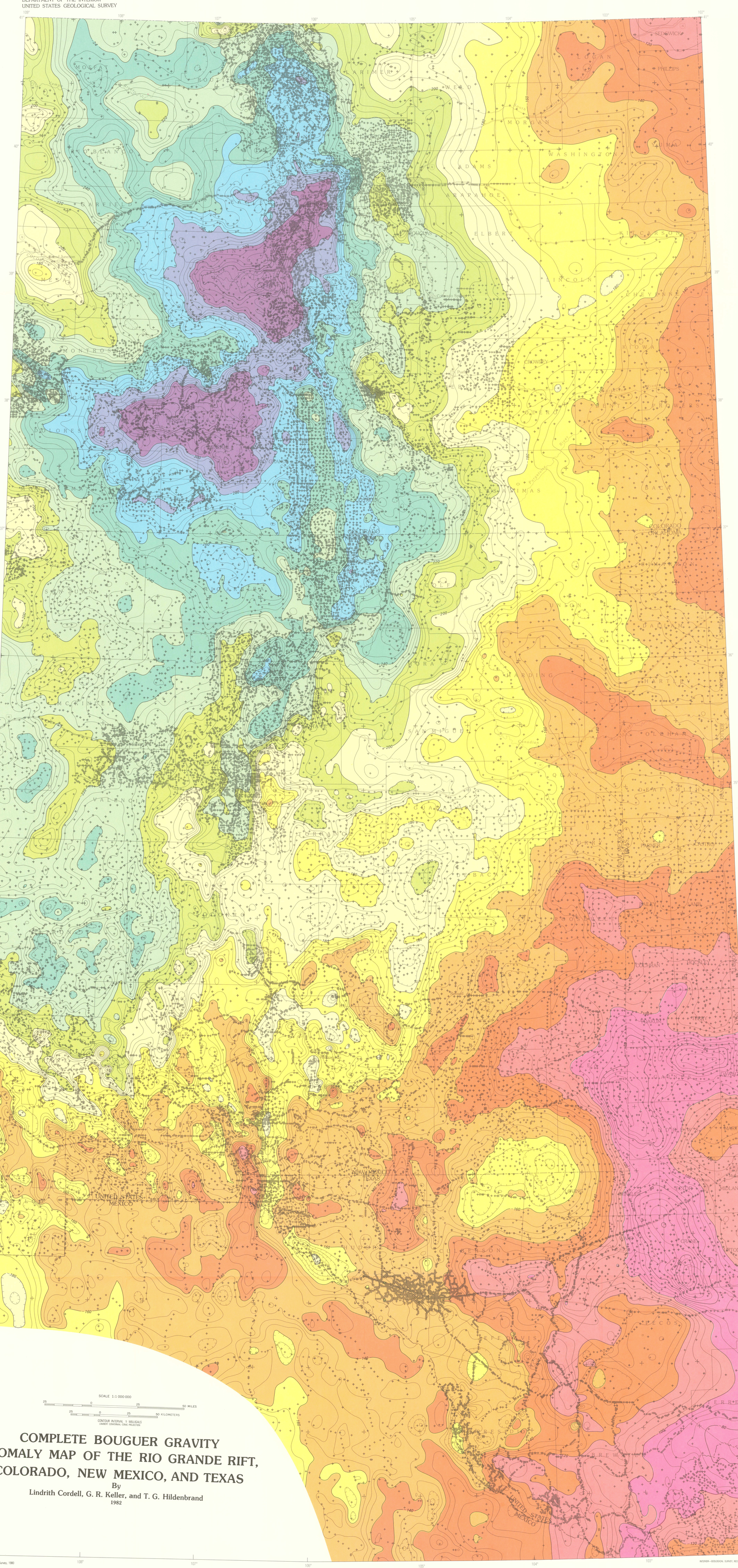

COMPLETE BOUGUER GRAVITY ANOMALY MAP OF THE RIO GRANDE RIFT, COLORADO, NEW MEXICO, AND TEXAS

By
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Base from U.S. Geological Survey, 1980

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BOUGUER GRAVITY

EXPLANATION

- Below −300
- −300 to −280
- −280 to −260
- −260 to −240
- −240 to −220
- −220 to −200
- −200 to −180
- −180 to −160
- −160 to −140
- −140 to −120
- −120 to −100
- Above −100

INTRODUCTION

The Rio Grande rift has been the focus of a concerted geological and geophysical study during the past decade (Chapin and Seager, 1975, Cordell, 1978, and Riecker, 1979, provide recent review articles and current topical research papers). Gravity data have contributed significantly to this work, both in delineating the master graben faults beneath alluvial cover, and in providing clues about the fundamental underlying structure of the deep crust and upper mantle. The Bouguer gravity map of the rift is intended to provide: 1) a synoptic view of the regional gravity field of the rift in context with adjacent Colorado Plateau, High Plains, southern Rocky Mountains, and southern Basin and Range tectonic provinces; 2) a determination of the regional "background" gravity field as a useful reference datum for topical gravity analysis; and 3) an index to the present coverage of available data. We discuss here only the data themselves and certain broad features of the Bouguer anomaly.

DATA

The data set comprises about 48,000 gravity station principal facts (observed gravity, elevation, latitude and longitude). Data were provided by U.S. Geological Survey, U.S. Department of Defense, Cheveron Oil Company, Shell Oil Company, Hart Brown, Scott Smithson, Eugene Davis, Carlos Aiken, Keller, Cordell, and anonymous contributors. For completeness, the map includes coverage of the State of Colorado, even though a Bouguer anomaly map of Colorado at the same scale was published by Behrendt and Bajwa in 1974. Minor disagreement between the two maps reflects different reference datum and reduction formulae, and some differences in the data sets and terrain correction and contouring procedures. A preliminary version of the Rio Grande rift gravity map (Cordell, Keller, and Hildenbrand, 1978) was prepared for the International Symposium on the Rio Grande Rift organized by C.E. Chapin and K.H. Olsen, October, 1978, at Santa Fe, New Mexico (Riecker, 1979).

Terrain correction of the gravity data is essential because of the rugged topography of the region of the Rio Grande rift. In most of the region, the data warrant interpretation at 1:250,000 scale or larger and would provide considerable material for topical geologic studies. Density of gravity station coverage is indicated on the map, although locations are approximate and not all of the stations are shown. (For cartographic purposes, the area was divided into 1 km square cells and cells containing one or more stations are indicated by a "+" symbol.) Further information about the data and the availability of the data tapes and subsequent updates are available from the authors. A generalized version of the gravity map is shown on figure 1 as a locality index.

THE GRAVITY EQUATIONS

Observational gravity data comprise measurements of g, the magnitude of the acceleration of the Earth's gravitational field. This quantity is primarily of interest to geodesists; first order effects due to the Earth's main field mask the more subtle gravity effects related to geologic structure in the crust and upper mantle. For geological study, we consider various derivative "anomalies" showing departure of g from some predicted value representing main-field effects. The Bouguer anomaly, shown here, is the standard anomaly for geological analysis.

The nature of the Bouguer anomaly is apparent in the governing equations. These equations are included here to document calculations and expansions used by the U.S. Geological Survey (unpublished computer program by R. H. Godson, U.S. Geological Survey, 1978) which differ in minor detail from other reduction formulae. Departing from standard mathematical notation, we show the equations approximately as computer-coded to minimize error due to round-off.

The basic equation for the complete Bouguer anomaly, including terrain and curvature correction, is

$$c_{ba} = g - g_{theor} + c_{fa} + \rho'(c_{bouguer} + c_{terrain} + c_{curv}) \qquad (1)$$

where

g = observed gravity, in milligals, relative to the IGSN 71 gravity datum (Morelli and others, 1974)

g_{theor} = theoretical gravity on the surface (sea level) of the 1967 reference figure (International Assoc. of Geodesy, 1967).

$$= 978031.843 + \sigma\ (15727.66 + \sigma\ (-15762.337 + \sigma\ (6083.534 + \sigma\ (-1089.748 + \sigma\ (69.43))))),$$

where

$\sigma = 0.0001\ \phi^2$, and ϕ = latitude, in degrees.

This representation of the theoretical gravity formula was based on a modified Chebychev expansion (G.I. Evenden, U.S. Geological Survey, oral commun., 1980) of the closed form 1967 gravity formula (International Assoc. of Geodesy, 1967, p. 58)

c_{fa} = "free-air" correction for distance of station above or below sea level.

$$= h(0.30877 + \sigma\ (-0.0013398 + \sigma\ (0.0013553 + \sigma\ (-0.0005329 + \sigma\ (0.0000911)))) - h(0.072 \times 10^{-6})),$$

where

h = elevation of station in meters, positive if above sea level.

ρ' = ratio of reduction density, ρ, to the standard reduction density of 2.67 gm/cm³ (approximately the average of measured density of crystalline rocks), that is,

$\rho' = \rho/2.67$.

$c_{bouguer}$ = Bouguer correction for rock mass between the station and sea level. (A special definition applies to marine surveys). The rock mass is treated as an infinite horizontal slab of thickness h and density ρ.

$$c_{bouguer} = -0.1119\ h \qquad (2)$$

$c_{terrain}$ = terrain correction, a modification of the Bouguer slab approximation taking into account departure, caused by topography, from the assumed horizontal slab. For the rift map, terrain correction was made by the procedure of Plouff (1977) as discussed below.

c_{curv} = Earth's curvature correction, another modification of the Bouguer slab approximation.

$$= -h(1.4639108 \times 10^{-3} + h(-3.532715 \times 10^{-7} + h(4.449648 \times 10^{-13}))).$$

By definition, the free-air gravity anomaly (fig. 3) is

$$f_{aa} = g - g_{theor} + c_{fa}. \qquad (3)$$

Terrain corrections were made by means of the computer program of Plouff (1977) used in conjunction with digital terrain data for the conterminous United States obtained from the U.S. Department of Defense. Topography was originally digitized from 1:250,000 scale contour maps on a 61 m (200 ft) grid. For the U.S. Geological Survey terrain data set these data were regridded and averaged at a grid interval of 30" of latitude and longitude (about 800 m). Terrain correction was made for the region 0.895 km to 167 km radially from each gravity station. Correction from 0 to 0.895 km was ignored, representing an assumption that the station occurs at the center of a flat field 1.8 km in diameter. Inasmuch as many stations are at benchmarks along roads in deep canyons, or on trails along ridges, some systematic error is probably present.

For purposes of contouring by computer, complete Bouguer anomaly values at irregularly distributed field stations were represented on a 2.5 km grid by means of a minimum curvature interpolation formula (Briggs, 1974) programmed with modifications for the U.S. Geological Survey by M. W. Webring in 1977.

The Bouguer anomaly, as equation (1) shows, represents an attempt to remove from the observed gravitational acceleration both the effect of the Earth's main field and the effect that, due to topography, gravity is observed on an Earth whose radius is locally variable. The intent of the corrections is to remove from the Earth its normal, systematically distributed mass leaving the observational (Earth's) surface as a sort of exuvium enclosing anomalous masses suspended in vacuo. Inasmuch as only the magnitude of g is measured, its vector properties are lost. The main field is three to five orders of magnitude larger than effects of local geologic sources and, consequently, the orientation of the vector is little changed in the vicinity of these sources. To an approximation, the Bouguer anomaly can be considered to represent the vertical component of the gravity effect of anomalous masses and thereby can be represented as a scalar, rather than a vector, quantity.

Although the Bouguer anomaly is probably the least contrived gravity anomaly which is geologically interpretable, it contains one potential operational artifact related to the reduction density. Error in the choice of reduction density, which is inevitable because the density of surficial deposits varies, will cause the Bouguer anomaly to tend to mimic topography or inverted topography, as is apparent in the Bouguer correction equations (1) and (2). Total relief in the Rio Grande region of nearly 4000 m causes the error to be potentially significant. Local error of 5-10 mgals can be expected, particularly where large topographic relief occurs in low-density volcanic terrane, as in southwestern Colorado and southwestern New Mexico.

Regional error related to the reduction density problem is present also. For example, the Bouguer anomaly is lower, (fig. 1), and elevation is higher, (fig. 2) in the Colorado Plateau relative to the High Plains. With other geophysical data (Cordell, 1978, Thompson and Zoback, 1979) this has been interpreted to reflect partial or incipient melting of the uppermost mantle beneath the Plateau. The apparent difference in Bouguer anomaly between the Colorado Plateau and the High Plains would be somewhat reduced, however, if a reduction density of 2.4 g/cm³, representing the lithology comprising the extra elevation of the Plateau, had been used in place of the standard reduction density of 2.67 g/cm³. Thus a "geologic correction" for near-surface density deviation from the reduction density probably should be incorporated in the Bouguer anomaly wherever possible. Decker and others (1975) did apply such a correction in an analysis of the rift in southern New Mexico.

BROAD FEATURES OF THE GRAVITY MAP

Specific features in the gravity map will not be discussed here, except that the rift anomaly, the Malpais anomaly, and the southern New Mexico trend, warrant brief comment. The Rio Grande graben or chain of grabens along the axis of the rift is filled with as much as 5 km of low density alluvial sandstone, causing a gravity low. Beneath the graben-fill the crust is penetrated by mantle-derived material causing a broader gravity high. At still greater depths (> 40 km) anomalously low density material, attributed to partial or incipient melting of the upper mantle, causes a very broad gravity low. Thus, the gravity expression of the rift comprises a low within a high within a low. Although interpreters have tended to emphasize one or another of these three anomaly components, all three are present and characterize the rift (see Cordell, 1976 and 1978). It is the positive anomaly component, to the extent that this represents the addition of new material and a net volume increase and extension of the crust, that is perhaps fundamentally characteristic of extension and "rifting". The positive anomaly component is indistinct in Colorado but appears in central and southern New Mexico as a broad feature related either to disseminated sources or to sources deep within the crust or at its base.

In west central New Mexico, west of the graben and well within the Colorado Plateau, a large, north-northeast trending positive gravity anomaly is associated with extensive Neogene-Recent tholeiitic basalt of the Malpais field (label M in fig. 1). The gravity anomaly zig-zags generally northward from the basalt field across the Plateau near the west border of the gravity map. The anomaly could reflect Precambrian basement structure. However, because of its association with Neogene tholeiite of obvious rift affinity, we suggest alternatively that it represents one finger of the southward digitation of the Rio Grande rift.

A well developed northwest alignment of gravity trends extends across the southern part of the map (label T in fig. 1) and may represent a major buried transverse structural discontinuity.

RELATIONSHIP OF BOUGUER GRAVITY TO ELEVATION

A generalized topographic map of the area covered by the gravity map is shown in figure 2. Broad features of the Bouguer gravity and elevation maps are similar in outline, as is commonly observed.

Although the correlation between Bouguer gravity and elevation is generally attributed to isostasy, geological factors are involved as well. Geology, and corresponding density, is commonly correlated with topography; examples representing a broad band of wave lengths include constructional volcanic topography; inversion of topography on anticlines; valleys (or mountains) along rifts; and basalt-capped mesas formed as erosional remnants. All of these occur together along the Rio Grande rift in southwest Colorado, where the Bouguer gravity-elevation correspondence is perhaps most obvious in figures 1 and 2. The presence of these and other geology-elevation effects causes complications in investigation of isostasy.

A free-air gravity anomaly map of the rift is shown in figure 3. Station free-air anomaly data were initially gridded at 2.5 km and then regridded at 40 km by moving averages. In the free-air anomaly (equation 3), in contrast with the Bouguer anomaly (equation 1), the effect of rock mass above the reference horizon at sea level is not removed because this mass excess is assumed to be isostatically compensated by a corresponding mass deficiency at depth. Compensation is generally considered to be either "local" or "regional" (Heiskanen and Vening Meinesz, 1958). Compensation occurs directly underneath very broad features (local compensation), resulting in a low (near zero) value of the free-air anomaly. Smaller features, by contrast, are considered to be "regionally" compensated, in which case the load is distributed; a non-zero free-air anomaly would be flanked by a broader anomaly of opposite sign, but integration over the surface would yield approximately zero. The terminology is confusing in that "local" refers to large features and "regional" refers to small features.

None of these generalizations are evident in figure 3, suggesting that our area (1300 by 650 km) is too small for local compensation to be noticed and that, perhaps owning to interference from many individual features, individual regional-compensation dipoles are not identified.

Figure 4 shows radial Fourier amplitude spectra for gravity and elevation data from a 640 by 640 km area between 33° and 39° north. The data were represented by running averages on a 10 by 10 km grid. Wave lengths larger than about 250 km are poorly represented because there isn't room for many of these in a 640 km wide sample.

To judge from figure 4, the gravity and elevation spectra become dissimilar at wave lengths less than about 110 km. Wave length is measured from peak to peak; in terms of anomaly width, measured from inflection point to inflection point and, therefore, equal to half a wave length, our data could be interpreted to indicate local isostatic compensation at anomaly widths as small as 55 km. Local isostatic compensation at anomaly widths as small as 55 km may occur in the Rio Grande rift, but we doubt it. We suggest, alternatively, that the correlation of the gravity and elevation spectra in this band is in part related to geologic, rather than entirely local-isostatic factors.

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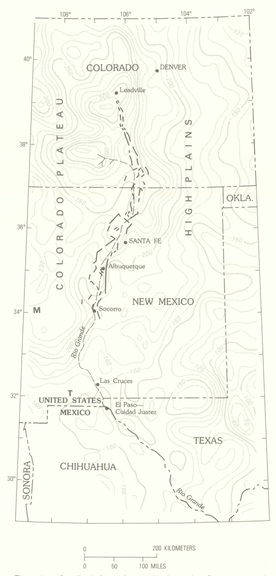

Figure 1. — Locality index and generalized complete Bouguer anomaly map. Gravity averaged on a 20 km grid; contour interval 10 mgals. Heavy lines show major faults of Rio Grande graben north of Socorro, New Mexico (Cordell, 1978), dashed line shows Rio Grande. Label **M** locates Malpais positive gravity anomaly and label **T** locates northwesterly gravity trend, mentioned in text.

Figure 2. — Generalized elevation map — elevation of gravity stations averaged onto a 20 km grid. Contour interval is 200 m relative to sea level datum. Base same as figure 1.

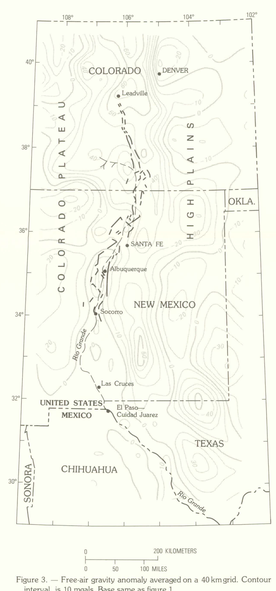

Figure 3. — Free-air gravity anomaly averaged on a 40 km grid. Contour interval is 10 mgals. Base same as figure 1

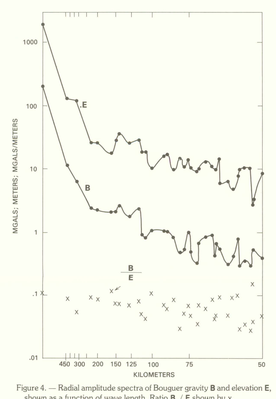

Figure 4. — Radial amplitude spectra of Bouguer gravity **B** and elevation **E**, shown as a function of wave length. Ratio **B** / **E** shown by x.

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