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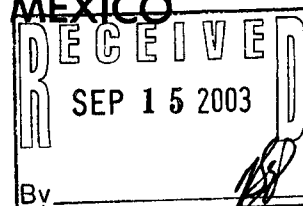
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# GRAVIMETRIC EXPRESSION OF GRABEN FAULTING IN SANTA FE COUNTRY AND THE ESPAÑOLA BASIN, NEW MEXICO

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## INTRODUCTION

The Española basin generally is considered to be one in a chain of graben along the axis of the Rio Grande rift, and contains the type locality of the upper Cenozoic, graben-filling Santa Fe Group (Galusha and Blick, 1971; Manley, 1979). Disagreement exists, however, on the position, and even the existence, of the graben-border faults. This paper concerns the delineation of faults by gravity data, based on the premise that the sandy, poorly consolidated Santa Fe Group has low density relative to the graben basement.

A long history of structural interpretation of the Española basin is cited and evaluated in three recent papers. Kelley (1979) characterizes the basin as fault-bounded. Manley (1979) emphasizes a narrow axial graben (the Velarde graben) within the basin, whereas Baltz (1978) characterizes the basin as essentially a syncline. The question of whether the basin is fundamentally a graben or a syncline is important, because the geometry of a keystone-shaped graben requires crustal extension and "rifting," whereas a synclinal fold does not. Actually, Baltz too describes major zones of normal faulting, although he maps displacement along the easternmost basin edge in a sense opposite to that of some previous workers.

Such differing interpretations suggest that scientific reproducibility is not being realized, and therefore, that the limit of resolution of geologic mapping has been reached. I have suggested previously (Cordell, 1970, 1976, 1979) that throughout the Rio Grande rift, the pattern of exposed faults commonly provides few and unreliable clues to the configuration of the graben-bounding master faults to 1 to 5 km depths, as delineated by gravity data. Possible factors in this are: (1) stratigraphic throw on growth faults increases unpredictably with depth; (2) some exposed faults are secondary slump features; and (3) most of the master faults are covered by an alluvial veneer and cannot be seen at the surface.

In this spirit, I show here gravity data from the Española basin, including previously unpublished data, with the aim of delineating buried master faults. In a nutshell: the gravity data do not establish the existence of faults, although this is the preferred interpretation. If faults are present, the gravity data show their approximate positions.

## GRAVITY DATA

Locations of gravity stations and a complete Bouguer-anomaly map of a region centered on Santa Fe Country and the Española basin are shown in Figure 1. Data from 208 stations near Los Alamos are from Budding (1978) and were provided by A. J. Budding (personal commun., 1978). The rest of the stations were measured by me in the course of a program of regional gravity mapping of the Rio Grande rift. Observed gravity is measured relative to a network of U.S. Department of Defense base stations and is reduced to the IGSN-71 datum (Morelli and others, 1974). Terrain correction, by means of

the computer program of Plouff (1977), was made to a distance 167 km from each station. Innermost terrain correction for a zone extending to either 1.0 or 2.67 km from the station was made by means of templates overlaying topographic maps. A reduction density of  $2.5 \text{ gm/cm}^3$  was used for the Bouguer and terrain corrections.

## REGIONAL GRAVITY FEATURES

The trace of the Rio Grande graben across the area of Figure 1 is depicted in two ways. A fine dashed line shows the extent of the Santa Fe Group (including some older and younger graben-filling units). Normally, this is a wedge edge and thus only delimits an outer envelope of the graben. Heavy dashed lines show steep gravity gradients which may mark graben faults, as discussed below. Prominent gravity features not related to the Cenozoic faulting in the Española basin occur over the pre-rift (Laramide-age) Nacimiento fault and the syn-rift (Pleistocene) Valles caldera. Other anomalies delineate lithologic boundaries in Precambrian terrane in the Sangre de Cristo Mountains east of the Española basin.

Less prominent in Figure 1 is a general gravity decrease westward, and possibly, a broad gravity positive along the axis of the rift related to features in the deep crust and upper mantle. These important features have been interpreted variously, as reviewed by Cordell (1978). They don't concern us here except that we must keep in mind that these deep features can cause unaccounted-for gradients of 1 to 2 milligals per km in gravity data being modeled here entirely in terms of basin-fill density contrast with basement rocks. The principal effect of ignoring these regional features would be to reduce local gravity gradients along the sides of the basin, and consequently, make gravity-based estimates of structural relief too small.

## GRAVITY EXPRESSION OF GRABEN-BORDER FAULTS

Steep gravity gradients delineate all but the southern borders of the Española structural basin (fig. 1). On the east side of Figure 1, from south to north, steep gravity gradients are associated with the northernmost end of the fault zone near Rosario, whence the border shifts en echelon eastward a distance of perhaps 25 km and continues due northward generally parallel and west of the Sangre de Cristo mountain front. On the west side, from south to north, the main border of the linked Santo Domingo and Española structural basins begins east of San Ysidro, about 35 to 40 km west of the Rosario fault zone and trends northeastward 40 km to the St. Peter's dome area, whence it zigzags abruptly northwest. Relationship of gravity to thickness of basin fill is complicated by the contribution of unusually low-density rocks in the area of the Jemez volcanic field. North of Valles caldera, however, the border of the structural basin again trends northeastward, generally along the Abiquiu fault zone. On the north, the Espa-

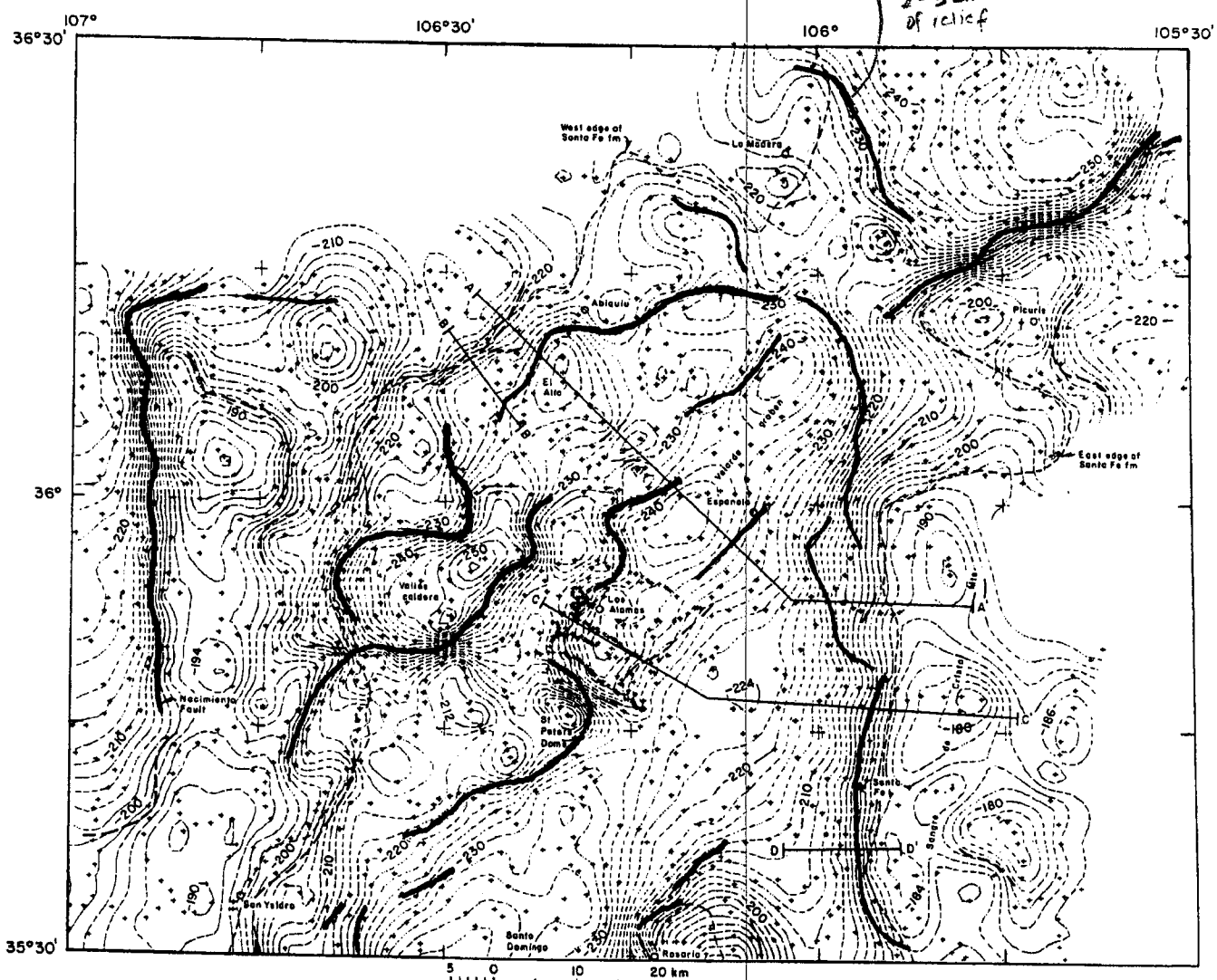


Figure 1. Complete Bouguer-anomaly gravity map centered on the Española basin section of the Rio Grande rift. Contour interval 2 mgals; reduction density  $2.5 \text{ gm/cm}^3$ . Gravity stations indicated by "+". Hachures indicate local closed minima. Limit of Santa Fe Group and related graben-filling rocks shown by fine dashed line. Locus of principal gravity inflection points shown by heavy dashed lines (from fig. 6). Profile bars show locations of profiles A, B, C and D (figs. 2-5).

ñola basin is truncated by a major, northwest-trending structural ridge connecting Precambrian massifs in the area between La Madera and Picuris. Possibly 2 to 3 km of structural relief exist across this ridge separating the Española and Taos-San Luis basin sections of the Rio Grande rift. Very steep gravity gradients delineate the southern edge of the Taos basin along a northeast-trending fault zone north of Picuris.

Gravity profiles across linear gravity gradients are shown at locations A, B, C and D on Figure 1. These are interpreted in terms of inferred thickness of low-density rocks, as discussed below. "Low-density rocks" can be considered to comprise primarily Miocene-Pliocene Santa Fe Group, although older "low-density rocks" undoubtedly are present. Regional considerations (Cordell, 1976, fig. 5) suggest that most of the pre-Neogene sedimentary rocks have been eroded from this region in the course of stripping of Laramide uplifts. The grav-

ity models were calculated for two density contrasts ( $-0.3$  and  $-0.5$  grams per cubic centimeter) which represent my best estimate of the range of density contrasts to be expected on the basis of sample density measurements and *in situ* density profiles from the region.

Profile A-A' crosses the northern part of the Española basin from the Abiquiu fault zone on the west across the Velarde graben to the Sangre de Cristo Mountains on the east. The profile and derived interpretational models are shown in Figure 2. A linear regional gravity field decreasing west-northwestward at a rate of 0.32 milligals per kilometer was determined by inspection. This amount of westward decrease of the regional Bouguer gravity field is typical of the central and northern sections of the Rio Grande rift (Cordell, 1976), and is attributed to anomalously low density of the upper mantle under the Colorado Plateau to the west, relative to normal

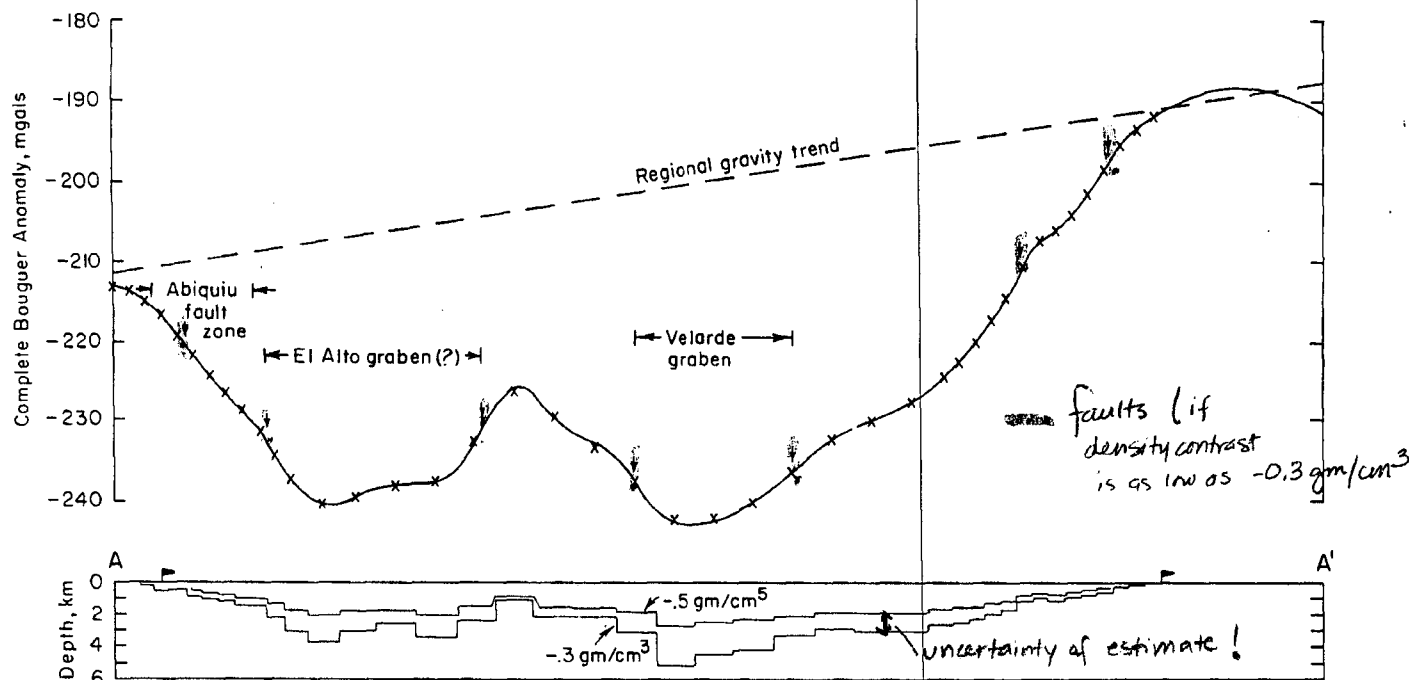


Figure 2. Profile A-A' (see fig. 1 for location). Lower graph shows depth to base of low-density graben fill, calculated from the gravity data for two different density contrasts ( $-0.3$  and  $-0.5$   $\text{gm}/\text{cm}^3$ , as indicated). Horizontal and vertical scales in the derived graben-fill models are the same and are indicated on the "depth" ordinate of the lower figure. Flags show the approximate limits of graben fill as determined from geologic mapping. In the upper figure, the Bouguer anomaly profile (fig. 1) is shown by solid line, and gravity effect calculated from the  $-0.3$   $\text{gm}/\text{cm}^3$  model is indicated by "x". (Fit of the  $-0.5$   $\text{gm}/\text{cm}^3$  model is generally better.) Vertical arrows show inflection points, as determined from Figure 6.

upper mantle under the High Plains province to the east. In addition to very broad upper-mantle-related gravity features, a narrower regional positive gravity anomaly commonly is observed along the axis of the rift; this anomaly is attributed to high-density material within the lower and middle parts of the crust (Cordell, 1976; Decker and Smithson, 1975). Such a positive gravity feature is not obvious in profile A, and is assumed not to be present. If it is present, its effect would be to make the gravity gradients along the basin edges appear too gentle and the derived structural relief too small.

Subject to uncertainties about the regional gravity field, the derived models shown in Figure 2 indicate 2.5 to 5 km of low-density rocks in the deepest part of the basin within the Velarde graben. The step-shaped appearance of the model is an artifact of the computer program, which uses prismatic elements. The vertical-sided prism edges are not (of course) faults, but faults can be located approximately where the calculated thickness of fill changes abruptly. In the case of profile A-A', faults might be located with some confidence at the points indicated by arrows (inflection points, as will be discussed below) if the density contrast is as low as  $-0.3$   $\text{gm}/\text{cm}^3$ . For a density contrast of  $-0.5$   $\text{gm}/\text{cm}^3$ , however, it would be difficult to argue that faults are required to explain the gravity data. For example, on the eastern side of the basin, for a distance 15 km west of the Santa Fe Group wedge-edge, the gravity data are consistent with a  $7^\circ$  regional dip basinward as suggested by Baltz (1978). Farther to the west, in the Velarde graben and a somewhat similar-looking feature to the west of that, near El Alto, the low-density material does thicken

abruptly, particularly on the west side of the Velarde graben, and faulting seems the more likely explanation.

Sedimentary facies effects on the downthrown side of a fault scarp may give rise to a gradational decrease in density contrast near the fault, causing an apparent gentling of the gravity gradient (Cordell, 1979), although this could not be determined from the reconnaissance data at hand. Taking the data at face value, my preferred interpretation would be faulting and homoclinal dip basinward on the east side of the basin, with large faults bounding the Velarde and El Alto grabens. I emphasize that existence of the inferred faults is not proved by the gravity data.

Essentially the same conclusion for the west side of the basin can be drawn from profile B-B' (fig. 3), located approximately 5 km south and west of profile A-A'. The western half of profile B-B' is controlled poorly by data. A fault could be interpreted in the eastern part of profile B-B', as indicated by the inflection-point arrow.

A profile from the southern end of the Velarde graben eastward to the Sangre de Cristo Mountains is shown in profile C-C' (fig. 4). Fault margins of the Velarde graben do seem a reasonable interpretation here, although even here, faults are not required by the data. In the eastern half of the profile, the inflection point is located about 3 km basinward from the edge of the Santa Fe Group.

Profile D-D' (fig. 5) crosses the southern end of the Sangre de Cristo front in the Española basin. Here, an abrupt 300-to-400-m thickening occurs about 1.5 km west of the edge of the Santa Fe Group, perhaps indicative of a fault. Even so, the

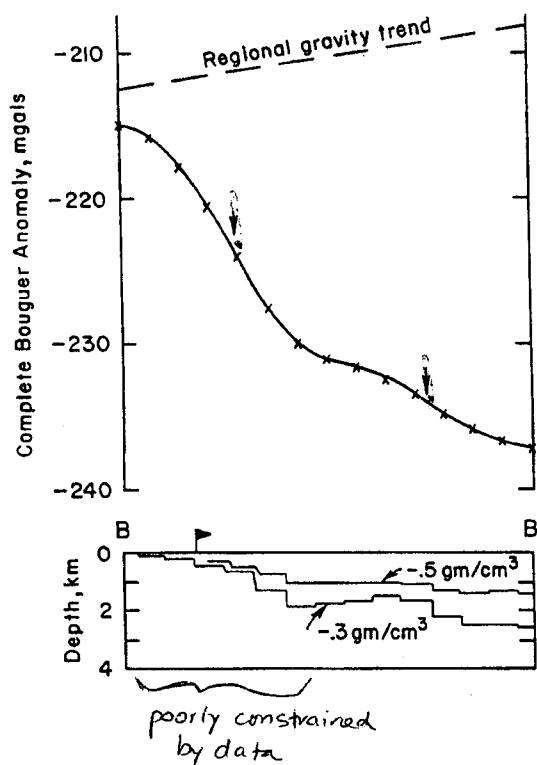


Figure 3. Profile B-B' (see fig. 1 for location). Lower graph shows depth to base of low-density graben fill, calculated from the gravity data for two different density contrasts ( $-0.3$  and  $-0.5 \text{ gm/cm}^3$ , as indicated). Horizontal and vertical scales in the derived graben-fill models are the same and are indicated on the "depth" ordinate of the lower figure. Flags show the approximate limits of graben fill as determined from geologic mapping. In the upper figure, the Bouguer anomaly profile (fig. 1) is shown by solid line, and gravity effect calculated from the  $-0.3 \text{ gm/cm}^3$  model is indicated by "x". (Fit of the  $-0.5 \text{ gm/cm}^3$  model is generally better.) Vertical arrows show inflection points, as determined from Figure 6.

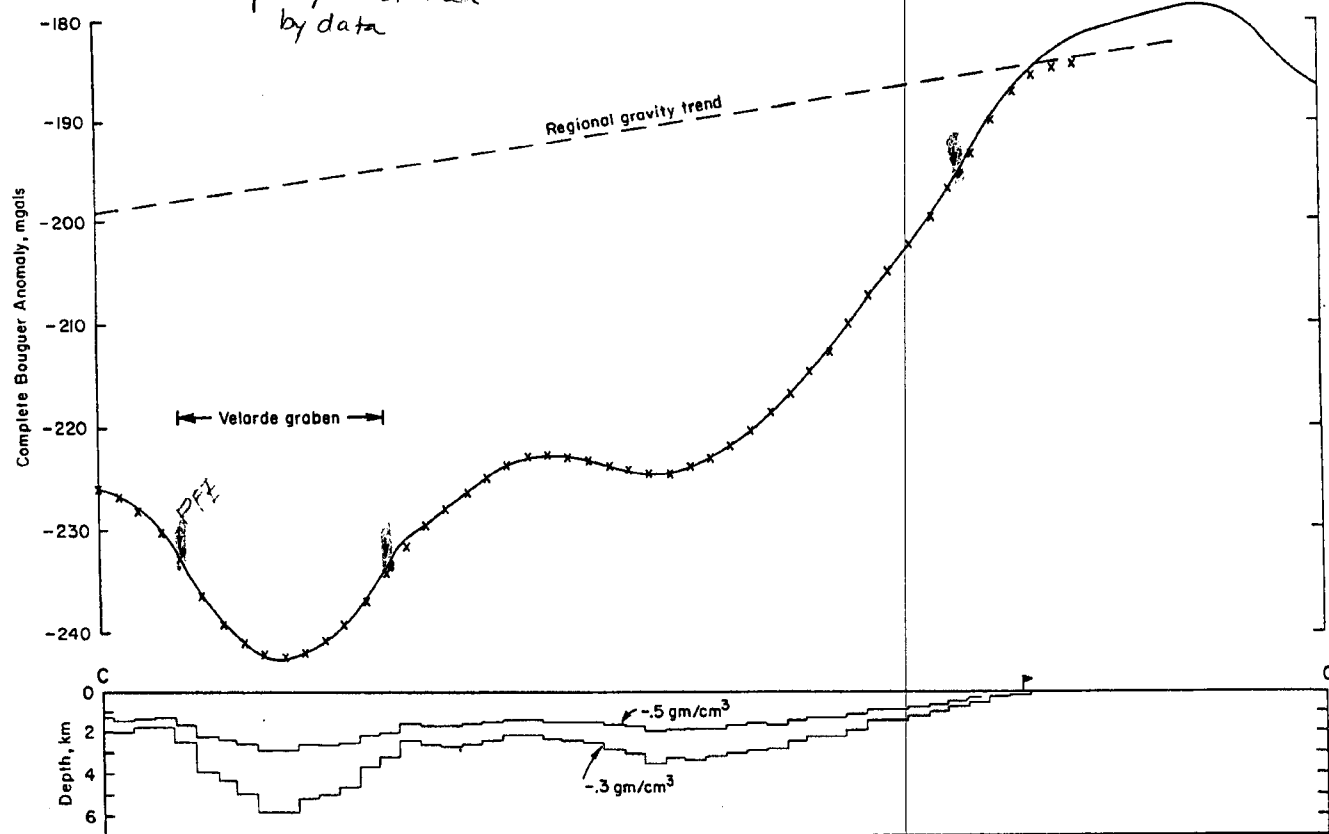


Figure 4. Profile C-C' (see fig. 1 for location). Lower graph shows depth to base of low-density graben fill, calculated from the gravity data for two different density contrasts ( $-0.3$  and  $-0.5 \text{ gm/cm}^3$ , as indicated). Horizontal and vertical scales in the derived graben-fill models are the same and are indicated on the "depth" ordinate of the lower figure. Flags show the approximate limits of graben fill as determined from geologic mapping. In the upper figure, the Bouguer anomaly profile (fig. 1) is shown by solid line, and gravity effect calculated from the  $-0.3 \text{ gm/cm}^3$  model is indicated by "x". (Fit of the  $-0.5 \text{ gm/cm}^3$  model is generally better.) Vertical arrows show inflection points, as determined from Figure 6.

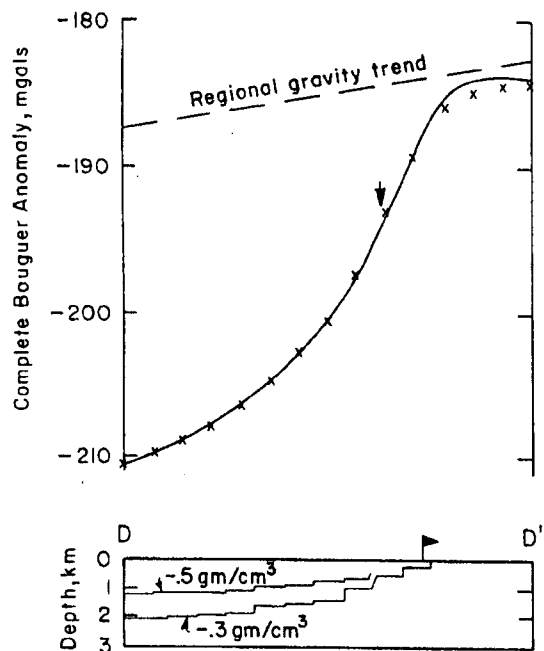


Figure 5. Profile D-D' (see fig. 1 for location). Lower graph shows depth to base of low-density graben fill, calculated from the gravity data for two different density contrasts ( $-0.3$  and  $-0.5$  gm/cm<sup>3</sup>, as indicated). Horizontal and vertical scales in the derived graben-fill models are the same and are indicated on the "depth" ordinate of the lower figure. Flags show the approximate limits of graben fill as determined from geologic mapping. In the upper figure, the Bouguer anomaly profile (fig. 1) is shown by solid line, and gravity effect calculated from the  $-0.3$  gm/cm<sup>3</sup> model is indicated by "x". (Fit of the  $-0.5$  gm/cm<sup>3</sup> model is generally better.) Vertical arrows show inflection points, as determined from Figure 6.

profile gives the impression that most of the structural relief is accomplished by homoclinal dip basinward.

A horst-like structure (figs. 1, 2), separating the Velarde and El Alto inferred grabens, extends from Valle caldera perhaps 40 km northeastward. This is depicted in the profiles as a basement high, but it could be related instead to Cenozoic intrusive and extrusive rocks of the Jemez volcanic field.

Although the profiles do not establish uniquely the existence of faults anywhere in the Española basin, they do indicate various zones in which faults seem to be the most reasonable interpretation, especially in light of regional structural style. The profiles do not locate these faults very well, however, because of the step-like aspect of the prism-based models. As an aid in delineating possible fault traces in plan view, I have constructed a gravity gradient map (fig. 6). The gravity gradient is defined here in terms of the Bouguer gravity anomaly function  $g(x,y)$ , with  $x,y$  the horizontal coordinates in a Cartesian system, as

$$|\nabla g(x,y)| = \sqrt{(\partial g / \partial x)^2 + (\partial g / \partial y)^2},$$

i.e., the scalar amplitude of the horizontal component of the Bouguer gravity-anomaly gradient.

Gradient maxima, forming ridge lines in Figure 6, delineate gravity inflection points, which are approximately coincident

with vertical or very steep-sided faults or other density discontinuities. Recognizable ridge lines are marked on Figures 1 and 6 by heavy dashed lines.

Certain of these inflection-point lines can be interpreted as delineating fault zones in the sense that if faults are present, this is probably where they are located. Their aerial patterns show that, as in the Albuquerque basin to the south, the eastern border faults involve linear, en echelon, north-trending zones, whereas within the basin and at the west border of the basin, trends are conjugate northeast-northwest. Valles caldera is located where the western graben border shifts from the St. Peter's dome area abruptly northwestward a distance of perhaps 40 km. As elsewhere in the rift, the gravity data suggest a relatively few, widely spaced master faults. In many places, these are arranged in en echelon configuration suggestive of the "relay fault" concept applied to the region by Kelley (1979).

## DISCUSSION

Strictly speaking, the question of the fundamental structural characterization of the Española basin as a graben or a syncline is beyond the resolution of the gravity data. The question has important general consequences and would be worth answering. Perhaps, a detailed seismic reflection profile would be helpful here.

Regional geologic and geophysical data from the Rio Grande rift (Chapin and Seager, 1975; Cordell, 1978; Riecker, 1979) would seem to make the existence of extensional faulting at shallow levels along the axis of the rift in the Española basin almost a certainty. In places in the Española basin, gravity and geologic data taken together do seem to indicate significant faulting (e.g., Manley's (1979) Velarde graben). Further evidence for faulting in the Velarde graben is provided by repeat-leveling data of Reilinger and York (1979), showing a 15-to-20-km-wide zone of subsidence at an apparent rate of 1 cm per year, associated with anomalous seismic activity northwest of Española.

But structural relief in the Española basin is not particularly large. As an exercise, suppose in profile A-A', that all the structural relief occurs on hypothetical, 60°-dipping normal faults positioned at the inflection points, denoted by the arrows. Depending on which density model is preferred, the amount of horizontal extension implied (fault throw times  $\cotan 60^\circ$ ) is between 1 and 5 km. That is 2 to 8 percent of the width of the basin and an amount comparable to the amount of Cenozoic vertical movement in the Española basin. More extension would result if dips of the faults could be shown to decrease with depth.

## ACKNOWLEDGMENTS

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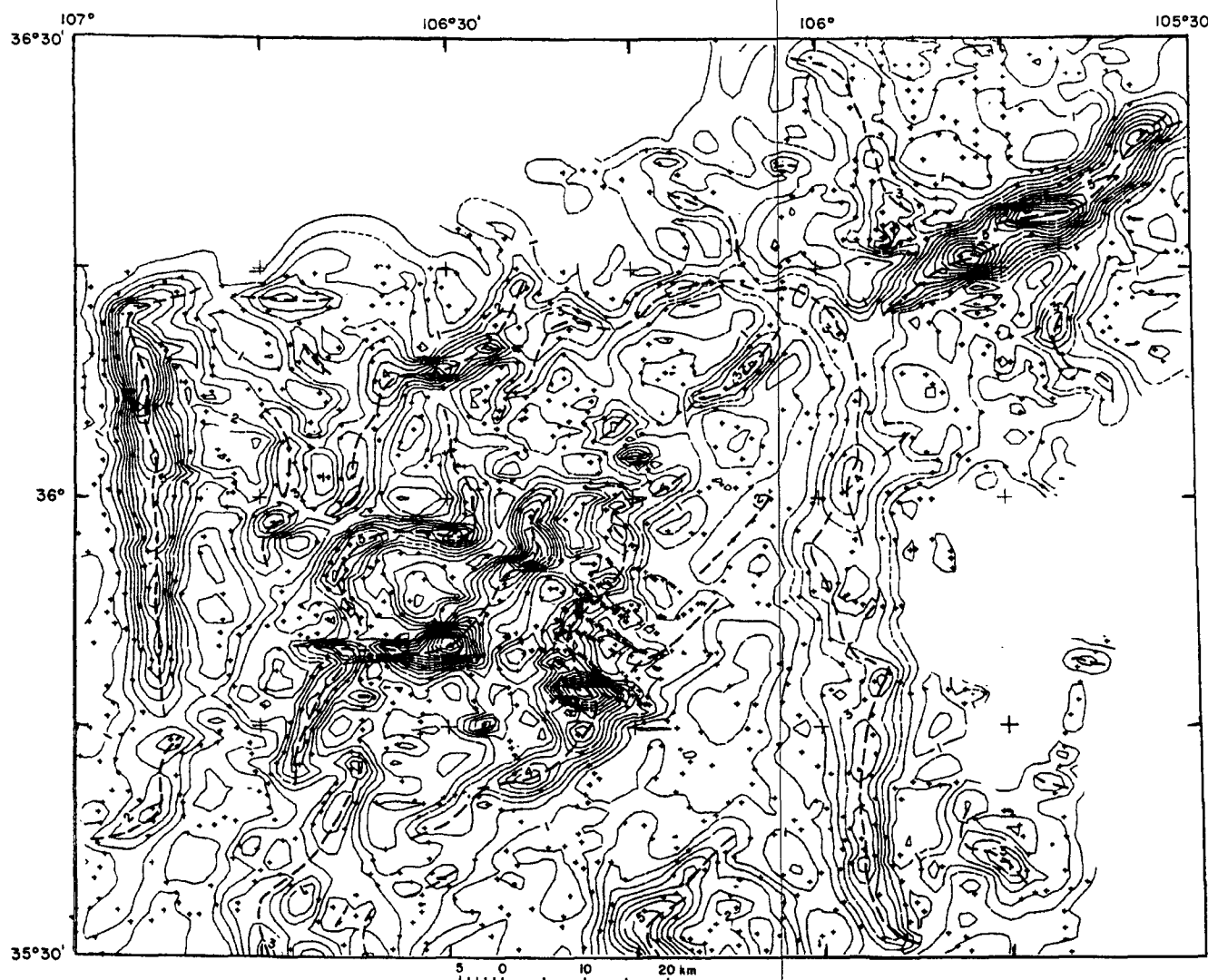


Figure 6. Gravity gradient (amplitude of horizontal component of gravity gradient (contour interval = 0.5 mgals/km)). Heavy dashed lines show significant maxima marking the locus of gravity-anomaly inflection points, and by inference, the approximate location of major faults or steep lithologic contacts.

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