



Lithospheric thinning and the late Cenozoic thermal and tectonic regime of the northern Rio Grande rift

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LITHOSPHERIC THINNING AND THE LATE CENOZOIC THERMAL AND TECTONIC REGIME OF THE NORTHERN RIO GRANDE RIFT

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INTRODUCTION

The Rio Grande Rift is a system of narrow, elongate, en echelon tectonic rift valleys extending 1000 km from Colorado to Mexico and separating the Colorado Plateau-Basin and Range provinces from the Southern Rocky Mountains-Great Plains provinces (Fig. 1). These rift valleys are bounded by normal faults and are located between vast, elevated regional uplifts (Kelly, 1952; Chapin, 1971). Regional extension at the north and south ends of the rift began 23-29 m.y. B.P. (Lipman and Mehnert, 1975; Chapin and Seager, 1975) followed by basaltic andesite volcanism 26-20 m.y. B.P. and accelerated basaltic volcanism at 5 m.y. B.P. (Chapin and Seager, 1975), with olivine tholeiites on the Taos Plateau (Lipman, 1969). Hence the Rio Grande Rift is a Cenozoic continental feature involving rift tectonics similar in many respects to other components of the world rift system such as the East African Rift, the Baikal Rift and the Rhinegraben.

Current geophysical data across the northern Rio Grande Rift provide a picture of a crust smoothly varying in thickness from 40 km in western New Mexico to 50 km in eastern New Mexico, overlying an upper mantle whose velocity varies from 7.9 to 8.1 km/s (Roller, 1965; Stewart and Pakiser, 1962). Seismicity generally occurs along the western boundary of the rift (Olsen and others, 1976) indicating tectonism west of the Rio Grande. Interpretations of local gravity anomalies along the rift indicate basins, ranging in depth from 2 to 4 km, are filled with continental sediments and volcanics and bounded by normal faults (Andreassen and Kane, 1961; Joesting and others, 1961; Cordell, 1976). Within the rift, microearthquake studies (Sanford and others, 1973) and seismic refraction profiles (Topozada and Sanford, 1976) indicate an upper crustal velocity of approximately 5.8 km/s relative to 6.1 km/s external to the rift.

The general picture is not consistent with surface structure, seismicity and heat flow. A decrease in crustal velocities within the rift (Sanford and others, 1973) indicates extension and possible thinning of this zone. Microearthquake reflections show an interface at 18 km between Socorro and Albuquerque, with reduced capabilities to propagate S waves (Sanford and others, 1973). Surface heat flow data from Reiter and others (1975) indicate a narrow geothermal anomaly of high heat flow extending from Colorado to southern New Mexico along the western boundary of the rift. Broader anomalies occur over the Zuni Mountains, southern Rocky Mountains and northeastern New Mexico.

In this paper, a crust-mantle structure beneath the Colorado Plateau, northern Rio Grande Rift and southern Rocky Mountains is derived from long wavelength negative Bouguer gravity data. Two-dimensional fits of calculated and measured surface heat flow using finite element modeling and gravity models support thinning of the lithosphere and intrusion of material from the low velocity zone into the upper mantle and lower crust beneath the rift. The time term inherent in the requirement of an anomalous heat source to fit the rift thermal

anomaly will be used to indicate the need for initiation of convection of material into the lower crust in late Cenozoic time (15 m.y. B.P.) to be consistent with the magnitude of the present thermal anomaly and distribution of extrusive surface volcanism along the rift.

NEGATIVE BOUGUER ANOMALIES AND THE RIO GRANDE RIFT

Long wavelength, negative Bouguer gravity anomalies occur beneath the Rio Grande Rift and associated physiographic provinces as can be seen by analysis of the Bouguer anomaly map of the United States (Woollard and Joesting, 1964). In order to facilitate analysis of these anomalies, a residual Bouguer gravity profile was constructed along 36°N latitude (Fig. 2A). This profile extends from 110°W longitude to

104°W longitude. Other anomalies of varied shape generally extend northward several hundred kilometers to 40°N in Colorado and southward to ~34°N in New Mexico.

Procedures for evaluating the long wavelength anomalies and calculation of thinning of the lithosphere are outlined in Searle (1970). Gradients for the Rio Grande Rift have the range 0.2-0.8 mgals/km, averaging 0.5 mgals/km, suggesting that the light material causing the anomaly is at considerable depth and has small density contrast. East of ~104°W, Bouguer anomalies are generally >-180 mgals. Similarly, although with less precision, in eastern Arizona beneath the Colorado Plateau, the anomalies west of ~109-110°W are >-180 mgals. If a constant regional background of -80 mgals is assumed, the negative residual Bouguer anomalies range from an average of -45 to -85 mgals at 35°N and 38°N respectively.

The normal lithospheric plate is assumed to extend to a depth of 100 km (Julian, 1970; McGetchin and Silver, 1972). The sialic crust is 42 km thick beneath the Colorado Plateau and southern Rocky Mountains with density averaging 2.75 g/cm³ from seismic refraction data. The density of the underlying mantle is taken as 3.35 g/cm³, corresponding to an average Pn velocity of 7.9 km/s (Roller, 1965; Stewart and Pakiser, 1962). The low velocity material intruding the lithosphere is considered to be continuous with the low velocity zone (LVZ) beneath the lithospheric plate. Two-dimensional computer modeling (Talwani and others, 1959) was used to calculate the size and shape of the LVZ intrusion and intermediate mantle, the density of which probably varies both vertically and horizontally. Clearly, the model is dependent on the density contrast and is one of many which might fit the gravity data.

LONG WAVELENGTH GRAVITATIONAL MODEL AT LATITUDE 36°N

Several density contrasts are required to prescribe two-dimensional gravity fit and the preferred crust-mantle struc-

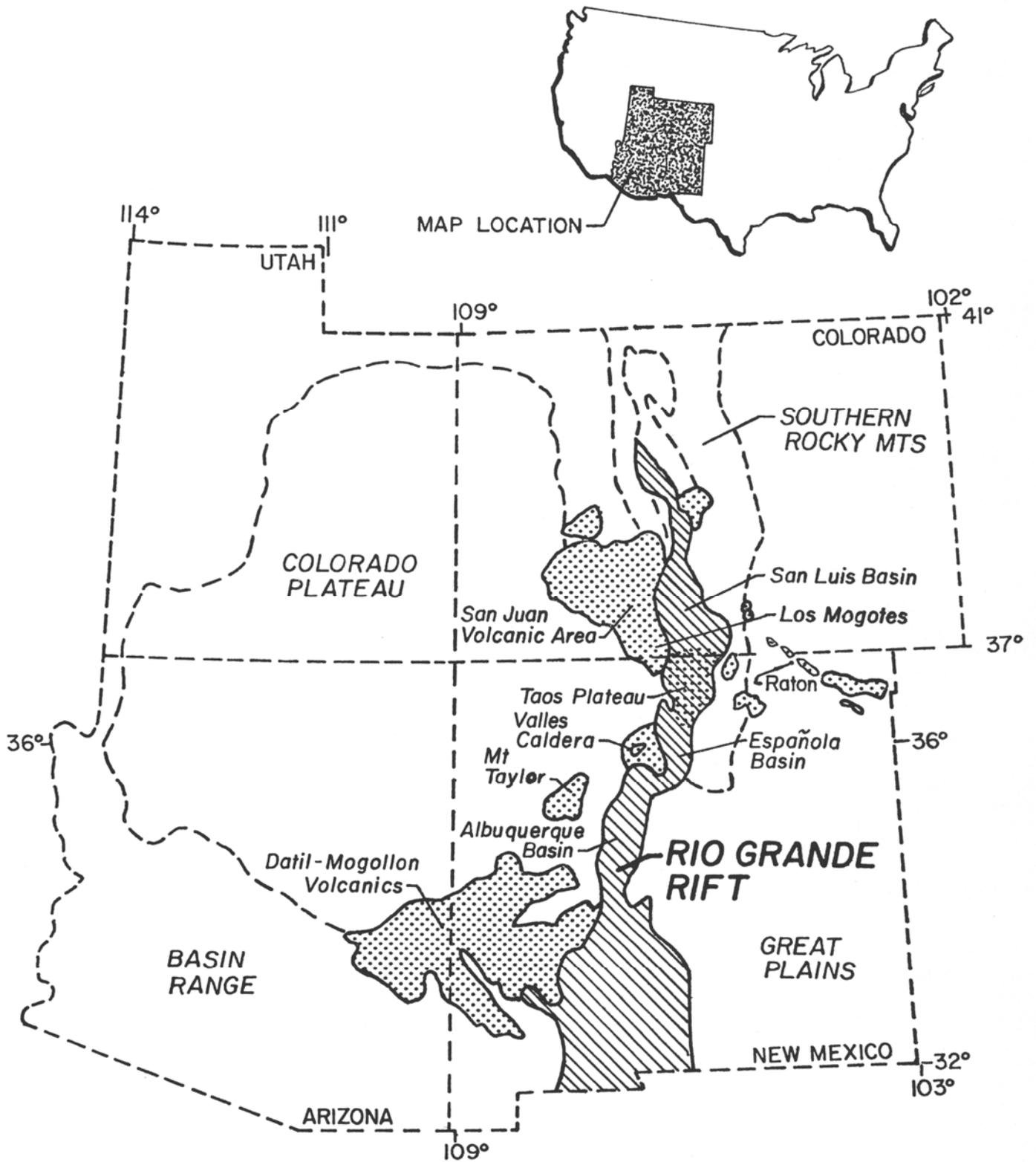


Figure 1. Physiographic provinces associated with the Rio Grande Rift. Arrows indicate centers of the Albuquerque, Española and San Luis Basins in the northern rift. Surface volcanics are indicated by name for appropriate stippled patterns.

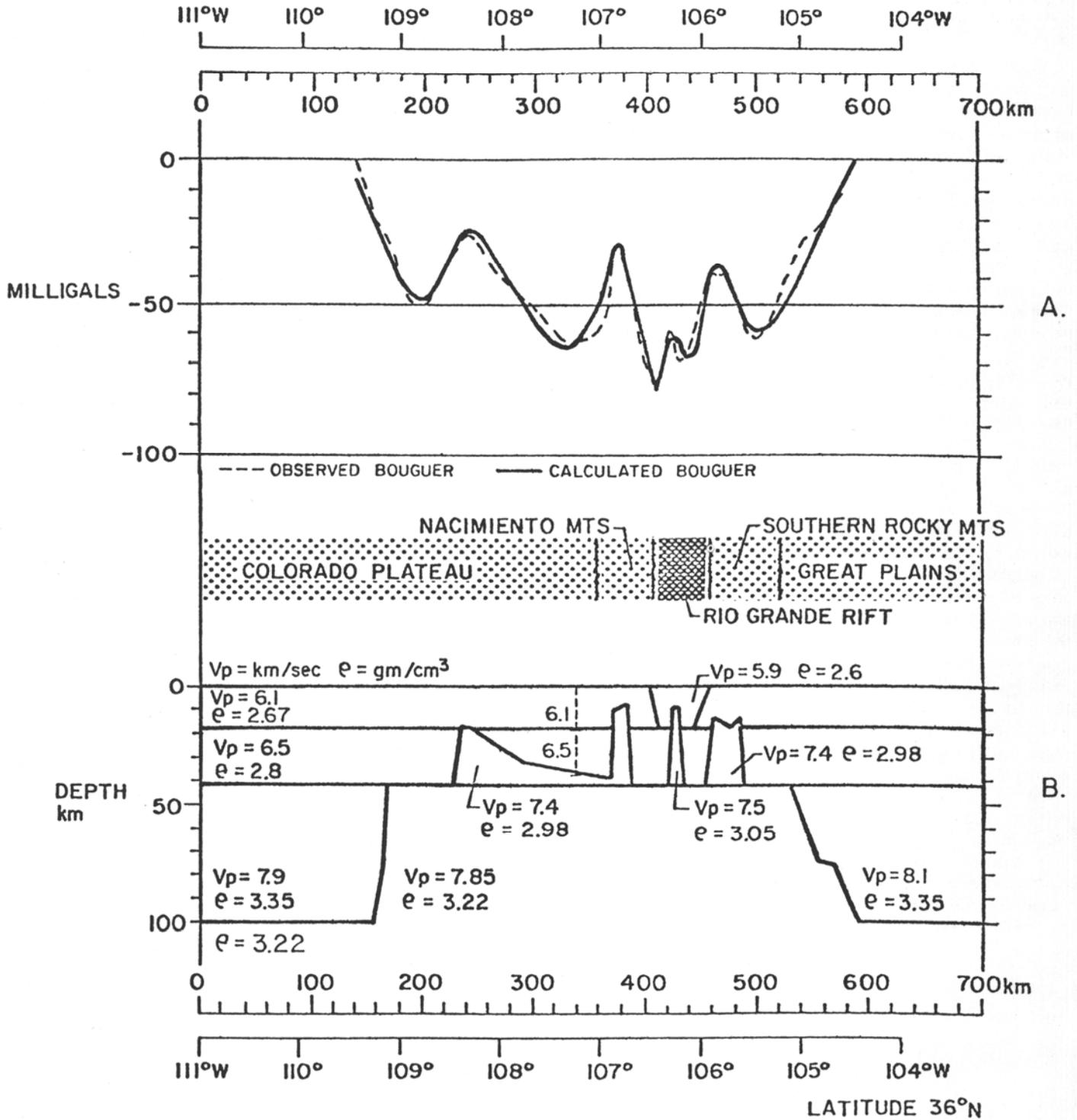


Figure 2. Gravity interpretation for thinning of lithosphere due to intrusion of low velocity material beneath the northern Rio Grande Rift.

A) The dashed line is the residual Bouguer anomaly. Data for this anomaly are from Woollard and Joesting (1964). The solid line is the calculated residual due to structure and densities shown in the gravity model.

B) Structure of attenuated lithosphere and intruding low velocity zone from long wavelength Bouguer data. The dashed line represents the Gasbuggy profile with velocities from Toppozada and Sanford (in press). Depths are heavy ticks.

ture (Fig. 2B). A density contrast of -0.13 g/cc ($\rho = 3.22 \text{ g/cc}$) provides an intrusion of the LVZ into the thinned, overlying lithosphere. Several mafic intrusions, which overlie the upwarp of LVZ, extend into the crust with a positive density contrast of $+0.18 \text{ g/cc}$ ($\rho = 2.98 \text{ g/cc}$). Densities for the LVZ intrusion are consistent with petrologic observations on crystalline rock fragments recovered from kimberlites of the Moses Rock Dike on the Colorado Plateau. McGetchin and Silver (1972) have interpreted a crust-mantle model consisting of spinel lherzolite, and minor amounts of spinel websterite, plagioclase eclogite and hydrated lherzolite to have a density range $3.24 < \rho < 3.3 \text{ g/cc}$ for the upper mantle. The lower crust is characterized by mafic amphibolite and an underlying mafic granulite gneiss having $2.90 < \rho < 3.0$. Hence, the densities of the gravity model are consistent with kimberlite data from the Colorado Plateau. Similar values for mafic crustal intrusions have been noted from seismic refraction profiles beneath the East African Rift (Searle, 1970; Girdler, 1975). The major intrusion of the LVZ is 60 km high and 400 km wide ranging from latitude 109°W to 104°W (Fig. 2b). Mafic intrusions extend 26-30 km into the upper crust above the upwarp.

Shallow structure beneath the Rio Grande Rift consists of a mafic intrusion with a slightly higher density contrast of $+0.25 \text{ g/cc}$ ($\rho = 3.05 \text{ g/cc}$) centered between the normal faults bounding the rift. This intrusion is overlain by a slightly less dense -0.07 g/cc ($\rho = 2.60 \text{ g/cc}$) material within the rift which extends to the base of the upper crust. The anomalous upper crustal material within the rift is presumed to reflect large amounts of fractured material associated with normal faulting and crustal attenuation. Sanford and others (1973) have noted the presence of a P wave velocity of 5.8 km/s implying a less dense upper crust within the rift in the Albuquerque Basin from microearthquake studies, which is consistent with the reinterpretation of Gasbuggy travel time data by Topozada and Sanford (1976). It is of interest that several attempts were made to fit the sharp Bouguer lows in the rift without the anomalous upper crustal material (-0.07 g/cc). These fits were abandoned because very high aspect ratios and very shallow surface expressions were required to explain the mafic intrusion beneath the rift.

The general shape of the LVZ intrusion and thinned crust beneath the northern Rio Grande Rift is similar to geometries noted for the thinned lithosphere beneath the East African Rift (Searle, 1970; Girdler, 1975). Gravity models for the East African Rift preceded seismic refraction profiles; however, seismic analysis supported the presence of low velocity mafic intrusions into the upper crust beneath the Gregory portion of the East African Rift (Griffiths, 1972).

HEAT FLOW, RADIOACTIVITY, AND THERMAL CONDUCTIVITY

General trends of heat flow for the Colorado Plateau-Southern Rocky Mountains outlined by Roy and others (1972) are based on reduced heat flow from a few data points. Reiter and others (1975) published a large number of heat flow values along the rift and Decker and Smithson (1975) added values across the southern rift. Data from Reiter and others (1975) provide heat flow boundary conditions for two-dimensional finite element thermal models along the northern Rio Grande Rift.

The correlation of radioactivity in the upper crust and surface heat flow has been observed to be a linear relation

$$Q_s = Q_r + Ad \quad (1)$$

Where Q_s is surface heat flow in units of $10^{-6} \text{ cal/cm}^2 \text{ s}$ (H EU), A is the heat production of surface rocks in units of 10^{-3} (HGU), d is the slope of the line (dimensions of depth), and Q_r (the intercept value) is the heat flow below of some layer whose thickness is related to A (Birch and others, 1968). Constant heat production with depth will be used in the finite element models because of simplicity of distribution within elements. Use of surface flux which varies with position and a constant heat production requires variations in Q_r . Hence, although there are large inter-regional differences in average Q_r such as modeled by Blackwell (1971), smaller variations about the average within a region can be used for realistic, two-dimensional modeling. Because no heat production measurements are provided by Reiter and others (1975), one either uses assumptions of regional averages or the few known values within the rift. Heat production for the deep geothermal well west of the Valles Caldera is 4.87 HGU (Kolstad and others, 1976). Decker and Smithson (1975) measured 7 new values whose mean is 3.67 ± 1 HGU. Great Plains heat production is 4.5 HGU (Roy and others, 1968). Since there is some spread in these values, an arbitrary 4.86 HGU will be used for the rift whereas 4.5 HGU will be used for the Colorado Plateau and Great Plains.

Upper crustal values for thermal conductivity are taken as 6.5 CU ($1 \text{ CU} = 10^{-3} \text{ cal/cm s } ^\circ\text{C}$) (Roy and others, 1968). Blackwell (1971) indicated these values are an average of about 100 plutonic rocks in the U.S., corrected for a slight temperature dependence. Conductivity for the lower crust is assumed to be 5.0 CU, about the value for gabbro at temperatures above $200\text{-}300^\circ\text{C}$ (Birch and Clark, 1940). Schatz and Simmons (1972) showed radiative conductivity of dunite and enstatite of the upper mantle of 7-8 CU and total conductivity of 9-12 CU for $750 < T < 1250^\circ\text{C}$. At depths greater than 30 km, conductivity has a relatively large pressure effect. From 100 to 200 km depth, conductivities range from 8 to 13 CU. Clearly, the range in variation in thermal conductivities must be within a factor of approximately three.

Solution of the steady-state heat conduction equation by the finite element method (Browning and others, 1974), subject to selected boundary conditions, provides thermal models with contoured isotherms. For purpose of two-dimensional simulation of crust and mantle heat flow and thermal models, a constant value of Ad is removed from the surface heat flow to provide the basal, reduced heat flow Q_r . Boundary conditions assume the top of the model is constrained to $T = T_o$, no horizontal flux is allowed across the lateral boundaries and variations of reduced heat flux Q_r , are applied at the base. Data from surface heat flow measurements 20 minutes north and south of latitude 36°N are from the Reiter and others (1975) compilation of regional values.

TWO-DIMENSIONAL FIT OF MEASURED HEAT FLOW

Fits to regional heat flow were obtained by varying K , the crustal structure and adding heat sources. Initially, models assumed uniform layers of thermal conductivity similar to models proposed by Roy and others (1972) and Blackwell (1971) for the crust and mantle described previously. Two-dimensional heat flow fits were unsuccessful. When the variation in K of 25 to 50% of initial values exceeded reasonable

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limits, crustal structure was modified by approximately 5%. Fits to the southern Rockies anomaly (approximately 2.0 HFU) and the anomaly at approximately 108°W were successful except for approximately 0.8 HFU of the rift anomaly. If both modifications failed to produce a fit, anomalous heat sources were added in the lower crust.

Two-dimensional models of structure, measured and calculated heat flow fit and temperature distributions are shown in Figure 3. The heat flow fit requires a slight increase in height (approximately 4 km) of the mafic intrusion beneath the San Juan Basin. The rift thermal anomaly required addition of two sources of varying magnitude and dimension directly beneath the western portion of the rift although one uniform source would probably have sufficed. The upper source extends 10-19 km from the top of the model and is located essentially beneath normal faults flanking the western boundary of the rift. Equivalent heat flow from this source is 0.94 HFU. The lower source extends from depths of 19 to 42 km with an equivalent flux of 2.3 HFU. The fit of measured and calculated flux is within the range of error of surface heat flow values (Reiter and others, 1975). Numbers within individual blocks of material in Figure 3B can be keyed to values of thermal conductivity and effective heat flux via Table 1.

GEOHERMAL GRADIENTS

Thermal profiles at the center of the Rio Grande Rift (Fig. 4) indicate gradients of 25-32°C/km. Comparison of rift geotherms with a normal oceanic geotherm suggests temperatures would reach the melt temperature at relatively shallow depths. Petrologic constraints of mantle xenolithic suites which provide pressure-temperature (P-T) relations support such high geotherms. A new websterite xenolith suite from Abiquiu, New Mexico (Baldrige, 1976), places a lower limit on the pressure and a narrow band on temperature. These xenoliths indicate the geotherm in northern New Mexico must pass above approximately 17 kb pressure or approximately 50 km depth for temperatures of $1000 \pm 50^\circ\text{C}$ (Baldrige, personal communication, 1976). Spinel lherzolite xenoliths of the southern rift at Kilbourne Hole and west Potrillo Mountains (Reid, 1976) provide upper and lower constraints on the geotherm, consistent with thermal models of the southern rift (Reiter and others, 1975) which have gradients similar to the thermal models for the northern rift, hence high geotherms along the rift are justified. Experimental petrology indicates the position of a wet upper mantle solidus in P-T space; however, there is an ambiguity if the amount of water in the reactions is unknown. Ringwood (1975) suggested the upper mantle can accrue 20% partial melting in the temperature range 1200-1300°C if 0.1% water is present. McGetchin and Silver (1972, Fig. 4) had indicated presence of approximately 20% partially hydrated spinel lherzolite below the M discontinuity. Hence, geothermal gradients would suggest partial melt of lower crust and upper mantle beneath the northern rift at depths of 30-45 km (Fig. 4).

TIME DEPENDENT ANALYSIS OF ANOMALOUS CRUSTAL HEAT SOURCES

Steady-state thermal models which fit the surface heat flow require anomalous heat sources below normal concentrations of radioactive sources in the upper crust. These anomalous lower crustal heat sources imply a time-dependence for the source. One-dimensional effects of the present rate of heat loss

can be solved analytically to estimate whether the geothermal anomaly is increasing or decreasing with time. For this purpose, consider two models described in Lachenbruch and others (1976). The first model would be that of a source where magma is moved instantaneously into place at time $t=0$ at temperature (0) above its surroundings; thereafter magma stagnates and loses its heat by conduction (Model II, Lachenbruch and others, 1976). The second model assumes heat liberated at a constant rate Q_0 starting at $t=0$ on the roof of the magma chamber (Model III, Lachenbruch and others, 1976). Heat liberation is simply the surface heat flow due to these anomalous sources minus the reduced heat flow for that province. Surface measurements for the geothermal anomaly of northern rift show a maximum value of 2.8 HFU and reduced heat flow for the southern Rockies is 1.4 HFU (Roy and others, 1972), hence the rate of heat loss is approximately 1.4 HFU for the rift.

Two calculations of one-dimensional time-dependence for the anomalous heat sources bracket the nature of change in the geothermal anomaly along the rift. The first calculation simulates the constant heat loss across the roof of the magma chamber, hence heat loss Q at the surface increases with time. From initiation of constant Q_0 , 15 to 20 m.y. are required to produce the present thermal anomaly of 1.4 HFU, depending on the depth to the top of the source (Fig. 5A). The upper portion of Figure 5A indicates the time-dependent growth of the anomaly and its edge effects assuming a depth of 20 km to the top of the larger source shown in Figure 3B. The second calculation simulates an instantaneously emplaced magma immediately allowed to stagnate, hence the surface flux initially increases then decreases with time (Fig. 5B). For the 1.4 HFU anomaly and depths of 18 km the regional anomaly would lose 82% of its heat in 5 m.y.

Use of steady-state models and the anomalous heat source dictated by the two-dimensional fit is probably only an estimate. Variations of thermal conductivities by more than an order of magnitude would not provide a fit to the 0.8 HFU anomaly over the rift whereas changes of 25 to 50% provided the fit to the 108°W anomaly and the southern Rockies anomaly, each having surface flux of approximately 2 HFU. A source with effective heat flow $Q_0 > 2$ HFU produced the remaining 0.8 HFU anomaly for the Rift. A constant heat source within the crust implies either radioactive material concentrated at great depths in the crust or convective supply of material to revitalize that source. Lack of evidence for deep radioactive sources and presence of extensive surface volcanics supports convective supply as a reasonable mechanism to generate the thermal anomaly. Because of steady-state solutions and uncertainties in depth of sources we adopt a conservative 5 to 10 m.y. to produce the geothermal anomaly of the rift.

PARTIAL MELTING AND SEISMIC ATTENUATION

The low velocity zone (LFZ) in the upper mantle is now a well established feature in tectonic regions (Anderson and Sammis, 1970). The velocity reversal may be due to high temperature, solid-solid phase changes, a decrease in density, or the onset of partial melting. Changes in velocity alone, if attributed to effect of temperature and pressure, give unreasonably high thermal gradients and heat flow values, and partial melting is required to satisfy seismic data (Anderson

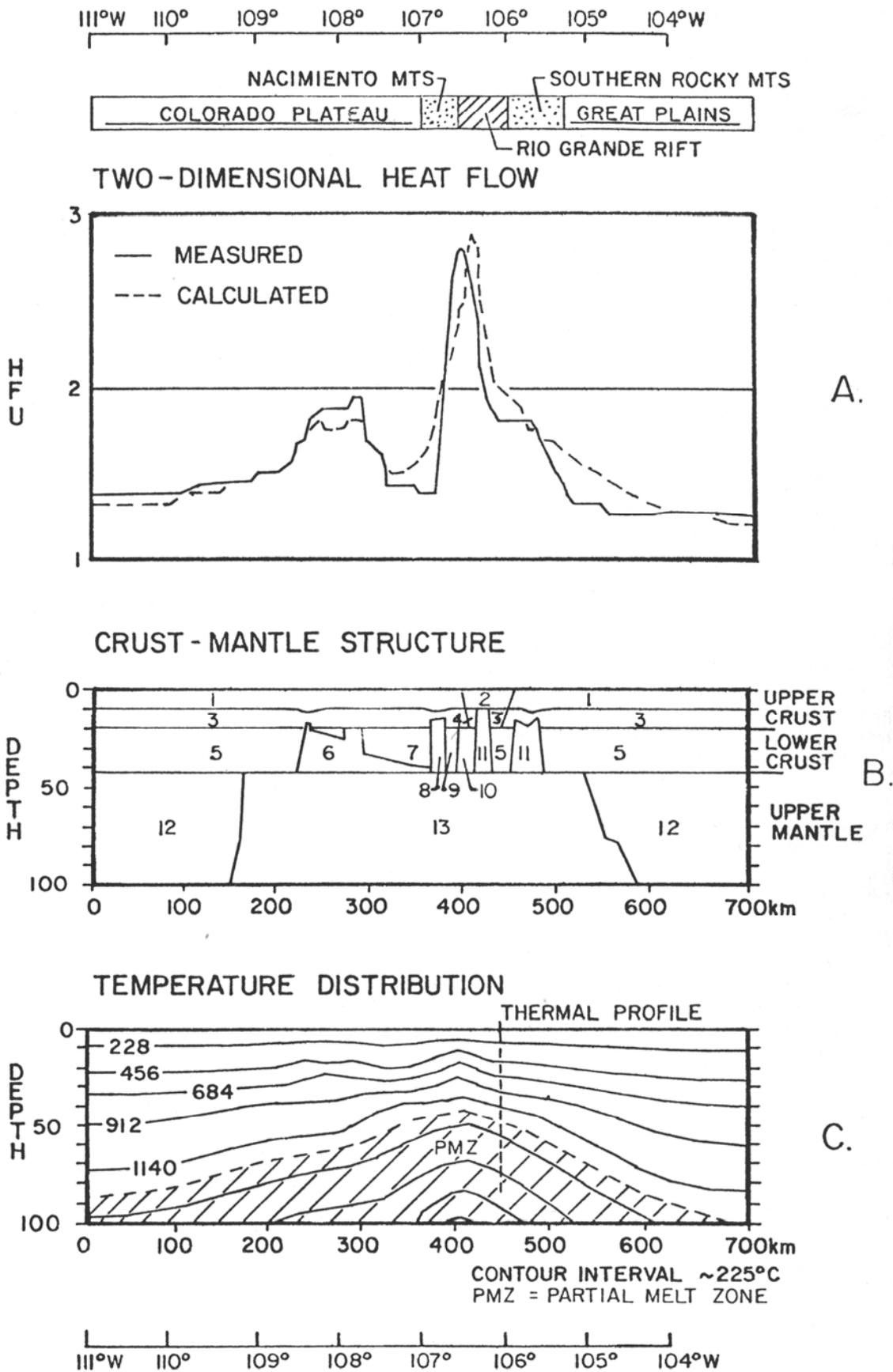


Figure 3. Steady-state thermal model across northern Rio Grande Rift at latitude 36°N. A) Calculated and measured two-dimensional surface heat flow. B) Structural geometry of crust and mantle. Numbers within blocks are keyed to material properties in Table 1. C) Isotherms for lithosphere beneath northern Rio Grande Rift. The PMZ is based on conservative estimates of 0.1% H₂O in the upper mantle. Temperatures below PMZ have no physical meaning.

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Table 1
Thermal Properties for Crust-Mantle Model at 36°N
Numbers Key Properties to Structure in Figure 3b

KEY	THERMAL CONDUCTIVITY 10^{-3} cal/cm s °C	HEAT GENERATION ¹ (in equivalent HFU) 10^{-6} cal/cm ² s	REMARK
1	6.5	0.45	Upper Crust
2	7.5	0.486	Rifted Upper Crust
3	6.5		Upper Crust
4	8.5	0.94	Upper Crustal Source
5	5.0		Lower Crust
6	8.5		Mafic Intrusion
7	3.0		Lower Crust
8	6.0		Mafic Intrusion
9	7.5		Lower Crust
10	8.5	2.3	Lower Crustal Source
11	5.0		Mafic Intrusion
12	10.0		Upper Mantle
13	12.0		Anomalous Upper Mantle

1. Heat generation x thickness = $HGU \times d = HFU$

and Sammis, 1970). Because the melting point gradient for most silicates is approximately 4°C/km, intersection of the geotherm with the solidus requires release of latent heat or the possibility of heat transfer by fluid motion. Hence, the melting point gradient should be the limiting gradient in partially molten regions of the upper mantle. Solid-solid phase changes removing spinel and including garnet only reduce velocities by 1%, so the low velocity zone must be either a region of different composition than the surrounding mantle, or it is partially molten.

Regional studies of body and surface waves for the Basin and Range and central Mexico (Helmberger, 1973; Fix, 1975), suggest the presence of an LVZ beneath much of western North America. The LVZ extends from depths of 75 to 125 km and suggests a significant change in the attenuation factor Q for seismic amplitudes. Typically, crustal values for Q are 450. The attenuation factor for the Basin and Range has been estimated as a Q of 50. An extension of the LVZ from the Basin and Range in Arizona into southwestern New Mexico suggests an associated low Q (York and Helmberger, 1973). Microearthquake reflections of S waves from a sharp discontinuity within the rift indicate a zone of very low rigidity at depths of 18-30 km in the crust beneath Socorro and Belen, New Mexico. The model of deep crustal structure from long wavelength negative Bouguer gravity data indicates a decrease in density and velocity in the upper mantle beneath the northern rift. The thermal model reported in this paper implies significant partial melting in the uppermost mantle.

Deep geomagnetic sounding with wide spaced two-dimensional magnetometer arrays indicate ridges of highly conductive material underlie the Basin and Range (0.2 S/m) and ridges of still higher conductivity underlie the southern Rockies (Porath, 1971; Gough, 1974). The Great Plains has a more resistive upper mantle whereas the Colorado Plateau is similar or intermediate between the Great Plains and Basin and

Range. If partially molten upper mantle rocks are modeled as an olivine dunite residual surrounded by a basaltic melt having conductivity 2 to 4 orders of magnitude higher, it is possible to obtain conductivity values >0.1 S/m at quite shallow depths of <100 km with 5-20% partial melt using the best data for mineral and melt conductivities (Shankland, personal communication, 1976) consistent with shallow conductive structures at depths of approximately 45 km beneath the rift (Porath, 1971). Without partial melt, unreasonably high temperatures, $>1700^\circ\text{C}$ for peridotite melts, are required to obtain these conductivities in solids. Hence electrical conductivity anomalies provide substantial evidence and an effective probe for the presence of partial melt in the upper mantle. Occurrence of two general magnitudes of surface heat flow along the Rio Grande Rift, the broad southern Rockies anomaly of approximately 2 HFU and the narrow Rio Grande Rift anomaly approximately >2.5 HFU, suggest the more densely spaced magnetometer arrays could be used to spatially describe partially melted heat sources along the rift.

TECTONIC IMPLICATIONS

Geologic evidence for deformation in the Espanola basin consists of normal faulting and subsequent slow downwarping of the rift valley to trap continental sedimentation between 26

THERMAL PROFILES AT THE CENTER OF THE RIO GRANDE RIFT

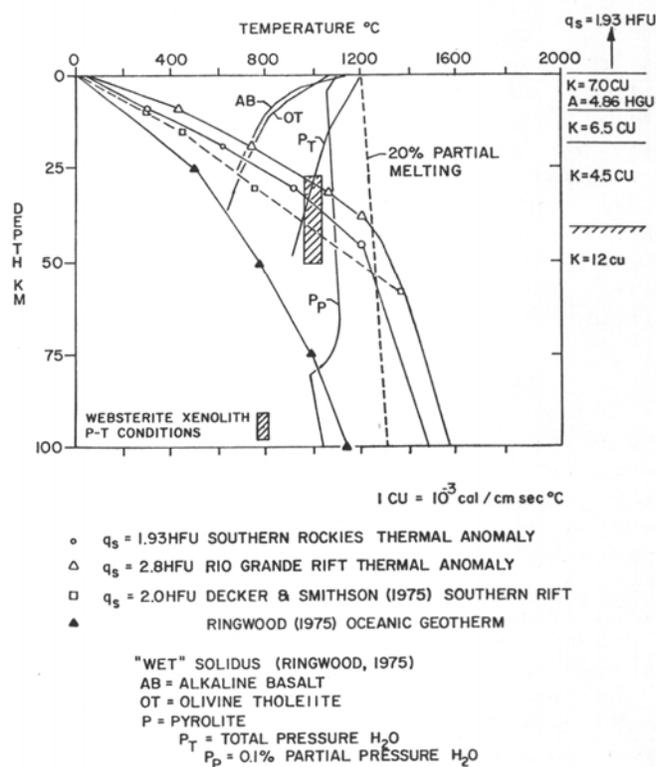


Figure 4. Thermal profiles of the northern Rio Grande Rift. Partial melting of a "wet" pyrolite upper mantle is suggested by the geotherm intersecting the solidus P_p at a depth of 35-50 km. Websterite xenolith conditions place a lower control but have no upper control on the pressure range.

GROWTH OF SURFACE ANOMALY FOR STABLE MAGMA CHAMBER

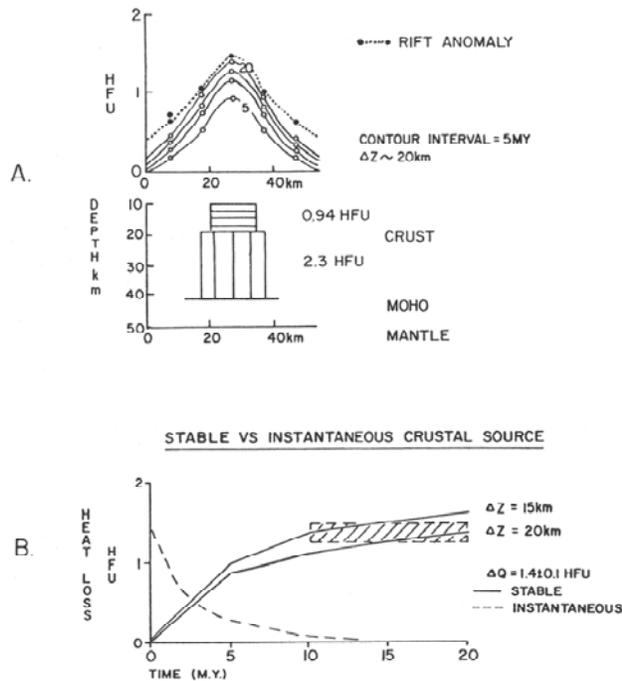


Figure 5. Time-dependence of heat sources in the crust. A) Time-dependence of stable magma chamber and resulting surface heat flow anomaly. The magma chamber and resulting surface anomalies are shown schematically. Solution assumes constant heat flow Q_0 through the roof of magma chamber (Model III). B) Plot of cumulative heat loss Q_0 versus time using both heat sources of Figure 3B for stable source vs. instantaneous source. The former is resupplied from mantle whereas the latter is cut off from supply (Model II). Effect of depth to top of lower crustal heat source shown by lines $\Delta z = 15$ and 20 km. An anomaly of 1.4 HFU and depth 18.6 km to lower source suggests approximately 10 - 15 m.y. necessary to generate thermal anomaly of the rift.

and 10 m.y. B.P. (Fig. 6). A small extrusion of volcanics occurred in the Ortiz Mountains during late Oligocene and early Miocene time. No volcanism occurred in the Espanola basin between extrusion of the Ortiz and Jemez volcanics. Late Miocene to Holocene (9.1 to 0.05 m.y.B.P.) volcanics of the Jemez Mountains overlie the sediments along the west flank of the basin.

The lull probably represents deep convective intrusion of the anomalous heat source in the lower crust beneath the rift. If the source had stabilized to a magma chamber approximately 5 - 10 m.y. B.P., it would have created the present geothermal anomaly and supplied regional volcanic features of the Jemez basalts, Taos Plateau olivine tholeiites, early alkaline-olivine basalts and latite andesites of the Mt. Taylor stratovolcano (Lipman and Mehnert, 1975), and basalts of the Los Mogotes shield complex in southern Colorado (Fig. 6B). Chapin and Seager (1975) suggested that basaltic volcanism is increasing, implying that heat sources for the present thermal

anomaly are being resupplied from the thickened, mobile low velocity zone.

CONCLUSIONS

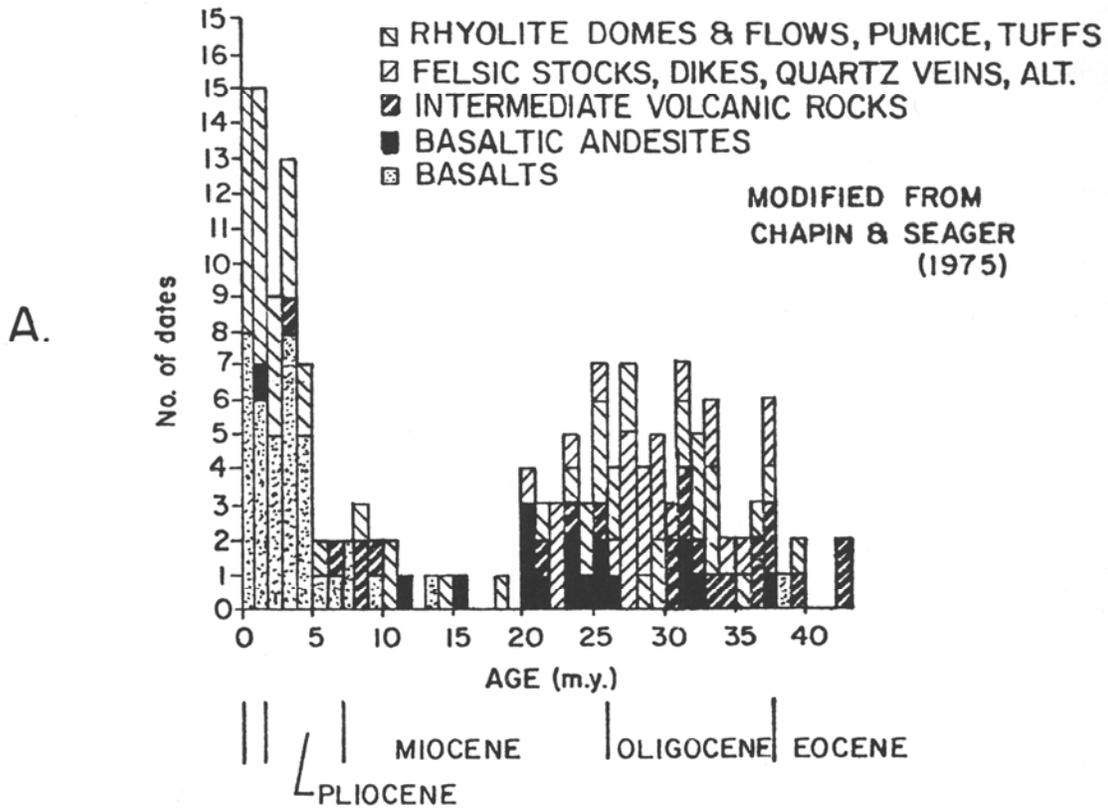
Long wavelength negative Bouguer gravity anomalies at latitude 36°N between longitudes 110° and 104°W in northern New Mexico have been interpreted in terms of an intrusion of low velocity mantle material into a thinned, overlying lithosphere. The upper mantle portion of this intrusion is approximately 60 km high and approximately 400 km wide. Mafic intrusions which thin the crust extend 26 - 30 km above the upper mantle intrusion, generally piercing the upper crust. Thermal models of crust-mantle structure from gravity models which fit two-dimensional surface heat flow indicate that anomalous heat sources at depths of 10 - 40 km in the deeper crust beneath the Rio Grande Rift generate the surface geothermal anomaly. Crustal geothermal gradients of approximately $30^\circ\text{C}/\text{km}$ suggest > 5 - 10% partial melting of the crust at 30 - 45 km. This partial melt zone is interpreted to represent a thickening of the low velocity zone beneath the northern rift. One-dimensional analytic solutions for heat loss above a crustal magma chamber supplied from the mantle indicate this source stabilized approximately 5 - 10 m.y.B.P. Surface volcanism of northern New Mexico began approximately 10 m.y. B.P. to provide several major extrusive centers associated with the major thermal anomaly along the rift.

Negative Bouguer gravity data and surface heat flux support the thesis for thinning of the lithosphere by an intrusion of mantle material from the low velocity zone beneath the northern Rio Grande Rift. Crust-mantle structure is consistent with both gravity and surface flux, experimental thermal conductivities, sparse heat production data and sparse seismic refraction data. Little modification ($< 10\%$) is required from the gravity model to provide the thermal model and the two dimensional fit of calculated and measured flux. Considered separately, neither model is sufficient to prove the thesis. Viewed together, the changes in conductivity structure are consistent with the general interpretation of lateral density inhomogeneities beneath the rift in the crust and upper mantle. When regional phase velocity and wave dispersion studies, electrical conductivity distributions, shallow partial melt of the upper mantle from the thermal model, and the sparse xenolith controls on the "wet" solidus from petrology are considered, compelling evidence is consistent with a mobile, buoyant intrusion of LVZ into the lithosphere beneath the rift.

The thermal regime suggests initial melting of the upper mantle, if the material is a "wet" spinel lherzolite or pyrolite at depths of 35 - 50 km, with increased partial melting (approximately 20%) creating gravitational unstable magma chambers which buoyantly rise and fractionate into the varied, relatively young basaltic magma suites found along the western flank of the rift. The long, linear trend of the regional geothermal anomaly and the surface distribution of young (< 10 my. old) volcanics are consistent with emplacement of a magma chamber in the lower crust by convection from the intruded LVZ along the west flank of the rift 10 m.y. B.P. and subsequent generation of the present thermal anomaly. The vertical buoyancy from the negative density contrasts in the upper mantle and added thermal expansion and convection in the lower crust contributed to a renewed uplift and extensional fragmentation of the linear rift valleys comprising the central and northern Rio Grande Rift.

TECTONISM OF ESPANOLA BASIN

CENOZOIC VOLCANISM IN NEW MEXICO



TECTONIC EVOLUTION OF THE NORTHERN RIFT

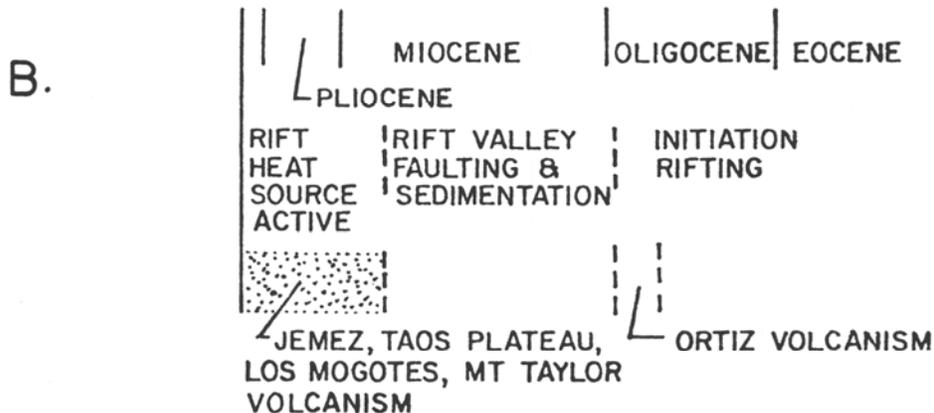


Figure 6. Tectonism of Rio Grande Rift at 36°N. A) K/Ar and fission track age dates of igneous rocks in New Mexico (modified from Chapin and Seager, 1975). Most dates with age > 20 m.y. B.P. are from southern New Mexico. B) Tectonic implications of rifting, sedimentation, emplacement of heat sources and volcanism.

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REFERENCES

- Anderson, D. L., and Sammis, C., 1970, Partial melting in the upper mantle: *Phys. Earth Planet. Int.*, v. 3, p. 41-50.
- Andreason, G. E., and Kane, M.F., 1961, Isostatic compensation in the Sangre de Cristo Mountains, New Mexico: U.S. Geol. Survey Prof. Paper 424-D, p. D277-D281.
- Baldrige, W. S., 1976, Petrology of an ultramafic xenolith/xenocryst suite from the Northern Rio Grande Rift, New Mexico: *Rocky Mtn. Sec. Geol. Soc. America Abs. with Prog.* v. 8, p. 567.
- Birch, F., and Clark, H., 1940, The Thermal Conductivity of Rocks and its Dependence Upon Temperature and Composition, Parts I and II: *Am. J. Sci.*, v. 238, p. 529-558, 613-635.
- Roy, R. F., and Decker, E. R., 1968, Heat Flow and Thermal History in New York and New England, *in* Zen, E. and others, ed., *Studies in geology Northern and Maritime Provinces*: New York, Interscience, p.437-451.
- Blackwell, D. D., 1971, The thermal structure of the continental crust, *in* Hancock, J. G., ed.: *Am. Geophys. Un. Monograph 14*, p. 169-184.
- Browning, R. V., Miller, D. G., and Anderson, C. A., 1974, TSAAS: Finite element thermal and stress analysis of axisymmetric solids with orthotropic temperature-dependent material properties: *Los Alamos Sci. Lab., Inf. Rpt. 5599*, 49 p.
- Chapin, C. E., 1971, The Rio Grande Rift, Part I: Modifications and additions: *New Mexico Geol. Soc. Guidebook, 22nd Field Conf.*, p. 191-201.
- and Seager, W., 1975, Evolution of the Rio Grande Rift in the Socorro and Las Cruces areas: *New Mexico Geol. Soc. Guidebook, 26th Field Conf.*, p. 297-322.
- Cordell, L. E., 1976, Aeromagnetic and gravity studies of the Rio Grande graben in New Mexico between Belen and Pilar: *New Mexico Geol. Soc. Spec. Pub. 6*, p. 62-70.
- Decker, E. R. and Smithson, S. B., 1975, Heat flow and gravity interpretation across the Rio Grande Rift in southern New Mexico and Texas: *Jour. Geophys. Research*, v. 80, p. 2542-2552.
- Fix, J. E., 1975, The crust and upper mantle of central Mexico: *Geophys. Jour. R. Astr. Soc.*, V. 43, p. 453-499.
- Girdler, R. W., 1975, The great negative Bouguer gravity anomaly over Africa: *EOS (Am. Geophys. Union Trans.)*, p. 516-519.
- Gough, D. E., 1974, Electrical conductivity under western North America in relation to heat flow seismology and structure: *Jour. Geomag. Geoelectr.*, v. 26, p. 105-123.
- Griffiths, D. H., 1972, Some comments on the results of a seismic refraction experiment in the Kenya Rift: *Tectonophysics*, v. 15, p. 151-156.
- Helmberger, D. V., 1973, On the structure of the low velocity zone: *Geophys. Jour. R. Astr. Soc.*, v. 34, p. 251-263.
- Joesting, H. R., Case, J. E., and Cordell, L. E., 1961, The Rio Grande trough near Albuquerque, New Mexico: *New Mexico Geol. Soc. Guidebook, 12th Field Conf.*, p. 148-150.
- Julian, B. R., 1970, Regional variations in upper mantle structure beneath North America [Ph.D. thesis] : Pasadena, Calif. Inst. Tech., 206 p.
- Kelly, V. C., 1952, Tectonics of the Rio Grande depression of central New Mexico: *New Mexico Geol. Soc. Guidebook, 3rd Field Conf.*, p. 93-105.
- Kolstad, C., McGetchin, T. R., and Laughlin, A. W., 1976, Pluton thermal evolution modeling and observations in GT-2: *EOS (Am. Geophys. Union Trans.)*, v. 57, p. 350.
- Lachenbruch, A. K., Sass, J. M., Monroe, R. J., and Moses, T. H., Jr., 1976, Geothermal setting and simple heat conduction models for the Long Valley Caldera: *Jour. Geophys. Research*, v. 81, p. 769-783.
- Lipman, P. W., 1969, Alkalic and tholeiitic basaltic volcanism related to the Rio Grande depression, southern Colorado and northern New Mexico: *Geol. Soc. America Bull.*, v. 80, p. 1343-1354.
- and Mehnert, H. H., 1975, Late Cenozoic basaltic volcanism and the development of the Rio Grande depression in the southern Rocky Mountains: *Geol. Soc. America Memoir 144*, p. 119-154.
- McGetchin, T. R., and Silver, L. T., 1972, A crust-upper mantle for the Colorado Plateau based on observations of crystalline rock fragments in the Moses Rock Dike: *Jour. Geophys. Research*, v. 77, p. 7022-7037.
- Olsen, K. H., Cash, D. J., Bridwell, R. J., 1976, Seismicity of north-central New Mexico and its relationship to contemporary tectonics: *Rocky Mtn. Sec. Geol. Soc. America Abs. with Prog.*, v. 8, p. 615-616.
- Porath, H., 1971, Magnetic variation anomalies and seismic low-velocity zone in the western United States: *Jour. Geophys. Research*, v. 76, p. 2643-2648.
- Reid, J. B., Jr., 1976, Upper and lower limits to the geothermal gradient beneath the southern Rio Grande rift: *Rocky Mtn. Sec. Geol. Soc. America Abs. with Prog.*, v. 8, p. 621.
- Reiter, M. C., Edwards, C. L., Hartman, H., and Weidman, C., 1975, Terrestrial heat flow along the Rio Grande Rift, New Mexico and Colorado: *Geol. Soc. America Bull.*, v. 86, p. 811-818.
- Ringwood, A. E., 1975, Composition and petrology of the earth's mantle: *New York, McGraw-Hill*, 618 p.
- Roller, J. C., 1965, Crustal structure in the eastern Colorado Plateaus province from seismic refraction measurements, *Bull. Seis. Soc. America*, v. 55, p. 107-119.
- Roy, R. F., Decker, E. R., Blackwell, D. D., and Birch, F., 1968, Heat flow in the United States: *Jour. Geophys. Research*, v. 73, p. 5207-5221.
- Blackwell, D. C., and Decker, E. R., 1972, Continental heat flow *in* Robertson, E., ed., *Nature of the solid Earth*: New York, McGraw-Hill, p. 506-543.
- Sanford, A. R., Alptekin, O., and Topozada, T. R., 1973, Use of reflection phases on microearthquake seismograms to map an unusual discontinuity beneath the Rio Grande Rift: *Bull. Seis. Soc. America*, v. 63, p. 2021-2034.
- Schatz, J. F., and Simmons, M. G., 1972, Thermal conductivity of earth material at high temperatures: *Jour. Geophys. Research*, v. 77, p. 6966-6783.
- Searle, R. C., 1970, Evidence from gravity anomalies for thinning of the lithosphere beneath rift valleys in Kenya: *Geophys. Jour. R. Astr. Soc.*, v. 21, p. 13-31.
- Stewart, S. W., and Pakiser, L. C., 1962, Crustal structure in eastern New Mexico interpreted from the Gnome Explosion: *Bull. Seis. Soc. America*, v. 52, p. 1017-1030.
- Talwani, M., Worzel, J. C., Landisman, M., 1959, Rapid gravity computations for two-dimensional bodies with application to the Mendocino submarine fracture zone: *Jour. Geophys. Research*, v. 68, p. 49-59.
- Topozada, T. R., and Sanford, A. R., in press, Crustal structure in central New Mexico interpreted from the Gasbuggy Explosion: *Seis. Soc. America Bull.*
- Woollard, G. P., and Joesting, H. R., 1964, Bouguer gravity map of the United States: *Am. Geophys. Un. and U.S. Geol. Survey*.
- York, J. E., and Helmberger, D. V., 1973, Low velocity zone variations in the southwestern United States: *Jour. Geophys. Research*, v. 78, p. 1883-1886.