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**Geophysical Study of the Crust and
Upper Mantle Beneath the
Central Rio Grande Rift and
Adjacent Great Plains and Colorado Plateau**

University of California

LOS ALAMOS SCIENTIFIC LABORATORY

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Geophysical Study of the Crust and Upper Mantle Beneath the Central Rio Grande Rift and Adjacent Great Plains and Colorado Plateau

Mark E. Ander

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GEOPHYSICAL STUDY OF THE CRUST AND UPPER MANTLE BENEATH THE CENTRAL RIO GRANDE RIFT AND ADJACENT GREAT PLAINS AND COLORADO PLATEAU

Mark E. Ander

The tectonics and structure of the Rio Grande rift have been influenced by a series of northeast-trending shear zones delineated by several structural lineaments. These lineaments penetrate lithosphere to great depths and act as conduits for magma. The Jemez lineament is most pronounced of these lineaments having extruded more magma than any of the other lineaments or the Rio Grande rift itself. Recent geophysical studies indicate the Jemez lineament may be a crustal-age boundary and is associated with anomalously low P velocity from 25- to 140-km depth between Mount Taylor and the Jemez Mountains and greater than normal heat flow.

As part of the national hot dry rock (HDR) geothermal program conducted by Los Alamos Scientific Laboratory, a regional deep magnetotelluric (MT) survey of Arizona and New Mexico was performed. The main objective of the MT project was to produce a regional geoelectric contour map of the pervasive deep electrical conductor within the crust and/or upper mantle beneath the Colorado Plateau, Basin and Range Province, and Rio Grande rift. Three MT profiles cross the Jemez lineament. Preliminary one-dimensional analysis of the data suggest the lineament is associated with anomalously high electrical conductivity very shallow in the crust.

An MT/audiomagnetotelluric (AMT) study of a 161 km² HDR prospect was performed on the Zuni Indian Reservation, New Mexico. First, 121 AMT soundings were done to detail near-surface electrical structures. No significant near-surface anomalous features or lateral discontinuities, other than topographic differences, were found. The detailed MT study consisted of 26 soundings. The average tipper strike is N60°E above 100 s period and represents the structural trend within Precambrian basement. The Jemez lineament is located just southeast of the Zuni prospect and strikes approximately N55°E. This strongly suggests a relationship between the deep structure beneath the Zuni prospect and the Jemez lineament. MT modeling indicates three relatively homogeneous layers, the deepest (below 15 km) having a resistivity of 50 ohm-m in the northwest decreasing to 5 ohm-m to the southeast toward the Jemez lineament.

Two-dimensional gravity modeling of a 700-km gravity profile at 34°30'N latitude was used to study the crust and upper mantle beneath the Rio Grande rift. Several models of each of three consecutive layers were produced using all available geologic and geophysical constraints. Layer I, from surface to 20 km, represents sedimentary stratigraphy and upper crust. Layer II, from 20- to 50-km depth, represents lower crust and Moho boundary. Layer III, from

50- to 200-km depth, represents upper mantle. The study showed that the asthenospheric bulge associated with the rift is much wider than expected. The eastern edge of the bulge is located about 60 km east of the rift center, while the western edge of the bulge is about 280 km west of the rift center.

Two short-wavelength anomalies along the gravity profile were analyzed using linear optimization techniques. Analysis of one anomaly, the Chimney Hill gravity high, indicates it is due to a shallow intrusive body that transects the Jemez lineament. The intrusive controls the location of the Zuni volcanic field, one of the major volcanic fields of the Jemez lineament. The other anomaly is the Lucero gravity high, located on the western boundary of the Albuquerque-Belen basin of the Rio Grande rift. Analysis of this anomaly indicates that a recently emplaced very shallow intrusive body beneath the Lucero uplift was controlled by the rift bounding fault and elements of the northeast-trending shear system.

CHAPTER I

INTRODUCTION

Regional Geology

The Rio Grande rift is one of the major continental rifts of the world. It is a Cenozoic feature consisting of long, narrow, interconnected, elongate, en echelon tectonic rift valleys. It shares many features with other continental rift zones such as the East African rift, the Rhinegraben and the Baikal rift (Burke, 1978; Jiracek, et al., 1979a,b, 1980; Ramberg, 1978; Salveson, 1978). The Rio Grande rift extends northward from Chihuahua, Republic of Mexico through New Mexico up into central Colorado (Chapin, 1971; Tweto, 1979; Seager and Morgan, 1979) and separates the Great Plains on the east from the Colorado Plateau and Basin and Range on the west (Fig. 1). Traditionally the rift has been divided into three main segments (Chapin, 1979). The northern section, from Leadville to Alamosa, Colorado parallels the northwest-trending regional Precambrian structural grain, tapering northward and disappearing into a broad-block faulted zone that extends into Wyoming. The central section, from Alamosa, Colorado to Socorro, New Mexico consists of northerly-trending en echelon basins separated by transverse northeast-trending structural lineaments. The southern section, from Socorro, New Mexico to Chihuahua, Republic of Mexico, consists of a broader region of parallel north-trending basins grading into the Basin and Range Province to the south and southwest.

The evolution of the Rio Grande rift is fundamentally related to that of the Colorado Plateau (Chapin and Seager, 1975; Chapin,

Figure 1. Base location map showing the major geologic provinces for the southwestern United States (modified from Bridwell, 1976).

1971). Whatever the genesis of the Rio Grande rift, its tectonics and structure may have been influenced by a series of northeast-trending shear zones delineated by several structural lineaments (Fig. 2) (Chapin et al., 1978). These structural flaws seem to penetrate the lithosphere to great depths and may act as conduits for magma. Such conduits for magma develop more easily where the lineaments are intersected by other structures such as faults, other lineaments, or intrusive structures.

Although the lineaments substantially predate the rift, Chapin et al. (1978) have suggested that the lineaments appear to be presently acting as a system of transform faults in conjunction with the rift spreading center. Part of the apparent transform nature of these lineaments might be explained by a component of right shift motion along the rift. Right shift motion across the central portion of the rift has been suggested by Woodward (1977). It is not clear at this time that there is either right or left shift along the entire length of the rift. It may be that the lack of clear evidence is an indication of no net shift. Studies on block faulting along the lineaments indicate a left lateral shear (Chapin et al., 1978). The Jemez lineament is certainly the most pronounced of the lineaments, having "leaked" more magma than any of the other lineaments or the Rio Grande rift itself.

The northeast-trending lineament system transecting the Rio Grande rift (Fig. 2) is part of a larger system of major northeast-trending mineral belts that pervade the western United States (Fig. 3) (Landwehr, 1967). Landwehr (1967) has suggested that these belts have a common geologic history and structure. He suggests that

Figure 2. Generalized map of Rio Grande rift and major crustal lineaments (modified from Chapin et al., 1978).

Figure 3. Major belts of mineralization in western United States (modified from Landwehr, 1967).

their origin is due to a response to a common regional left-lateral shear stress occurring sometime in the early Precambrian. These shear zones have then acted as loci of repeated crustal adjustment in response to later regional stresses, not necessarily in the same direction as the original shear. He also suggested a genetic relationship between the formation of crustal magma reservoirs in which mineralized zones have formed, and crustal rupture associated with shearing.

Radiogenic age dating on Precambrian crystalline rocks throughout the southwestern United States show that the Jemez lineament is either a Precambrian crustal age boundary or is closely parallel to a Precambrian crustal age boundary (Van Schmus, in press, 1980) (Fig. 4). In either case, the crustal age boundary approximately parallels the northeast-trending Precambrian lineament system. The rocks to the northwest of the crustal age boundary range from 1.69 to 1.78 G.y., while the rocks to the southeast of the crustal boundary range from 1.61 to 1.68 G.y. This conclusion is based upon data collected mostly by Silver (Silver and Baker, 1967; Silver et al., 1977; Silver, 1978).

Regional Geophysics

Recent geophysical studies indicate that the Jemez lineament is associated with greater than normal heat flow (Edwards et al., 1978), with a low seismic velocity zone from 25 to 140 km depth inferred from teleseismic P-wave delay studies (Spence et al., 1979), and with anomalously high electrical conductivity at shallow depths inferred from a regional deep magnetotelluric (MT) sounding survey

Figure 4. Map of United States showing the major inferred basement chronologic regions (from Van Schmus, in press, 1980).

and a detailed magnetotelluric/audio magnetotelluric (MT/AMT) survey (Ander et al., 1980a,b; Ander, 1980). The high electrical conductivity is probably associated with partial melting in the mid- to upper-crust along the lineament. Some preliminary results of the regional MT survey along with the results of the detailed MT/AMT survey will be discussed.

Most of the known large-scale crustal structure in the Rio Grande rift and adjacent Great Plains and Colorado Plateau has been inferred from several seismic refraction profiles (Fig. 5). A north-south unreversed refraction profile in the Great Plains near the eastern border of New Mexico used the GNOME nuclear explosion near Carlsbad, New Mexico as the source. The results indicated a Pn velocity of 8.0 to 8.2 km/s and a crustal thickness of 50 km (Stewart and Pakiser, 1962). A reversed refraction profile between Hanksville, Utah and Chinle, Arizona gave a Pn velocity of 7.8 km/s and an inferred crustal thickness of 40 to 45 km for the Colorado Plateau (Roller, 1965). An unreversed north-south refraction profile, GASBUGGY, along the eastern boundary of the Colorado Plateau indicates a Pn velocity around 7.9 km/s and a crustal thickness of about 40 km (Toppozada and Sanford, 1976). An unreversed north-south refraction profile, DICE THROW, along the axis of the rift from central New Mexico to the New Mexico - Colorado border, gave a low Pn velocity of 7.6 km/s and a crustal thickness of 34 km (Olsen et al., 1979). Thus the data from these refraction profiles show that the rift zone is a region of substantial crustal thinning. Rayleigh wave dispersion studies throughout the region further substantiate the theory of crustal thinning beneath the rift (Keller et al., 1979)

Figure 5. Index map of seismic refraction studies in southwestern United States (modified from Keller et al., 1979).

(Fig. 5). A simplified east-west velocity structure model of the crust and upper mantle has been constructed from these seismic studies (Fig. 6).

Regional Bouguer gravity studies show that a broad north-south-trending gravity low coincides with the Rio Grande rift (Cordell, 1976, 1978). The Bouguer gravity low is similar to the negative Bouguer gravity anomaly over the East African rift (Girdler et al., 1969; Girdler, 1975). Girdler interpreted the East African rift anomaly to be caused by lithospheric thinning and intrusion of low density asthenospheric material into the more dense upper mantle. A similar interpretation for the Rio Grande rift anomaly has been given by Bridwell (1976) and Cordell (1976, 1978). Superimposed upon this gravity low is a sharp Bouguer gravity high centered on the rift (Cordell, 1976). The sharp gravity high has been interpreted as due either to crustal thinning accompanied by intrusion of higher density upper mantle material (mantle bulge) or possibly relatively dense material within the crust. The seismic velocity model given in figure 6 does not support either model.

Approach

In this paper two-dimensional gravity modeling of a 700-km-long gravity profile at 34°40'N latitude is used to study the crust and upper mantle beneath the Rio Grande rift. Several variable density models of three consecutive layers are produced using all available geologic and geophysical constraints. Layer I, from the surface to 20 km depth, represents the sedimentary stratigraphy and the upper crust. Layer II, from 20 to 50 km depth, represents the

Figure 6. P-wave velocity structure of the crust and upper mantle across the Rio Grande rift inferred from refraction seismic data.

lower crust and the Moho boundary. Layer III, from 50 to 200 km depth, represents the upper mantle. Several short wavelength anomalies along the profile are of substantial interest and are analyzed using linear optimization techniques. These anomalies are associated with layer I. One anomaly is the Chimney Hill gravity high (Ander et al., 1979; in preparation, 1980c). Analysis indicates that this anomaly is due to a shallow intrusive body that transects the Jemez lineament and controls the location of the volcanic vents that form the Zuni Volcanic field. Another anomaly is the Lucero gravity high (Ander and Huestis, 1978), located at the western boundary of the Albuquerque-Belen basin of the Rio Grande rift. Analysis of this anomaly indicates that a very shallow intrusive body has been recently emplaced and that the emplacement may have been controlled by the rift bounding fault as well as the northeast-trending shear system. In addition to the study of these short wavelength anomalies, a variable density Bouguer slab representing stratigraphic density variations was constructed along the entire length of the profile. It was used to produce a variable density Bouguer anomaly profile. The layer II study deals primarily with the geometry of the Moho boundary and the density contrast across the boundary along the profile. The layer III study deals entirely with the geometry of the asthenosphere/lithosphere boundary along the profile.

The magnetotelluric study of the Jemez lineament is discussed in Chapter II. Chapter III is devoted to an analysis of the appropriate densities to be used in the gravity modeling. Chapter III also discusses the possible lateral density contrasts within the crust. Chapter IV gives a detailed description of the simple Bouguer

gravity profile and discusses the possible sources for its short wavelength structure. Chapter V is a tutorial explanation of the basics of gravity ideal body theory and the application of linear programming to this theory. Ideal body theory using linear programming is the linear optimization technique that is applied to the Chimney Hill and Lucero gravity anomalies. This chapter is included because it is not yet a well-known technique. Only a very small number of papers exist in the literature dealing with this new analysis technique. Chapters VI and VII give the analysis of the Chimney Hill and Lucero anomalies, respectively. Chapter VIII is devoted to the study of two-dimensional models produced for layers I, II, and III.

CHAPTER II

MAGNETOTELLURIC STUDIES

As part of the resource evaluation and exploration program conducted by the Los Alamos Scientific Laboratory (LASL) for the Hot Dry Rock (HDR) Geothermal program, a regional MT survey of New Mexico, Arizona, and Colorado is being performed. The survey consists of over 200 sites along several long profiles with site spacings of 15 to 20 km (Fig. 7). The MT lines are being located in areas where the integrated results of analysis of other geophysical and geologic studies indicate the greatest potential for HDR resources (Aiken and Ander, in press, 1980) while also traversing tectonic province boundaries. The MT study is aimed at mapping the depth to a deep electrical conductor over a large region.

Much of the data in this study have already been collected and are in the analysis stage. With the exception of the first 56 sites collected, all the remaining sites are being collected using the remote reference MT noise reduction technique developed by Gamble et al. (1979a,b).

The locations of the profiles are as follows:

1. A south-north line with 17 sites from Yuma in southwest Arizona to Seligman, Arizona, concentrating on the Aquarius and Castle Dome HDR prospects and traversing the Colorado Plateau/Basin and Range Province boundary. The Castle Dome area coincides with a large amplitude gravity low and with a 70°C/km temperature gradient measured in the center (Shearer, 1979). Volcanic rocks, possibly suggesting a caldera not indicated on the published geologic maps,

Figure 7. Index map of Arizona, New Mexico, and southern Colorado showing locations of magnetotelluric profiles (modified from Ander, 1980).

occur in the same area (Gutman et al., 1980). The Aquarius area is associated with high heat flow, shallow Curie depth, a gravity low and appears to be associated with a shallow depth to the crustal electrical conductive zone (Aiken, 1976; West and Laughlin, 1979; Aiken and Ander, 1979; Aiken and Ander, in press, 1980).

2. There are 25 sites along a south-north profile in central Arizona from Tucson northward through Phoenix to Flagstaff, traversing the Colorado Plateau/Basin and Range boundary. The area around Tucson is inferred to have relatively high heat flow, greater than 2.5 heat flow units (HFU) (Shearer, 1979) ($1 \text{ HFU} = 41.8 \text{ mW/m}^2$). Chemical geothermometry measurements indicate heat flow greater than 2.5 HFU to the northeast of Phoenix. There are geothermal gradients greater than 36°C/km to the southeast of Phoenix (Swanberg et al., 1977; Hahman et al., 1978).

3. Twenty-five sites are along a south-north line starting in the Chiricahua Mountains in southeast Arizona passing through the thermally anomalous Safford-Clifton region (Swanberg et al., 1977; Hahman et al., 1978), through the Datil-Mogollon volcanics, over the Colorado plateau boundary, across the northeast-trending Jemez lineament at Springerville, and then to Sanders, Arizona. The Jemez lineament is interpreted to pass through Springerville, Mt. Taylor, and the Valles Caldera (Mayo, 1958).

4. An east-west line consisting of 10 sites runs from St. Johns, Arizona, in the Springerville area, to Magdalena, New Mexico, where it connects with a University of New Mexico MT study of the Rio Grande rift (Jiracek et al. 1979a,b; 1980). The Rio Grande rift study involves 33 sites located in the vicinity of the deep seismic

reflection lines measured by the Consortium for Continental Reflection Profiling (COCORP) (Brown et al., 1979) in the central Rio Grande rift.

5. The longest profile consists of 36 sites from Torreon, New Mexico, to Kingman, in western Arizona, traversing the Rio Grande rift, passing through Flagstaff, Arizona, and the Aquarius region. This profile passes through the Zuni HDR prospect (Laughlin and West, 1975) where a detailed MT/AMT survey has been completed by LASL. The survey consists of 119 AMT stations and 26 MT stations.

6. There are 15 sites along an east-west profile from Gallup, New Mexico to Albuquerque, New Mexico that passes over Mount Taylor.

7. There are 20 sites planned along an east-west line north of the New Mexico - Colorado border, again traversing the rift.

8. Five sites have been occupied in southeast Arizona connecting two nonproprietary MT surveys consisting of 40 sites occupied by Geotronics Corp. (1979), resulting in a station distribution that is a continuous east-west profile from El Paso, Texas to Tucson, Arizona along 32°N latitude.

9. A telluric-magnetotelluric survey has been carried out in the Jemez Mountains of northern New Mexico to characterize the geothermal system of the Valles Caldera. This study is being integrated with a regional northwest-southeast survey supported by the U. S. Geological Survey (U.S.G.S.) (Hermance, 1979; Hermance and Pedersen, 1980).

At present about three-fourths of the soundings have been recorded and processed. Analysis and interpretation of many of these

data are underway.¹ Preliminary results from the Zuni Mountains area of the Jemez lineament in New Mexico will be discussed.

Electromagnetic techniques can be used to map deep electrically-conductive structures. Lateral variations in the depth of the electrical conductor may imply variation in the depth of isotherms. Interpretations can be based on a correlation between worldwide heat flow and the depth to the deep electrically conductive layers of the crust and upper mantle, as demonstrated by Adam (1978).

Magnetotellurics have been used widely for determination of electrical conductivity in geothermal exploration, most recently by Hermance and Pedersen (1977), Stanley et al. (1977), Jiracek et al. (1977), Wannamaker (1978), and Morrison et al. (1979), and by several geophysical contractors. Deep crustal and upper mantle MT studies have been performed, for example, by Madden and Swift (1969), Rankin and Reddy (1973), Word et al., (1971), Mitchell and Landisman (1971a,b), and Jiracek et al. (1979b, 1980).

In general the electrical resistivity structure of the earth's crust and upper mantle can be divided into three regions: (1) a surface layer of low resistivity (usually less than 75 ohm-m) associated with sediments and ground water; (2) a high resistivity layer (usually over 1000 ohm-m) associated with low porosity crystalline basement containing very little water; and (3) a deep conductive layer. The deep conductive layer is generally assumed to be

¹The MT sounding curves and related response functions for the data collected by LASL have been open filed but not published. They are available at the National Security and Resource Study Center at LASL. An open filed publication containing all the data is planned for after the completion of the data collection early in 1981.

associated with the upper mantle and is believed to be due to partial melting or possibly temperature dependent semiconduction (Shankland and Waff, 1977). It has been shown (Lebedev and Khitarov, 1964) that the bulk resistivity of rocks can be reduced several orders of magnitude to approximately 10 ohm-m by adding a few percent partial melt. Many investigators, however, have found a conductive layer in the crust extending into the mantle rather than confined to within the mantle (Garland, 1975; Jiracek et al., 1979b; Ander et al., 1980b). Feldman (1976) has suggested that the crustal conductive zone is due to partial melting caused by a significant decrease of the melting temperature in the granitization process at the amphibolite-granulite facies boundary. It may be that the reduced melting temperature is due to the action of water released during dehydration accompanying granitization. If this is so, then the temperature at this boundary can be determined by knowing the granite melting curve and the depth to the boundary. Stanley et al. (1977) have considered four possible mechanisms to explain crustal conductive zones: (1) enhanced ionic mobility due to increased pore fluid and increased temperature, (2) semiconduction effects, (3) partial melting, and (4) thermal alteration. Recent measurements of electrical properties of granite indicate that the only dominant controlling factors of resistivity (assuming no partial melt) are the quantity and chemistry of free water and the temperature (Olhoeft, in press, 1980). Olhoeft suggests that hydrostatic and lithostatic pressure, structurally bound water, oxygen fugacity, and other parameters have only a minor effect upon the electrical resistivity. Determination of the temperature may therefore be complicated.

Porath (1971) also gives an alternative explanation for the presence of a crustal conductive zone that can be considered unrelated to composition or temperature at depth. Large electrical current systems established in major surface conductors will bias any nearby MT soundings. These electrical currents are channeled in the conductor in regions of major lateral conductivity contrast such as along the seacoast, in large sedimentary basins, and in deep continental rift valleys. MT soundings located near one of these major current systems may bias the apparent resistivity sounding curves to indicate an anomalously conductive zone and possibly lead to the interpretation of a deep crustal feature. These lateral effects are particularly enhanced if the MT sounding is located over a highly resistive surface. An in-depth modeling study of the effect that laterally displaced good conductors have on MT sounding curves is needed to refine our understanding of this type of bias. Care must be taken to anticipate the location of such current systems.

Porath's explanation can certainly explain some interpretations of the deep electrical conductor, but there are many MT observations showing a crustal conductive zone in areas well removed from suspected large electrical current systems. One example is obtained from the deep crustal MT survey described by Chaipayungpun and Landisman (1977), which was conducted in the high plains in eastern Colorado. Another example is obtained from the MT survey of Mitchell and Landisman (1971a,b) in West Texas.

The depth of any crustal conductor should be verified whenever possible with other geophysical and geologic data sets, such as gravity, magnetics, heat flow, seismics, and regional geology. The

results of all these techniques may be correlated with crustal isotherms, which in turn may be related to the depth of the deep conductor. Crustal heat production calculations show that 60% of the surface heat flow is produced in the crust (Pollack and Chapman, 1977a,b). Lateral increases in heat production in the crust cause lateral increases in temperature and surface heat flow. Consequently lateral variations in depth of the deep conductive zone should correlate with variations in surface heat flow regardless of whether the conductor is within the crust or upper mantle.

Adam (1978) compared the variation of heat flow with the depth to the deep conductor from data sets from around the world listed in Adam (1976). He defined conductive layers at three different depths in the crust and mantle and gave a relationship between their depths and the regional surface heat flow. The first conducting layer is the crustal conductor. The top of the second conducting layer is in the upper mantle and has a maximum lower bound of 200 km. The top of the third conducting layer is also in the upper mantle and has a minimum upper bound of 100 km and a maximum lower bound of 600 km. He gave an exponential formula for the relation between the depth to the crustal conductor and the surface heat flow (Fig. 8). If the interpreted crustal conductors are entirely an artifact of lateral conductivity contrasts then a relationship would not exist between the depth to the crustal conductor and surface heat flow.

Both the Rio Grande rift and the Jemez lineament have greater than normal heat flow (Fig. 9). The rift exhibits heat flow consistently above 2.5 HFU while the Jemez lineament has heat flow ranging

Figure 8. Empirical relation between the depth to crustal conductive zone and heat flow (modified from Adam, 1978).

from 1.5 to 2.5 HFU, with a few measurements above 2.5 HFU. One area of particularly high heat flow is the region to the west of Grants and south of Gallup, New Mexico. The highest value measured in this region is 3.0 HFU and is located south of the town of Zuni on the Zuni Indian reservation.

As a part of LASL's resource evaluation for HDR, both a regional deep MT sounding survey and a 161 km² detailed MT/AMT survey were planned for the region (Fig. 10). The data collection for the regional survey was contracted to Williston McNeal and Associates and Argonaut Enterprises. The data collection for the detailed survey was contracted to Woodward-Clyde Consultants. The detailed survey was located in the area of highest heat flow and has been completed. The main objectives of the detailed study were to perform a detailed electrical evaluation of a possible HDR prospect to determine if a deep-seated body of high-temperature basement rock is present and to

Figure 9. Heat flow map of northern New Mexico and southern Colorado (modified from Edwards et al., 1978).

Figure 10. Map of western New Mexico showing Cenozoic volcanism, Rio Grande rift and location of Los Alamos Scientific Laboratory magnetotelluric sites.

evaluate the MT/AMT method for exploring HDR prospects. The objectives of the regional survey were to investigate the geometry of the pervasive deep electrical conductor in this region and to place the results of the detailed site into a regional context. The recently developed remote reference MT noise reduction technique developed by Gamble (1979a,b) has been used on the data at all stations for which results will be presented here.

In using the remote reference technique, data are simultaneously collected with two independent five-component systems. The two orthogonal electric components are sensed with an L-shaped array of three nonpolarizing porous pots, using copper-copper sulfate electrodes usually with a 150 m spacing or greater between the pots. The three mutually orthogonal magnetic components are sensed using a three-component cryogenic superconducting quantum interference device (SQUID) magnetometer. SQUIDS are preferred over conventional coil magnetometers because of the high signal-to-noise ratios and because of the flat response from dc to some high frequency value, usually chosen to be between 10 and 100 Hz. The magnetometer is partly buried to reduce wind noise and often is covered with a carefully-shaped aluminum can. The aluminum can reduces wind noise and also acts as a single pole, -6dB/octave filter, with a -3dB point around 50 Hz. Usually the data collected at remote stations and base stations are synchronized by clocks or by radio station WWVB. The Woodward Clyde system uses real time data processing and thus FM telemeters the data from the remote system back to the base. The Argonaut system uses WWVB. The Williston McNeal system did not use the remote reference technique. Only the data collected by Argonaut

Enterprises and Woodward-Clyde Consultants will be discussed. The MT data were processed using standard stochastic processing techniques. Bendat and Piersol (1971) describe the data processing techniques used, and Vozoff (1972) describes most of the important earth response functions determined in MT data processing.

A portion of the interpretation of the northern profile is shown in figure 11. The estimate of the depth to deep electrical conductor based on one-dimensional inversion is shown for both the strike and perpendicular to strike MT components. The one-dimensional inversions for the regional MT data were done using the algorithm developed by W. L. Anderson (1979). This algorithm uses a Marquart nonlinear least squares inversion technique. The Jemez lineament passes through station 41. Note that the conductive zone comes very close to the surface beneath the lineament. A portion of the central profile is shown in figure 12. The Jemez lineament passes through station 32. Again the conductive zone shallows beneath the lineament. It also shallows between stations 31 to 43, where heat flow is 3.0 HFU or greater.

A portion of the southern profile is shown in figure 13. The Jemez lineament passes through station 46. The depth to the conductive zone estimated from the component parallel to strike also shallows beneath the lineament. These results, though preliminary and based solely on one-dimensional inversion, indicate that the Jemez lineament is associated with anomalously high electrical conductivity at shallow depths. Note that the conductive zone may be relatively shallow between stations 46 and 53, suggesting the possibility of high surface heat flow. Measured heat flow in these areas ranges

Figure 11. Portion of northern magnetotelluric profile indicating the estimates of depth to deep electrical conductor for both polarizations based on one-dimensional analysis, showing inferred 50 ohm-meter contour interval. The Jemez lineament passes through station 41.

Figure 12. Portion of central magnetotelluric profile indicating the estimates of depth to deep electrical conductor for both polarizations based on one-dimensional analysis, showing inferred 50 ohm-meter contour interval. The Jemez lineament passes through station 32.

Figure 13. Portion of southern magnetotelluric profile indicating the estimate of depth to deep electrical conductor for both polarizations based on one-dimensional analysis, showing inferred 50 ohm-meter contour interval. The Jemez lineament passes through station 46.

from 1.5 to 2.0 HFU, which is lower than expected based on the depth to the crustal electrical conductor. This apparent discrepancy may be explained in several ways. First, the assumption of low porosity crystalline basement rock containing little water may be in error. Substantial water at depths greater than 10 km, when combined with elevated temperatures, may produce a shallow crustal conductor. Second, electrical current channeling in a good conductor displaced laterally from the MT sites, if not accounted for, may bias the MT sounding curves toward more conductive at depth, possibly leading to the interpretation of a shallow conductive zone. Third, near-surface ground water movement, if unaccounted for, may bias the heat flow measurements downward, masking the true higher heat flow. Fourth, if both data sets are substantially correct, then the discrepancy may be due to recently intruded magma or recently developed partial melt in the mid crust. If the mid-crustal melt had developed recently enough, then it would not be sensed by the heat flow technique but would be sensed by the MT technique.

This profile obliquely crosses the Plains of San Augustin. The San Augustin basin apparently has undergone left-lateral movement (Chapin, 1971) and parallels the northeast-trending Precambrian structural lineament system, suggesting that the lineament system may have controlled the development of the basin. Elston (1970) and Elston et al. (1970) suggest that the San Augustin basin is a bifurcation of the Rio Grande rift. If this is the case, the existence of a recently developed magma chamber similar to the one recently discovered in the Albuquerque-Belen basin (Sanford et al., 1977) could reasonably account for the discrepancy in the two data sets. Further

detailed analysis of the MT data, coupled with theoretical modeling of the effect of possible major conductive current channeling systems such as the Rio Grande rift along with a critical analysis of the heat flow data may aid in explaining this apparent discrepancy.

Although these three estimates of the depth to deep electrical conductor are based only on one-dimensional inversion and as such represent a preliminary interpretation, it is still apparent that the Jemez lineament is associated with an anomalously shallow electrical conductor, most probably associated with magma. The completed detailed MT/AMT survey helps to confirm these conclusions. To obtain a more complete picture, considerably more analysis, modeling, and interpretation are needed along with a synthesis of this data set with the MT data collected by Jiracek et al. (1979a,b).

The detailed survey consisted of 119 scalar AMT stations and 26 tensor MT stations (Fig. 14). The AMT sites were spaced 1.6 km apart in a grid pattern. In scalar AMT the ratio of the horizontal electric(E)-field component to the horizontal magnetic(H)-field component normal to it is computed. The electric field sensor is composed of two 50-m cables grounded at either end. The magnetic field sensor is a ferrite-cored coil with a response that is linear with frequency from less than 10 Hz to 40 KHz. Notch filters are used to reduce effects of "cultural noise" from 60 and 120 Hz power lines and higher harmonics. The apparent resistivities were determined from the E to H ratios measured at 10 different frequencies varying logarithmically from 12 Hz to 10.2 KHz. The purpose of the AMT was to search for any near-surface electrical structures or lateral contacts. None were found, although terrain effects near the edges

Figure 14. Location map of magnetotelluric/audio magnetotelluric detailed survey for Zuni hot dry rock prospect (modified from Hackman and Olson, 1977).

of mesas were observed. The detailed MT survey consisted of 6 soundings to 2000 s, 12 soundings to 1000 s, and 8 soundings to 500 s in period. The MT stations were spaced 3.2 km apart on a grid overlying the AMT grid. Stations 19 and 33 were chosen as reference sites and were occupied by each contractor. A deep well located at Sec. 5, T9N, R18W in the northern portion of the study area was used for stratigraphic control to basement.

Figure 15 shows the apparent resistivity sounding curves taken at station 33 by Woodward-Clyde Consultants. The component of apparent resistivity parallel to electrical strike is the lower sounding curve and the component of apparent resistivity perpendicular to electrical strike is the upper sounding curve. These sounding curves are typical of all 26 of the MT sounding curves. The MT curves show the same trend as the AMT results from 0.01 to 0.1 s period. Above about 1.0 s all the curves show a distinct rise in the apparent resistivity by 50 to 100 ohm-meters followed by a decrease in apparent resistivity at the long period end of the spectrum. The quality and consistancy of the data and results are exceptionally good. Using real time data processing in the field to analyze data quality while on the site, it is possible to substantially reduce the random errors, especially in the mid-band from 1 to 10 s where the signal strength is notoriously low in the MT spectrum. Woodward-Clyde's estimates were obtained by averaging over a sufficiently large data base to acquire the desired data quality. This is a distinct advantage of real time data processing. The curve fit is a least squares polynomial that may vary from third to eighth order, depending on the lowest order which passes through at least 80% of

Figure 15. Apparent resistivity sounding curve taken at station 33, Zuni hot dry rock prospect, by Woodward-Clyde Consultants. The lower sounding curve is the apparent resistivity parallel to electrical strike.

the error bars. Note that some fine structure in the spectrum has been missed by the polynomial curves.

Figure 16 shows the apparent resistivity sounding curve taken at the same station by Argonaut Enterprises. Although this sounding is noisier than the previous sounding, due to a smaller statistical base, the two soundings are almost identical. This would typically be considered a good MT sounding. The mid-band from 1 to 10 s is generally noisy due to low signal strength. The long period data are generally noisy because of insufficient recording time in the long period band. Note that much of the fine structure seen on the previous sounding also shows up in this sounding. This suggests that much of the fine structure in good quality MT soundings may be real and not just due to statistical scatter.

There are numerous other earth response functions normally calculated in an MT survey (Vozoff, 1972), which, when taken together confirm the presence of a relatively flat-lying, layered two-dimensional electrical subsurface. One of the calculated earth response functions is the electrical tipper strike direction (Fig. 17).

The electrical strike direction in the detailed area is generally undefined at very short periods, but from about 1 to 100 s the electrical strike aligns with the dominant surface structures with a mean of about N30°W along the gentle anticlines and synclines. This is also the direction of the deep canyon that cuts through the mesa terrain to the southeast. At longer periods, above 100 s, the strike rotates about 90° to a distinct and consistent N60°E. This rotation is often abrupt and almost certainly represents a different trend within the metamorphic Precambrian basement. The Jemez lineament is

Figure 16. Apparent resistivity sounding curve taken at station 33, Zuni hot dry rock prospect, by Argonaut Enterprises. The lower sounding curve is the apparent resistivity parallel to electrical strike.

Figure 17. Estimate of electrical strike directions for the short period and the long period portions of the magnetotelluric spectrum at Zuni hot dry rock prospect (structural geology modified from Hackman and Olson, 1977).

located just to the southeast of the Zuni prospect and strikes approximately N55°E. This strongly suggests a relationship between the deep structure beneath the Zuni prospect and the Jemez lineament. One-dimensional inversion was performed on each pair of sounding curves at each station using the algorithm developed by Petrick et al. (1977). This algorithm utilizes a ridge-regression least squares routine.

Eight stations were chosen for two-dimensional modeling along a line perpendicular to the deep electrical strike (Fig. 18). The MT sounding curves are given in Appendix A. The one-dimensional inversions were used as starting models for two-dimensional modeling. These sites were also chosen because their deep strike directions were closest to the estimated mean strike. The MT sounding curves and associated one-dimensional inversions for these eight stations are given in Appendix A2. The patched together one-dimensional inversions for the profile are shown in figure 19.

Three consecutive runs of the two-dimensional inverse code, developed by Jupp and Vozoff (1977) were made. The 28 block two-dimensional starting model derived from the one-dimensional inversions is shown in figure 20. Both the transverse electrical and transverse magnetic components were used to model the apparent resistivity amplitude and phase at eight frequencies: 13.16, 6.711, 1.218, 0.406, 0.1096, 0.0282, 0.0101, and 0.0034 Hz. The modeling results are shown in figure 21. The maximum error for the electric field polarization perpendicular to strike was 1.1 ohm-meters amplitude at station 91 at 0.0034 Hz and 14.9° phase at station 89 at 0.1096 Hz. The root mean square (r.m.s.) error for this polarization

Figure 18. Station location map of magnetotelluric sites used to produce a two-dimensional model across the Zuni hot dry rock prospect (topography modified from Hackman and Olson, 1977).

Figure 19. Patched together one-dimensional inversions along profile perpendicular to electrical strike across the Zuni hot dry rock prospect.

Figure 20. Simplified 28 block two-dimensional starting model derived from patched together one-dimensional inversions for profile across the Zuni hot dry rock prospect.

Figure 21. Two-dimensional electrical model based on detailed Zuni prospect magnetotelluric survey.

was 0.45 ohm-meters amplitude and 4.99° phase. The maximum error for the magnetic field polarization perpendicular to strike was 0.75 ohm-meters amplitude at station 57 at 0.0282 Hz and 5.47° phase at station 89 at 0.1096 Hz. The r.m.s. error for this polarization was 0.31 ohm-meters amplitude and 5.47° phase. Consequently the model gives an excellent fit to the apparent resistivity sounding curves. The top 800 m is very conductive, overlying resistive electrical basement. The depth to Precambrian basement in the reference well is 767 m. From 800 m to 15 km the rocks are resistive. Below 15 km the rocks become much more conductive. The deep conductive zone grades from less conductive to the northwest to more conductive to the southeast in the direction of the Jemez lineament.

CHAPTER III

ROCK TYPES, DENSITIES, AND LATERAL DENSITY VARIATIONS

For purposes of gravity modeling, the rocks in layer I, surface to 20 km depth, are subdivided into four main units and assigned bulk densities. The Cenozoic sediments are assigned a density of 2.2 g/cm^3 ; the Cretaceous and Jurassic units are assigned a density of 2.4 g/cm^3 ; the Triassic units down to crystalline basement are assigned a density of 2.57 g/cm^3 ; and crystalline basement down to the Conrad discontinuity at 20 km depth is assigned a density of 2.67 g/cm^3 . These densities are similar to those chosen by other workers in the rift (Ramberg et al., 1978; Cordell, 1976; Decker et al., 1975; Joesting et al., 1961; Mattick, 1967; Sandford, 1968; Birch, University of New Mexico, personal communications, 1979; Birch, 1980). The "standard" density for granite of 2.67 g/cm^3 for upper crustal crystalline rocks may be somewhat low; 2.70 or 2.71 g/cm^3 is probably a better estimate. This is because the regional upper crustal rock types in New Mexico consist of medium-grade metamorphic rocks including: quartzite, quartz-mica schist, greenstone, and lesser amounts of gneiss and metarhyolite. The plutonic igneous rocks are intruded into the regional metamorphic country rock. They include mainly granite, local gabbro and diorite and some dike rocks.

Unfortunately there have been few systematic studies of the densities of metamorphic rocks in the United States and none at all in New Mexico. The densities of upper crustal metamorphic rocks may vary as much as from 2.6 to 2.8 g/cm^3 (Smithson and Decker, 1973). Densities of major upper crustal intrusive igneous rocks can be as

high as 3.0 g/cm^3 for gabbro (Clark, 1966). Ultramafic dike rocks can have even higher densities.

Since the actual gravity analyses described here were performed, Lee Russell at Shell Oil Co. has provided his estimates of density for Rio Grande rift sediments. His estimates are based on compensated formation density logs taken in two oil exploration wells in the Albuquerque-Belen basin. One well, Shell Laguna No. 1 is located on the basin flank. The other well, Shell Isleta No. 1, is located in the deep basin. Russell's results are

	<u>Basin Flank</u>	<u>Deep Basin</u>
Tertiary	2.2 g/cm^3	2.4 g/cm^3
Mesozoic	2.35 g/cm^3	2.45 g/cm^3
Paleozoic	2.65 g/cm^3	2.7 g/cm^3
Precambrian	2.7 g/cm^3	2.7 g/cm^3 .

Shell's density estimates are close to those used in this paper except for the Paleozoic rocks, which are higher. Clearly this data suggests that the sedimentary material within the deep basin is more dense than sedimentary material on the flanks of the basin. Knowledge of such lateral density contrasts is extremely important when applying gravity analyses to fault structural analyses within and on the flanks of deep basins. Cordell (1979) has suggested a different model based on gravity analysis, in which the density of rift fill is greater on the flanks than in the center of the rift.

There are only a few places along or near the profile where crystalline basement rocks are exposed. Precambrian is exposed along the profile only in New Mexico in the Lucero uplift, the Manzano Mountains, and the Pedernal uplift. The crystalline rocks in the

Manzano Mountains consist mainly of metasedimentary rocks including: quartzite, gneiss, some schist, and some coarse-grained intrusive granite (Machette, 1978). In the Pedernal uplift, exposed Precambrian consists predominately of granite gneiss with some schist, quartzite, greenstone, and metagranite (Kelley, 1972). In the next section it will be shown that the rocks of the Pedernal uplift are substantially more dense than the surrounding country rock. There is a very small sliver of Precambrian granite gneiss exposed in the Lucero uplift. There is also a small sliver of gabbroic intrusive rock exposed between the Able Hill fault and the Comanche fault along the western margin of the rift, in the Lucero uplift (Machette, 1978). Ander and Huestis (1978), using gravity analysis, have shown that the upper crustal intrusive rocks beneath the Lucero uplift are considerably denser than the surrounding crystalline country rock. Gravity analysis on the Lucero anomaly will be presented below. Further, along the western half of the profile, Ander et al. (1979, in preparation 1980c) have shown that an intrusive of high density relative to the surrounding country rock exists beneath the Zuni volcanic field. Thus it is clear that there are major lateral heterogeneities in the upper crust along the profile.

The seismic V_p data (Fig. 6) suggest broad regional lateral variations in both crustal and upper mantle rock densities. The data also indicate the presence of a Conrad discontinuity at about 20 km depth. The P-wave velocity and the density for any particular rock are in direct proportion (Birch, 1961). The P-wave velocity structure of the crust shows that the densities for both the upper and the lower crust are anomalously low beneath the rift. This suggests that

the upper crust may have a density on the order of 2.60 g/cm^3 just beneath the rift.

The densities of the lower crust and upper mantle (layers II and III) are less well constrained than those of the upper crust (layer I). For this study, the lower crust was modeled using two different densities for comparison, 2.80 g/cm^3 and 2.94 g/cm^3 . The upper mantle was assigned a density of 3.35 g/cm^3 . Some researchers have used a density of 2.8 g/cm^3 for the lower crust, (Keller et al., 1979; Bridwell, 1976) while others (Thompson and Zobach, 1978) used 2.94 g/cm^3 . There have been very few direct observations on lower crustal rocks obtained for the region of interest. McGetchin and Silver (1972) studied xenoliths from the 30-m.y. old Moses dike rocks in the Four Corners region of the Colorado Plateau. Their studies suggest a lower crust consisting of mafic granulite gneiss, mafic amphibolite, chlorite schist, and serpentine schist. Their studies also indicate an upper mantle composed mainly of hydrated spinel hercynite and about 25% eclogite. They conclude that the lower crust beneath the Colorado Plateau in the Four Corners region has a more mafic composition than the lower crust beneath the continental shield or elsewhere in the western United States. Also, their work suggests that the upper mantle is slightly more silicic in this area than in other areas where xenolith studies have been performed. This suggests that the lower crust beneath the Colorado Plateau may be somewhat denser than the lower crust beneath the Great Plains and that the upper mantle beneath the Colorado Plateau may be somewhat less dense than the upper mantle beneath the Great Plains. McGetchin and Silver conclude that the density of the lower crust beneath the

Colorado Plateau ranges from 2.8 g/cm^3 just below the Conrad discontinuity to 2.93 g/cm^3 at the base of the crust and that the upper mantle density just below the Moho is 3.24 g/cm^3 increasing to 3.4 g/cm^3 at a depth of 80 km.

Another line of evidence to suggest that a density contrast exists between the crust of the Colorado Plateau and the crust of the Great Plains comes from age dates on the crystalline rocks. As mentioned in the introduction, the Jemez lineament appears to be a Precambrian crustal age boundary with the older rocks to the northwest (Fig. 4). Although there is no known systematic age versus density relationship for metamorphic rocks as there is for sedimentary rocks, one might expect to see a density contrast across a major crustal boundary such as the Jemez lineament.

Padovani and Carter (1977) studied xenoliths from the Kilbourne Hole area of the southern Rio Grande rift. They concluded that the lower crust in this region consists of dry granulites and is rich in felsic minerals. Padovani [Massachusetts Institute of Technology, (MIT) personal communications, 1980] has recently determined a density range of 2.9 to 3.1 g/cm^3 for the granulites at the base of the crust.

Warren et al. (1979) studied inclusions in the Fra Cristobal basalts from the Engle basin of the Rio Grande rift near Truth or Consequences, New Mexico. Four general types of inclusions were found: megacrysts, lherzolites, pyroxenites, and granulites. Warren et al. (1979) determined density estimates from modes and mineral compositions, giving the base of the lower crust a density of about 3.0 g/cm^3 and the top of the upper mantle a density of about 3.3

g/cm³. Warren (Los Alamos Scientific Laboratory, personal written communications, 1980) explained how these estimated densities were arrived at in a table reflecting "typical" assemblages (Table 1). The density values were taken from the literature.

The densities of the lower crust given by Padovani (MIT, personal communication, 1980) and Warren et al. (1979) for locations southeast of the Jemez lineament are slightly lower than that reported by McGetchin and Silver (1972) for a location northwest of the lineament. Thus there is an apparent discrepancy between this observation and the suggestion made by McGetchin and Silver (1972), that the lower crust beneath the Colorado Plateau is slightly more silicic, and consequently less dense, than the lower crust beneath the continental shield or elsewhere in the western United States. The discrepancy is unresolvable at this time. There are at least two

TABLE 1

DENSITY ESTIMATES FOR THE INCLUSIONS IN THE FRA CRISTOBAL BASALTS
OF THE ENGLE BASIN BASED ON TYPICAL ASSEMBLAGES
Density (g/cm³) [% Mineral Phase]

	<u>Lherzolite</u>	<u>Megacrysts</u>	<u>Granulites</u>
Olivine	3.30 [70%]	3.35 [25%]	-
Clinopyroxene	3.30 [10%]	3.35 [50%]	3.40 [20%]
Orthopyroxene	3.30 [20%]	-	3.40 [20%]
Plagioclase	-	2.6 [25%]	2.70 [60%]
Average density	3.30	3.16	2.98
Probable depth (km)	>35	28-35	<28

possible explanations for the discrepancy. First, it is very difficult to get a precise and accurate estimate of in situ bulk densities from rock samples removed from their original environment. Second, the number of estimated densities for lower crustal rocks based on xenoliths or basalt inclusions is extremely small: three to be exact. The extremely small data base causes a large random error in the bulk density estimate for any one crustal region and allows for a high probability for bias in that estimate. For this reason and because xenoliths and inclusions are hand samples of the actual crustal rocks of interest, it is clear that many more xenoliths and inclusions need to be studied. A larger data base will reduce the errors in the density estimates as well as other physical estimates obtained from xenoliths and thus give tighter constraints on geophysical modeling.

Birch (1961) has shown that a systematic relationship exists between rock density, ρ , and elastic properties for materials with constant mean atomic weight, $\bar{m}$, or for isostructural compounds. Several investigators have attempted to generalize this relationship (Anderson and Nafe, 1965; Anderson, 1967b; Shankland, 1972; Shankland and Chung, 1974). Birch's law is given by

$$V_p = a(\bar{m}) + b\rho + c,$$

where a , b , and c are empirical constants. The values assigned to these constants found in the literature range from -0.70 to -0.79 for a , 2.76 to 3.35 for b , and 12.59 to 14.04 for c . The difference in

values of these constants is due to the choice of empirical data sets used to derive the constants.

Applying Birch's law and assuming a relatively constant mean atomic weight, the densities given by the xenolith and inclusion studies for the lower crust and upper mantle are inconsistent with the seismic velocity model (Fig. 6). A comparison of the P-wave velocities for the lower crust and upper mantle from the reversed Roller data and the unreversed Dice Throw data suggest a decrease in densities beneath the rift relative to those beneath the Colorado Plateau. Yet Warren et al. (1979) and McGetchin and Silver (1972) give similar densities for the base of the crust and the top of the mantle for both the Colorado Plateau and the Rio Grande rift. It is known that seismic refraction profiling determines the compressional velocity only at the top of each layer and an unreversed profile cannot determine a dipping interface; if the interface dips the apparent velocity down dip is less than the true velocity (Telford et al., 1976; Dobrin, 1976). Dice Throw was shot from south to north. This information, combined with the seismic velocity model and density data, suggests a northward dip to the Moho. The dip angle, α , may be calculated from the formula

$$\alpha = \sin^{-1} \left(\frac{V_0}{V_{ad}} \right) - \sin^{-1} \left(\frac{V_0}{V_1} \right),$$

where V_{ad} is the apparent velocity down dip, V_0 is the true velocity above the interface, and V_1 is the true velocity below the interface. If 6.8 km/s is taken as V_0 , 7.8 km/s is taken as V_1 , and 7.6 km/s is taken for V_{ad} , then the dip to the Moho is calculated to be 2.8°. A

2° northward dip to the Moho has been suggested by others (Topozada and Sanford, 1976; Olsen et al., 1979). The low P-wave velocity for the lower crust (6.4 km/s for DICE THROW and 6.5 km/s for GASBUGGY as compared to 6.72 km/s for GNOME and 6.8 km/s for ROLLER) may be due to a decrease in density just below the 20 km discontinuity under the rift, relative to the Colorado Plateau. Alternatively, the low velocity may also be due to a northward dip of the 20 km discontinuity beneath the rift. The second alternative seems somewhat more reasonable because geophysical measurements indicate the existence of a thin, recently emplaced magma body at 18 to 22 km depth with a northward dip beneath the southern Albuquerque-Belen basin of the Rio Grande rift (Sanford et al., 1977).

A density of 3.22 g/cm^3 was assigned to the low density asthenospheric mantle material. This density is similar to those given by other researchers (Girdler et al., 1969; Girdler, 1975; Bridwell, 1976; Thompson and Zobach, 1978; Decker and Smithson, 1975). This asthenosphere density value is based upon a crust/mantle model for the Basin and Range derived from seismic data by D. L. Anderson (1967a). The extrapolation of this asthenosphere density beneath the Basin and Range to a rift environment asthenosphere is necessary due to a lack of asthenosphere data beneath rifts.

Lateral density variations in the stratigraphy, as seen for instance in the Shell Oil Company density data from the Rio Grande rift, will have an effect only on the short wavelength, low amplitude portion of the Bouguer gravity spectrum. Lateral density variations in the upper crust are well documented. Such variations will have an effect on the somewhat longer wavelengths, higher amplitude portion

of the Bouguer gravity spectrum. These variations are often marked by very steep gradients, as seen in the Chimney Hill and Lucero studies and in the Pedernal uplift. These stratigraphic and upper crustal variations have very little effect on the very long wavelength high amplitude portion of the spectrum. A local scale residual density anomaly within the lower crust will usually have a subdued effect upon the short wavelength portion of the spectrum, due to upward continuation. These lower crustal anomalies are similar to the lateral density variations documented in the upper crust. A regional lateral density variation may have a major effect on the long wavelength, high amplitude portion of the spectrum caused by the Moho geometry and possibly shallow lithosphere/asthenosphere boundaries. The crustal boundary suggested by Van Schmus (in press, 1980) could have such a regional lateral density contrast associated with it. Perhaps the Rio Grande rift, which some believe represents a Paleozoic suture (Eaton, 1979), may also be a major crustal boundary, associated with a density contrast.

A summary of the densities used for the gravity modeling (Chapter VIII) is given in Table 2.

TABLE 2
DENSITIES USED IN THE GRAVITY MODELING

<u>Rocks</u>	<u>Density (g/cm³)</u>
Cenozoic units	2.2
Cretaceous to Jurassic units	2.4
Triassic units to crystalline basement	2.57
Crystalline basement to Conrad discontinuity	2.67
Lower crust: just below Conrad discontinuity	2.8
Lower crust: just above Moho	2.94
Upper mantle: lithosphere	3.35
Upper mantle: asthenosphere	3.22

CHAPTER IV

SIMPLE BOUGUER GRAVITY PROFILE AT 34°40'N LATITUDE

Both pre-existing and new gravity data were used in the study. The pre-existing gravity data were taken from the United States Defense Mapping Agency Gravity Library; 45 points were used. The new data were collected during the summer of 1978 using the University of New Mexico Wordon gravity meter and during the fall of 1979 using the Los Alamos Scientific Laboratory LaCoste gravity meter; 24 additional points were collected. Thus the gravity profile at 34°40'N consists of 69 points (Appendix C, Table C1.).

The simple Bouguer gravity anomaly profile is given in figure 22. The Bouguer anomaly profile contains a broad regional low, centered at about $X = 180$ km. The distance X is measured from the west end of the profile at 0 km to the east end at 700 km. Along the profile there are several shorter wavelength anomalies of interest. Just east of the New Mexico - Arizona state line at $X = 145$ km is a shorter wavelength positive anomaly. This is the Chimney Hill gravity anomaly (Ander et al., 1979, in preparation 1980c), located approximately where the Jemez lineament crosses the profile. A linear optimization study has been performed on the gravity anomaly and is described in Chapter VI. The study suggests that the anomalous body is an upper crustal mafic intrusive with an upper contact no deeper than 5 km.

Between $X = 180$ km and 260 km there is a sharp positive (measured west to east) gradient in the Bouguer gravity. The anomaly peaks at the Lucero uplift just to the west of the Albuquerque-Belen

Figure 22. Simple Bouguer anomaly profile at 34°40'N latitude. Dots show gravity station locations of data points along profile.

basin, then falls off sharply in the basin. A detailed gravity study of the Lucero anomaly using linear optimization techniques has been performed (Ander and Huestis, 1978) as part of a larger gravity study of the southern Albuquerque-Belen basin. This study is described in Chapter VII. The sharp positive gradient was decomposed into two components: the regional component, having a steep gradient, and a residual component. The regional component consists of a sharp positive gradient from $X = 180$ to 250 km and a decreasing gradient from 250 to 290 km. This regional component extends north and south along the rift at least the length of the Albuquerque-Belen basin (Fig. 23). The western positive gradient can be traced much the length of the rift (Figs. 23 and 24) and is interpreted to be due to crustal thinning beneath the rift and associated intrusion of high density mantle material (see Chapter VIII, layer II, 20 to 50 km depth). The residual component is interpreted to be caused by a large mafic intrusive body emplaced along the western margin of the rift beneath the Lucero uplift (Ander and Huestis, 1978).

There is a trough in the simple Bouguer anomaly over the Manzano Mountains where a peak would appear if the data points No. 34, 35, and 36 had been terrain corrected. Just to the east at $X = 343$ km, there is another trough in the Bouguer anomaly. This trough runs north-south and is just east of the Manzano Mountains (Fig. 23). It is evident from the surface geology and stratigraphy in nearby wells, wells No. 5 and 6 in Table 3, that this gravity low can only be explained by density contrasts within the Precambrian crust.

There is another short wavelength positive Bouguer anomaly located between $X = 380$ km and Vaughn, New Mexico at $X = 440$ km. The

Figure 23. Gravity map from 34°00' to 36°30'N latitude and from 105°30' to 108°00'W longitude (modified from Cordell et al., 1978).

RIO GRANDE RIFT

CONTOUR INTERVAL 20 mgals

Figure 24. Simple Bouguer gravity map of New Mexico and Colorado (modified from Wollard and Joestings, 1964).

residual anomaly over the background regional is 25 mgals. From $X = 390$ to 401 km there is Precambrian crystalline rock exposed at the surface. These crystalline rocks form the Pedernal uplift. The crystalline rocks were exposed by a combination of late Pennsylvanian and early Permian uplift, and late Tertiary regional uplift (Darton, 1928a,b; Kelley, 1972). The exposed rocks of the Pedernal uplift consist predominately of granitic gneiss with some schist, quartzite, greenstone, and granite (Kelley, 1972). The surface expression of the modern Pedernal uplift extends from just south of the gravity profile at $34^{\circ}36'$ to the southern end of the Rockies just east of Santa Fe, New Mexico. It has been suggested by Kelley (1972) that the modern western flank of the Pedernal uplift is steep. Steep gravity gradients apparently associated with the western flank of the Pedernal uplift substantiate this. The 25 mgal positive anomaly probably is related to the Pedernal uplift. Based on the Pedernal gravity anomaly, the eastern boundary of the uplift is also steep and is at Vaughn, New Mexico rather than at the eastern extent of the exposed Precambrian. The distance from the westernmost exposure of Precambrian crystalline rock to Vaughn is 45 km. The average thickness of the sedimentary column in this region, taken from well data, is 1.7 km. Two-dimensional gravity modeling (Talwani et al., 1959) of a surface block 45 km wide and 1.7 km thick with a density contrast of 0.2 g/cm^3 will produce a maximum anomaly of 13.1 mgals. Even if a high density contrast of 0.3 g/cm^3 is used, the maximum anomaly is still only 19.7 mgals, which is still less than the observed 25 mgal gravity anomaly. Either the density of the Precambrian basement in this area must be considerably greater than that of

the surrounding basement or the exposed Precambrian basement must be underlain by a more dense intrusive. Further studies on the Pedernal gravity anomaly, in particular linear optimization studies similar to those performed on the Chimney Hill gravity high and the Lucero gravity anomaly, may yield bounds on the density contrast and depth of burial of the anomalous mass.

CHAPTER V

IDEAL BODY THEORY AND LINEAR PROGRAMMING

Several short wavelength anomalies along the gravity profile are of special interest. Two of the anomalies, the Chimney Hill gravity high associated with the Zuni volcanic field and the Lucero gravity high associated with the Lucero uplift, have been analyzed using linear optimization techniques.

It is well known that a continuum of perfect gravity data cannot be inverted to yield a unique density solution. Further, the problem is compounded by the fact that all real gravity observations consist of a finite number of noisy measurements and not an infinite number of perfect measurements. The typical approach taken in gravity residual analysis is to make a sufficient number of assumptions necessary to produce a model that satisfies the data. Sometimes this process is performed several times to produce a suite of models. Unfortunately, such an approach is often unreliable. An alternative approach is to obtain parameters that are common to all the models of the infinite set that fit the data. This alternative approach has been taken in the analysis of the Chimney Hill gravity anomaly and the Lucero gravity anomaly. These anomalies were analyzed using linear programming to obtain bounds on the density contrast, depth, and minimum thickness of the source. A causative body, confined to a specified region, can be constructed such that it has the greatest lower bound on the maximum density and gives rise to the observed data. Such a body is unique and is called an ideal body. The theory of ideal bodies for gravity anomaly interpretations was developed by

Parker (1974, 1975). The application of linear programming to ideal body theory is explained by Safon et al. (1977). Linear programming (Gass, 1975) as applied to ideal body calculations is an optimization scheme that allows one to calculate that unique density distribution, confined to a preassigned region, which has the smallest possible maximum density while still producing the observed data. The only assumption made in the analysis of the residual is two-dimensionality.

The basic philosophy put forward in Parker's first paper (1974) is that properties of the source of the anomaly should be sought that are common to all possible models of the source fitting the finite set of gravity data. If such properties can be discovered, then these are fundamental, unique properties of the source. The easiest physical properties to investigate are density, depth of burial, and geometry of the source. The Parker papers deal primarily with the lower bound on the maximum density. He showed that if certain numerical constants could be found for a given data set then these constants parameterize a uniform body of least possible density called the ideal body. This ideal body is unique, for there is only one uniform body of that density (the lower bound on the maximum density) consistent with the data. For any higher value of density there are an infinite number of uniform bodies consistent with the data. For any lower value of density there are no uniform bodies consistent with the data.

Consider a scalar model property $m(\vec{r})$, the density, where $\vec{r}$ is a vector coordinate in real space. Assume we have N real observations of gravity data. If the model is confined to a region V

(which has been defined at the onset of the problem), then the gravity observations g_j are related to the model density by the field equation:

$$g_j = \int_V G_j(\vec{r}) m(\vec{r}) dV \quad j=1,2,\dots,N; \quad (1)$$

where $G_j(\vec{r})$ is the Green's function appropriate to the j^{th} measurement and $m(\vec{r}) \geq 0$ everywhere within V . Parker (1975) has shown that a sufficient condition for the existence of a positive lower bound on the largest value of m confined to V is that there exists $N + 1$ constants, $M_0, \alpha_1, \alpha_2, \dots, \alpha_n$, where $M_0 > 0$, such that a function defined by

$$m_0(\vec{r}) = \begin{cases} M_0 & \text{where } \sum_{i=1}^n \alpha_i G_i > 0 \\ 0 & \text{where } \sum_{i=1}^n \alpha_i G_i \leq 0 \end{cases} \quad (2)$$

satisfies the potential field Eq. (1). Further, M_0 is the greatest lower bound on the largest value of density $m(\vec{r})$, and the model defined by $m_0(\vec{r})$ meets that bound. The solution $m_0(\vec{r})$ is the ideal body and depends on both the observed data and the confining region V .

The analytical solutions for $N=1$ and $N=2$ are given by Parker (1974). Unfortunately no analytic method of solving the ideal body problem exists for $N>2$. A good numerical approximation to the

solution of the ideal body problem can be found for arbitrary N using linear programming (Safon et al., 1977).

The general linear programming problem is formulated as follows:

minimize the linear objective function

$$f = \sum_{i=1}^n C_i X_i \quad (3)$$

subject to the constraints

$$\sum_{j=1}^n a_{ij} X_j = b_i \quad X_j \geq 0; \quad m < n; \quad i=1,2,\dots,m. \quad (4)$$

The coefficients C_i are known. A set of variables (X_j) satisfying all the constraints is a feasible solution vector. The set of all such vectors constitutes the feasible solution space. Consequently the linear programming problem can be restated as follows. Among all feasible solution vectors, find that which minimizes (or maximizes) the objective function. To maximize

$$f = \sum_{i=1}^n C_i X_i$$

simply minimize

$$f = \sum_{i=1}^n -C_i X_i .$$

We may generalize to include inequality constraints. An inequality can be easily transformed into an equality. Consider

$$\sum_{j=1}^n a_{ij}x_j \geq b_i .$$

This may be put into equation form by subtracting the non-negative slack variable x_{n+1} leading to

$$\sum_{j=1}^n a_{ij}x_j - x_{n+1} = b_i \text{ where } x_{n+1} \geq 0 .$$

Similarly the constraint

$$\sum_{j=1}^n a_{ij}x_j \leq b_i$$

is equivalent to

$$\sum_{j=1}^n a_{ij}x_j + x_{n+1} = b_i \text{ where } x_{n+1} \geq 0 .$$

We may further generalize by removing the positivity constraint on the decision variables. If a variable x_j is unrestricted in sign, then it can be replaced by $x_j' - x_j''$ where $x_j' \geq 0$ and $x_j'' \geq 0$. If $x_j \geq l_j$ then the new variable $x_j' = x_j - l_j$ is automatically non-negative. Also, if a variable x_j is restricted such that $x_j \leq u_j \leq 0$, then the substitution $x_j' = u_j - x_j$ produces a non-negative variable x_j' .

From this discussion we see that a given linear programming problem can be put in different equivalent forms by suitable manipulations. Two forms in particular are useful. These are the standard and canonical forms. A linear programming problem is said to be in standard format if all restrictions are equalities and all variables are non-negative and is said to be in canonical form if all variables are non-negative and all the constraints are of the $\geq$ type. Standard algorithms exist for solving the linear programming problem in standard form in a finite number of steps. In particular, the simplex method developed by Dantzig (1949) and the revised simplex method developed by Dantzig (1953) and Orchard-Hays (1954) are most useful. The revised simplex method is a systematic procedure for implementing the steps of the simplex method in a smaller array, thus saving space.

To apply the linear programming algorithm to the two-dimensional gravity ideal body problem, consider a bounded two-dimensional region V to which the ideal body solution will be confined. The region is then subdivided into n polygonal prisms. Because the ideal body has smooth boundaries, we may in principle approximate the body arbitrarily closely by making the prisms small enough. In practice we are limited by the computational abilities of the computer and/or economics. Next assume we have N gravity observation points on or outside the boundary of V (usually on the earth's surface). Let the gravity anomaly produced by a unit density in the j^{th} prism at the i^{th} observation point be called a_{ij} . Thus we have N constraint equations with n unknowns:

$$g_i = \sum_{j=1}^n a_{ij} m_j \quad i = 1, 2, \dots, N; n > N \quad (5)$$

where m_j is the density of the j prism. A necessary but not sufficient condition to produce a solution is $n > N$. The constants a_{ij} may be easily calculated using the Talwani method (Talwani et al., 1959).

To approximate the gravity ideal body solution we must minimize the maximum value of m_j . Assume there is some unknown m_0 such that $m_j - m_0 \leq 0$. This gives n additional constraints and one more unknown. The ideal body is then approximated by minimizing the objective function m_0 . In order to apply the simplex method, these inequalities must be transformed into equalities by introducing n unknown slack variables. Thus the gravity ideal body linear programming problem has $N + n$ constraints in $2n + 1$ unknowns.

We can generalize the problem by including the case of noisy gravity data in the linear programming formalism. Assume that the i^{th} gravity observation has a maximum allowable absolute value of error of E_i . We introduce $2N$ additional constraints and N additional unknowns: $\pm e_i \leq E_i \quad i = 1, 2, \dots, N$. These inequalities must be transformed into equalities by introducing N unknown slack variables. Thus Eq. (5) becomes:

$$g_i = \sum_{j=1}^n (a_{ij} m_j + e_i) \quad i = 1, 2, \dots, N; n > N \quad (6)$$

Thus the gravity ideal body linear programming problem for the noisy data case has $3N + n$ constraints in $2N + 2n + 1$ unknowns.

As an example, the details of the computer calculations used to produce a trade-off curve will now be discussed. The example given is for the exact data case from the Lucero study, profile A - A'. The region V partitions are given in Appendix B, Tables B3 and B4 and the associated trade-off curves are shown in figures 25 and 26. The residual gravity data observations are 0.5 mgals at 30.0 km, 27.6 mgals at 42.5 km, 22.6 mgals at 44.0 km, and 7.4 mgals at 52.75 km. The initial partition is shown in figure 27. It was chosen such that the top of the region V touched the earth's surface. It was given a width of 17.5 km and a thickness of 3.125 km. The prisms are 0.625 km^2 . Previous experience from running many such calculations aided in choosing a tight partition on the first guess. One of the properties of an ideal body is that it must always touch the top of the region V. In the initial run we want to find out how thick the ideal body is, assuming it touches the earth's surface. The initial run shows the ideal body touching the bottom of V and has an objective function of 0.3534 g/cm^3 . Because the ideal body touches the base of V, in run B the depth of V is increased beneath the deepest portion of the ideal body. Again we get the same ideal body and objective function. This tells us that the greatest lower bound on the density contrast of the causative body is 0.3534 g/cm^3 . This information is plotted as point #1 on both trade-off curves. Next we begin to confine the maximum allowable thickness of the body. Run C restricts the body to 2.5 km thickness. Consequently the objective function increases to 0.3590 g/cm^3 . This information is plotted as

Figure 25. Example of ideal body trade-off curve. Assumed maximum density contrast vs least upper bound on depth to top of body for Lucero gravity anomaly profile AA'.

Figure 26. Example of ideal body trade-off curve. Assumed maximum density contrast vs minimum thickness of body for Lucero gravity anomaly profile AA'.

Figure 27. Example of partitions for ideal body calculations.

point #2 on the trade-off curve in figure 26. Runs D, E, F, and G further confine the body, which further increases the density. The information is plotted as points #3 to 6 on the trade-off curve in figure 26. The trade-off curve just produced can be interpreted as giving a minimum thickness if a maximum allowable density contrast is assumed. The curve gives the bounds on the infinite solution set. All solutions confined to a given layer thickness have maximum densities plotting on or above the value of the curve at that thickness. This curve gives us two important pieces of information about the causative body. It tells us the least possible maximum density contrast allowed (point #1). If one can, from geologic prejudices, assign a maximum possible density contrast then the curve will give the minimum thickness of the causative body.

Next we want to push the top of the region V down below the surface while not bounding the bottom of the ideal body from below. Run H has the top of V at 0.25 km. Again the objective function begins to increase relative to run A. The results are plotted as point #7 on the trade-off curve in figure 25. In runs I, J, and K we continue to push the top of the confining region V deeper until the objective function far exceeds any geologically reasonable density contrast. The results of runs I, J, and K are plotted as points #8, 9, and 10. The trade-off curve gives the greatest lower bound on the maximum density contrast versus the depth to the top of the body, or arguing in reverse gives the maximum density contrast versus the least upper bound on the depth to the top of the body. The trade-off curve also gives the bounds on the infinite solution set. Like the trade-off curve in figure 26, the infinite solution set is located on

the concave side of the trade-off curve in figure 25. No solutions are found on the convex side. This trade-off curve also gives us two important pieces of information about the causative body. Like the curve in figure 26, it tells us the least possible maximum density contrast allowed (point #1). If using geologic prejudice we can assign a maximum possible density contrast, then the curve will give the maximum depth to the top of the body.

Only four data points were needed to obtain these results. The more data points used in the calculations, the tighter will be the bounds on the infinite solution set. Experience tells us that increasing the number of data points used from one to about four will have a substantial effect on the tightness of the bounds of the infinite solution set. Above about four data points, adding an additional data point will have a much smaller effect on the bounds of the solution set, unless that additional data point deviates substantially from the trend established by the previous data points.

CHAPTER VI

THE CHIMNEY HILL GRAVITY ANOMALY AND THE ZUNI VOLCANIC FIELD

The Zuni volcanic field consists of a northeast-trending chain of late Cenozoic basaltic vents, forming a band 90 km long and 1 to 15 km wide. It is located along the southeastern edge of the Colorado Plateau and is part of the Jemez volcanic lineament (Mayo, 1958; Laughlin et al., 1972; Luedke and Smith, 1978) (Fig. 2). The chain is not parallel to the lineament but rather transverse to it. The Jemez lineament strikes approximately N55°E. However, the chain is parallel to a major basement structure associated with the large positive Chimney Hill gravity high (Ander et al., 1979). The volcanic field is also parallel to northeast-trending normal faults that cut some of the older volcanic rocks. The field overlies a section of Permian through Mesozoic age sedimentary rocks that are exposed along the flanks of the Zuni uplift. The northernmost vents in the field are located on the uplift, along faults that cut the Precambrian igneous and metamorphic complex exposed in the core of the uplift (Goddard, 1966).

The Zuni volcanic field covers parts of four 1° x 2° quadrangles; there are geologic compilations for three of them: Gallup, Socorro, and Albuquerque (Hackman and Olson, 1977; Machette, 1978; Wyant and Olson, 1978 respectively). A geologic compilation from the St. Johns quadrangle is not complete. Parts of the volcanic field and chemical analyses of some of the basalts have been described in the literature (Laughlin et al., 1972; Dellachaie, 1973; Laughlin and West, 1975; Gawell and Laughlin, 1975; Renault, 1970; Lipman and

Moench, 1972). Characteristics of the lava flows, beautifully displayed at Bandera Crater and along Interstate Highway 40 near Grants, have been described by Nichols (1946) and Hathaway and Herring (1970). A complete description of the volcanic field, the petrology of the lavas, and the geophysical studies on the associated Chimney Hill anomaly has been given by Ander et al. (in preparation, 1980c).

The chain of vents is oriented N38°E with the exception of a northerly-trending section that crosses the Zuni uplift (Fig. 28). The section across the Zuni uplift follows the faults visible there (Goddard, 1966). Northeast-trending normal faults and vents are parallel to the prominent Chimney Hill gravity high (Ander et al., 1979). The anomaly is 90 km long and 30 km wide and extends southwest from the southern edge of the Zuni uplift. The volcanic chain follows the eastern edge of the anomaly.

There are 74 vents in the field; all have erupted lavas and tephra of basaltic composition. Vent types include simple cinder cones, spatter ramparts and cones, small shields, maare, and collapse pits. Geomorphically, the volcanic chain generally is younger from south to north (Ander et al., in preparation, 1980c).

The basaltic lavas show a bimodal distribution of alkalic and tholeiitic basalts. There is no systematic variation of basalt composition with time, vent type, or position within the field (Ander et al., 1979; in preparation, 1980c).

The Zuni volcanic field was active from around 2 m.y. to about 1000 years ago. This activity was contemporaneous with activity elsewhere along the Jemez volcanic lineament; activity at the Mt. Taylor field, located immediately northeast of the chain, ranged

Figure 28. Map of Zuni volcanic field vent locations.

from 3.5 to 1 m.y.; and at the Springerville field, located to the southwest, ranged from about 3 m.y. to 22,000 years before present (Luedke and Smith, 1978).

The source vents for the Zuni volcanic field are shown superimposed on the complete Bouguer anomaly map of figure 29. Also shown on the map are the locations of the deep MT sounding sites discussed below. The gravity data used in the production of the map are from the U.S. Defense Mapping Agency gravity data bank. A positive northeast-trending gravity anomaly, the Chimney Hill gravity high, extends southwest from the Zuni uplift. The anomaly is 90 km long and 30 km wide. The Zuni volcanic vents are parallel to the eastern edge of the gravity anomaly. This strongly suggests a causal relationship between the location of the vents and the orientation of the structure producing the gravity anomaly.

A gravity profile A-A' perpendicular to the major axis of the anomaly was taken for analysis. One of the most important problems in the interpretation of gravity measurements is that of separating the surface gravity field into its independent components and ascribing geological structures to each of the parts. For this study the regional component was obtained from the Bouguer gravity by a simple smoothing technique. Figure 30 shows the gravity profile A-A' and the assumed regional. The regional was chosen in such a way as to reflect best the long wavelength structure of the gravity signal, and at the same time to produce a reasonably conservative estimate of the residual.

The residual gravity profile A-A' was analyzed using ideal body theory. Linear programming was applied to obtain bounds on the

Figure 29. Bouguer anomaly map of Chimney Hill anomaly showing Zuni volcanic field vent locations.

Figure 30. Chimney Hill gravity anomaly profile AA' showing assumed regional anomaly.

density contrast, depth, and minimum thickness of the causative body. The analysis was performed using both perfect data and noisy data. In the noisy data case a 1 mgal error bar was assumed. Results of the analysis are shown as trade-off curves in figures 31 and 32. The actual partitions used in obtaining these results are given in Appendix B, Tables B1 and B2.

The limiting case, where the anomalous body reaches the surface, gives 0.1 g/cm^3 as the lowest bound on the maximum density contrast for perfect data and 0.077 g/cm^3 for the noisy data. If 0.4 g/cm^3 is taken as the geologically reasonable upper limit on the maximum density contrast, then the maximum depth of burial is 3.5 km and the minimum thickness is 2.2 km for the perfect data. For the noisy data the maximum depth of burial is 5.25 km and the minimum thickness is 2 km.

Two oil wells located on the northwestern flank of the anomaly at Sec 32, T9N, R15W and Sec 17, T9N, R14W were used to estimate a depth to basement of 1.16 km. An oil well located just to the south of the anomaly at Sec 11, T2N, R16W indicates a depth to basement of 1.67 km. There are no deep wells located over the anomaly. Over the area of the anomaly the sediments are nearly flat or deformed slightly into gentle folds with limbs dipping 3° to 5° . There is no evidence in the surface geology to suggest stratigraphic thinning or basement uplift. Consequently there is no direct evidence for stratigraphic thinning associated with the anomaly. Figure 32, using noisy data, indicates a minimum thickness of 2 km for the anomalous body with a high-density contrast of 0.4 g/cm^3 assuming it touches the surface. Thus it is safe to assume that the anomaly is

Figure 31. Trade-off curve for assumed maximum density contrast vs least upper bound on depth to top of body for the Chimney Hill gravity profile AA'.

Figure 32. Trade-off curve for assumed maximum density contrast vs minimum thickness of body for the Chimney Hill gravity profile AA'.

not due to a horst structure. This requires that the anomalous body must be within the Precambrian basement. If 1.4 km is taken as the average depth to basement and it is assumed that this is the maximum upper limit on the depth to the top of the body, then 0.14 g/cm^3 is the lowest bound on the maximum density contrast for perfect data and 0.11 g/cm^3 for noisy data. Figure 33 gives density bounds for sources confined below 1.4 km depth. Confining the body below 1.4 km does not substantially increase the minimum thickness of the anomalous body. The minimum thickness is 2.25 km for noisy data and 2.5 km for perfect data assuming a maximum density contrast of 0.4 g/cm^3 .

The regional MT survey passes over the gravity anomaly and associated volcanic field (Fig. 7). An electrical conductive anomaly, if found to be associated with the gravity anomaly, might suggest the presence of either partial melt or magma. The MT sounding curves and results of the one-dimensional inversion for stations 32, 33, and 44 (Fig. 29) do not suggest the presence of an upper crustal conductivity anomaly shallower than 9 km.

A shallow mafic intrusion within the Precambrian basement is proposed to account for the large positive anomaly. The age of its emplacement is unknown. This large basement structure has controlled the development of the Zuni volcanic field as evidenced by the vent locations. The conduits have been preferentially developed where the Jemez lineament was obliquely crossed by the eastern boundary (density contrast $\geq 0.1 \text{ g/cm}^3$) of the intrusive body. The structure also exhibits some control on the deformation of the sedimentary section. Normal faulting associated with the chain of volcanic vents follows this trend. The Nutria monocline, a major Laramide structural

Figure 33. Trade-off curve for assumed maximum density contrast vs minimum thickness of body for the Chimney Hill gravity profile AA', assuming the source is confined below 1.4 km depth.

feature, about 45 km long, marks the western boundary of the Zuni uplift. The beds of the monocline have dips as great as 80° , but flatten out abruptly to dips of less than 10° within about 1.5 km at the northwestern boundary of the intrusive structure. The truncation of the strike of the Nutria monocline at the northwest boundary of the positive anomaly may suggest that the intrusive body predates and controls the southern extent of the Nutria monocline.

CHAPTER VII

THE LUCERO UPLIFT ANOMALY

The Lucero uplift is a westward-tilted fault block on the southwestern border of the Albuquerque-Belen basin (Fig. 34) of the Rio Grande rift. The eastern boundary of the uplift marks the border of the Colorado Plateau and the Rio Grande rift. To the southeast are the Ladron Mountains. The uplift is bounded to the north by the Rio Puerco fault zone, a major zone of scissor faults also on the western boundary of the rift (Slack and Campbell, 1976). The western boundary of the Lucero uplift is somewhat unclear. The westward dipping beds of the uplift merge gently into the Acoma Sag to the west. Callender and Zilinski (1976) have chosen a somewhat conservative width of 20 km for the uplift. The uplift exposes Pennsylvanian through late Cenozoic sediments. The Lucero uplift is predominately a Laramide uplift structure due to compressional tectonics (Kelley and Wood, 1946; Kelley and Clinton, 1960). Evidence for this exists in the Lucero monocline at the northern end of the Lucero uplift, gravity sliding off the monocline, and in upthrusting seen along the Comanche fault (Fig. 34). The Lucero monocline has been described by Slack and Campbell (1976) and Callender and Zilinski (1976). Superimposed upon Laramide vertical tectonics is subsequent mid- to late-Tertiary crustal extension (Kelley and Wood, 1946; Kelley and Clinton, 1960). The Comanche fault is a high-angle westward dipping reverse fault. It has been suggested (Callender and Zilinski, 1976) that the fault has been rotated counterclockwise by mid- to late-Tertiary tilting. The Comanche fault has a maximum stratigraphic

Figure 34. Structural geology map of Lucero uplift region (modified from Callender and Zilinski, 1976).

separation of about 1200 m at the base of Mesa Aperejo and decreases to about 30 m just north of Carrizo Arroyo (Callender and Zilinski, 1976).

Rifting in the Albuquerque-Belen basin is interpreted to have started around 30 m.y. ago by Chapin and Seager (1975). The Santa Fe fault is the rift-bounding fault along the Lucero front. The Santa Fe fault is an eastward dipping high-angle normal fault with over 3500 m of stratigraphic separation, determined from exposed stratigraphic section in the Lucero uplift and the Shell Santa Fe #2 well. It is the youngest major structural feature in the Lucero uplift. Structural evidence indicates there have been at least three episodes of Quaternary movement along the Santa Fe fault at the northern end of the Lucero Uplift, with individual offsets of as much as 20 m. (Callender and Zilinski, 1976; Kelley et al., 1976).

Late Cenozoic igneous activity occurred throughout the Lucero area. The extrusives consist of young basalts that range from alkaline to tholeiitic in composition, and range from 0.32 to 7.2 m.y. in age. Baldridge (personal written communication, September 1980) tentatively identifies four main eruptive sequences: (1) a 7 m.y.-old basanite eruption; (2) a 4 m.y.-old eruption of mainly olivine tholeiite; (3) the 3 m.y.-old eruption of a small shield volcano and flow of low-alkali olivine tholeiite basalts; and (4) a 1 to 2 m.y.-old eruption of a suite of basanitic to mugearitic lavas, this last eruption sequence being controlled by a north-northeasterly-trending hinge of the Lucero uplift.

An older, 27 ± 1.0 m.y.-old, mafic intrusive complex is located just north of Salado Arroyo (Callender and Zilinski, 1976)

(Fig. 34). The intrusive consists of quartz diorite, biotite-rich diorite, and biotite-rich olivine gabbro. Preexisting faults may have controlled the emplacement of the intrusive complex.

A simple Bouguer anomaly map of the Lucero region and adjacent Rio Grande rift is shown in figure 35. The location of the data points used to produce the Bouguer map is shown in figure 36. United States Defense Mapping Agency gravity data is very sparse in the area of the Sierra Lucero, Largo Embayment, and the rift between the Sierra Lucero and Belen, New Mexico. Initially 14 additional points were collected to aid in the map production and subsequent analysis. Since the analysis on the Lucero anomaly was performed, Ander et al. (in preparation, 1980d) have collected an additional 120 gravity points in this region. The data have been terrain corrected. A complete Bouguer anomaly map of the Socorro 1:250,000 Army Map Sheet (AMS) has been produced using this new data along with the same composite data base used to produce the recently published Complete Bouguer Gravity Anomaly Map of the Rio Grande Rift by Cordell et al. (1978). Also included were 49 previously unpublished gravity points obtained from the Hawaii Institute of Geophysics, University of Hawaii gravity data base compiled and collected by G. P. Woollard. A portion of the map is given in figure 37. The map was made using a transverse Mercator projection so that it will overly the AMS sheet. The gravity site locations used to produce this map are given in figure 38.

The simple Bouguer anomaly map (Fig. 35) indicates a regional north-south trend increasing from about -230 mgals on the west to about -200 mgals through the Sierra Lucero, then rapidly decreasing

Figure 35. Simple Bouguer gravity anomaly map of Lucero uplift region and adjacent Rio Grande rift.

Figure 36. Location of gravity data points used in the simple Bouguer anomaly map of Lucero uplift region and adjacent Rio Grande rift.

Figure 37. A portion of the complete Bouguer gravity anomaly map of the Socorro, New Mexico, $1^\circ \times 2^\circ$ sheet, showing the Lucero uplift region and adjacent Rio Grande rift (from Ander et al., in preparation 1980c).

Figure 38. Gravity site locations used to produce the map shown in Figure 35.

to about -220 mgals in the rift. The sharp gradients marking the western boundary of the rift wrap around the north end of Ladron Mountain and then end to the northeast, just south of Bernardo, marking the south end of the Albuquerque-Belen basin. There are two fairly obvious short wavelength positive gravity closures on the map. One is centered on the Sierra Lucero, the Lucero anomaly, and the other on Ladron Peak, the Ladron anomaly.

A comparison of figure 35 with the complete Bouguer anomaly map (Fig. 37) indicates that no new relevant information has been obtained for either the Lucero or Ladron anomalies. In the southwestern corner of the Albuquerque-Belen basin where no gravity data previously existed, figure 35 suggests the presence of a structural bench, essentially outlined by the -215 mgal contour interval. Such an interpretation, although not inconsistent with all available data in this area is due to undersampling. The complete Bouguer anomaly map on the other hand, suggests the presence of a northwest-trending structural high, which separates a small basin within the embayment from the main portion of the southern Albuquerque-Belen basin. This small basin is represented by the -215 mgal and -220 mgal gravity enclosures. Another new feature present in the gravity data is a north-trending high. This high is located between Interstate Highway 25 and State Road 47 from Bernardo to Belen, New Mexico and probably represents a horst structure.

As mentioned in the previous section, one of the most important problems in the interpretation of gravity measurements is that of separating the surface gravity field into its independent components and ascribing geological structures to the parts. For this

study, the regional gravity anomaly map (Fig. 39) was obtained from the simple Bouguer anomaly map (Fig. 35) by a series of frequency domain low pass filtering, gridding, and smoothing steps (Nettleton, 1954). In the area of the Largo embayment, where data is extremely sparse, the regional anomaly was made to fit the simple Bouguer anomaly so that no artificial anomalies would be developed on the residual anomaly map. Thus the regional gravity anomaly best reflects the long wavelength structure across the western boundary of the rift. The residual gravity anomaly map (Fig. 40) was obtained by subtracting the regional anomaly map from the simple Bouguer anomaly map at each gravity data point.

Three anomalies appear on the residual Bouguer anomaly map. The first anomaly, located just to the south of Ladron Peak, has an areal extent of about 600 km^2 and has a maximum amplitude of over 15 mgals. The second anomaly is located in the Lucero uplift, adjacent to the Colorado Plateau and has an areal extent of about 1300 km^2 . This anomaly has two local highs. One is centered on Salado Arroyo between Mesa Aparejo and Mesa Carrizo in the Lucero uplift and is over 25 mgals. The other is centered on Mush Mountain and is over 15 mgals. It is uncertain whether there is a single source or multiple sources for the anomaly. The third anomaly is located just to the west of Albuquerque and is centered on Cerro Colorado, a volcanic neck. The Cerro Colorado anomaly was not readily apparent in the simple Bouguer anomaly map. The anomaly has an areal extent of approximately 350 km^2 and a maximum amplitude of 15 mgals.

Analysis, using linear programming and ideal body theory, was applied to profiles AA' and BB' across the two local highs of the

Lucero anomaly and to profile CC' across the anomaly centered on Cerro Colorado. The use of ideal body theory is exceptionally well suited to anomalies defined by sparse data sets. Analysis was not applied to the anomaly located to the south of Ladron Peak because an almost total lack of gravity data in the Largo embayment just to the north made it impossible to produce a reasonable profile for analysis. The results of analysis are shown as trade-off curves in figures 41 through 46. The partitions used in obtaining these results are given in Appendix B, Tables B3 through B8.

For profile AA', the limiting case where the anomalous body touches the surface gives 0.35 g/cm^3 as the lowest bound on the maximum density contrast for perfect data and 0.25 g/cm^3 for the noisy data case. If 0.7 g/cm^3 is taken as the geologically reasonable upper limit (the case of a dense mafic intrusion) on the maximum density contrast, then the maximum depth of burial is 0.65 km and the minimum thickness is about 1.0 km for the perfect data case. For the noisy data case the maximum depth of burial is 1.25 km and the minimum thickness is still about 1.0 km. Similarly for profile BB', the limiting case where the anomalous body reaches the surface gives 0.23 g/cm^3 as the greatest lower bound on the density contrast for perfect data and 0.14 g/cm^3 for the noisy data. Again, if 0.7 g/cm^3 is taken as the geologically reasonable upper limit on the maximum density contrast, then the least upper bound of the anomalous body is 0.78 km and the minimum thickness is 0.55 km. For the noisy data case, the least upper bound of the body is 1.45 km and the minimum thickness is still about 0.55 km.

Figure 41. Assumed maximum density contrast vs least upper bound on depth to top of body for profile AA'.

Figure 42. Assumed maximum density contrast vs minimum thickness of body for profile AA'.

Figure 43. Assumed maximum density contrast vs least upper bound on depth to top of body for profile BB'.

Figure 44. Assumed maximum density contrast vs minimum thickness of body for profile BB'.

Figure 45. Assumed maximum density contrast vs least upper bound on depth to top of body for profile CC'.

Figure 46. Assumed maximum density contrast vs minimum thickness of body for profile CC'.

The trade-off curves for AA' and BB' preclude either horst blocks or undulations of the Precambrian surface as the sole sources of the causative bodies. It is assumed that a horst model would have a positive anomalous density contrast of 0.27 g/cm^3 . In that case, the maximum depth and minimum thickness bounds on the anomalous body are incompatible with the thickness of the stratigraphic column, estimated to be no greater than 1.5 km (Kelley, 1977). Instead, the anomalous body is interpreted to be a large shallow mafic intrusion.

The eastern portion of the Lucero anomaly extends into the rift (Fig. 47). Two major faults, the Comanche upthrust and the rift-bounding Santa Fe fault, pass through the eastern portion of the anomaly. These faults may have structurally controlled the emplacement of the eastern part of the intrusion. The fact that the Santa Fe fault transects the anomaly and that the anomaly does not appear truncated by the presence of the fault, suggests that the anomalous body must have intruded after the rift formation and after the major offset on the fault had occurred. The 27 m.y.-old mafic intrusive complex located just north of Salado Arroyo cannot be a small part of the much larger anomalous body. If the 27 m.y. intrusive were a portion of the much larger anomalous body, then this would imply that the vast majority of the offset along the Santa Fe fault occurred prior to 27 m.y. ago. But this cannot be so because substantial Quaternary and late Tertiary offsets along the Santa Fe fault have been clearly documented, (Callender and Zilinski, 1976; Kelly et al., 1976).

The surface morphology, in the region of the eastern portion of the Lucero anomaly that extends into the rift, gives

Figure 47. Tectonic map of the Albuquerque basin with residual gravity anomaly superimposed (modified from Woodward et al., 1977).

circumstantial evidence of a possible Quaternary emplacement of the body. Elevated topography and heavily incised arcuate drainage (Fig. 48) suggests possible doming of the Tertiary rift fill above this portion of the suspected anomaly. Of course it is possible that this correlation is merely coincidental. Although the Lucero uplift is a Laramide feature, the high relief of the Sierra Lucero Mountains today clearly indicates more recent uplift. If Baldrige's suggestion is correct, that a 1 to 2 m.y.-old eruptive sequence was controlled by a north-northeast-trending hinge of the Lucero uplift and that none of the earlier events appeared to be controlled by this hinge, then the hinge may have been activated about 1 to 2 m.y. ago by uplift due to intrusion accompanied by eruption along the hinge. Further investigation of the structure in the Lucero uplift and a detailed study of the pediment surfaces of the rift fill adjacent to the Lucero uplift might help refine the age of emplacement.

For profile CC', across the Cerro Colorado gravity anomaly, the trade off curves (Figs. 45 and 46) for perfect data give 0.26 g/cm^3 as the greatest lower bound on the density contrast for the limiting case where the anomalous body reaches the surface. The curves give 0.16 g/cm^3 for the noisy data case. As before, if 0.7 g/cm^3 is taken as the geologically reasonable upper limit on the maximum density contrast, then for the perfect data case, the maximum depth of burial is 0.37 km and the minimum thickness is about 0.5 km. For the noisy data case the maximum depth of burial is 0.82 km and the minimum thickness is also about 0.5 km. According to Wright (1943) and Callender (University of New Mexico, personal written communication, 1980), Cerro Colorado is a volcanic dome, probably

Figure 48. Topography below 5800 ft and drainage map of a portion of the Rio Grande rift just east of the Lucero uplift.

Pliocene in age, that was covered by rift fill then partially exhumed by later erosion. The dome consisted mainly of trachyte lavas and pyroclastics. After dome formation, a quartz latite plug filled the central part expanding the dome. The dome was then buried by rift fill. Later erosion associated with the Rio Puerco exposed the upper portion of the dome. It is suggested that the gravity anomaly associated with the Cerro Colorado intrusive is due to the still buried portion of the dome.

There is a northeasterly trend to the Lucero residual anomaly as a whole (Fig. 47), perhaps indicating that the regional Precambrian lineament system aided in structurally controlling the emplacement of part, if not all of the suspected intrusive complex. The anomaly is bounded to the northwest and southeast by gradients with a consistent strike of $N55^{\circ}E$. The Jemez lineament also strikes at $N55^{\circ}E$. Two lineaments are then suggested: (1) the southeastern border appears on line with the Tijeras-Cañoncito fault system located on the opposite side of the rift and may include the Los Lunas volcanic field, forming an extension of the Tijeras lineament across the Rio Grande rift; and (2) the northwestern border of the Lucero anomaly aligns with Cerro Colorado, the Albuquerque volcano chain, and the truncation of the Sandia Mountains along the Placitas and San Francisco faults and will be referred to as the Albuquerque lineament. Although there is presently no structural evidence for a relationship among the features of the Albuquerque lineament, the alignment of the features is striking. The proposed Albuquerque lineament is roughly parallel to the Tijeras-Cañoncito fault system and may be due to a component of the northeast-trending shear system.

Of course lacking structural evidence, the alignment may also be just a coincidence.

The northeast-trending Tijeras fault system and the Los Angeles fault system, located farther to the northeast, were originally mapped by Darton (1928a,b) then again by Read and Andrew (1944) and Read et al. (1944). Stearns (1953) suggested the two fault systems were causally related. More recent work done by Miller et al. (1963), Kelley (1963), Johnson (1973, 1975), Bachman (1975), Lisenbee (1976), and Booth (1976) indicate that the Tijeras fault system and Los Angeles fault system are part of a major northeast-trending crustal shear zone, which may be followed 175 km from the Albuquerque area into the Sangre de Cristo Mountains of northern New Mexico. The system is now referred to as the Tijeras-Cañoncito fault system. The most recent description of the system is given by Lisenbee et al. (1979). The Tijeras-Cañoncito fault system has numerous Tertiary intrusive bodies and mineral deposits associated with it and is within the Bisbee-Morenci mineral belt (Lisenbee et al., 1979). The Tijeras-Cañoncito fault system has undergone at least four episodes of movement (Lisenbee et al., 1979). The earliest documented movement occurred in the Precambrian and was left slip. The latest documented movement occurred in the Quaternary. The late Cenozoic deformation along the system is believed to be in response to uplift and tilting of the Sandia fault block due to extensional tectonics associated with rifting (Kelley and Northrop, 1975; Lisenbee et al., 1979).

Kelley and Northrop (1975) have suggested that the Tijeras fault system can be extended to the southeast into the

Albuquerque-Belen basin, possibly to the Ladron uplift. Both aeromagnetic and gravity data suggest that the fault system extends into the basin (Cordell, 1976). An extension of this major fault system into the rift seems most probable. But an extension of the fault system to either the northwestern bounding fault or the southeastern bounding fault of the Ladron uplift does not seem likely. Because the Tijeras lineament is most probably a member of the northeast-trending shear zones described by Chapin et al. (1978) (shown in Fig. 2), then it too should appear to be acting as a transform fault in conjunction with rifting. As shown in figure 2, the portions of the lineaments to the west of the rift are shifted to the north relative to the portions of the lineaments to the east of the rift. Projecting the Tijeras lineament to the Ladron uplift does not fit this pattern. A projection of the lineament along the southeastern border of the Lucero residual gravity anomaly does fit the pattern. Such a projection may also aid in explaining the sinuous nature of the Comanche thrust fault and the presence of the Largo embayment. The strike of the Comanche fault is relatively straight along the Lucero front but bends sharply to the southwest at the northern end of the Largo embayment where the Tijeras lineament is projected across the rift. Perhaps this southwestern trend of the Comanche fault is in fact controlled by an extension of the Tijeras lineament across the rift. Also such a projection would pass through the Cat Hills volcanic field, suggesting that the conduits for the magma may have been structurally controlled by the lineament (possibly by the intersection of the lineament with rift related faulting).

CHAPTER VIII

REGIONAL GRAVITY STUDY OF PROFILE 34°40'N LATITUDE

Two-dimensional gravity modeling (Talwani et al., 1959) to a depth of 200 km was used to construct a crust-upper mantle profile across the Rio Grande rift. The profile extends from 110°W longitude in Arizona, across the state of New Mexico to 103°W longitude in Texas at a latitude of 34°40'N. This 640-km-long profile crosses the rift at Belen, New Mexico in the Albuquerque-Belen basin. Several variable density models of three consecutive earth layers were produced using all available geologic and geophysical constraints. Each model was normalized to a density of 2.67 g/cm³. Layer I, from the surface to 20 km depth, represents the sedimentary stratigraphy and the upper crust. Layer II, from 20 to 50 km depth, represents the lower crust and the Moho boundary. Layer III, from 50 to 200 km depth, represents the upper mantle.

These layers are variable density Bouguer slabs. The gravity signal produced by each slab can be computed from the Bouguer slab formula. A variable density Bouguer anomaly is produced by subtracting the gravity effect of each layer from the free air anomaly. The free air anomaly, g_{FA} , is given by

$$g_{FA} = g_{obs} - (g_{1967} - FAC) ,$$

and the Bouguer anomaly, g_{BA} , is given by

$$g_{BA} = g_{obs} - (g_{1967} - FAC + BC_1 + BC_2 + BC_3)$$

or

$$g_{BA} = g_{FA} - (BC_1 + BC_2 + BC_3),$$

where g_{obs} is the observed gravity, g_{1967} is the gravity reference field for a spheroidal earth model, FAC is the free air correction, and BC_1 , BC_2 , and BC_3 are the Bouguer corrections for slabs I, II, and III respectively. It assumed that all lateral density variations below 200 km depth contribute very little to the structure of the surface gravity signal over a distance of 700 km. Based on this assumption, if all lateral density variations above 200 km depth can be accounted for in the modeling, then all structure in the calculated Bouguer anomaly should vanish, leaving only a flat earth response. Obviously, one's ability to determine lateral density variations in the earth decreases rapidly with depth. Thus gravity analysis based on a single earth model may lead to erroneous conclusions, whereas investigating a suite of all reasonable earth models may lead to greater insight.

Layer I - 0 to 20 km Depth

The stratigraphic model (Fig. 49) for the 640-km long profile was inferred from existing geologic maps and deep well data. Geologic maps exist for the Clovis (Fisher, 1977), Fort Sumner (Kelley, 1972), and Socorro (Machette, 1978) $1^\circ \times 2^\circ$ quadrangles. A geologic map for the Saint Johns $1^\circ \times 2^\circ$ quadrangle is presently being developed (Intra Search). Fifteen wells were used along the profile

Figure 49. Density model of sedimentary stratigraphy along the 34°40' profile and its gravity response. All densities in g/cm³.

(Table 3). The well data was obtained from the open files of the New Mexico Oil and Gas Commission, Santa Fe, New Mexico. In the 149-km-long stretch between Well No. 1 Well and No. 2, other wells to the north and south of the profile were consulted to aid in the interpretation. In the region of the rift, the cross section given in Figure 20-D of Kelley (1977) was used. On the Colorado Plateau side a

TABLE 3
LOCATIONS OF THE WELLS USED TO PRODUCE THE STRATIGRAPHIC PROFILE
ALONG 34°40'N LATITUDE

<u>Well No.</u>	<u>Location</u>	
1	Arizona	Sec 12, T13N, R25E
2	New Mexico	Sec 5, T5N, R7W
3	New Mexico	Sec 29, T6N, R1W
4	New Mexico	Sec 19, T5N, R3E
5	New Mexico	Sec 23.231, T6N, R7E
6	New Mexico	Sec 19.212, T6N, R7E
7	New Mexico	Sec 21.341, T6N, R10E
8	New Mexico	Sec 11.11, T5N, R11E
9	New Mexico	Sec 9.44, T6N, R25E
10	New Mexico	Sec 22.31, T5N, R26E
11	New Mexico	Sec 21.11, T4N, R27E
12	New Mexico	Sec 16.42, T5N, R31E
13	New Mexico	Sec 10.323, T5N, R32E
14	New Mexico	Sec 1.33, T5N, R34E
15	New Mexico	Sec 18.344, T5N, R37E

regional structural-stratigraphic cross section developed by Wengerd (1962) was used.

The partitions for two-dimensional gravity modeling of the stratigraphic profile are given in Appendix D, Table D1. The actual elevation at each observation point of the gravity profile was used for the density model. The gravity signal, from the density model, was also calculated at each observation point of the profile. Thus, the calculated gravity has been corrected for terrain to a crude first order. The density model represents a variable density Bouguer slab. The model was normalized to an assumed upper crustal reference density of 2.67 g/cm^3 . In a standard Bouguer correction all mass from sea level to the observation point is assigned a specific density, usually 2.67 g/cm^3 , and it is tacitly assumed that all mass below sea level has the same reference density. This is obviously not always the case. In a variable density Bouguer correction all masses above sea level are assigned their assumed densities, whereas masses below sea level that differ from the reference density are assigned their density contrast relative to the assumed reference density, usually 2.67 g/cm^3 . The variable density Bouguer correction is superior to the standard Bouguer correction because it takes into consideration all known lateral density variations resulting in a Bouguer anomaly representing only unknown lateral density variations.

The results of the variable density slab calculations are shown in figure 49 and Appendix C, Table C2. Figure 50 shows the simple Bouguer anomaly resulting from the standard Bouguer slab calculation and the Bouguer anomaly resulting from the variable density Bouguer slab calculation. The results show the expected

Figure 50. Simple Bouguer anomaly resulting from standard Bouguer slab calculation and Bouguer anomaly resulting from variable density Bouguer slab calculation along the $34^{\circ}40'$ profile.

positive shift in the anomaly. The minimum shift, 1.1 mgal, occurred at data point #46 located just east of the Manzano Mountains. Because a constant bias in a regional gravity signal will have no effect on the interpretation, a 1.1 mgal bias can be subtracted from the resulting Bouguer anomaly obtained from the variable density Bouguer slab. When this is done, the mean shift between the Bouguer anomalies produced from the standard Bouguer slab calculation and the variable density Bouguer slab calculation is 8.6 mgal. The maximum shift is 67.5 mgal and occurs at data point #30 located at $X = 276.75$ km on the western flank of the Rio Grande rift. In the rift area the Bouguer anomaly due to the variable density slab is considerably different from the simple Bouguer anomaly. The simple Bouguer anomaly has an anomalous low, presumably due to the rift valley fill. The variable density Bouguer anomaly has a very large positive anomaly between stations 28 through 32 inclusively. This large positive anomaly is associated with the western side of the rift and the Lucero uplift gravity anomaly. The anomaly is considerably larger than the positive anomaly described in the Lucero uplift gravity study. Well No. 3, Shell Santa Fe No. 2, is located very close to the high anomaly peak at $X = 276.8$ km. This well gives good control on the stratigraphic section in this portion of the rift, eliminating the possibility of a serious failure of the model.

With the exception of the high amplitude, short-wavelength anomaly defined by stations 28 to 32, all other calculated Bouguer values do not vary by more than 11 mgal between the standard Bouguer calculations and the variable density calculations. Two conclusions can be drawn. First, the standard Bouguer slab calculation can mask

large, in this case very large, short-wavelength crustal anomalies, which the variable density Bouguer slab calculation may reveal. Secondly, the 11 mgal maximum difference (neglecting the high amplitude, short-wavelength differences that have no effect on long-wavelength anomalies) between the two different methods of Bouguer slab calculations is very small compared with the 150 to 200 mgal anomalies possibly associated with Moho geometry and the additional 150 to 200 mgal anomalies possibly associated with lithosphere/asthenosphere boundary geometry across the rift (see layer II and layer III). Consequently the major effort needed to produce a long variable density Bouguer slab is not required if the intent is solely deep crustal and upper mantle modeling. The small difference produced between the two different Bouguer slab calculations will in general be lost in the noise of layer II and layer III modeling, not to mention unaccounted-for lateral density variations in the crust or upper mantle.

Layer II - 20 to 50 km Depth

Before discussing the results of the Moho geometry study, it should be noted that all densities used in all models studied in layers II and III were subtracted from an arbitrary density of 2.67 g/cm^3 . This was done strictly for convenience; it affects only the constant bias level, and should offer no conceptual difficulty because only lateral density variations are of interest in this study. One might argue that an effort should be made to account for all radial variation of density within the earth. Such an effort would be unnecessarily difficult and fruitless, yielding only the

theoretically calculated gravity field of a homogeneous layered earth with the upper 200 km missing. Such information is not germane to the questions of Moho boundary and lithosphere-asthenosphere boundary geometry.

Layer II, from 20 to 50 km, includes the lower crust, Moho boundary, and upper mantle, beneath and to the west of the rift. The depth to the Moho boundary is constrained at only four locations: 40 to 45 km from the Chinle-Hanksville reversed refraction profile; 40 km from the GASBUGGY unreversed refraction profile; 32 km from the DICE THROW unreversed refraction profile in the rift; and 50 km from the GNOME unreversed refraction profile. Beyond these four control points the geometry of the mantle-crust boundary is unknown. Figure 51 shows all the various layer II models considered in this study, 22 models in all. The partitions for two-dimensional gravity modeling of the layer II models is given in Appendix D, Table D2. Figure 51a shows several simple possible geometries for the Moho boundary. A crustal density of 2.8 g/cm^3 and an upper mantle density of 3.35 g/cm^3 representing normal lithospheric mantle material were assumed. Although a lower density for the mantle of 3.22 g/cm^3 representing asthenospheric mantle material, and a more probable density of 2.94 g/cm^3 for the lower crust could have been used, the densities chosen represent a maximum upper bound on the density contrast across the Moho boundary. Consequently this initial investigation will give a reasonable estimate on the maximum possible variation in the gravity field caused by the Moho geometry.

Figure 52 gives the gravity results for the density models shown in figure 51a. Each curve represents a selected pair of

Figure 51. Layer II - Moho boundary models. All densities in g/cm^3 .

Figure 51. (Cont.) Layer II - Moho boundary models. All densities in g/cm^3 .

Figure 52. Gravity response functions of Moho models, type A.

eastern and western boundaries. First the gravity response functions of three possible western boundaries, nos. 1, 2, and 3, were investigated in combination with the eastern boundary no. 6. The maximum variation for these models is located at $x = 265$ km and is 15.4 mgals. In comparison with the total possible variations in amplitude of both the Moho models and the upper mantle models (layer III) in the vicinity of the rift, the effects of the various possible geometries of the western boundary are negligible and can be ignored.

A similar situation does not exist for the eastern boundary. Choosing western boundary no. 2 as an average representative boundary in combination with eastern boundaries nos. 4, 5, 6, 7, and 8, figure 52 shows a wide variety of possible gravity response functions. Without further seismic control on the Moho boundary just east of the rift, it is impossible to choose the proper response function, given the assigned densities. Although it is presently impossible to determine the eastern geometry of the Moho, boundaries of the type nos. 4, 5, and 7 might be more intuitively probable or pleasing over boundaries of the types nos. 6 or 8, boundary no. 6 being worse than no. 8. Boundaries of the type 4, 5, and 7 have a small maximum possible variation of 37.1 mgal located at $X = 336$ km. The total maximum variation in all the models is 230 mgal and occurs at $X = 375$ km. Neglecting boundary no. 6, the maximum variation occurs between boundaries 8 and 4 at $X = 400$ km and is 119 mgal.

At this point, the possibility of pulling any concrete information from the gravity data about Moho geometry and/or lithosphere-asthenosphere geometry beneath the rift may appear hopeless. This is because I have modeled only the Moho boundaries so far and obtained a

wide variety of response functions. One might think the situation will become considerably more complex when densities of the lower crust and upper mantle are permitted to vary, when various combinations of lithosphere and asthenosphere upper mantle boundaries are assumed, and when reasonable lateral density variations in the crust are considered. In an effort to discover possible common denominators in the confusion of many bounded variables, I will continue by tacitly assuming a Moho geometry of type 2 for the western boundary and types 7 and 8 for the eastern boundary and keep in mind the weakness of the eastern boundary assumption. The types 2 and 7 boundaries both have a slope of 20° . The type 8 boundary has a slope of 2° .

Now assume a more reasonable lower crustal density of 2.94 g/cm^3 , shown in figure 51b. This gives a density contrast across the Moho boundary of 0.41 g/cm^3 . The results are shown in figure 53. The curves shown in figure 53 are similar in shape and character to those in figure 52. The maximum variation between these two curves is 77 mgal and occurs at $X = 400 \text{ km}$. Consequently the difference between choosing a 2.8 g/cm^3 and a 2.94 g/cm^3 lower crust is a maximum possible discrepancy of 38 mgal, ignoring boundary type 6.

Now assume that low density asthenospheric material with a density of 3.22 g/cm^3 abuts against the crust beneath the rift as shown in figure 51c. If the lower crust is assigned a density of 2.8 g/cm^3 then the density contrast across the Moho beneath the rift is 0.42 g/cm^3 . This Moho model is somewhat similar to the Girdler (1975) and Bridwell (1976) type models. Both investigators assumed that the asthenosphere abuted against crustal material with no

Figure 53. Gravity response functions of Moho models, type B.

intervening lithospheric mantle material in the rift area. This assumption is based upon the concept that the lithosphere must decrease to zero thickness before plate separation can occur across a rift. The question is: has the Rio Grande rift actually advanced to this stage? The response function results are shown in the lower two curves of figure 54 and are essentially identical in shape to the two curves of figure 53. If the lower crust is assigned the density of 2.94 g/cm^3 as shown in figure 51d, the gravity response function curves for the two eastern boundaries 6 and 7 are given in the upper two curves of figure 54.

Next assume that the asthenosphere abuts against the crust beneath the rift and adjacent Colorado Plateau as shown in figures 51e and 51f. Figure 55 shows the response function results assuming a lower crustal density of both 2.8 g/cm^3 and 2.94 g/cm^3 .

The simplified velocity structure model of figure 6 suggests the possible existence of an additional lower crustal layer beneath the Great Plains with a density intermediate between 2.94 g/cm^3 and 3.35 g/cm^3 . The existence of such a layer is uncertain; compare, for example, the compressional velocity structure interpretation for the Great Plains from the Gnome shot given by Keller et al. (1979) and that given by Olsen et al. (1979). For the Moho models shown in figures 51g and 51h an intermediate density of 3.08 g/cm^3 was assumed. Figure 56 shows the response function results.

Figure 57 shows a composite of all the Moho models with lower crustal density of 2.8 g/cm^3 . Figure 58 shows a composite of all the Moho models with lower crustal density of 2.94 g/cm^3 . Both sets of

Figure 54. Gravity response functions of Moho models, types C and D.

Figure 55. Gravity response functions of Moho models, types E and F.

Figure 56. Gravity response functions of Moho models, types G and H.

Figure 57. Gravity response functions for all Moho models with a lower crustal density of 2.8 g/cm^3 .

curves are similar, except that figure 58 includes the three models with an additional lower crustal layer with density 3.08 g/cm^3 .

Because all the models with a lower crustal density of 2.8 g/cm^3 have the same structure beneath the Great Plains, all the response curves converge to the same field strength of about 174 mgal at the eastern-most point. Going west toward the rift the response curves diverge radically, due to a lack of control on the depth to the Moho in this region. The maximum variation in these curves is 228 mgal and occurs at about $X = 380 \text{ km}$. If the eastern boundary no. 6 is ignored, then the divergence is not as great. The maximum variation then becomes 120 mgal and occurs at $X = 390 \text{ km}$. To the extreme west, the response curves fall into two categories, those that approach an asymptote of about 380 mgal for models with upper mantle density of 3.35 g/cm^3 beneath this portion of the Colorado Plateau and those that approach an asymptote of about 329 mgal for models with lower crustal density of 3.22 g/cm^3 beneath this portion of the Plateau. The difference between these two western asymptotes is 51 mgal. The difference between the western and eastern asymptotes is 206 mgal for a Colorado Plateau upper mantle density of 3.35 g/cm^3 and 155 mgal for an upper mantle density of 3.22 g/cm^3 .

The response functions for all the models with lower crustal density of 2.94 g/cm^3 do not vary as much as those for lower crustal density of 2.8 g/cm^3 . This is because of the lower density contrast. With the exception of model types G and H, all response curves have an eastern asymptote of about 342 mgal. If the additional lower crustal layer suggested in figure 6 exists beneath the Great Plains, then this asymptote will rise. For an assumed density of 3.08 g/cm^3

Figure 58. Gravity response function for all Moho models with a lower crustal density of 2.94 g/cm^3 .

for this layer, model types G and H, the eastern asymptote will rise to about 394 mgal, a 52 mgal increase. Westward toward the rift the response curves again diverge due to the lack of Moho boundary control. None of the models used in the production of these curves contained an eastern Moho boundary no. 6. The maximum variation in these curves is 95 mgal and occurs at $X = 380$ km. To the extreme west, the response curves again fall into two categories, those that approach an asymptote of about 494 mgal for models with a Colorado Plateau upper mantle density of 3.35 g/cm^3 and those that approach an asymptote of about 446 mgal for models with a Colorado Plateau upper mantle density of 3.22 g/cm^3 . The difference between these two western asymptotes is about 48 mgal. This is close to the difference given in figure 57, as it should be because the density contrasts are identical. The difference between the western and eastern asymptotes, again ignoring model types G and H, is 152 mgal for a Colorado Plateau upper mantle density of 3.35 g/cm^3 and 104 mgal for an upper mantle density of 3.22 g/cm^3 beneath the Plateau. Consequently the choice of a lower crustal density of 2.8 g/cm^3 , as opposed to 2.94 g/cm^3 , will produce a lateral east-west error in field strength of about 53 mgal. This will then lead to error in assumed lateral density contrasts to account for the 53 mgal lateral offset in field strength. Further, the choice of 2.8 g/cm^3 , as opposed to 2.94 g/cm^3 , will produce about a 25 mgal greater uncertainty in the gravity field at $X = 380$ to 390 km.

Using the set of response function curves in figure 58, a set of relative Bouguer anomaly curves were produced, figure 59. The curves were produced by subtracting the curves in figure 58 from the

variable density Bouguer anomaly in figure 50. The curves in figure 59 are then the variable Bouguer anomalies produced by the various variable density Bouguer slabs, each 50 km thick comprised of a combination of the layer I model and the appropriate layer II model.

The only real change in the structure of the variable density Bouguer anomaly, after compensating for layer II, occurs in the vicinity of the Rio Grande rift. The large positive anomaly centered on the rift in the response functions of layer II has had a marked effect. The 46 mgal offset between the Lucero anomaly high and the eastern side of the rift, seen in figure 50, has been slightly reduced to 35 mgal. But the longer wavelength structure has changed such that the sharp low seen at the eastern-most edge of the rift in figure 50 has become more accentuated in figure 59. This is because the steepest gradients occurred between $X = 200$ and 300 km in figure 50 but the removal of the positive anomaly associated with crustal thinning just beneath the rift has shifted the steepest gradients to between $X = 300$ and 400 km. If one attempts to fit a rough straight line regional between say $X = 180$ and 400 km, the unexplained low associated with the eastern side of the rift is about 20 to 30 mgal, depending on which layer II model is used. One thing is clear: in order to properly investigate gravity anomalies on the order of 50 km or greater across the rift, one must consider crustal thinning beneath the rift.

Layer III - 50 To 200 Km Depth

Layer III, from 50 to 200 km depth includes both lithospheric mantle material and asthenospheric mantle material. It is assumed

Figure 59. Relative Bouguer anomaly produced from a variable density₃ Bouguer slab 50 km thick using all layer II models with a lower crustal density of 2.94 g/cm³.

that all lateral density variations below 200 km depth contribute very little to the structure of the surface gravity signal over a horizontal distance of 700 km. Such an assumption is very difficult to check. This assumption is implicit in all gravity models of the rift or Colorado Plateau produced to date: the Bridwell model (1976), the Thompson and Zoback model (1978), and the Decker and Smithson model (1975). It was also implicit in the Girdler model (1975) of the East African rift. Consequently, based on this assumption, if all lateral density variations have been accounted for (except for those density variations that produce short wavelength surface anomalies), then the proper layer III model response function when subtracted from the proper variable density Bouguer anomaly produced by layer I plus layer II will result in a flat Bouguer anomaly. The layer III models to be presented here indicate that the assumption is reasonable in that all lateral variations in the gravity field over the 700-km-long profile can be explained by lateral density variations at depths less than 120 km.

Based on deep seismic reflection studies, Archambeau et al. (1969) have suggested that major lateral structure variations exist only to a depth of possibly 200 km beneath North America. This work was based on two nuclear explosions, the Bilby and the Shoal, and one earthquake, the Fallon earthquake, at the Nevada Test Site. Their results indicate that a low velocity zone exists beneath the Colorado Plateau. The often quoted value for the Colorado Plateau lithosphere thickness of 80 km comes from this work (their figure 19, page 5846). But in fact, their work shows that extreme lateral structural variations exist beneath this region to depths up to 200 km and that the

low-velocity zone may be as shallow as 60 km (again their Fig 19, page 5846).

The thickness of the lithosphere has been inferred to be 100 km beneath the stable craton (Masse', 1973), based on a composite of 8 out of 10 major seismic reflection profiles radiating in all directions from the Early Rise chemical explosion detonated in Lake Superior in 1963. The two profiles not included in the study because of anomalous structure were designated ER8 and ER10. Profile ER8 runs from Lake Superior to the northeast corner of Colorado and profile ER10 runs from Lake Superior to the Mexican border of southwestern Texas. Profile ER8 suggests a very rapid thinning of the lithosphere to about a thickness of 60 km in northeast Nebraska (Masse', 1973). Green and Hales (1968) have studied three profiles using the Early Rise explosion. The three profiles were ER10, ER11, from Lake Superior to the Arkansas-Louisiana border passing through Little Rock, Arkansas and an arc profile at a radius of 1200 km from the Early Rise shot point from West Virginia to the Kansas-Nebraska border. The best fit model inferred from a composite of the data from these three profiles does not include a low-velocity zone, although the possible presence of a low-velocity zone was not ruled out. Dowling and Nuttli (1964) studied the low-velocity channel in the upper mantle for the U.S. using the same profiles from both the Bilby and the Gnome nuclear explosions. Their conclusions were that the top of the asthenosphere is at a depth of 70 km below northern Arizona and central New Mexico and a depth of 125 km, if the asthenosphere exists at all, below southern Oklahoma and western Arkansas.

As a consequence, some control on the thickness of the lithosphere beneath the Colorado Plateau exists for layer III modeling purposes. Based on these deep reflection seismic studies the lithosphere thickness for the Plateau is probably between 60 and 80 km. Further, it may seem reasonable to expect that the lithosphere is thickest toward the center of the Plateau and thins toward the Basin and Range Province where, again based on seismic studies, the lithosphere thickness is expected to be very close to the crustal thickness (Niazi and Anderson, 1965; Johnson, 1967). Unfortunately very little control on lithospheric thickness exists for the Great Plains. The fine structure on lithospheric thickness throughout the central U.S. is almost completely unknown. It is even possible that a low-velocity zone does not even exist at all (Green and Hales, 1968; Dowling and Nuttli, 1964; Jordan, 1979). For layer III modeling purposes, it will be assumed that the lithospheric thickness cannot be less than 90 km or greater than 120 km beneath eastern New Mexico and western Texas.

Some researchers have suggested that lateral structural heterogeneities may exist to considerably greater depths than 200 km beneath the continents. For instance, experimental isostasy studies performed by Lewis and Dorman (1970) suggest that the level of compensation for the continental U.S. may be at 700 km depth. This work was based on a local isostatic compensation model. A shallower level of compensation might be obtained by using a regional isostatic compensation model. A deep reflection seismic study based on $S_c S_1$ waves (nearly vertically traveling shear waves reflected once from the core-mantle boundary) performed by Sipkin and Jordan (1975) detected

a significant lateral structural heterogeneity between the oceanic upper mantle and the continental upper mantle to depths exceeding 400 km. This observation led Jordan to suggest the concept of the tectosphere (Jordan, 1979).

The tectosphere is defined to be that region of the crust and upper mantle occupied by the coherent mass known as plates. The lithosphere is then confined strictly to the uppermost layer of material having significant strength. Beneath the oceans the lithosphere and tectosphere are essentially the same. Beneath the continents the tectosphere may have significantly greater thickness than the lithosphere, the cratonic tectosphere having thicknesses of 400 km or greater. The tectosphere, in tectonically active regions such as along active continental margins, the Basin and Range Province, or Rio Grande rift, is expected to be considerably thinner than the tectosphere beneath the stable craton. Consequently it might be expected that the tectosphere thickens from west to east along the gravity profile. Jordan (1979) has hypothesized that the tectosphere is comprised of more viscous, less dense material than the rest of the upper mantle. Therefore, there may be a very long-wavelength regional gravity signal, more positive to the west, along the profile due to the variation in tectosphere thickness. Its magnitude is completely unknown and can only be assumed to be negligible at this time. If not negligible, its effect upon the analysis that follows will be to reduce the ratio of Great Plains lithosphere thickness to Colorado Plateau lithosphere thickness.

Looking ahead at the analysis, a 10 km change in lithospheric thickness beneath the Great Plains is accompanied by an almost 50

mgal change in the gravity field strength. As a first order calculation of the effect of the thickening tectosphere, assume the tectosphere is 50 km thick along the western coast at $X = -960$ km, 400 km thick in western Arkansas at $X = 1440$ km, and then thins again to 50 km along the eastern coast at $X = 2960$ km. This gives an 8.3° dip to the lower tectosphere boundary beneath the profile. According to the upper mantle density study performed by Press (1968, 1969), using the Monte Carlo method, the upper mantle has a maximum density contrast range of 0.1 g/cm^3 for any given depth down to 400 km. If a density contrast of -0.1 g/cm^3 is assumed for the tectosphere model, then the gravity field difference between $X = 0$ km and $X = 700$ km will be 331 mgal, based on two-dimensional modeling. This difference, if present, would be easily detectable, giving rise to a 65 km increase in lithospheric thickness beneath the Great Plains. This is not seen in the analysis. If a density contrast of -0.01 g/cm^3 is assumed for the tectosphere model, then the gravity field difference between $X = 0$ km and $X = 700$ km will be 33 mgal. This difference would give rise to less than a 10 km thickening of the lithosphere beneath the Great Plains. Such a thickening is permissible because the layer III models given below can tolerate an additional lithospheric thickness of 10 to 30 km beneath the Great Plains, depending upon the layer II model chosen, and still remain within the assumed limits. Based on this simplistic model, it would seem that if the tectosphere exists, its density contrast is less than about -0.01 to -0.03 g/cm^3 .

Eighteen different layer III models have been considered (models 11 and 16 are identical). These models are shown in figure 60 and their resulting response functions are shown in figures 61,

Figure 60. Layer III - asthenosphere models.

Figure 61. Gravity response functions of asthenosphere models 1 through 8.

62, and 63. The partitions for two-dimensional gravity modeling of the layer III models are given in Appendix D, Table D3. The first eight models investigate the geometry of the western lithosphere-asthenosphere boundary. The next 10 models investigate the geometry of the eastern lithosphere-asthenosphere boundary. For the first eight models a lithospheric thickness of 100 km was assumed beneath the Great Plains. This appears to be a very good assumption based on the results of models 9 through 13. The slope of the eastern lithosphere-asthenosphere boundary was assumed to be 23° for the first 13 models. This appears to be a reasonable assumption based on the results of models 14 through 19. The slope of the western lithosphere-asthenosphere boundary was assumed to be 23° for models 1 through 6 and 5° for models 7 and 8. The Colorado Plateau lithospheric thickness was assumed to be 100 km for models 1, 2, and 4, 80 km for models 3, 5, 7, and 8, and 65 km for model 6. Model 1 is essentially the Bridwell model (1976).

The response functions for models 1 through 8 are given in figure 61. The response functions for models 9 through 13 are given in figure 62. Attempting to match the curves in Figs 61 and 62 with the variable density Bouguer anomalies of figure 59 gives interesting results. The only layer III models that come close to fitting the western end of the curves in figure 59 are models 6 and 8. If model 6 is constrained to fit layer II curves B1, B2, D1, and D2, then the Great Plains lithosphere is constrained to be 100 km thick. For the layer II models G1 and H the Great Plains lithosphere must be 90 km thick. If model 6 is constrained to fit layer II models F1, F2, and F3, then the Great Plains lithosphere is constrained to be 90 km

Figure 62. Gravity response functions of asthenosphere models 9 through 13.

Figure 63. Gravity response functions for asthenosphere models 14 through 19.

thick. For layer II model G2 the lithosphere must be 80 km thick. If model 8 is used then the lithosphere beneath the Great Plains must be 2 or 3 km thinner for all cases.

Models 14 through 19 investigate the slope of the eastern lithosphere-asthenosphere boundary. These models all assume a lithospheric thickness of 100 km beneath the Great Plains and therefore only strictly apply to layer II model types B and D. The gravity response functions for these models are given in figure 63. Trying to match these curves with the curves in figure 59 suggests a slope of anywhere from about 20 to 80°. Again, the lack of control on the depth to the Moho around $X = 400$ km prevents obtaining greater precision on the dip of the eastern lithosphere-asthenosphere boundary. Therefore no further modeling of this dip using other Great Plains lithosphere thicknesses was done.

Although model 8 comes close to fitting the western end of the curves in figure 58, it is not a realistic model. The model has a continuous western lithospheric thickness of 80 km to $X = -10,000$ km. This was done to account for gravity edge effects. Unfortunately, the first point at which the model lithosphere reaches 80 km is at $X = -50$ km, over half way across the Colorado Plateau toward the Basin and Range. Consequently, only some type of layer III model similar to model 6 can accurately account for the gravity and seismic data assuming the densities used. All 18 of the layer III models have the asthenosphere coming to within 50 km of the surface beneath the Rio Grande rift. This constraint may be relaxed and still meet the requirements of the observed data. Beneath the rift the lithosphere-asthenosphere boundary can be pushed to 60 or perhaps 65 km,

but no deeper, and still meet the observed data. The effect of this would be to push the lithosphere thickness to 80 km beneath the Colorado Plateau and to 105 to 125 km beneath the Great Plains, depending on the layer II model assumed. Even with this constraint relaxed, the data require a layer III geometry similar to model 6.

This is a rather surprising result for three reasons. First, the lithosphere-asthenosphere boundary beneath the Colorado Plateau is required to be very different from that modeled by Bridwell at 36°N latitude. Secondly, the axis of the asthenospheric bulge appears to be at about $X = 190$ km rather than centered about the rift at $X = 300$ km, as the Bridwell model suggests. Thirdly, the depth to the lithosphere-asthenosphere boundary beneath the rift may be as deep as 60 or perhaps 65 km and still meet the requirements set by the data. The Bridwell model accounts for no lithospheric mantle material, placing the top of the asthenosphere at the base of the crust beneath the rift. Girdler (1975) did the same thing in his model of the East African rift. There is no evidence in the seismic or gravity data sets to demand that the top of the asthenosphere is at the base of the crust beneath the Rio Grande rift. A similar conclusion for the East African rift is likely because the gravity signature across both rifts are very similar (compare Girdler, 1975 and Cordell, 1978). This does not mean that the asthenosphere does not abut against the base of the crust beneath the rift at 34°40' or at 36°, only that there is no evidence that it does. In fact, one might expect such a condition to exist where the Rio Grande rift merges with the Basin and Range Province.

The results of the gravity analysis on Moho geometry and lithosphere/asthenosphere boundary geometry are summarized in figure 64.

Because the Bridwell model is located farther to the north along the Rio Grande rift, because a natural extension of this work would be to investigate profiles across the rift both to the north and to the south of 34°40' profile, because the Bridwell model gives such different results from those obtained here, and because the Bridwell model has been informally questioned by other researchers, I decided to re-do the Bridwell model. First I reconstructed the model as closely as possible, based on the model illustration in the Bridwell paper (1976). The two-dimensional model partitions are given in Appendix D, Table D4. The gravity response function results are given in figure 65. Encouragingly, the results were identical to those obtained by Bridwell. Next using data from the U.S. Defense Mapping Agency gravity data bank I produced the gravity profile across the rift at 36°N latitude. All available data within 10' of either side of 36° were used to produce the profile shown in figure 66. The actual data used is given in Appendix C, Table C3. The profile was disheartening. Only one data point was available between 107° and 109°W longitude, essentially across the entire San Juan basin. The gravity profile based on the DMA data did not look like the gravity profile shown in Bridwell's paper; only the short wavelength anomalies near the center of the rift were similar, whereas the flanks of the profile were quite dissimilar. If the short-wavelength anomalies near the rift's center are aligned in figures 65 and 66, one easily sees a 50 mgal discrepancy at 100°W longitude

Figure 64. Summary of possible bounds on Moho geometry and lithosphere/asthenosphere boundary geometry beneath the Rio Grande rift at 34°40'.

Figure 65. Gravity response function for the Bridwell (1976) crust/upper mantle, model at 36°N latitude across the Rio Grande rift.

between the two curves. On the western end of the line the DMA profile has an approximate slope of about 30 mgal/100 km dipping toward the rift between 109° and 110°W longitude, whereas the Bridwell profile has an approximate slope of 90 mgal/100 km dipping toward the rift. On the eastern end of the line, the DMA profile has an approximate slope of about 15 mgal/40 km dipping away from the rift between 103° and 104°W longitude, whereas the Bridwell profile has an approximate slope of 25 mgal/40 km dipping toward the rift! Bridwell (1976) claimed to have taken his profile from the gravity map of Woollard and Joestings (1964), shown in figure 24. I produced a gravity profile along 36°N latitude from the Woollard and Joestings map. This profile is shown in figure 67 and is essentially identical to the one produced from the DMA data. Therefore the flanks of the Bridwell profile bear very little resemblance to reality. Consequently the Bridwell model must be discounted. The actual DMA profile has a much flatter and lower magnitude gravity field for the Colorado Plateau portion. This strongly suggests a considerably thinner lithosphere beneath the Colorado Plateau than the Bridwell model indicates. It may also suggest a much wider asthenospheric bulge than the Bridwell model indicates. Before any real conclusions can be drawn about the nature of the lithosphere along this profile, gravity data must be collected between 107° and 108°W longitude and a detailed study must be performed.

Discussion

Isostatic considerations demand that the thinned lithosphere in west-central New Mexico be accompanied by high regional elevation.

Figure 66. Gravity profile at 36°N latitude across the Rio Grande rift made from U.S. Defense Mapping Agency data. Dots indicate data points.

Figure 67. Profile at 36°N latitude across the Rio Grande rift extrapolated from the Wollard and Joestings gravity map (1964) (Fig. 24). Dots indicate points taken from the 20 mgal contours of the Wollard and Joestings map.

This is indeed the case (see for example Cordell, 1978 or Eaton, 1979). In fact, the axis of the asthenospheric bulge coincides well with the axis of the lowest values of the simple Bouguer gravity anomaly, best seen in figure 24, and both of these axes coincide with the continental divide.

The unexpected result of a much wider asthenospheric bulge with an axis displaced over 100 km west of the the rift axis undoubtedly reflects on the genesis of the Rio Grande rift as well as the southeastern portion of the Colorado Plateau. Chapin (1971) has synthesized a model of rifting, suggesting that mantle convection gives rise to greater westward velocity of that portion of the continental plate west of the rift relative to that portion to the east. Through this process the Basin and Range Province is formed, with the rift resulting from the Colorado Plateau pulling away from the Great Plains. The thinning lithosphere gives rise to a bulge of lower density mantle material. The relatively thick crust to the east of the rift then rides up on the bulge creating the great structural relief seen to the east of the Rio Grande. The relatively subdued topography seen to the west, on the margin of the Colorado Plateau, is due to normal faulting accompanying crustal thinning caused by the westward movement of the Plateau away from the rift and bulge.

There are two possible explanations for the data and results presented here. The first explanation is that the entire bulge is directly related to discrete rifting. This possibility raises the question of which came first, the rift or the bulge? If the bulge occurred as a response to rifting as suggested by Chapin (1971), then a much narrower bulge, more axially symmetric about the rift, would

be expected. If, on the other hand, the bulge preceded the rift, then the non-alignment of the two axes is not surprising. North-trending asthenospheric bulging, due to a mantle heat source beneath the eastern edge of the Colorado Plateau, would produce large east-west-trending extensional stresses at the surface. Because the Colorado Plateau has appeared to act as a single competent unit throughout geologic time, the release of these stresses within the Plateau would be impeded by its inherent strength. This extensional stress would then propagate to the zone of nearest major crustal weakness for release. If the Rio Grande rift were a Paleozoic suture, as some researchers believe (Chapin and Seager, 1975; Eaton, 1979), then the suture would act as a locus of repeated crustal adjustment in response to such a regional stress, thus producing the observed rift. This model also offers an explanation for the most recent stress data. Zoback and Zoback (in press, 1980) have compiled the most recent map of least principle stress directions for the western United States. Their data include geologic data (mainly observations of fault slip and the alignment of volcanic vents and dikes), earthquake focal mechanisms, and in situ stress measurements. The map indicates that the axis of the asthenospheric bulge beneath western New Mexico is associated with present day east-west least principle stresses as is the Rio Grande rift. To the west of the bulge the modern least principle stress axes rotate to the north-northeast direction, i.e., roughly east-west compression.

The second explanation is that the asthenospheric bulge is primarily due to basin and range type crustal extension with the Jemez lineament acting as the southeastern boundary of the Colorado

Plateau. The Albuquerque-Belen basin may then be a transition between the rift north of the Jemez lineament and the Basin and Range Province to the south and southwest. Certainly the region of west-central New Mexico south of the Jemez lineament has many features in common with the Basin and Range Province. It is associated with crustal extension (Zoback and Zoback, in press, 1980), a thin lithosphere (this paper), high regional elevation (for example Cordell, 1978), and high heat flow (Edwards et al., 1978). Zoback and Zoback (in press, 1980) have included the Rio Grande rift, as well as much of west-central New Mexico, in the same stress environment as the Basin and Range Province. If this second explanation is correct, then the Jemez lineament is chosen as the probable southeastern boundary of the Colorado Plateau. This is because the model demands that the Colorado Plateau boundary must lie somewhere in the vicinity of the lineament and trend in a northeast direction and because geologic and geophysical data, described earlier in this paper, suggest that the lineament is a major active crustal boundary.

Both explanations would account for the observed data. Neither model is mutually exclusive of the other for they share common elements such as crustal extension and lithospheric thinning. It is possible that a more correct model may be a hybrid of the two models described above. A natural extension of this work would be to perform similar gravity investigations along other profiles across the rift both to the north and to the south of the 34°40' profile. Such investigations will most likely aid in refining the above models.

CHAPTER IX

CONCLUSIONS

Preliminary analysis of the regional deep MT investigations across the Jemez lineament indicate that the lineament between Mount Taylor and Springerville is associated with anomalously shallow, high-electrical conductivity. The detailed Zuni study indicates that in the vicinity of the lineament the lineament strongly influences the electrical strike direction within the crust.

At periods below about 100 s the electrical strike is either non-existent or aligns with the dominant surface structures with a mean strike of about N30°W. At periods above about 100 s the electrical strike rotates abruptly to a consistent and distinct N60°E and represents the electrical strike for the Precambrian metamorphic basement. The Jemez lineament trends N55°E. A two-dimensional model was developed from a 17 km long MT sounding profile perpendicular to electrical strike and consisting of eight soundings. The model predicted a depth of 800 m to electrical basement. This model is supported by data from a nearby well where depth to basement was measured at 767 m. Below 15 km the model indicates that the crust becomes much more conductive. The crustal conductive zone grades from less conductive (50 ohm-meters) to the northwest to more conductive (5 ohm-meters) to the southeast, in the direction of the Jemez lineament.

The fact that the lineament is defined by late Cenozoic volcanism suggests that the anomalously high electrical conductivity is due to magma intruded along the lineament. This conclusion, when

coupled with the conclusion by other researchers that the lineament is associated with an anomalously low P-wave velocity from 25 to 140 km depth measured between Mount Taylor and the Jemez Mountain, greater than normal heat flow, and may be associated with a crustal age boundary, strongly suggests that the Jemez lineament is a true structural feature rather than just a coincidental alignment of volcanic vents.

The Zuni volcanic field is one of the major volcanic fields of the Jemez lineament. The vents for the Zuni field parallel the eastern edge of a 90 km long, 20 km wide positive gravity anomaly with a maximum residual of 34 mgal. Ideal body calculations on the residual anomaly show that the anomalous body must have a maximum density contrast greater than 0.08 g/cm^3 , is buried no deeper than 5.25 km, and has a minimum thickness of 2 km. The anomalous body is interpreted to be a mafic intrusive. The age of emplacement is unknown. There is some suggestion that the intrusive predated and controlled the southern extent of the Nutria monocline, a Laramide feature.

The Lucero uplift is located on the southwestern margin of the Albuquerque-Belen basin. It is a Laramide uplift. There is a large positive residual gravity anomaly associated with the uplift. The anomaly maximum exceeds 25 mgal and is located on the rift-bounding Santa Fe fault. Ideal body calculations on the residual anomaly show that the anomalous body must have a maximum density contrast greater than 0.35 g/cm^3 , is buried no deeper than 1.25 km, and has a minimum thickness of 1.0 km. The anomalous body is interpreted to be a mafic intrusive. The emplacement of the intrusive has

probably been controlled by the Santa Fe fault. Several lines of evidence indicate a young age of intrusion, possibly less than 2 m.y. First, the Santa Fe fault has 3.5 km of Cenozoic stratigraphic offset that does not apparently affect the anomaly. Second, the eastern edge of the Lucero uplift is marked by the high topography of the Sierra Lucero suggesting young uplift centered on the gravity high. Third, recent doming of sediment fill found over the eastern part of the anomaly is indicated by topographically elevated unconsolidated rift-fill sediments and a heavily incised arcuate drainage. Finally, there is the suggestion that a 1 or 2 m.y. eruptive sequence was controlled by a north-northeast-trending hinge of the Lucero uplift, possibly activated by uplift caused by shallow intrusion.

Conduits for magma develop more easily at the intersection of major crustal features such as lineaments, faults, and/or intrusive bodies. The vent locations for the Zuni volcanic field occurred where a shallow intrusive body transects the Jemez lineament. Also, the Jemez volcanic field occurs at the intersection of the Rio Grande rift and the Jemez lineament. The emplacement of part, if not all, of the intrusive body has most probably been controlled by the intersection of the western rift-bounding fault and elements of a north-east-trending shear zone. The southern boundary of the intrusive appears to be controlled by the N55°E striking southwestern extension of the Tijeras lineament across the Rio Grande rift. The Tijeras lineament trends N55°E. The northern boundary of the gravity anomaly forms a conspicuous alignment of features trending N55°E: the north-western border of the Lucero gravity anomaly, the Cerro Colorado

intrusive dome, the Albuquerque volcano chain, and the northern truncation of the Sandia Mountains.

A good knowledge of lateral density contrasts is extremely important when applied to gravity analyses of geologic structures. Although some density data are available in the literature for various rock types and portions of the lithosphere and asthenosphere, specific reliable estimates are difficult to obtain. The density values used in this study are given in Table 2.

The two-dimensional gravity modeling of layer I, from the surface to 20 km depth, along the 34°40'N latitude profile shows that the standard Bouguer slab calculation can mask large amplitude short-wavelength anomalies that a well-constrained variable density Bouguer slab calculation may reveal. In the vicinity of the Rio Grande rift, the standard slab calculation masked over 65 mgal of an anomaly that the variable density slab calculation revealed. The mean difference between the two calculations, 8.6 mgal, was very small compared to the 150 to 200 mgal anomalies associated with Moho geometry and the additional 150 to 200 mgal anomalies associated with the lithosphere/asthenosphere boundary geometry across the rift. Consequently it is not necessary to produce a variable density Bouguer slab model if the intent is solely to investigate Moho geometry and the lithosphere/asthenosphere boundary in the upper mantle.

Investigation of geophysical constraints on Moho geometry and density for modeling of layer II, 20 km to 50 km depth, showed the following: Moho geometry is poorly constrained east of the rift around Vaughn, New Mexico; there are some suggestions that a lateral density contrast in the crust may exist between the Colorado Plateau

and the Great Plains; and that further xenolith studies may be helpful in constraining the geophysical modeling of layer II. The poor seismic constraint on the Moho geometry beneath Vaughn, New Mexico produces a maximum variation of 95 mgal in the layer II models considered. Several researchers have used a lower crustal density of 2.8 g/cm^3 ; however a density of 2.94 g/cm^3 appears more reasonable. The choice of 2.8 g/cm^3 , as opposed to 2.94 g/cm^3 , will produce a lateral east-west error of about 53 mgal. This error would then lead to further error in assumed lateral density contrasts. In addition, the choice of 2.8 g/cm^3 will produce about a 25 mgal greater uncertainty in the gravity field just west of Vaughn, New Mexico as compared to the uncertainty produced by a 2.94 g/cm^3 lower crust.

There is little seismic control on the lithosphere/asthenosphere boundary geometry. The lithosphere thickness is probably between 60 and 80 km beneath the Colorado Plateau and between 90 and 120 km beneath the Great Plains. With these constraints, layer III modeling, from 50 to 200 km depth, shows that the lithosphere beneath the rift can be no thicker than 65 km. There is no evidence in the seismic or gravity data to demand that the top of the asthenosphere be at the base of the crust beneath the Rio Grande rift, as suggested by previously published gravity models. The layer III gravity modeling indicated that the axis of the asthenospheric bulge beneath the rift at $34^{\circ}30'N$ latitude is about 110 km west of the rift. The eastern edge of the bulge is located about 60 km east of the rift center, while the western edge of the bulge is about 280 km west of the center of the rift. The bounds on the possible geometries for the Moho boundary and the lithosphere/asthenosphere

boundary are summarized in the generalized cross section shown in figure 64.

The result of a much wider asthenospheric bulge, with an axis displaced over 100 km west of the Rio Grande rift, was unexpected and must reflect on the genesis of the rift and the southern portion of the Colorado Plateau. Two possible explanations present themselves: (1) the entire asthenospheric bulge is directly related to the rift and the bulge precedes and creates the rift along an old north-trending Paleozoic suture, or (2) the asthenospheric bulge is primarily due to basin and range type crustal extension with the Jemez lineament, possibly acting as the southeastern boundary of the Colorado Plateau. If the second model is correct, then the Albuquerque-Belen basin may be the transition zone between the rift and the Basin and Range Province.

Linear programming applied to gravity ideal body theory was used to analyze the Chimney Hill and Lucero positive gravity high anomalies. This new analysis technique has proven to be an extremely valuable exploration tool. Using sparse and noisy data one may calculate absolute bounds on the density contrast and geometry of the causative body. Unlike the standard forward modeling or inversion approaches, which produce non-unique models, this technique gives valuable unique information about the causative body.

APPENDIX A

MAGNETOTELLURIC SOUNDING CURVES

Appendix A contains the eight MT sounding curves used to produce the two-dimensional electrical model shown in Fig. 21. This data was taken by Woodward-Clyde Consultants Inc. for Los Alamos Scientific Laboratory.

All the data points within each sounding curve are plotted with a 50% confidence error bar, unless the error bar height does not exceed the symbol height. The fitted curve is a least squares polynomial that may vary from third to eighth order. The determination of the xy and yx principal sets is arbitrary, but once chosen they are fixed within a recording band. The principal sets within a band are chosen so as to assure continuity of a curve's principal direction over all bands.

The mean skin depth, calculated from $\text{depth} = 0.5\sqrt{\rho T}$ at each data point, is smoothed by a fourth order polynomial fit, then printed for each resistivity set at progressive depths over the period range.

Figure 68. Apparent resistivity sounding curve for magnetotelluric station 25, remote referenced to station 27, Zuni hot dry rock prospect.

Figure 69. Apparent resistivity sounding curve for magnetotelluric station 27, remote referenced to station 25, Zuni hot dry rock prospect.

Figure 70. Apparent resistivity sounding curve for magnetotelluric station 29, remote referenced to station 63, Zuni hot dry rock prospect.

Figure 71. Apparent resistivity sounding curve for magnetotelluric station 57, remote referenced to station 23, Zuni hot dry rock prospect.

Figure 72. Apparent resistivity sounding curve for magnetotelluric station 59, remote referenced to station 61, Zuni hot dry rock prospect.

Figure 73. Apparent resistivity sounding curve for magnetotelluric station 87, remote referenced to station 53, Zuni hot dry rock prospect.

Figure 74. Apparent resistivity sounding curve for magnetotelluric station 89, remote referenced to station 88, Zuni hot dry rock prospect.

Figure 75. Apparent resistivity sounding curve for magnetotelluric station 91, remote referenced to station 93, Zuni hot dry rock prospect.

APPENDIX B

IDEAL BODY CALCULATIONS

The computer code used in performing the ideal body calculations consists primarily of a revised simplex algorithm (Gass, 1975) that has been written specifically for this problem and an algorithm for establishing a two-dimensional constraining region, which is divided into rectangular prisms. The following tables give the code input parameters used to build the necessary prisms and to obtain the solution, or objective function. In every case several different prism sizes and constraining regions were used. Only the solutions used in the preparation of the trade-off curves are shown in the tables. Experience obtained from running over 100 such calculations aided in choosing prism sizes and constraining regions that facilitated a very rapid convergence of the objective function. The accuracy of many of the final solutions were checked. It was found that in all cases the final accepted objective function was well within 5% of the true solution.

In the tables

- X = the distance from the origin to the data point in km
- B = the magnitude of the residual anomaly at the data point in mgal
- M = the designation number for a group of prisms all having the same size
- X0 = the starting point of each group of prisms in the x-direction in km

D = the depth of the upper bound of each group of prisms
in km

DX = the x-dimension of each prism in a particular group in
km

DZ = the z-dimension of each prism in a particular group in
km

NX = the number of prisms in a group in the x-direction

NZ = the number of prisms in a group in the z-direction

OF = the objective function in g/cm^3 .

TABLE B1

CHIMNEY HILL GRAVITY HIGH
PERFECT DATA CASE

$X(\text{km}) = 23.75 \quad 36.4 \quad 42.0 \quad 47.5 \quad 54.5 \quad 63.9 \quad 70.5$
 $B(\text{mgals}) = 9.15 \quad 26.71 \quad 32.61 \quad 33.53 \quad 18.77 \quad 7.59 \quad 3.15$

Trade-off Curve Point	M	X0 (km)	D (km)	DX (km)	DZ (km)	NX	NZ	OF(g/cm ³)
1	1	15.0	0.0	2.5	2.5	22	2	0.095
	2	15.0	5.0	2.5	5.0	22	1	
	3	15.0	10.0	5.0	5.0	11	2	
2	1	20.0	1.25	2.5	2.5	18	3	0.135
	2	20.0	8.75	2.5	5.0	18	1	
3	1	20.0	2.5	2.5	2.5	18	3	0.213
	2	20.0	10.0	2.5	5.0	18	1	
4	1	20.0	3.75	1.25	1.25	36	3	0.460
	2	32.5	7.50	2.5	5.0	9	1	
5	1	20.0	0.0	2.5	2.5	20	4	0.105
6	1	15.0	0.0	1.25	2.5	44	3	0.129
7	1	10.0	0.0	1.25	2.5	48	2	0.180
8	1	0.0	0.0	1.25	1.25	76	2	0.334
9	1	0.0	0.0	1.25	0.625	76	2	0.651
10	1	20.0	1.4	1.25	2.5	40	1	0.136
	2	20.0	3.9	2.5	2.5	20	5	
11	1	20.0	1.4	1.25	2.5	40	3	0.136
	2	20.0	8.9	2.5	2.5	20	1	
12	1	20.0	1.4	1.25	2.5	40	3	0.150
13	1	7.5	1.4	1.25	2.5	60	2	0.206
14	1	0.0	1.4	1.25	1.25	76	2	0.374

TABLE B1 (Cont.)

CHIMNEY HILL GRAVITY HIGH
PERFECT DATA CASE

X(km)	=	23.75	36.4	42.0	47.5	54.5	63.9	70.5
B(mgals)	=	9.15	26.71	32.61	33.53	18.77	7.59	3.15

Trade-off

Curve Point	M	X0 (km)	D (km)	DX (km)	DZ (km)	NX	NZ	OF (g/cm ³)
15	1	0.0	1.4	0.625	1.25	152	1	0.715

TABLE B2

CHIMNEY HILL GRAVITY HIGH
NOISY DATA CASE, 1 MGAL ERROR BAR ASSUMED

X (km) = 23.75 36.4 42.0 47.5 54.5 63.9 70.5
B (mgals) = 9.15 26.71 32.61 33.53 18.77 7.59 3.15

Trade-off Curve Point	M	X0 (km)	D (km)	DX (km)	DZ (km)	NX	NZ	OF (g/cm ³)
16	1	20.0	0.0	1.25	2.5	40	1	0.076
	2	20.0	2.5	2.5	2.5	20	3	
	3	20.0	10.0	2.5	5.0	20	1	
	4	20.0	15.0	5.0	5.0	10	2	
17	1	20.0	1.25	1.25	2.5	40	1	0.099
	2	20.0	3.75	2.50	2.5	20	3	
	3	20.0	11.25	2.50	5.0	20	1	
	4	20.0	16.25	5.0	5.0	10	2	
18	1	20.0	2.5	1.25	2.5	40	1	0.137
	2	20.0	5.0	2.5	2.5	20	3	
	3	20.0	12.5	2.5	5.0	20	1	
	4	20.0	17.5	5.0	5.0	10	1	
19	1	20.0	5.0	1.25	1.25	40	4	0.353
20	1	15.0	0.0	1.25	2.5	48	1	0.100
	2	15.0	2.5	2.5	2.5	24	3	
21	1	5.0	0.0	1.25	2.5	56	2	0.124
	2	5.0	5.0	2.50	2.5	28	1	
22	1	5.0	0.0	1.25	1.25	56	2	0.173
	2	5.0	2.5	1.25	2.5	56	1	
23	1	0.0	0.0	1.25	1.25	75	2	0.324
24	1	0.0	0.0	0.625	1.25	140	1	0.632

TABLE B2 (Cont.)

CHIMNEY HILL GRAVITY HIGH
NOISY DATA CASE, 1 MGAL ERROR BAR ASSUMED

X (km) = 23.75 36.4 42.0 47.5 54.5 63.9 70.5
B (mgals) = 9.15 26.71 32.61 33.53 18.77 7.59 3.15

Trade-off Curve Point		M	X0 (km)	D (km)	DX (km)	DZ (km)	NX	NZ	OF (g/cm ³)
25	1		20.0	1.4	1.25	2.5	40	1	0.096
	2		20.0	3.9	2.5	2.5	20	5	
26	1		20.0	1.4	1.25	2.5	40	1	0.093
	2		20.0	3.9	2.5	2.5	20	4	
27	1		7.5	1.4	1.25	2.5	50	2	0.112
	2		7.5	6.4	2.5	2.5	25	2	
28	1		7.5	1.4	1.25	2.5	50	3	0.138
29	1		0.0	1.4	1.25	2.5	76	2	0.192
30	1		0.0	1.4	1.25	1.25	76	2	0.355
31	1		0.0	1.4	0.625	1.25	152	1	0.683

TABLE B3

LUCERO GRAVITY ANOMALY, PROFILE AA'
PERFECT DATA CASE

X (km) = 30.0 42.5 44.0 52.75
 B (mgals) = 0.5 27.6 22.6 7.4

Trade-off Curve Point	M	XO (km)	D (km)	DX (km)	DZ (km)	NX	NZ	OF (g/cm ³)
1	1	37.5	0.0	0.625	0.625	28	5	0.353
	2	41.25	3.125	0.625	0.625	6	3	
2	1	37.5	0.25	0.625	0.5	28	5	0.445
	2	40.0	3.0	0.625	0.5	8	3	
3	1	37.5	0.55	0.625	0.5	28	5	0.586
4	1	37.5	0.75	0.5	0.5	35	4	0.816
5	1	37.5	1.0	0.5	0.5	35	4	1.299
6	1	37.5	0.0	0.625	0.5	28	5	0.359
7	1	37.5	0.0	0.5	0.5	35	4	0.396
8	1	37.5	0.0	0.5	0.5	35	3	0.485
9	1	25.0	0.0	0.5	0.5	80	2	0.690
10	1	0.0	0.0	1.25	0.25	76	2	1.338

TABLE B4

LUCERO GRAVITY ANOMALY, PROFILE AA'
 NOISY DATA CASE, 1 MGAL ERROR BAR ASSUMED

X (km) = 30.0 42.5 44.0 52.75
 B (mgals) = 0.5 27.6 22.6 7.4

Trade-off
 Curve

Point	M	X0 (km)	D (km)	DX (km)	DZ (km)	NX	NZ	OF (g/cm ³)
11	1	37.5	0.0	0.625	1.25	28	5	0.246
12	1	38.75	0.25	0.5	0.625	17	8	0.289
	2	51.5	0.25	0.5	0.5	6	3	
13	1	38.75	0.5	0.5	0.625	17	8	0.349
	2	51.5	0.5	0.5	0.5	6	3	
14	1	38.75	0.75	0.5	0.625	17	8	0.431
	2	51.5	0.75	0.5	0.5	6	3	
15	1	38.75	1.0	0.5	0.5	13	8	0.545
	2	51.5	1.0	0.5	0.5	6	3	
16	1	38.75	1.25	0.5	0.5	13	6	0.721
	2	51.5	1.25	0.5	0.5	6	3	
17	1	38.75	1.5	0.5	0.5	13	5	1.026
	2	50.0	1.5	0.5	0.5	9	2	
18	1	37.5	0.0	0.625	0.625	28	5	0.263
19	1	35.0	0.0	0.625	0.5	32	5	0.30
20	1	32.5	0.0	0.625	0.5	40	4	0.356
21	1	32.5	0.0	0.625	0.5	52	3	0.457
22	1	0.0	0.0	1.25	0.5	76	2	0.669
23	1	0.0	0.0	1.25	0.25	76	2	1.309

TABLE B5

LUCERO GRAVITY ANOMALY, PROFILE BB'
PERFECT DATA CASE

X (km) = 30.0 37.5 44.5 53.5
 B (mgals) = 2.7 17.7 15.4 0.5

Trade-off Curve Point	M	X0 (km)	D (km)	DX (km)	DZ (km)	NX	NZ	OF (g/cm ³)
1	1	28.75	0.0	0.625	0.625	30	5	0.227
2	1	28.75	0.25	0.625	0.5	30	5	0.297
3	1	28.75	0.5	0.625	0.5	30	5	0.416
4	1	29.0	0.75	0.5	0.5	37	4	0.659
5	1	29.0	1.0	0.5	0.5	37	4	1.341
6	1	29.0	0.0	0.5	0.5	37	4	0.235
7	1	29.0	0.0	0.5	0.5	47	3	0.300
8	1	0.0	0.0	1.25	0.5	76	2	0.435
9	1	0.0	0.0	1.25	0.25	76	2	0.853

TABLE B6

LUCERO GRAVITY ANOMALY, PROFILE BB'
 NOISY DATA CASE, 1 MGAL ERROR BAR ASSUMED

X (km) = 30.0 37.5 44.5 53.5
 B (mgals) = 2.7 17.7 15.4 0.5

Trade-off Curve Point	M	X0 (km)	D (km)	DX (km)	DZ (km)	NX	NZ	OF (g/cm ³)
10	1	28.75	0.0	0.625	1.25	30	5	0.135
11	1	28.75	0.25	0.625	1.25	30	5	0.162
12	1	32.5	0.5	0.625	0.625	24	6	0.194
	2	28.75	0.5	0.625	0.625	4	2	
13	1	32.5	0.75	0.625	0.625	24	6	0.243
	2	28.75	0.75	0.625	0.625	4	2	
14	1	32.5	1.0	0.625	0.625	24	5	0.322
	2	28.75	1.0	0.625	0.625	4	2	
15	1	32.5	1.25	0.5	0.5	30	5	0.458
	2	28.75	1.25	0.5	0.5	5	2	
16	1	32.5	1.5	0.5	0.5	30	5	0.748
	2	28.75	1.5	0.5	0.5	5	2	
17	1	32.5	1.75	0.5	0.25	30	5	1.483
	2	28.75	1.75	0.5	0.25	5	2	
18	1	27.5	0.0	0.625	0.625	40	4	0.183
19	1	25.0	0.0	0.625	0.5	48	3	0.289
20	1	0.0	0.0	1.25	0.5	76	2	0.420
21	1	0.0	0.0	1.25	0.25	76	2	0.828

TABLE B7

CERRO COLORADO GRAVITY ANOMALY, PROFILE CC'
PERFECT DATA CASE

X (km) = 30.0 34.5 35.75 38.75 42.5 45.0
 B (mgals) = 0.5 9.5 11.0 15.6 6.7 1.0

Trade-off

Curve Point	M	X0 (km)	D (km)	DX (km)	DZ (km)	NX	NZ	OF(g/cm ³)
1	1	32.5	0.0	0.625	0.5	24	5	0.262
2	1	32.5	0.25	0.5	0.5	30	4	0.429
3	1	32.5	0.5	0.5	0.5	23	4	1.100
4	1	32.5	0.0	0.5	0.5	30	3	0.287
5	1	32.5	0.0	0.5	0.5	30	2	0.402
6	1	17.5	0.0	0.5	0.25	80	2	0.766
7	1	2.5	0.0	0.5	0.25	160	1	1.504

TABLE B8

CERRO COLORADO GRAVITY ANOMALY, PROFILE CC'
 NOISY DATA CASE, 1 MGAL ERROR BAR ASSUMED

X (km) = 30.0 34.5 35.75 38.75 42.5 45.0
 B (mgals) = 0.5 9.5 11.0 15.6 6.7 1.0

Trade-off
 Curve

<u>Point</u>	<u>M</u>	<u>X0 (km)</u>	<u>D (km)</u>	<u>DX (km)</u>	<u>DZ (km)</u>	<u>NX</u>	<u>NZ</u>	<u>OF (g/cm³)</u>
8	1	32.5	0.0	0.625	0.625	20	8	0.163
9	1	32.5	0.25	0.625	0.625	20	8	0.210
10	1	32.5	0.5	0.625	0.625	20	5	0.303
11	1	32.5	0.75	0.5	0.5	25	5	0.549
12	1	32.5	1.0	0.5	0.25	22	6	1.631
13	1	32.5	0.0	0.625	0.625	24	5	0.165
14	1	30.0	0.0	0.625	0.5	28	4	0.212
15	1	22.5	0.0	0.625	0.5	48	3	0.268
16	1	0.0	0.0	1.25	0.5	76	2	0.382
17	1	0.0	0.0	1.25	0.25	76	2	0.737

APPENDIX C

GRAVITY DATA FOR PROFILES AT $34^{\circ}40'$ AND 36°N LATITUDE.

TABLE C1

GRAVITY DATA FOR NEW MEXICO STATE PROFILE AT 34°40'N LATITUDE

Data Bases

D = Defense Mapping Agency

L = Los Alamos Scientific Laboratory

No.	Data Base	X (km)	Latitude		Longitude		Elevation (m)	F.A.A. (mgals)	S.B.A. (mgals)
			(deg)	(min)	(deg)	(min)			
1	D	8.6	34	42.00	109	53.83	1628.9	-21.2	-203.5
2	D	23.8	34	42.95	109	43.80	1706.3	-14.3	-205.2
3	D	35.75	34	40.72	109	36.17	1743.5	-13.9	-209.0
4	D	42.8	34	41.86	109	31.68	1745.6	-15.7	-211.0
5	D	57.5	34	43.67	109	21.95	1761.8	-20.2	-217.4
6	D	67.8	34	43.73	109	15.25	1767.2	-17.2	-214.9
7	D	86.0	34	41.60	109	3.22	2070.9	+9.2	-222.3
8	D	94.1	34	42.45	108	58.01	2092.2	+5.4	-228.5
9	D	103.75	34	43.12	108	52.53	1998.0	-3.8	-227.4
10	D	110.9	34	44.38	108	46.93	2077.2	+2.3	-230.0
11	D	125.25	34	43.32	108	37.70	2132.1	+10.5	-227.9
12	D	133.4	34	42.04	108	32.27	2204.9	+25.4	-221.1
13	D	139.25	34	42.19	108	28.43	2215.6	+37.6	-210.2
14	D	145.4	34	43.10	108	24.38	2239.4	+44.0	-206.4
15	D	152.8	34	41.82	108	19.59	2259.8	+30.3	-222.4
16	D	160.5	34	44.55	108	14.53	2259.8	+26.0	-226.7
17	D	167.75	34	44.68	108	9.84	2229.3	+17.6	-231.6
18	D	180.25	34	42.14	108	1.66	2158.0	+2.6	-238.8
19	D	183.0	34	41.77	107	59.41	2158.3	+3.8	-237.5
20	D	185.5	34	43.96	107	57.90	2199.7	+14.8	-231.1
21	D	189.75	34	44.18	107	55.22	2197.6	+13.7	-232.1
22	D	207.0	34	43.23	107	43.73	2265.3	+27.0	-226.3
23	D	216.1	34	41.05	107	37.91	2213.5	+28.0	-219.5
24	D	221.15	34	42.35	107	34.64	2191.2	+30.9	-214.1
25	D	231.2	34	44.52	107	27.95	1809.6	+7.9	-194.4
26	D	244.0	34	44.85	107	19.44	1923.9	+23.9	-191.2
27	D	255.25	34	41.72	107	12.20	1919.3	+34.7	-179.9
28	D	263.6	34	41.83	107	6.86	1746.2	+15.2	-180.0
29	D	272.75	34	44.11	106	57.94	1545.6	-36.4	-209.3
30	D	286.0	34	42.60	106	51.90	1599.9	-42.8	-221.9
31	D	295.5	34	42.45	106	45.64	1468.5	-58.0	-222.7
32	D	310.0	34	42.46	106	36.19	1558.7	-49.7	-224.1
33	D	318.2	34	42.47	106	30.82	1723.3	+1.9	-190.8
34	D	322.75	34	42.23	106	27.85	1844.6	+11.5	-194.8
35	L	328.0	34	42.10	106	24.05	2855.37	+123.6	-196.4
36	D	333.75	34	41.91	106	20.42	2111.9	+56.3	-179.9
37	L	338.25	34	40.80	106	17.27	2034.84	+37.3	-190.3

TABLE C1 (Cont.)

No.	Data Base	X (km)	Latitude		Longitude		Elevation (m)	F.A.A. (mgals)	S.B.A. (mgals)
			(deg)	(min)	(deg)	(min)			
38	D	343.25	34	40.89	106	14.17	1960.2	+20.7	-198.6
39	L	348.20	34	40.85	106	11.05	1926.34	+25.0	-190.5
40	D	354.50	34	42.63	106	7.84	1883.1	+25.4	-185.1
41	D	359.25	34	40.90	106	3.63	1862.3	+20.5	-187.7
42	D	364.25	34	40.89	106	0.46	1852.6	+16.6	-190.5
43	L	379.00	34	40.85	105	51.00	1863.24	+13.1	-195.4
44	D	384.25	34	41.00	105	47.00	1900.7	+19.6	-192.9
45	L	389.75	34	40.82	105	43.65	1932.74	+30.6	-185.6
46	L	397.5	34	40.50	105	38.60	1970.84	+41.2	-179.2
47	L	401.70	34	40.25	105	35.40	1940.97	+46.1	-171.0
48	L	406.75	34	39.75	105	32.43	1889.6	+45.8	-165.6
49	L	414.50	34	39.95	105	27.29	1866.29	+40.9	-167.8
50	L	422.0	34	41.05	105	22.70	1940.66	+50.0	-167.1
51	L	436.3	34	39.80	105	14.20	1780.34	+23.9	-175.2
52	L	448.25	34	40.30	105	5.95	1690.4	+0.9	-188.2
53	L	480.0	34	40.65	104	44.65	1508.8	-16.0	-184.7
54	L	491.25	34	38.85	104	37.22	1479.2	-15.9	-181.3
55	L	501.0	34	38.84	104	30.85	1402.4	-24.8	-181.7
56	L	515.75	34	40.72	104	21.20	1334.4	-30.5	-179.8
57	L	520.2	34	40.65	104	15.75	1382.6	-25.4	-180.0
58	L	545.8	34	39.15	104	01.15	1497.2	-4.9	-172.4
59	L	556.9	34	40.70	103	54.00	1431.3	-8.5	-168.6
60	L	570.25	34	41.50	103	46.50	1436.5	-5.9	-166.6
61	L	581.25	34	40.65	103	38.15	1440.8	+1.2	-159.9
62	L	594.15	34	38.00	103	29.70	1395.4	+1.8	-154.3
63	L	605.25	34	38.00	103	22.30	1414.9	+0.4	-157.8
64	L	619.75	34	39.60	103	12.80	1358.8	-1.9	-153.9
65	D	637.75	34	44.24	103	00.96	1333.2	-3.4	-152.5
66	D	663.5	34	44.52	102	44.07	1234.4	-18.8	-156.8
67	D	684.75	34	44.50	102	30.15	1198.2	-20.3	-154.3
68	D	706.9	34	44.45	102	15.47	1173.5	-21.4	-152.7
69	D	730.5	34	44.58	102	00.18	1132.9	-17.8	-144.5

TABLE C2

MODELING RESULTS FOR THE VARIABLE DENSITY BOUGUER SLAB
ALONG THE 34°40'N LATITUDE GRAVITY PROFILE

Data Bases

D = Defense Mapping Agency

L = Los Alamos Scientific Laboratory

No.	X (km)	<u>Longitude</u>		F.A.A. (mgals)	Layer I Model Gravity	Variabl Density B.A.
		(deg)	(min)			
1	8.6	109	53.83	-21.2	179.3	-200.5
2	23.8	109	43.80	-14.3	187.7	-202.0
3	35.75	109	36.17	-13.9	191.7	-205.6
4	42.8	109	31.68	-15.7	191.9	-207.6
5	57.5	109	21.95	-20.2	193.7	-213.9
6	67.8	109	15.25	-17.2	194.2	-211.4
7	86.0	109	3.22	+9.2	226.0	-216.8
8	94.1	108	58.01	+5.4	227.5	-222.1
9	103.75	108	52.53	-3.8	218.2	-222.0
10	110.9	108	46.93	+2.3	226.2	-223.9
11	125.25	108	37.70	+10.5	231.9	-221.4
12	133.4	108	32.27	+25.4	239.2	-213.8
13	139.25	108	28.43	+37.6	240.4	-202.8
14	145.4	108	24.38	+44.0	242.8	-198.8
15	152.8	108	19.59	+30.3	244.9	-214.6
16	160.5	108	14.53	+26.0	244.8	-218.8
17	167.75	108	9.84	+17.6	241.7	-224.1
18	180.25	108	1.66	+2.6	234.3	-231.7
19	183.0	107	59.41	+3.8	234.3	-230.5
20	185.5	107	57.90	+14.8	238.4	-223.6
21	189.75	107	55.22	+13.7	238.1	-224.4
22	207.0	107	43.73	+27.0	244.5	-217.5
23	216.1	107	37.91	+28.0	239.4	-211.4
24	221.15	107	34.64	+30.9	237.0	-206.1
25	231.2	107	27.95	+7.9	196.1	-188.2
26	244.0	107	19.44	+23.9	209.2	-185.3
27	255.25	107	12.20	+34.7	207.6	-172.9
28	263.6	107	6.86	+15.2	182.8	-167.6
29	272.75	106	57.94	-36.4	106.5	-142.9
30	286.0	106	51.90	-42.8	110.5	-153.3
31	295.5	106	45.64	-58.0	111.1	-169.1
32	310.0	106	36.19	-49.7	143.1	-192.9
33	318.2	106	30.82	+1.9	182.3	-180.4
34	322.75	106	27.85	+11.5	197.1	-185.6
35	328.0	106	24.05	+123.6	301.0	-177.4
36	333.75	106	20.42	+56.3	231.5	-175.2
37	338.25	106	17.27	+37.3	224.1	-186.8

TABLE C2 (Cont.)

No.	X (km)	Longitude		F.A.A. (mgals)	Layer I Model Gravity	Variabl Density B.A.
		(deg)	(min)			
38	343.25	106	14.17	+20.7	215.9	-195.2
39	348.20	106	11.05	+25.0	211.8	-186.8
40	354.50	106	7.84	+25.4	206.5	-181.1
41	359.25	106	3.63	+20.5	203.8	-183.3
42	364.25	106	0.46	+16.6	201.9	-185.3
43	379.00	105	51.00	+13.1	200.8	-187.7
44	384.25	105	47.00	+19.6	205.0	-185.4
45	389.75	105	43.65	+30.6	211.7	-181.1
46	397.5	105	38.60	+41.2	219.3	-178.1
47	401.70	105	35.40	+46.1	212.7	-166.6
48	406.75	105	32.43	+45.8	204.7	-158.9
49	414.50	105	27.29	+40.9	201.7	-160.8
50	422.0	105	22.70	+50.0	209.3	-159.3
51	436.3	105	14.20	+23.9	191.5	-167.6
52	448.25	105	5.95	+0.9	181.4	-180.5
53	480.0	104	44.65	-16.0	160.7	-176.7
54	491.25	104	37.22	-15.9	157.0	-172.9
55	501.0	104	30.85	-24.8	148.4	-173.2
56	515.75	104	21.20	-30.5	140.5	-171.1
57	520.2	104	15.75	-25.4	145.6	-171.0
58	545.8	104	01.15	-4.9	158.1	-163.0
59	556.9	103	54.00	-8.5	151.2	-159.7
60	570.25	103	46.50	-5.9	151.8	-157.7

TABLE C3

GRAVITY DATA FOR NEW MEXICO STATE PROFILE AT 36°N LATITUDE

Data Bases
D = Defense Mapping Agency

No.	Data Base	X (km)	Latitude		Longitude		Elevation (m)	F.A.A. (mgals)	S.B.A. (mgals)
			(deg)	(min)	(deg)	(min)			
1	D	4.5	36	4.36	-109	57.18	1949.0	+28.0	-189.9
2	D	18.0	36	3.43	-109	48.55	1838.1	+24.2	-181.3
3	D	36.0	36	4.00	-109	36.10	1769.1	+16.1	-181.7
4	D	44.25	35	56.20	-109	30.60	1810.5	+26.5	-175.9
5	D	55	36	3.70	-109	23.50	2059.2	+41.3	-188.9
6	D	60	36	0.60	-109	20.00	2144.6	+35.3	-204.5
7	D	64.5	35	57.70	-109	17.00	2377.1	+54.2	-211.6
8	D	73.5	36	4.63	-109	11.00	2214.4	+45.7	-201.9
9	D	79.5	36	1.34	-109	6.94	2264.4	+58.6	-194.5
10	D	87.0	36	4.00	-109	2.00	2215.9	+52.9	-194.8
11	D	121.0	36	3.70	-108	40.70	1786.7	-18.2	-218.1
12	D	276.0	36	0.10	-106	56.00	2192.1	+7.0	-238.0
13	D	284.2	36	0.79	-106	50.64	2919.3	+108.0	-218.6
14	D	289.5	36	0.17	-106	47.01	2602.9	+84.4	-206.8
15	D	295.5	36	0.03	-106	42.92	2598.1	+78.1	-212.6
16	D	302.0	35	59.60	-106	38.60	2596.9	+61.1	-229.3
17	D	307.15	36	0.21	-106	35.20	2880.3	+76.1	-246.1
18	D	319.0	36	0.49	-106	27.39	2895.6	+62.0	-262.0
19	D	325.5	36	0.45	-106	23.03	3523.7	+111.4	-282.8
20	D	335.5	36	0.15	-106	16.32	2119.2	-8.0	-245.1
21	D	345.75	36	0.35	-106	9.59	2015.3	-30.8	-256.3
22	D	354.25	36	0.36	-106	3.87	1709.0	-51.8	-243.0
23	D	360.5	35	59.82	-105	59.62	1779.7	-32.7	-231.8
24	D	366.5	36	0.11	-105	55.71	1895.9	-1.9	-214.1
25	D	374.0	36	1.51	-105	50.78	2245.7	+39.6	-211.6
26	D	379.5	35	59.35	-105	47.04	2624.6	+82.2	-211.3
27	D	387.0	36	0.59	-105	42.05	2954.7	+107.4	-223.1
28	D	408.0	36	4.80	-105	28.00	2883.4	+73.8	-248.7

TABLE C3 (Cont.)

No.	Data Base	X (km)	<u>Latitude</u> (deg) (min)		<u>Longitude</u> (deg) (min)		Elevation (m)	F.A.A. (mgals)	S.B.A. (mgals)
29	D	417.5	35	59.13	-105	21.76	2236.6	+10.1	-240.0
30	D	422.5	35	58.13	-105	18.36	2167.7	+4.6	-237.7
31	D	427.75	35	56.63	-105	14.87	2147.9	+4.5	-235.6
32	D	432.5	36	1.72	-105	11.70	2290.6	+13.9	-242.3
33	D	440.0	36	2.42	-105	6.66	2269.5	+22.5	-231.3
34	D	445.5	36	0.90	-105	3.06	2208.0	+29.3	-217.5
35	D	449.25	36	4.34	-105	0.54	2220.8	+26.6	-221.7
36	D	459.0	36	1.65	-104	54.03	2155.2	+37.4	-203.6
37	D	466.5	36	1.19	-104	48.96	1995.8	+18.0	-205.2
38	D	477.0	36	0.40	-104	42.00	1889.5	+1.1	-210.2
39	D	483.0	36	2.66	-104	37.95	1928.5	+9.6	-206.0
40	D	492.0	36	0.80	-104	32.69	1901.3	+23.9	-188.6
41	D	497.5	35	58.96	-104	28.26	1885.3	+41.7	-169.1
42	D	504.75	35	56.64	-104	23.52	1717.7	+29.2	-169.9
43	D	511.0	36	3.30	-104	19.35	1768.3	+40.5	-157.2
44	D	519.0	36	2.76	-104	14.08	1850.7	+42.2	-164.7
45	D	526.0	36	1.38	-104	9.27	1821.9	+46.0	-157.7
46	D	533.5	36	1.85	-104	4.30	1746.6	+43.0	-152.3
47	D	545.5	35	59.75	-103	56.20	1688.9	+46.2	-142.6
48	D	555.75	36	0.17	-103	49.44	1656.9	+45.3	-139.9
49	D	566.25	36	0.00	-103	42.35	1414.3	+21.4	-139.7
50	D	576.75	36	2.95	-103	35.60	1462.6	+23.8	-139.7
51	D	586.0	36	0.39	-103	29.28	1483.8	+26.8	-139.1
52	D	597.25	35	59.92	-103	21.88	1494.1	+23.5	-143.5
53	D	603.75	35	59.92	-103	17.59	1454.8	+12.6	-150.0
54	D	611.5	36	0.50	-103	12.20	1407.0	+5.9	-151.3
55	D	618.0	36	0.80	-103	7.90	1375.9	-7.7	-161.6
56	D	638.5	35	58.96	-102	54.32	1314.8	-17.4	-164.5
57	D	648.25	35	59.02	-102	47.83	1266.8	-17.9	-159.7
58	D	673.5	36	4.0	-102	31.00	1219.2	-22.2	-158.7
59	D	719.25	36	3.22	-102	0.40	1104.9	-25.5	-149.1

APPENDIX D

GRAVITY MODEL PARAMETERS

Tables D1, D2, and D3 contain the gravity model parameters, used in the Talwani code (Talwani et al., 1953), to produce the models for layers I, II, and III respectively. Table D4 contains the gravity model parameters used to reproduce Bridwell's (Bridwell, 1976) gravity model of the crust and upper mantle at 36°N latitude across the Rio Grande rift. All the densities are in g/cm^3 and all the distances are in km. The vertical z-axis has its origin at sea level and is positive downward.

TABLE D1

DENSITY MODEL PARAMETERS FOR STRATIGRAPHIC COLUMN

All densities in g/cm^3 , all distances in km.

Block #1 $\rho = 2.40$		247.5	-0.6401	Block #6 $\rho = -0.27$	
x	z	218.0	-0.7010	x	z
85.0	-2.0422	69.0	-1.0668	266.0	+1.3716
86.0	-2.0709	-100.0	-1.0668	275.0	+0.9144
94.1	-2.0922	-100.0	-1.6459	275.0	+1.6154
103.75	-1.9980			266.15	+1.7069
110.9	-2.0772	Block #3 $\rho = 2.67$		266.0	+1.3716
125.25	-2.1321	x	z	Block #7 $\rho = -0.1$	
133.4	-2.2049	-100.0	-1.0668	x	z
139.25	-2.2156	69.0	-1.0668	266.15	+1.7069
145.4	-2.2394	218.0	-0.7010	275.0	+1.6154
152.8	-2.2598	245.5	-0.6401	275.0	+2.1946
160.5	-2.2598	265.0	-1.7374	266.25	+2.2860
167.75	-2.2293	265.75	0.0	266.15	+1.7069
180.25	-2.1580	-100.0	0.0	Block #8 $\rho = -0.27$	
183.0	-2.1583	-100.0	-1.0668	x	z
185.5	-2.1997	Block #4 $\rho = 2.2$		275.0	+1.8288
189.75	-2.1976	x	z	296.25	+1.4326
207.0	-2.2653	265.0	-1.7374	296.25	+1.9812
216.1	-2.2135	276.75	-1.5456	275.0	+2.7432
221.15	-2.1912	286.0	-1.5999	275.0	+1.8288
223.0	-2.1336	295.5	-1.4685	Block #9 $\rho = -0.1$	
206.0	-2.0422	310.0	-1.5587	x	z
152.5	-2.0726	315.0	-1.6459	275.0	+2.7432
88.5	-1.8898	315.0	-0.9144	296.25	+1.9812
85.0	-2.0422	315.0	-0.2742	296.25	+2.7432
Block #2 $\rho = 2.57$		296.25	0.0	275.0	+3.2766
x	z	265.75	0.0	275.0	+2.7432
-100.0	-1.6459	265.0	-1.7374	Block #10 $\rho = 2.40$	
0.0	-1.6459	Block #5 $\rho = -0.47$		x	z
8.6	-1.6289	x	z	296.25	0.0
23.8	-1.7063	265.75	0.0	315.0	-2.2742
35.75	-1.7435	296.25	0.0	315.0	-0.1524
42.8	-1.7456	296.25	+1.4326	306.25	0.0
57.5	-1.7618	275.0	+1.8288	296.25	0.0
67.8	-1.7672	275.0	+0.9144	Block #11 $\rho = -0.27$	
85.0	-2.0422	266.0	+1.3716	x	z
88.5	-1.8898	265.75	0.0	296.25	0.0
152.5	-2.0726			306.25	0.0
206.0	-2.0422			296.25	+0.2286
223.0	-2.1336			296.25	0.0
231.2	-1.8096				
244.0	-1.9239				
255.25	-1.9193				
263.6	-1.7462				
265.0	-1.7374				

TABLE D1 (Cont.)

Block #12 $\rho = 2.57$

x	z
306.25	0.0
315.0	-0.1524
315.0	0.0
306.25	0.0

Block #13 $\rho = -0.1$

x	z
296.25	+0.2286
306.25	0.0
315.0	0.0
315.0	+0.2134
296.25	+0.8534
296.25	+0.2286

Block #14 $\rho = 2.2$

x	z
317.25	-1.7069
318.2	-1.7232
322.75	-1.8446
324.0	-1.9202
321.75	-1.7374
317.25	-1.7069

Block #15 $\rho = 2.57$

x	z
315.0	-1.6459
317.25	-1.7069
321.75	-1.7374
324.0	-1.9202
323.75	-1.1278
315.0	-0.9144
315.0	-1.6459

Block #16 $\rho = 2.57$

x	z
327.5	-2.71272
328.0	-2.85537
333.75	-2.1119
338.25	-2.03484
343.25	-1.9602
348.20	-1.92634
354.50	-1.88831
359.25	-1.8623
364.25	-1.8526
379.0	-1.86324
384.25	-1.9007
389.75	-1.93274
390.5	-1.9507

388.5	-0.1
374.75	-0.09144
361.5	0.9144
348.5	-1.3045
337.5	-1.7069
330.0	-2.1641
327.5	-2.7127

Block #17 $\rho = -0.1$

x	z
441.5	0.0
2000.0	0.0
2000.0	+1.1582
633.75	+1.1582
612.25	+0.7925
590.0	+1.0973
580.0	+0.5791
521.5	+0.7620
441.5	0.0

Block #18 $\rho = 2.67$

x	z
315.0	-0.9144
323.75	-1.1278
324.0	-1.9202
327.5	-2.7127
330.0	-2.1641
337.5	-1.7069
348.5	-1.3045
361.5	-0.9144
374.75	-0.0914
388.5	-0.1
390.5	-1.9507
397.5	-1.97084
401.5	-1.9507
401.75	-0.4267
441.5	0.0
315.0	0.0
315.0	-0.9144

Block #19 $\rho = 2.57$

x	z
401.5	-1.9507
401.7	-1.94097
406.75	-1.8896
414.5	-1.86629
422.0	-1.94066
436.3	-1.78034
448.25	-1.6904
480.0	-1.5088

491.25	-1.4792
501.0	-1.4024
515.75	-1.3344
520.2	-1.3826
545.8	-1.4972
556.9	-1.4313
570.25	-1.43652
581.25	1.4408
594.15	-1.3954
605.25	-1.4149
619.75	-1.3588
637.75	-1.3332
663.5	-1.2344
684.75	-1.1982
706.9	-1.1735
730.5	-1.1329
2000.0	-1.1329
2000.0	0.0
441.5	0.0
401.75	-0.4267
401.5	-1.9507

TABLE D2

DENSITY MODEL PARAMETERS FOR LAYER II MODELS

All densities in g/cm^3 , all distances in km.MODEL: A1-6
Block #1 $\rho = 0.13$

x	z
-1000	20
2000	20
2000	50
600	50
335	32
260	32
250	40
-1000	40
-1000	20

Block #2 $\rho = 0.68$

x	z
-1000	40
250	40
260	32
335	32
600	50
-1000	50
-1000	40

MODEL: A2-4
Block #1 $\rho = 0.13$

x	z
-1000	20
2000	20
2000	50
333	50
310	32
270	32
250	40
-1000	40
-1000	20

Block #2 $\rho = 0.68$

x	z
-1000	40
250	40
270	32
310	32
333	50
-1000	50
-1000	40

MODEL: A2-5
Block #1 $\rho = 0.13$

x	z
-1000	20
2000	20
2000	50
343	50
320	32
270	32
250	40
-1000	40
-1000	20

Block #2 $\rho = 0.68$

x	z
-1000	40
250	40
270	32
320	32
343	50
-1000	50
-1000	40

MODEL: A2-6
Block #1 $\rho = 0.13$

x	z
-1000	20
2000	20
2000	50
600	50
335	32
270	32
250	40
-1000	40
-1000	20

Block #2 $\rho = 0.68$

x	z
-1000	40
250	40
270	32
335	32
600	50
-1000	50
-1000	40

MODEL: A2-7
Block #1 $\rho = 0.13$

x	z
-1000	20
2000	20
2000	50
360	50
310	32
270	32
250	40
-1000	40
-1000	20

Block #2 $\rho = 0.68$

x	z
-1000	40
250	40
270	32
310	32
360	50
-1000	50
-1000	40

MODEL: A2-8
Block #1 $\rho = 0.13$

x	z
-1000	20
2000	20
2000	50
600	50
330	40
310	32
270	32
250	40
-1000	40
-1000	20

TABLE D2 (Cont.)

MODEL: A3-6
Block #1 $\rho = 0.13$

x	z
-1000	20
2000	20
2000	50
600	50
335	32
270	32
260	40
-1000	40
-1000	20

Block #2 $\rho = 0.68$

x	z
-1000	40
260	40
270	32
335	32
600	50
-1000	50
-1000	40

MODEL B1
Block #1 $\rho = 0.27$

x	z
-1000	20
2000	20
2000	50
360	50
310	32
270	32
250	40
-1000	40
-1000	20

Block #2 $\rho = 0.68$

x	z
-1000	40
250	40
270	32
310	32
360	50
-1000	50
-1000	40

MODEL: B2
Block #1 $\rho = 0.27$

x	z
-1000	20
2000	20
2000	50
600	50
330	40
310	32
270	32
250	40
-1000	40
-1000	20

Block #2 $\rho = 0.68$

x	z
-1000	40
250	40
270	32
310	32
330	40
600	50
-1000	50
-1000	40

MODEL: C1
Block #1 $\rho = 0.13$

x	z
-1000	20
2000	20
2000	50
360	50
310	32
270	32
250	40
-1000	40
-1000	20

Block #2 $\rho = 0.68$

x	z
-1000	40
250	40
225	50
-1000	50
-1000	40

Block #3 $\rho = 0.55$

x	z
225	50
250	40
270	32
310	32
360	50
225	50

MODEL: C2
Block #1 $\rho = 0.13$

x	z
-1000	20
2000	20
2000	50
600	50
330	40
310	32
270	32
250	40
-1000	40
-1000	20

Block #2 $\rho = 0.68$

x	z
-1000	40
250	40
225	50
-1000	50
-1000	40

Block #3 $\rho = 0.55$

x	z
225	50
250	40
270	32
310	32
330	40
360	50
225	50

Block #4 $\rho = 0.68$

x	z
330	40
600	50
360	50
330	40

TABLE D2 (Cont.)

Block #4 $\rho = 0.68$

x	z
330	40
600	50
360	50
330	40

MODEL: D1

Block #1 $\rho = 0.27$

x	z
-1000	20
2000	20
2000	50
360	50
310	32
270	32
250	40
-1000	40
-1000	20

Block #2 $\rho = 0.68$

x	z
-1000	40
250	40
225	50
-1000	50
-1000	40

Block #3 $\rho = 0.55$

x	z
225	50
250	40
270	32
310	32
360	50
225	50

MODEL: D2

Block #1 $\rho = 0.27$

x	z
-1000	20
2000	20
2000	50
600	50
330	40
310	32
270	32
250	40
-1000	40
-1000	20

Block #2 $\rho = 0.68$

x	z
-1000	40
250	40
225	50
-1000	50
-1000	40

Block #3 $\rho = 0.55$

x	z
225	50
250	40
270	32
310	32
330	40
360	50
225	50

Block #4 $\rho = 0.68$

x	z
330	40
600	50
360	50
330	40

MODEL: E1

Block #1 $\rho = 0.13$

x	z
-1000	20
2000	20
2000	50
360	50
310	32
270	32
250	40
-1000	40
-1000	20

Block #2 $\rho = 0.55$

x	z
-1000	40
250	40
270	32
310	32
360	50
-1000	50
-1000	40

MODEL: E2

Block #1 $\rho = 0.13$

x	z
-1000	20
2000	20
2000	50
600	50
330	40
310	32
270	32
250	40
-1000	40
-1000	20

Block #2 $\rho = 0.55$

x	z
-1000	40
250	40
270	32
310	32
360	50
-1000	50
-1000	40

Block #3 $\rho = 0.68$

x	z
330	40
600	50
360	50
330	40

MODEL: E3

Block #1 $\rho = 0.13$

x	z
-1000	20
2000	20
2000	50
600	50
330	40
310	32
270	32
250	40
-1000	40
-1000	20

TABLE D2 (Cont.)

Block #2 $\rho = 0.55$

x	z
-1000	40
250	40
270	32
310	32
330	40
600	50
-1000	50
-1000	40

MODEL: F1
Block #1 $\rho = 0.27$

x	z
-1000	20
2000	20
2000	50
360	50
310	32
270	32
250	40
-1000	40
-1000	20

Block #2 $\rho = 0.55$

x	z
-1000	40
250	40
270	32
310	32
360	50
-1000	50
-1000	40

MODEL: F2
Block #1 $\rho = 0.27$

x	z
-1000	20
2000	20
2000	50
600	50
330	40
310	32
270	32
250	40
-1000	40
-1000	20

Block #2 $\rho = 0.55$

x	z
-1000	40
250	40
270	32
310	32
360	50
-1000	50
-1000	40

Block #3 $\rho = 0.68$

x	z
330	40
600	50
360	50
330	40

MODEL: F3
Block #1 $\rho = 0.27$

x	z
-1000	20
2000	20
2000	50
600	50
330	40
310	32
270	32
250	40
-1000	40
-1000	20

Block #2 $\rho = 0.55$

x	z
-1000	40
250	40
270	32
310	32
330	40
600	50
-1000	50
-1000	40

MODEL: G1
Block #1 $\rho = 0.27$

x	z
-1000	20
2000	20
2000	40
330	40
310	32
270	32
250	40
-1000	40
-1000	20

Block #2 $\rho = 0.41$

x	z
300	40
2000	40
2000	50
360	50
330	40

Block #3 $\rho = 0.68$

x	z
-1000	40
250	40
270	32
310	32
330	40
360	50
-1000	50
-1000	40

MODEL: G2
Block #1 $\rho = 0.27$

x	z
-1000	20
2000	20
2000	40
330	40
310	32
270	32
250	40
-1000	40
-1000	20

TABLE D2 (Cont.)

Block #2 $\rho = 0.41$

x	z
330	40
2000	40
2000	50
360	50
330	40

Block #4 $\rho = 0.68$

x	z
-1000	40
250	40
225	50
-1000	50
-1000	40

Block #3 $\rho = 0.55$

x	z
-1000	40
250	40
270	32
310	32
330	40
360	50
-1000	50
-1000	40

MODEL: H

Block #1 $\rho = 0.27$

x	z
-1000	20
2000	20
2000	40
330	40
310	32
270	32
250	40
-1000	40
-1000	20

Block #2 $\rho = 0.41$

x	z
300	40
2000	40
2000	50
360	50
330	40

Block #3 $\rho = 0.55$

x	z
225	50
250	40
270	32
310	32
330	40
360	50
225	50

TABLE D3

DENSITY MODEL PARAMETERS FOR LAYER III MODELS

All densities in g/cm^3 , all distances in km.

MODEL: #1	Block #3 $\rho = 0.68$	Block #2 $\rho = 0.55$
Block #1 $\rho = 0.68$		
x z	x z	x z
-10000 50	360 50	20 50
220 50	10000 50	360 50
100 100	10000 100	480 100
-10000 100	480 100	-100 100
-10000 50	360 50	20 50
Block #2 $\rho = 0.55$	MODEL: #3	Block #3 $\rho = 0.68$
x z	Block #1 $\rho = 0.68$	x z
220 50	x z	360 50
360 50	-10000 50	10000 50
480 100	120 50	10000 100
100 100	50 80	480 100
220 50	-10000 80	360 50
	-10000 50	
Block #3 $\rho = 0.68$	Block #2 $\rho = 0.55$	MODEL: #5
x z	x z	Block #1 $\rho = 0.68$
360 50	-10000 80	x z
10000 50	50 80	-10000 50
10000 100	120 50	20 50
480 100	360 50	-50 80
360 50	480 100	-10000 80
	-10000 100	-10000 50
	-10000 80	
MODEL: #2	Block #3 $\rho = 0.68$	Block #2 $\rho = 0.55$
Block #1 $\rho = 0.68$	x z	x z
x z	360 50	-10000 80
-10000 50	10000 50	-50 80
120 50	10000 100	20 50
0 100	480 100	360 50
-10000 100	360 50	480 100
-10000 50		-10000 100
		-10000 80
Block #2 $\rho = 0.55$		
x z	MODEL: #4	Block #3 $\rho = 0.68$
120 50	Block #1 $\rho = 0.68$	x z
360 50	x z	360 50
480 100	-10000 50	10000 50
0 100	20 50	10000 100
120 50	-100 100	480 100
	-10000 100	360 50
	-10000 50	

TABLE D3 (Cont.)

MODEL: #6

Block #1 $\rho = 0.68$

x	z
-10000	50
20	50
-14	65
-10000	65
-10000	50

Block #3 $\rho = 0.68$

x	z
360	50
10000	50
10000	100
480	100
360	50

Block #2 $\rho = 0.68$

x	z
360	50
10000	50
10000	80
430	80
360	50

Block #2 $\rho = 0.55$

x	z
-10000	65
-14	65
20	50
360	50
480	100
-10000	100
-10000	65

MODEL: #8

Block #1 $\rho = 0.68$

x	z
-10000	50
80	50
-250	80
-10000	80
-10000	50

MODEL: #10

Block #1 $\rho = 0.55$

x	z
-10000	50
360	50
450	90
10000	90
10000	120
-10000	120
-10000	50

Block #3 $\rho = 0.68$

x	z
360	50
10000	50
10000	100
480	100
360	50

Block #2 $\rho = 0.55$

x	z
-10000	80
-250	80
80	50
360	50
480	100
-10000	100
-10000	80

Block #2 $\rho = 0.68$

x	z
360	50
10000	50
10000	90
450	90
360	50

MODEL: #7

Block #1 $\rho = 0.68$

x	z
-10000	50
200	50
-145	80
-10000	80
-10000	50

Block #3 $\rho = 0.68$

x	z
360	50
10000	50
10000	100
480	100
360	50

MODEL: #11

Block #1 $\rho = 0.55$

x	z
-10000	50
360	50
474	100
10000	100
10000	120
-10000	120
-10000	50

Block #2 $\rho = 0.55$

x	z
-10000	80
-145	80
200	50
360	50
480	100
-10000	100
-10000	80

MODEL: #9

Block #1 $\rho = 0.55$

x	z
-10000	50
360	50
430	80
10000	80
10000	120
-10000	120
-10000	50

Block #2 $\rho = 0.68$

x	z
360	50
10000	50
10000	100
474	100
360	50

TABLE D3 (Cont.)

MODEL: #12

Block #1 $\rho = 0.55$

x	z
-10000	50
360	50
500	110
10000	110
10000	120
-10000	120
-10000	50

Block #2 $\rho = 0.68$

x	z
360	50
10000	50
10000	110
500	110
360	50

MODEL: #13

Block #1 $\rho = 0.55$

x	z
-10000	50
360	50
520	120
-10000	120
-10000	50

Block #2 $\rho = 0.68$

x	z
360	50
10000	50
10000	120
520	120
360	50

MODEL: #14

Block #1 $\rho = 0.55$

x	z
-10000	50
360	50
930	100
-10000	100
-10000	50

Block #2 $\rho = 0.68$

x	z
360	50
10000	50
10000	100
930	100
360	50

MODEL: #15

Block #1 $\rho = 0.55$

x	z
-10000	50
360	50
640	100
-10000	100
-10000	50

Block #2 $\rho = 0.68$

x	z
360	50
10000	50
10000	100
640	100
360	50

MODEL: #16

Block #1 $\rho = 0.55$

x	z
-10000	50
360	50
480	100
-10000	100
-10000	50

Block #2 $\rho = 0.68$

x	z
360	50
10000	50
10000	100
480	100
360	50

MODEL: #17

Block #1 $\rho = 0.55$

x	z
-10000	50
360	50
416	100
-10000	100
-10000	50

Block #2 $\rho = 0.68$

x	z
360	50
10000	50
10000	100
416	100
360	100

MODEL: #18

Block #1 $\rho = 0.55$

x	z
-10000	50
360	50
378	100
-10000	100
-10000	50

Block #2 $\rho = 0.68$

x	z
360	50
10000	50
10000	100
378	100
360	50

MODEL: #19

Block #1 $\rho = 0.55$

x	z
-10000	50
360	50
360	100
-10000	100
-10000	50

TABLE D3 (Cont.)

Block #2 $\rho = 0.68$

x	z
360	50
10000	50
10000	100
360	100
360	50

TABLE D4

DENSITY MODEL PARAMETERS FOR
BRIDWELL'S RIFT GRAVITY MODEL OF CRUST AND UPPER MANTLE
FOR PROFILE AT 36°N LATITUDE

All densities in g/cm³, all distances in km.

<u>Block #1 $\rho = 2.67$</u>		<u>Block #4 $\rho = 2.8$</u>		<u>Block #8 $\rho = 3.05$</u>	
x	z	x	z	x	z
-5000	0	-5000	18	421	8
405	0	235	18	430	8
410	18	230	42	430	18
385	18	-5000	42	432	42
385	8	-5000	18	420	42
373	10			421	18
373	18			421	8
-5000	18	<u>Block #5 $\rho = 2.98$</u>		<u>Block #9 $\rho = 2.8$</u>	
-5000	0	x	z	x	z
		235	18	430	18
		245	18	460	18
		290	32	452	42
		370	38	432	42
		373	18	430	18
		373	10		
		385	8	<u>Block #10 $\rho = 2.98$</u>	
		385	18	x	z
		390	42	460	18
		230	42	460	15
		235	18	474	18
				485	15
		<u>Block #6 $\rho = 2.8$</u>		485	18
		x	z	490	42
		245	18	452	42
		373	18	460	18
		370	38		
		290	32	<u>Block # 11 $\rho = 2.8$</u>	
		245	18	x	z
				485	18
		<u>Block #7 $\rho = 2.8$</u>		5700	18
		x	z	5700	42
		385	18	490	42
		421	18	485	18
		420	42		
		390	42	<u>Block #12 $\rho = 3.35$</u>	
		385	18	x	z
				-5000	42
				170	42
				167	75
				160	100
				-5000	100
				-5000	42

TABLE D4 (Cont.)

Block #13 $\rho = 3.22$

<u>x</u>	<u>z</u>
170	42
530	42
552	72
570	75
590	100
5700	100
5700	150
-5000	150
-5000	100
160	100
167	75
170	42

Block #14 $\rho = 3.35$

<u>x</u>	<u>z</u>
530	42
5700	42
5700	100
590	100
570	75
552	72
530	42

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