part of the Albuquerque basin are combined with older data to produce new Bouguer and isostatic residual gravity maps of the Albuquerque basin area. The new maps show three subbasins within the Albuquerque basin that are separated by northwest- and/or north-trending gravity highs. The configuration of the subbasins do not support a master "Rio Grande fault," which was previously proposed for the eastern margin of the Albuquerque basin based on seismic-reflection data. North–south-trending gravity gradients are similar to others in the region that may be related to strike-slip faults located along weaknesses developed during Precambrian time. Northwest gravity trends in the central part of the basin may reflect buried rift-related structures that are older than north-striking faults conspicuous at the surface. Northeast-trending accommodation zones are not apparent in the gravity maps. A gravity low in the southeastern part of the Albuquerque basin cannot be explained by thick basin fill, because the Grober-Fuqua deep oil exploration well indicates significantly thinner fill in the area of the low. Simple profile models were developed to test three different explanations for the gravity low. The only model that fits both gravity and drill-hole evidence is conceived as a buried, late Paleozoic(?) basin containing a significant amount of salt. Such a hypothesis is not unreasonable for this area, but more subsurface information should be acquired to verify the hypothesis.

INTRODUCTION

Following the early work of Chapin (1971), the basins of the Rio Grande rift have been the target of many studies. A number of recent studies have been summarized in a volume of papers edited by Keller and Cather (1994). Since 1996, a multi-agency project has focused investigations to develop an improved hydrologic model of the Albuquerque basin, referred to as the Middle Rio Grande basin study (http://rmmcweb.cr.usgs.gov/public/mrgb). One important input to development of the hydrologic model is knowledge of the vertical and horizontal extents of different hydrostratigraphic units within the basin fill. Geophysical studies are a key element to understanding the vertical dimension and to locating faults that may form the lateral bounds of hydrostratigraphic units. Gravity data are especially useful for determining the locations of major basement faults and the thickness of the basin sediments, because the large density contrasts between basin fill and surrounding country rock produce large variations in the gravity field.

Regional-scale compilation of gravity data in the Rio Grande rift area began with Cordell et al. (1982). Heywood (1992) compiled data for the State of New Mexico, and the University of Texas at El Paso (UTEP) maintains a database of the Rio Grande rift region. However, these compilations lack coverage of a large area in the southwestern part of the Albuquerque basin. UTEP and the U.S. Geological Survey (USGS) collaborated in a field effort to acquire gravity data in this area in 1997, motivated by the need for improved gravity coverage for the Middle Rio Grande basin study. The new data have been recently processed and incorporated with the older data, resulting in more complete gravity coverage of the basin.

The purpose of this report is to present the new gravity maps of the Albuquerque basin area and briefly discuss their principal features. We compare these features to the structural model of the basin based on drill-hole and seismic-reflection interpretations (Russell and Snelson, 1994), but leave a more detailed comparison for future work. In addition, we present several gravity models to explore an inconsistency between a deep drill hole and a gravity low in the southeastern part of the basin. The modeling leads us to conclude that a significant amount of salt must be present within a buried pre-Tertiary basin.

GEOLOGIC SETTING

The Albuquerque basin is one of the largest basins in the Rio Grande rift zone (Fig. 1). Drilling results show that the basin fill is locally as thick as 4.4 km (Lozinsky, 1994). Most of the fill is composed of synrift Quaternary and Tertiary Santa Fe Group sediments (Fig. 1), although locally more than 2 km of more-lithified lower Tertiary sediments are also buried within the basin (Lozinsky, 1994). Pre-Tertiary rocks are exposed on the rift shoulders (Fig. 1). These include Mesozoic units up to 2.5 km thick that are dominated by clastic lithologies, Paleozoic units 1–2 km thick that are chiefly clastic lithologies at the top and dominantly carbonate lithologies at the base, and Proterozoic igneous and metamorphic rocks (Kelley, 1977).

The deep structure of the rift basin is complex. Although somewhat different structural models have been previously proposed, all models show the Albuquerque basin divided into northern and southern por-

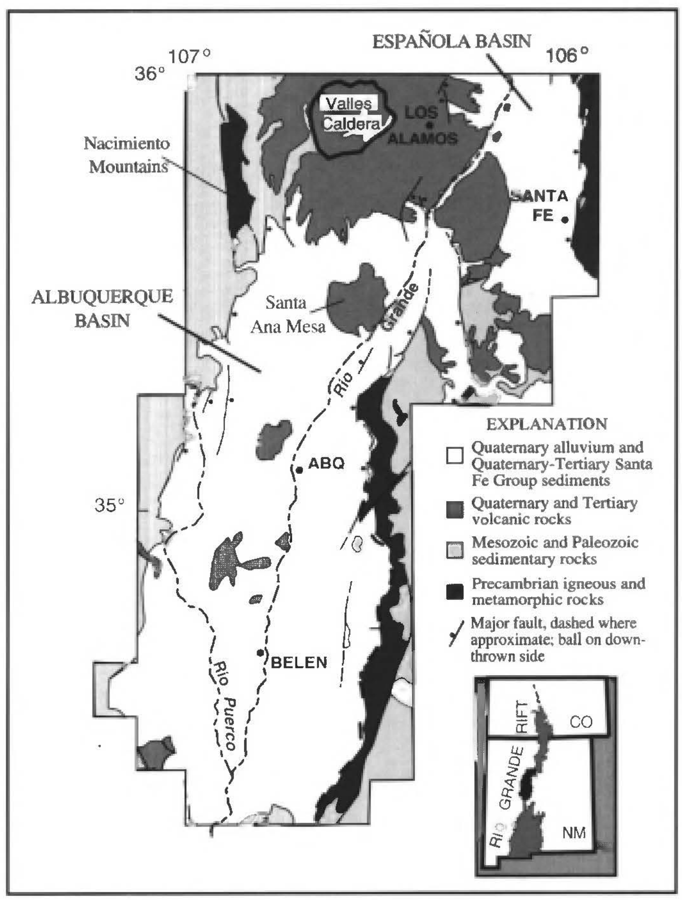

FIGURE 1. Index map showing regional geology of the Albuquerque basin area and its location within the Rio Grande rift. ABQ = Albuquerque. Geology generalized from Kelley (1977).

tions, with shallowly buried structural benches on parts of both east and west sides (Cordell, 1976; Birch, 1982; Russell and Snelson, 1994; Hawley, 1996). The differences between the models arise from whether the model was developed primarily from consideration of gravity data (Cordell, 1976; Birch, 1982; Hawley, 1996) or seismic-reflection interpretations (Russell and Snelson, 1994). These differences are described in a following section.

GRAVITY DATA DESCRIPTION

A field survey was undertaken during the summer of 1997 to fill in the large gap in gravity data coverage in the southwestern part of the Albuquerque basin, primarily southwest of Belen (Fig. 2). How these data were acquired, processed, and combined with existing data are briefly described here. A report is being prepared to explain the acquisition and processing of the new data in detail (C. L. Gillespie et al., unpubl. USGS report, 1999).

Station locations for the 1997 survey were determined using dual-frequency survey-grade Global Positioning System (GPS) units and differential measurements. The survey was tied to established gravity base stations so that the results could be consistent with the existing data base. The gravity base station originally established at the Belen Post Office could not be occupied because the building had been rebuilt. A new base station was established outside the rebuilt Post Office and tied to two other known base stations in Socorro and Albuquerque.

The gravity data were processed using standard reduction equations for free-air, Bouguer, and earth curvature corrections (Cordell et al., 1982) and a standard value of 2.67 g/cm^3 for the density of the Earth's crust. Corrections for the variation of gravity with latitude at each station were computed using the International Gravity formula of 1971

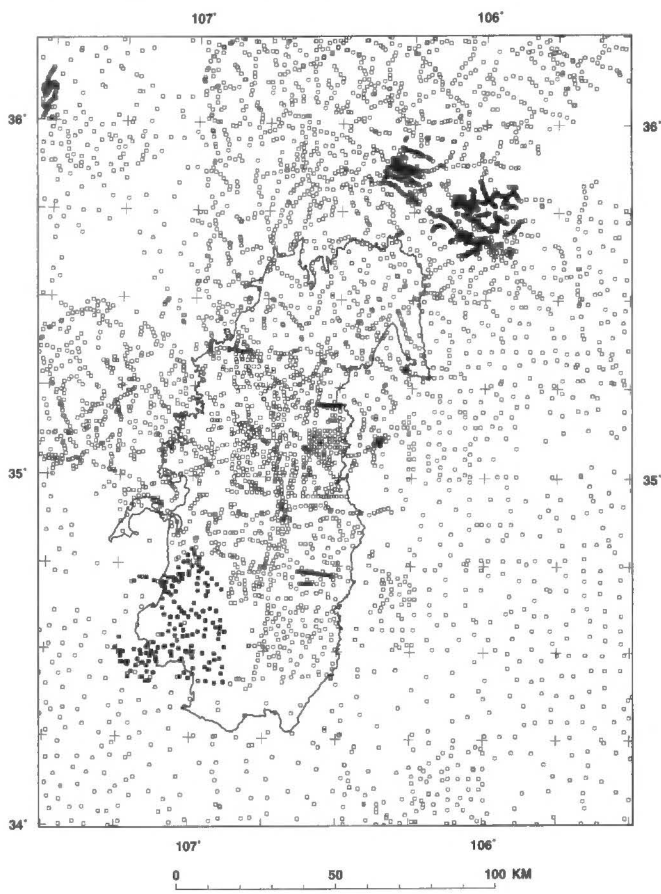

FIGURE 2. Location of stations for the present compilation of gravity data. New data stations in the Belen area are indicated by solid squares (C. L. Gillespie et al., unpubl. USGS report, 1999). Older data stations, from Heywood (1992) and The University of Texas at El Paso (UTEP) data files, are indicated by open squares. The Albuquerque basin is outlined for reference.

(Woollard, 1979). Inner-zone terrain corrections were calculated out to 895 m from each station using a standard Hammer technique (Hammer, 1939), in which average elevation estimates within circular zones surrounding the station are used to compute the gravity effect of each zone. Outer-zone terrain corrections for 0.895–167 km from each station were computed using the algorithm of Plouff (1977). This algorithm computes gravity effects based on digital elevation models having different sample intervals, taking advantage of decreased need for close sample spacings at great distances from the station. A digital elevation model with 15-arc-second sample interval was used closest to the station.

The final processing resulted in gravity data from which the theoretically expected gravitational pull of the earth and surrounding terrain at each station has been removed. These data are commonly called Bouguer gravity data, Bouguer gravity anomaly data, or complete Bouguer anomaly data (as opposed to simple Bouguer anomaly data that have not been corrected for terrain). The term "anomaly" comes from the concept that the data show the gravitational effects of masses that are anomalous compared to what is theoretically expected for a homogeneous earth with an assumed crustal density (in this case, a density of 2.67 g/cm^3).

The Bouguer gravity data for the new survey were combined with those from Heywood (1992) and additional data from the UTEP data base that were not contained in Heywood's compilation. Application of terrain corrections to some of the additional UTEP data were required before the combination. About 25 "bad" stations were removed from the combined data set where the gravity values had large, unexplained discrepancies with those of adjacent stations. The resulting compilation contains a total of 5390 data points in the study area (Fig. 2), which are available in digital form from the Department of Geological Sciences at UTEP. The compilation does not include all existing data for the area, such as unpublished data that have been recently collected near Santa Fe as part of the Summer of Applied Geophysical Experience (SAGE) program.

DISCUSSION OF THE GRAVITY MAPS

The Bouguer gravity data were gridded using the minimum-curvature program of Webring (1981), resulting in the Bouguer gravity map shown on Plate C, (this volume, p. 136). The traditional approach is to consider Bouguer gravity data as representing the anomalous gravity field due to structures primarily in the lithosphere. Thus, the anomalies shown in Plate C are essentially the sum of the gravitational effects of structures in the upper crust, lower crust, and upper mantle. This concept is demonstrated by a computer model for an east–west gravity profile that crosses the northern portion of the Albuquerque basin (Fig. 3; Keller and Baldridge, 1999). The model, which is constrained by deep seismic data in the region, shows that lithospheric thinning beneath the Rio Grande rift and the sedimentary fill in the basin are the main elements needed to explain the Bouguer anomalies.

The profile model of Figure 3 also demonstrates the large gravitational contribution of the lower crust and upper mantle to Bouguer gravity. In order to focus on density variations within the upper crust, a regional field is commonly removed from Bouguer gravity data. The regional field can be constructed in a number of ways, such as trend fitting, modeling, or wavelength filtering. However, a regional field that is based on an Airy isostatic model is most desirable because it is understandable in physical terms and easily repeated between studies. As discussed by Simpson et al. (1986), the exact parameters of the isostatic model need not be accurate, nor does the Airy mechanism of isostasy need be completely satisfied for construction of a useful regional field. However, they caution that the resulting maps should not be used as evidence for or against isostatic compensation.

The isostatic regional field for the Albuquerque basin area was computed out to a radius of 167 km using the program AIRYROOT by Simpson et al. (1983). Regional field values farther away than 167 km were obtained from the isostatic model field computed by Karki et al. (1961) for the world. We chose the same parameters to model the isostatic regional field as those determined for the statewide compilation by Heywood (1992). In his report, Heywood discusses the choice and application of these parameters in depth, and presents maps of the regional and residual fields. After removal of the isostatic regional field from the Bouguer gravity value at each station, the results were gridded (Webring, 1981) and are displayed in Plate D, (this volume, p. 137) as an isostatic residual gravity map. The most noticeable difference between the Bouguer and isostatic residual gravity maps (Plates C and D, respectively) is that gravity lows in the isostatic residual gravity map are more comparable in value within the basin area from north to south.

The principal features of the isostatic residual gravity map are the focus of the remaining discussion. The gray lines on the map (Plate D) mark steep gradients in the isostatic residual gravity field, following the horizontal-gradient method of Cordell (1979). The method is an objective way to generally locate steeply dipping faults that juxtapose rocks with significantly contrasting densities.

Basin structure

The isostatic residual gravity map (Plate D) primarily expresses variations in the thickness of the poorly consolidated basin sediments, which have low densities compared to the moderate to high densities of the surrounding country rock. In general, lower gravity values correspond to thicker fill, and indicate several discrete depressions within the Albuquerque basin (Plate D). First-order gravity lows indicate three major subbasins, which have been recognized previously (Cordell, 1976; Birch, 1982; Hawley, 1996). From north-to-south, we designate them as the Santo Domingo, Calabacillas, and Belen subbasins (Fig. 4). Although the Santo Domingo subbasin is often considered a basin separate from the Albuquerque basin (e.g., Lozinsky, 1994), we use the term "subbasin" for consistency.

Large gradients in the isostatic residual gravity map indicate the Santo Domingo subbasin is generally bounded on the east and west by north–south structures and on the north and south by northeast-trending structures (Plate D, Fig. 4). The La Bajada fault, which is commonly considered the northeastern limit of the Santo Domingo subbasin, does not coincide with the eastern boundary of the gravity-defined subbasin (Fig. 4). The La Bajada fault appears to be a younger, less significant structure than the basin margin. The 15-mGal gravity low coinciding with Santa Ana Mesa (Fig. 1, Plate D) indicates basin fill within the Albuquerque basin area reaches its maximum thickness here. Previous gravity modeling indicates almost 4 km of low-density (2.20–2.40 g/cm^3) fill (Birch, 1982). Drilling and seismic data are not available for corroboration in this area.

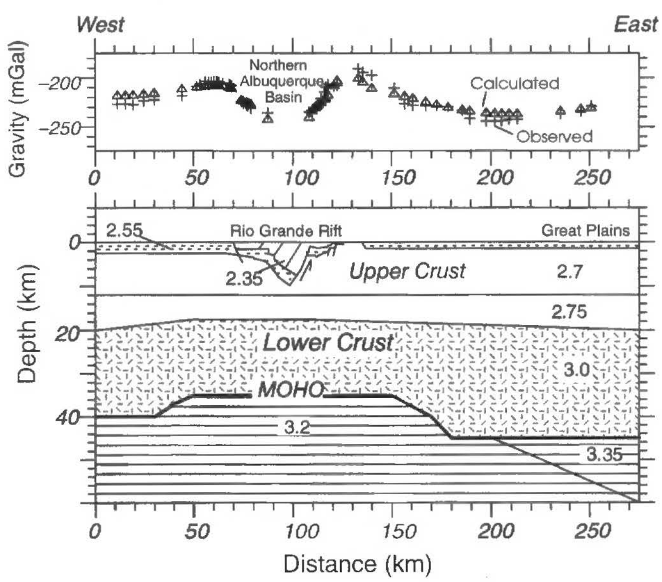

FIGURE 3. Crustal-scale cross-section constructed by modeling a Bouguer gravity profile across the northern portion of the Albuquerque basin. Seismic reflection and refraction profiles in the region (Russell and Snelson, 1994; Keller et al., 1998) were used as constraints. Numbers are densities in g/cm^3. Modified from Keller and Baldridge (1999).

The Calabacillas subbasin is generally bounded by north–south and northwest-trending structures (Fig. 4), as indicated by gradients in the isostatic residual gravity data (Plate D). It is separated from the Santo Domingo subbasin by a north- and northwest-trending gravity high (Plate D). The north-trending gravity high corresponds to the Ziana anticline of Kelley (1977; Fig. 4) and to a structural culmination in pre-Tertiary basement, evidenced in drillhole and seismic data (Russell and Snelson, 1994, line 50). The western gravity boundary of the Calabacillas subbasin generally coincides with Russell and Snelson's (1994) West Mesa fault, which they define as the eastern edge of the Laguna structural bench (Fig. 4). However, the eastern gravity boundary is located as much as 10 km east of their basin-bounding Rio Grande fault (Fig. 4), which is strong evidence against the existence of this fault. Lack of support for the Rio Grande fault also comes from consideration of subsurface stratigraphic trends in the Albuquerque area (Connell et al., 1998). The poor correspondence of their model to the gravity and subsurface data may be explained by the general lack of seismic and deep well data in this area, especially compared to the western part of the basin (Russell and Snelson, 1994).

The northwest-trending gravity gradients of the Calabacillas subbasin are crossed by numerous north–south faults mapped at the surface and

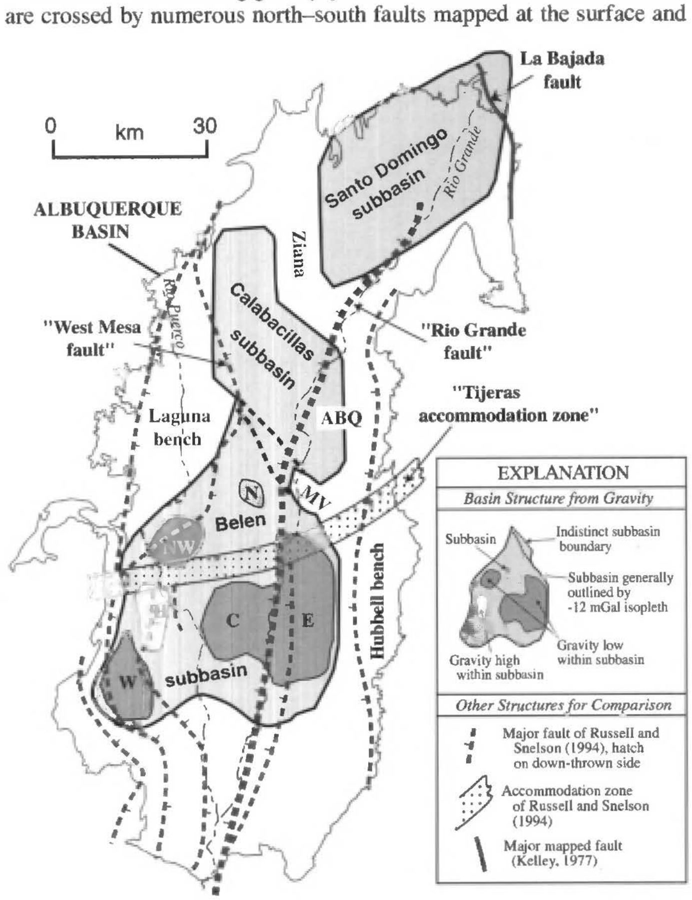

FIGURE 4. Simplified basin structure of the Albuquerque basin area from the isostatic residual gravity map, compared to other structural models and mapping. Subbasins (shaded areas) are outlined by generally following the -12 mGal isopleth from the isostatic residual gravity map (Plate D). Discrete gravity lows (deeper shading) and one high (white area) within the Belen subbasin are labeled for reference to the text. Major faults of Russell and Snelson's (1994) model are shown in heavy, short-dashed gray lines; their Rio Grande fault and its southern extension are shown heavier to emphasize the lack of correspondence to the gravity-defined subbasins. Their Tijeras accommodation or transfer zone (stippled band) is not apparent in the gravity data. The mapped La Bajada fault may not be the northeastern limit of the Santo Domingo basin, as commonly supposed. MV = Mountainview prong. ABQ = Albuquerque. Ziana = Ziana anticline of Kelley (1977).

expressed in aeromagnetic data (M. R. Hudson et al., unpubl. fault compilation, 1999; Grauch, 1999). The northwesterly gravity gradients may reflect older, deeper parts of the structural configuration of the basin (J. C. Cole et al., unpubl. abstract, 1999).

A northwest-trending gravity high is located between the Calabacillas and Belen subbasins on the eastern side (Plate D; MV, Fig. 4). Evidence from drill holes and seismic data indicates the gravity high at the Mountainview prong (MV, Fig. 4) is associated with a basement high (Russell and Snelson, 1994). Russell and Snelson (1994) interpreted the basement high as part of a shallow structural bench east of their Rio Grande fault (Fig. 4). Instead, the gravity data indicate a more three-dimensional picture, with a fairly narrow basement high oriented in a northwest direction. Maldonado et al. (1999) present additional geologic evidence against a north-trending Rio Grande fault in the vicinity of the Mountainview prong. The northwest trend given by the gravity high at the Mountainview prong can be extended farther northwest (Plate D) to provide a reasonable, albeit indistinct, separation between the Calabacillas and Belen subbasins (Fig. 4).

The isostatic residual gravity map indicates that the Belen subbasin is internally segmented but generally bounded by structures trending north–south, northwest and northeast (Plate D). The eastern boundary also corresponds to the western edge of the Hubbell structural bench (Fig. 4, Kelley, 1977). Discrete gravity lows occur in the north, northwest, central and east, and west parts of the subbasin (N, NW, C, E, and W, respectively, Fig. 4). North–south elongation is apparent for the gravity low along the eastern side and the gravity high near the western side of the Belen subbasin (E and H, respectively, Fig. 4). Faults defined by Russell and Snelson's (1994) structural model generally follow the bounds of most of these features (Fig. 4). A significant exception is shown by their West Mesa fault where it crosses through the center of the northwestern low (NW) rather than following the boundaries of the low. Several seismic lines cross the area (Russell and Snelson, 1994), but the discrepancy cannot be evaluated because the data from these lines have not been published. Another discrepancy is Russell and Snelson's (1994) Tijeras accommodation zone (Fig. 4), for which there is no clear expression in the gravity data. Maldonado et al. (1999) discuss this and additional evidence against the presence of this southwest-trending zone.

The north–south elongation of the gravity high (H), revealed by the new gravity data in the southwestern part of the basin, follows after the pattern of north-trending gravity gradients in other parts of the study area. Both the Calabacillas subbasin and the Belen subbasin are bounded on the east by steep, linear gravity gradients that are aligned north–south over a combined length of almost 100 km (Plate D). The extent and linearity suggest a strike-slip origin. Other linear north-trending gravity gradients are evident along both east and west sides of the Rio Grande rift region. Most notable is the gradient associated with the Nacimiento fault (e.g., Woodward et al., 1992) along the western side of the Nacimiento Mountains (Fig. 1) that aligns with the western gravity boundary of the Calabacillas basin (Plate D). Laramide lateral movement on north-striking faults is documented on many faults in this region, although the amount of movement is debated (e.g., Cather, 1992; Woodward et al., 1992). Lateral movement on north-striking faults is also documented during late Paleozoic pull-apart basin development (Barrow and Keller, 1994; Beck and Chapin, 1994; Woodward, 1996). These faults may have followed north–south basement weaknesses that originally developed during Precambrian time (Karlstrom et al., this volume).

Southeastern gravity low due to presence of salt?

Thick basin fill associated with the gravity lows in the northern, central, and western parts of the Belen subbasin (N, C, W, respectively, Fig. 4) are corroborated by well and seismic data (Russell and Snelson, 1994). Thick basin fill could reasonably account for the prominent eastern gravity low as well (E, Fig. 4), except for evidence from a deep drillhole in the area (Fig. 5, model A). This drillhole, the Grober-Fuqua #1 well (Plate D), indicates only 1384 m of Santa Fe Group resting on top of Triassic rocks (Lozinsky, 1988, 1994). Lozinsky (1988) inferred these relationships by comparing the sandstone petrology of Grober-Fuqua core to sandstone petrology of Tertiary and Mesozoic cores and surface rocks from elsewhere in the basin. He found that sandstone from the lower part of the Grober-Fuqua well was petrologically indistinguishable from Triassic sandstone mapped at the surface nearby and differed significantly from the sandstone petrology of Tertiary units.

To account for both the gravity low bounded by steep gradients and the relatively thin Santa Fe Group in the Grober-Fuqua well, one must explain unexpected low densities in the pre-Tertiary section within a relatively narrow and steep-sided feature. One hypothesis would entail a pull-apart basin of late Paleozoic (ancestral Rocky Mountains) age. Such basins, filled with thickened Pennsylvanian clastic units, have been documented from subsurface information in several places east and south of the Albuquerque basin (Beck and Chapin, 1994; Barrow and Keller, 1994; Broadhead, 1997; R. F. Broadhead, unpubl. NMBMMR report, 1999). However, a reasonable density contrast between basement and Paleozoic rocks (Fig. 5) requires an unreasonable basin depth (>10 km) to account for the magnitude of the gravity low (Fig 5, model B). Moreover, a basin this deep is far greater than depth estimates to the top of magnetic (crystalline) basement derived from aeromagnetic data (Fig. 5). The magnetic depth estimates on Figure 5 locate places where several different profile depth-estimation methods using different parameters gave common results (program PDEPTH in Phillips, 1997). The estimates are probably about 1.5 km too shallow, as evidenced by the northernmost and southernmost estimates compared to other constraints on basement depths (Fig. 5). Even allowing for this large an error, the estimates suggest a shallower basin shape that does not support the extreme depths required by Model B. A similar gravity model that assumes the low densities are contained entirely in the Precambrian basement would have the same difficulties fitting the gravity data and the magnetic depth estimates.

A third hypothesis meets both the gravity and drill-hole evidence by assuming a late Paleozoic(?) basin with unusually low densities, such as the modeled value of 2.38 g/cm^3 of Figure 5, model C. Low densities of normally moderately dense sedimentary units can be explained by the presence of significant quantities of rock salt, which has a density of 2.0–2.2 g/cm^3. Other common evaporites would not lower the overall density within the basin. Anhydrite, which has a mineral density of 2.96 g/cm^3 (Johnson and Olhoeft, 1984), would increase the overall density. Gypsum, which has a mineral density of 2.30 g/cm^3 (Johnson and Olhoeft, 1984), commonly converts to anhydrite below 400 m in a sedimentary rift environment (Jowett et al., 1993).

The presence of salt within the late Paleozoic section is not unreasonable for this area. The Permian Yeso Formation was deposited in marginal marine type environments in the southern part of the Albuquerque basin, including sabkha and hypersaline lagoons (Stanesco, 1991). It includes significant amounts of evaporites where it is exposed at the southern and southeastern edges of the Albuquerque basin (Kelley, 1977; Broadhead, 1997). Halite casts have been found in the Yeso Formation in the southern part of the Belen subbasin (R. Colpitts, verbal commun., 1998) and also farther south, along the eastern edge of the Soccoro basin (Smith et al., 1983, fig. 1-48.2c). Salt is or may have been present in Permian rocks in the subsurface in the Holbrook basin about 150 km to the west (Rauzi, 1996), in the Delaware basin about 300 km to the southeast (Keller et al., 1980), and in the Carrizozo basin about 50 km to the south (R. F. Broadhead, unpubl. NMBMMR report, 1999). In the Carrizozo basin, 900 feet (274 m) of salt were encountered in Standard of Texas #1 Heard well (Foster, 1959).

The unexpected conclusion that the gravity low in the southeastern part of the basin is due to an older (late Paleozoic?) basin containing a significant amount of salt is a consequence of the shallow depth to Triassic rocks inferred by Lozinsky (1988, 1994) in the Grober-Fuqua well. Although the petrologic deductions that led to his conclusion are compelling, the rocks have not been directly dated. The Grober-Fuqua well is the only deep well in the vicinity of the gravity low. Seismic-reflection lines cross the gravity low only at its very northern end

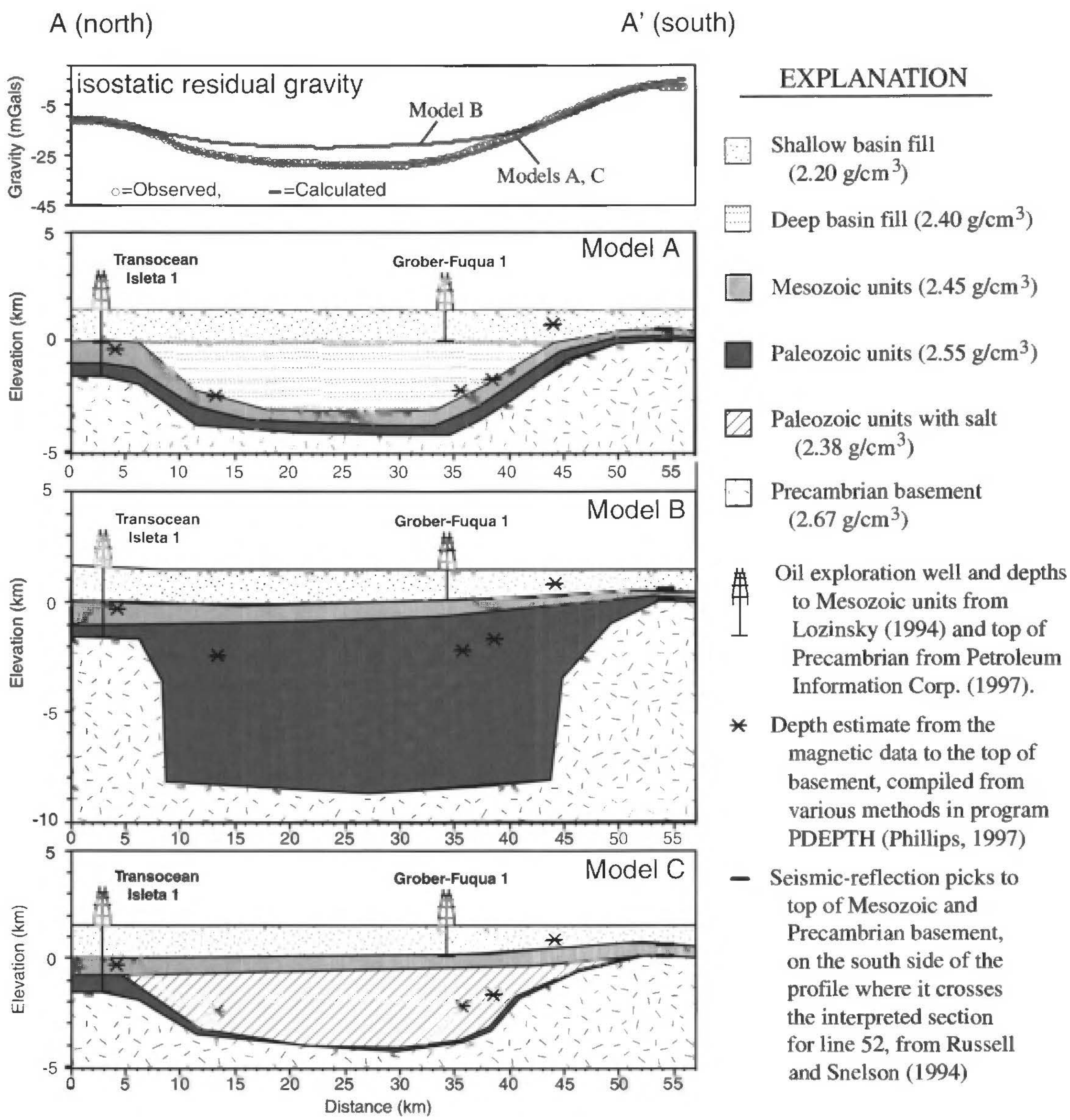

FIGURE 5. Highly simplified gravity models of a north–south profile (A–A' located on Plate D) to test the feasibility of three different explanations for the southeastern gravity low. Model A explains the gravity low as a Tertiary basin, but this model does not match the evidence for shallow depth to Triassic rocks in the Grober-Fuqua well (Lozinsky, 1988, 1994). Model B attempts to fit the low with a buried, late Paleozoic(?) basin filled only with clastic units. Even with a basin of 10 km depth, Model B does not account for the magnitude of the gravity low and it contradicts the shallower trend of the magnetic depth estimates to crystalline basement. Model C explains the low with a late Paleozoic(?) basin that contains a significant amount of salt intermixed with sediments. This is the only model that fits both drill-hole and gravity evidence. Model densities were determined primarily from density logs (except the hypothetical unit containing salt), and are similar to those found by Keller et al. (1980) and Birch (1982). Magnetic data used for the depth estimation were derived from the aeromagnetic compilation of Grauch (this volume).

(Russell and Snelson, 1994). Although the lines were not published, Russell and Snelson's interpretation of a shallow bench east of the Rio Grande in this area is possible corroboration for thin rift-basin fill. Additional subsurface information is required. In any case, the north–south elongation of the southeastern gravity low suggests it formed as a pull-apart basin, probably during the late Paleozoic.

ACKNOWLEDGMENTS

John Hawley was instrumental in pushing forward the importance of the isostatic residual gravity data for the Albuquerque basin area even in the face of apparent contradictions with seismic-reflection data. He also pointed out to us the apparent conflict between depths for the Grober-Fuqua well and the southeastern gravity low. Steve Cather, Jim Cole, and Dave Love provided helpful guidance during examination of the geologic evidence from that well. Kim Oshetski, Bill Smith, Albert Jimenez, and Steve Harder provided assistance with the gravity fieldwork. Jim Cole, Bob Kucks, and Sean Connell provided thoughtful suggestions on early manuscript drafts. The Pan American Center for Earth and Environmental Studies is supported by NASA cooperative agreement NCC5-209.

REFERENCES

Barrow, R. and Keller, G. R., 1994, An integrated geophysical study of the Estancia basin, central New Mexico: Geological Society of America, Special Paper 291, p. 171–186.

Beck, W. C. and Chapin, C. E., 1994, Structural and tectonic evolution of the Joyita Hills, central New Mexico: Implications of basement control on Rio Grande rift: Geological Society of America, Special Paper 291, p. 187–205.

Birch, F. S., 1982, Gravity models of the Albuquerque basin, Rio Grande rift, New Mexico: Geophysics, v. 47, p. 1185–1197.

Broadhead, R. F., 1997, Subsurface geology and oil and gas potential of Estancia basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 157, 54 p.

Cather, S. M., 1992, Suggested revisions to the Tertiary tectonic history of north-central New Mexico: New Mexico Geological Society, Guidebook 43, p. 109–122.

Chapin, C. E., 1971, The Rio Grande rift, Part 1: Modifications and additions: New Mexico Geological Society, Guidebook 22, p. 191–202.

Connell, S. D., Allen, B. D. and Hawley, J. W., 1998, Subsurface stratigraphy of the Santa Fe Group from borehole geophysical logs, Albuquerque area, New Mexico: New Mexico Geology, v. 20, p. 2–7.

Cordell, L., 1976, Aeromagnetic and gravity studies of the Rio Grande graben in New Mexico between Belen and Pilar: New Mexico Geological Society, Special Publication 6, p. 62–70.

Cordell, L., 1979, Gravimetric expression of graben faulting in Santa Fe Country and the Española Basin, New Mexico: New Mexico Geological Society, Guidebook 30, p. 59–64.

Cordell, L., Keller, G. R. and Hildenbrand, T. G., 1982, Bouguer gravity map of the Rio Grande rift, Colorado, New Mexico, and Texas: U.S. Geological Survey, Geophysical Investigations Series Map GP-949, scale 1:1,000,000.

Foster, R. W., 1959, Summary of well logs; *in* Griswold, G. B., 1959, Mineral deposits of Lincoln County: New Mexico Bureau of Mines and Mineral Resources, Bulletin 67, p. 110.

Hammer, 1939, Terrain corrections for gravimeter stations: Geophysics, v. 4., p. 184–194.

Hawley, J. W., 1996, Hydrogeologic framework of potential recharge areas in the Albuquerque basin, central New Mexico; *in* Hawley, J. W. and Whitworth, T. M., eds., 1996, Hydrogeology of potential recharge areas and hydrogeochemical modeling of proposed artificial-recharge methods in basin- and valley-fill systems, Albuquerque basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-file Report 402-D, p. 1–70.

Heywood, C. E., 1992, Isostatic residual gravity anomalies of New Mexico: U.S. Geological Survey, Water-resources Investigations Report 91-4065, 27 p.

Johnson, G. R. and Olhoeft, G. R., 1984, Density of rocks and minerals; *in* Carmichael, R. S., ed., CRC Handbook of physical properties of rocks, v. III: CRC Press, Boca Raton, Florida, p. 1–38.

Jowett, E. C., Cathles, L. M., III and Davis, B. W., 1993, Predicting depths of gypsum dehydration in evaporitic sedimentary basins: American Association of Petroleum Geologists Bulletin, v. 77, p. 402–413.

Karki, P., Lassi, K. and Heiskanen, W. A., 1961, Topographic-isostatic reduction maps for the world for the Hayford zones 18-1, Airy-Heiskanen System, T = 30 kilometers: Publications of the Isostatic Institute of the International Association of Geodesy, no. 35, 5 p.

Keller, G. R., Hills, J. M. and Djeddi, R., 1980, A regional geological and geophysical study of the Delaware Basin, New Mexico and west Texas: New Mexico Geological Society, Guidebook 31, p. 105–111.

Keller, G. R. and Cather, S. M., eds., 1994, Basins of the Rio Grande rift: structure, stratigraphy, and tectonic setting: Geological Society of America, Special Paper 291, 304 p.

Keller, G. R. and Baldridge, W. S., 1999, The Rio Grande rift: A geological and geophysical overview: Rocky Mountain Geology, v. 35, in press.

Keller, G. R., Snelson, C. M., Sheehan, A. F. and Dueker, K. G., 1998, Geophysical studies of crustal structure in the Rocky Mountain region: A review: Rocky Mountain Geology, v. 33, p. 217–228.

Kelley, V. C., 1977, Geology of Albuquerque basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 33, 59 p.

Lozinsky, R. P., 1988, Stratigraphy, sedimentology, and sand petrology of the Santa Fe Group and pre-Santa Fe Tertiary deposits in the Albuquerque basin, central New Mexico [Ph.D. dissertation]: Socorro, New Mexico, New Mexico Institute of Mining and Technology, 298 p.

Lozinsky, R. P., 1994, Cenozoic stratigraphy, sandstone petrology, and depositional history of the Albuquerque basin, central New Mexico: Geological Society of America, Special Paper 291, p. 73–82.

Petroleum Information Corp., 1997, Well history control system: database available from IHS Energy Group, 1675 Broadway, Suite 700, Denver, CO, 80202

Phillips, J. D., 1997, Potential-field geophysical software for the PC, version 2.2: U.S. Geological Survey, Open-file Report 97-725, 34 p.

Plouff, D., 1977, Preliminary documentation for a Fortran program to compute gravity terrain corrections based on topography digitized on a geographic grid: U.S. Geological Survey, Open-File Report 77-535, 45 p.

Rauzi, S. L., 1996, Concealed evaporite basin drilled in Arizona: Oil and Gas Journal, Oct. 21, p. 64, 66.

Russell, L. R. and Snelson, S., 1994, Structure and tectonics of the Albuquerque basin segment of the Rio Grande rift: Insights from reflection seismic data: Geological Society of America, Special Paper 291, p. 83–112.

Simpson, R. W., Jachens, R. C. and Blakely, R. J., 1983, AIRYROOT: A FORTRAN program for calculating the gravitational attraction of an Airy isostatic root out to 166.7 km: U.S. Geological Survey, Open-file Report 83-883, 66 p.

Simpson, R. W., Jachens, R.C., Blakely, R. J. and Saltus, R. W., 1986, A new isostatic map of the conterminous U.S. with a discussion on the significance of isostatic residual anomalies: Journal of Geophysical Research, v. 91, p. 8348–8372.

Smith, C. T., Osburn, G. R., Chapin, C. E., Hawley, J. W., Osburn, J. C., Anderson, O. J., Rosen, S. D., Eggleston, T. L. and Cather, S. M., 1983, Road log from Socorro to Mesa del Yeso, Joyita Hills, Johnson Hill, Cerros de Amado, Lomas de Las Cañas, Jornada del Muerto, Carthage, and return to Socorro: New Mexico Geological Society, Guidebook 34, p. 1–28.

Stanesco, J. D., 1991, Sedimentology and depositional environments of the Lower Permian Yeso Formation, northwestern New Mexico: U.S. Geological Survey, Bulletin 1808-M, 12 p.

Webring, M., 1981, MINC: A gridding program based on minimum curvature: U.S. Geological Survey, Open-file Report 81-1224, 41 p.

Woodward, L. A., 1996, Paleotectonics of the late Paleozoic Peñasco uplift, Nacimiento region, northern New Mexico: New Mexico Geological Society, Guidebook 47, p. 107–113.

Woodward, L. A., Hultgren, M. C., Crouse, D. L. and Merrick, M. A., 1992, Geometry of the Nacimiento-Gallina fault system, northern New Mexico: New Mexico Geological Society, Guidebook 43, p. 103–108.

Woollard, G. P., 1979, The new gravity system—changes in international gravity base values and anomalies values: Geophysics, v. 44, p. 1352–1366.