Geofísica Internacional
ISSN: 0016-7169
silvia@geofisica.unam.mx
Universidad Nacional Autónoma de México
México

Serrato Díaz, Gloria S.; Bandy, William L.; Mortera Gutiérrez, Carlos A.
Active rifting and crustal thinning along the Rivera-Cocos plate boundary as inferred from Mantle Bouguer gravity anomalies
Geofísica Internacional, vol. 43, núm. 3, july-september, 2004, pp. 361-381
Universidad Nacional Autónoma de México
Distrito Federal, México

Geofísica Internacional (2004), Vol. 43, Num. 3, pp. 361-381

Active rifting and crustal thinning along the Rivera-Cocos plate boundary as inferred from Mantle Bouguer gravity anomalies

Gloria S. Serrato-Díaz, William L. Bandy and Carlos A. Mortera Gutiérrez
Instituto de Geofísica, Universidad Nacional Autónoma de México, México, D. F., México

Received: October 2, 2002; accepted: December 2, 2003

RESUMEN

El graben El Gordo yace dentro de la litósfera oceánica al oeste de la Trinchera Meso-Americana a 18.15°N, 104.7°W. Se ha propuesto a este graben como una marca del hundimiento al suroeste de una zona activa de extensión ubicada entre las placas de Rivera y Cocos. Los resultados de un análisis de las anomalías de gravedad de Manto-Bouguer en el área de graben El Gordo, y en el área ubicada entre el graben y la Dorsal del Pacífico Este, son consistentes con esta propuesta, así como también con la propuesta de que la zona de extensión se puede estar propagando hacia la Dorsal del Pacífico Este. Específicamente: (1) Una disminución prominente en los valores de la Anomalía de Manto-Bouguer ocurre en el área del graben El Gordo, estando la disminución máxima sobre el complejo volcánico El Gordo, ubicado en el centro del graben. Esta disminución es modelada como el resultado de una intrusión de magma dentro de la corteza oceánica del graben centrada bajo el complejo volcánico El Gordo. Este modelo es respaldado por un flujo de calor en superficie alto en el área de este complejo. (2) Se observa un alto gravimétrico de la anomalía de Aire Libre NE-SW que se extiende desde el graben El Gordo hasta la Dorsal del Pacífico Este. Sin embargo, sólo la parte oeste de esta anomalía es observada en el mapa de Anomalía de Manto-Bouguer. El modelado de los valores de la Anomalía de Manto-Bouguer indica que esta anomalía puede deberse a un adelgazamiento de la corteza en esta región. Sin embargo, a diferencia del área del graben El Gordo, los datos gravimétricos y batimétricos son escasos en esta área, por lo que este resultado es preliminar.

PALABRAS CLAVE: Tectónica de placas, gravedad, Manto-Bouguer, océano Pacífico Este.

ABSTRACT

The El Gordo graben lies within the oceanic lithosphere west of the Middle America Trench at 18.15°N, 104.7°W. This graben has been proposed to mark the southwest tip of an active zone of extension located between the Rivera and Cocos plates. The results of an analysis of the Mantle Bouguer gravity anomalies in the area of the El Gordo graben, and in the area located between the graben and the East Pacific Rise, are consistent with this proposal, as well as the proposal that the zone of extension may be propagating towards the East Pacific Rise. Specifically: (1) A prominent decrease in the MBA values occurs in the area of the El Gordo graben, the maximum decrease being centered over the El Gordo volcanic complex, located in the center of the graben. This decrease is modeled as being the result of magma intrusion within the oceanic crust of the graben centered under the El Gordo volcanic complex. This model is supported by high surface heat flow in the area of this complex. (2) A NE-SW free-air gravity high is observed to extend from the El Gordo graben to the East Pacific Rise. However, only the western part of this anomaly is observed in the MBA map. Modeling of the MBA values indicate that this anomaly may be due to crustal thinning in this region. However, unlike the area of the El Gordo graben, gravity and bathymetric data is sparse in this area, so this result should be considered as preliminary.

KEY WORDS: Plate tectonics, gravity, Mantle-Bouguer, east Pacific ocean.

INTRODUCTION

El Gordo graben lies within the ~10 my old oceanic lithosphere located west of and adjacent to the Middle America Trench southwest of Manzanillo, Mexico (Figure 1). This graben has been proposed (Bandy, 1992; Bandy *et al*., 1995, 2000) to mark the westward extent of a zone of extension occurring within the oceanic lithosphere along the subducted part of the Rivera-Cocos plate boundary. This proposal was based on (1) the seafloor morphology of the area (Bourgois *et al*., 1988; Bandy 1992; Bandy and Hilde, 2000), (2) high surface heat flow (up to 208 mW/m^2) within the graben (Khutorskoy *et al*., 1994), (3) the alignment of the graben with the presently active southern Colima rift (Bandy *et al*., 1995), (4) the alignment of the graben with the pronounced bend in the geometry of the Wadati Benioff zone beneath western Mexico (Pardo and Suárez, 1995), and (5) plate motion studies which place the Rivera-Cocos Euler pole just west of the graben (Bandy, 1992; Kostoglodov and Bandy, 1995; Bandy *et al*., 1998a).

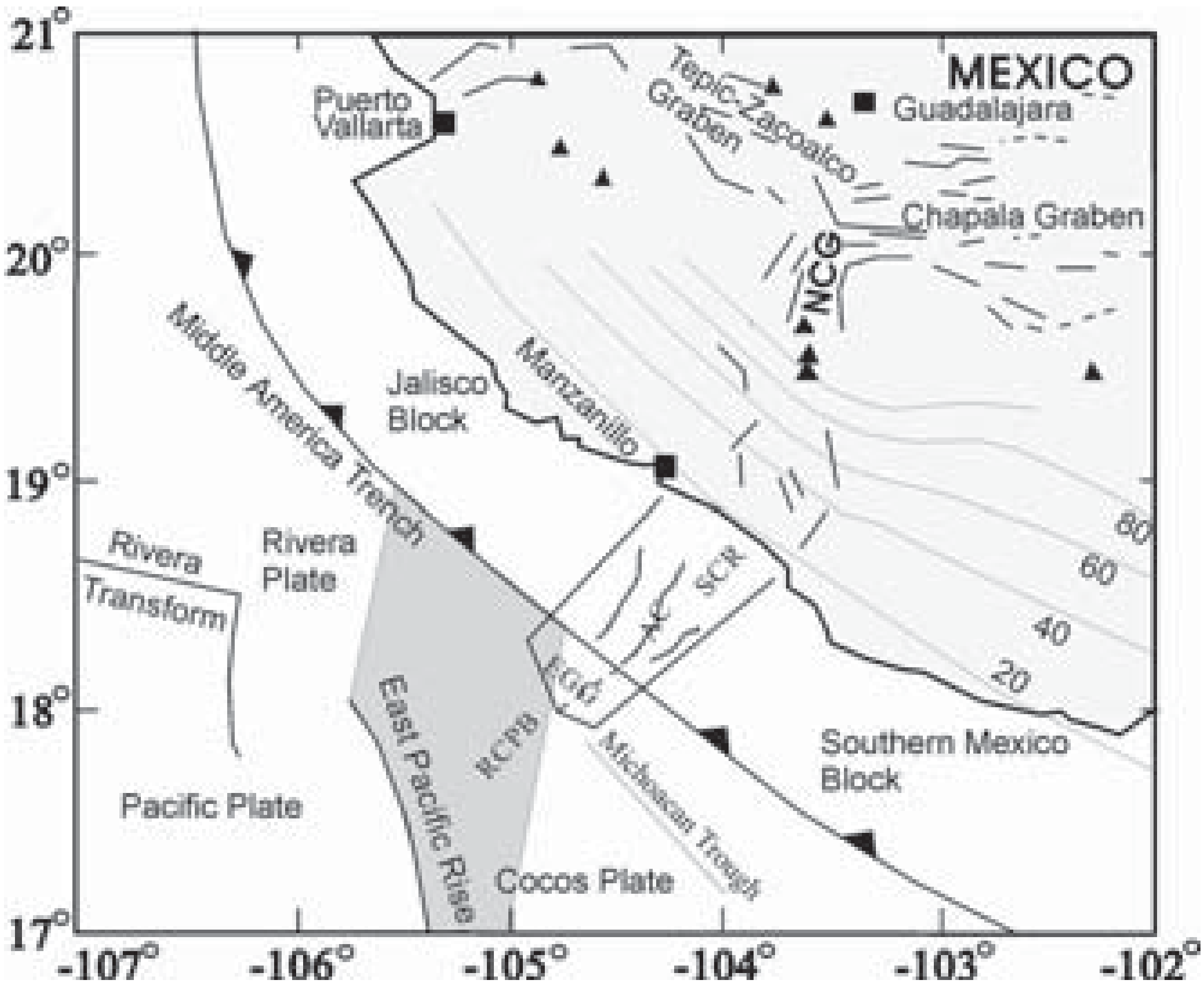

Fig. 1. Location map of the study area. Labeled contours are the depths to the top of the Wadati-Benioff zone from Pardo and Suárez (1995). Shaded area marks the location of the boundary between the Rivera and Cocos plates as presented by DeMets and Wilson (1997). AC = Armería Canyon; EGG = El Gordo graben; NCG = northern Colima graben; RCPB = Rivera-Cocos plate boundary; SCR = southern Colima rift.

Free-air gravity maps of the area constructed both from sea-surface gravity measurements and satellite altimetry data (Bandy, 1992; Bandy and Hilde, 2000; This study; Smith and Sandwell, 1997) exhibit a pronounced break (a 30 to 40 mGal decrease) in the gravity high associated with the western boundary of the Michoacán trough in the area of the El Gordo graben. Further, an area of high gravity values extends from the southern margin of the El Gordo graben to the East Pacific Rise. These observations led to the tentative proposal (Bandy, 1992) that the zone of divergence along the Rivera-Cocos plate boundary may be presently propagating southwestward, from the El Gordo graben towards the East Pacific Rise, and that the boundary between the Rivera and Cocos plates may eventually become a divergent boundary along its entire extent.

If these proposals are correct, then crustal thinning and associated magmatic activity should be occurring within the El Gordo graben and the area located between the El Gordo graben and the East Pacific Rise. The magmatic activity would be expected to produce a low density zone within the crust and upper mantle. Thus, the purpose of the present study is to model the density structure of the crust and upper mantle in the area extending from, and including, the El Gordo graben to the East Pacific Rise employing an analysis of the Mantle Bouguer Anomalies. This analysis indicates that the break in the gravity high associated with the western boundary of the Michoacán trough in the area of the El Gordo graben is not due to the effects of topography as the gravity low remains in the Mantle Bouguer Anomaly map. This MBA low is modeled as a zone of partial melt within the crust and upper mantle of the El Gordo graben. Further, the Mantle Bouguer anomaly map also exhibits a northeast southwest oriented region of high gravity values extending from the East Pacific Rise towards the El Gordo graben. Thus, this anomaly is not due to the effects of topography. This anomaly is modeled as being produced by thinning of the crust in this area. Thus, both the proposal of active extension within the El Gordo graben and the proposal of a southwest propagation of rifting along the Rivera-Cocos plate boundary from the El Gordo graben to the East Pacific Rise are consistent with the presently available gravity data.

GEOLOGICAL SETTING

The El Gordo graben lies within the oceanic lithosphere west of the Middle America Trench at 18.15°N, 104.7°W (Figure 1). Several major tectonic features intersect in the area of the graben; namely, the Middle America Trench, the Michoacán trough, the Colima rift, and a prominent bend in the Wadati-Benioff zone beneath western Mexico. It has been proposed (Bandy, 1992; Bandy *et al*., 2000) that the graben lies along the boundary between the Rivera and Cocos plates, and that it marks the westward extent of a zone of divergence between the Rivera and Cocos plates. If correct, the graben would thus be located at the triple junction formed by the Rivera, Cocos and North American plates. Additionally, if the North American plate in western Mexico is broken into several small crustal blocks (Mooser, 1972; Luhr *et al*., 1985; Allan *et al*., 1991), then the graben may well be located at a quadruple junction formed by the Rivera plate, the Cocos plate, the Jalisco block, and the Southern Mexico block.

Multibeam bathymetric and seismic reflection data (Bourgois *et al*., 1988; Bourgois and Michaud, 1991) indicate that the El Gordo graben is oriented NE-SW parallel to the trend of, and aligned with, the southern Colima graben (Figure 2). It is 40 to 50 km wide (NW-SE) and extends 35

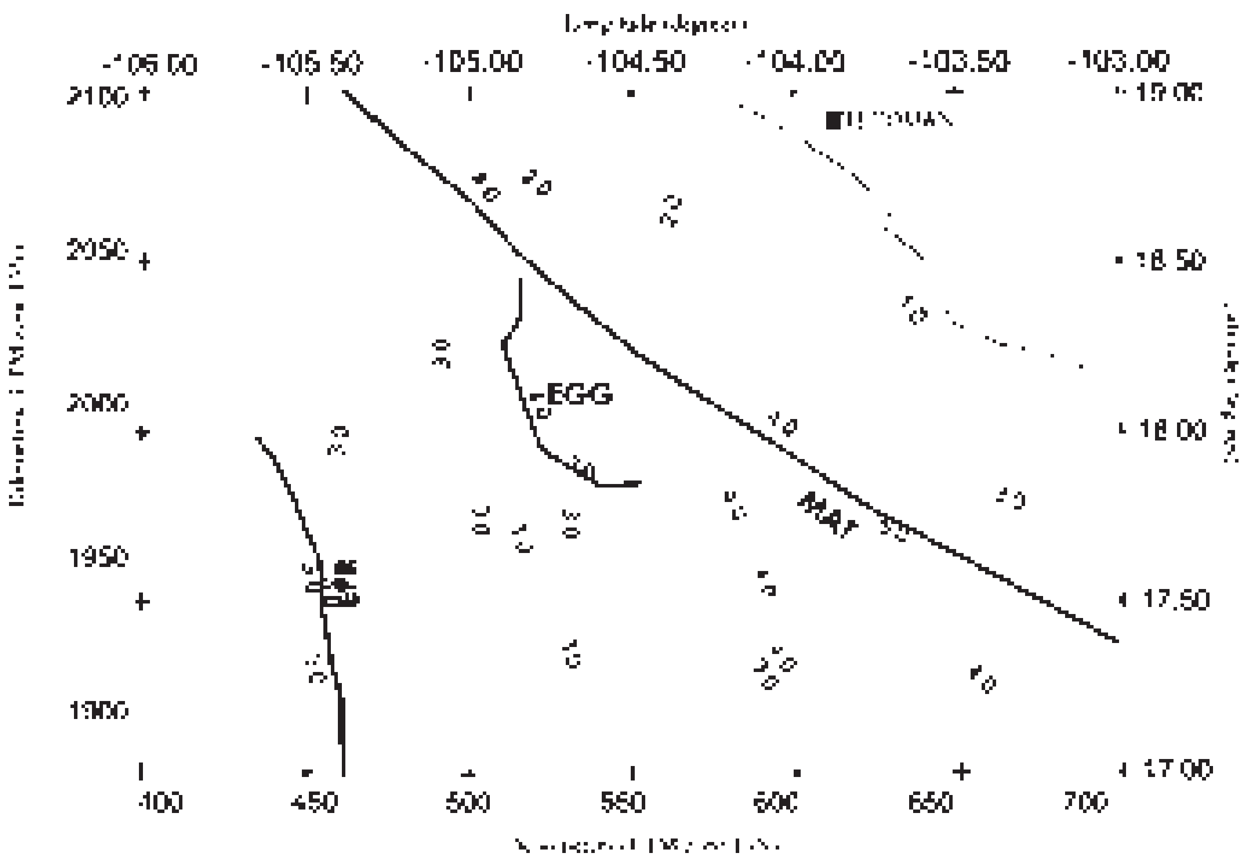

Fig. 2. Bathymetric map. Contour interval equals 250 meters. EGG = El Gordo graben; EPR = East Pacific Rise; MAT = Middle America Trench.

to 40 km towards the southwest away from the Middle America Trench. The graben floor lies at depths greater than 4 km. The escarpment forming its southwestern margin is slightly V-shaped and exhibits about 1 km of relief. The crust within the graben has been dated at 10 Ma, whereas, the crust forming the southwestern wall dates at 2.2 Ma (F. Michaud, Personal Communication, 1998). Thus, the western escarpment is part of the Michoacán trough system (Mammerickx, 1984). These ages are consistent with the ages determined from seafloor spreading produced magnetic lineations (Bandy, 1992; Lonsdale, 1995).

A prominent NE-SW oriented volcanic edifice, the El Gordo volcanic complex, lies within the El Gordo graben. This complex lies along the projection of the Armería submarine canyon that formed along a major NE-SW oriented fault within the southern Colima rift. The age of the volcanism is unknown; however, seismic reflection profiles (Bandy and Hilde, 2000) indicate that the larger volcanic edifices are sediment free, data suggesting that they may be recent features.

Surface heat flow studies (Vacquier *et al*., 1967; Prol-Ledesma *et al*., 1989; Khutorskoy *et al*., 1994) indicate substantially higher heat flow (79 to 208 mW/m^2) within the El Gordo graben in the vicinity of the El Gordo Volcanic complex relative to those obtained from the adjacent trench sediments (20 to 72 mW/m^2) as well as those obtained from sediments within the Michoacán trough (58 and 68 mW/m^2) just south of the graben (Figure 3). Thus, these data suggest that recent magmatic activity is occurring within the El Gordo graben.

Gravity maps (Figures 4 and 5) constructed from satellite altimetry data (Smith and Sandwell, 1997) and free-air anomaly maps constructed from sea surface gravity measurements (Bandy, 1992) both exhibit a pronounced (30 to 40 mGal) break in the free-air gravity high associated with the western margin of the Michoacán trough. Also, both data sets show a west to southwest plunging, gravity high extending from the El Gordo graben to the East Pacific Rise. This anomaly suggests the existence of a structural connection between the El Gordo graben and the East Pacific Rise.

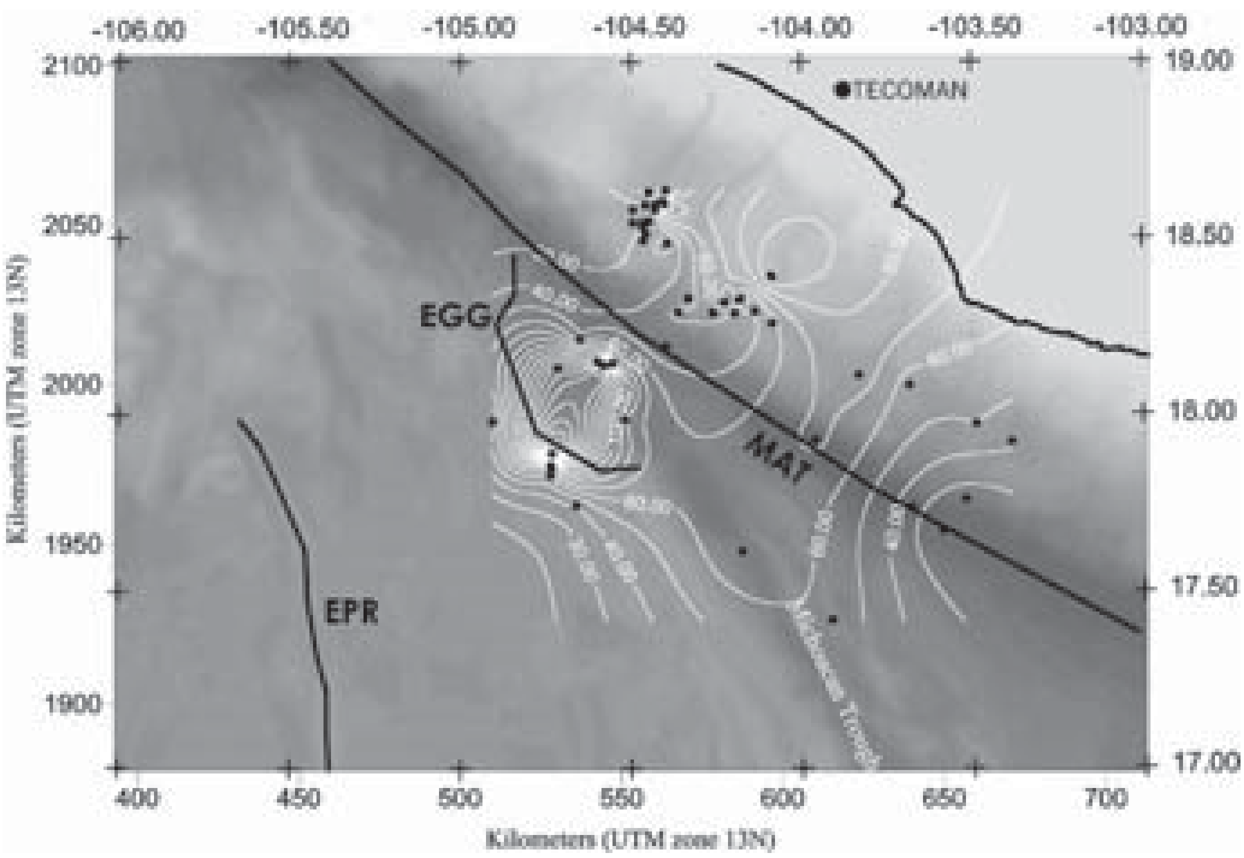

Fig. 3. Surface heat flow map. Contour interval equals 10 mW/m^2.

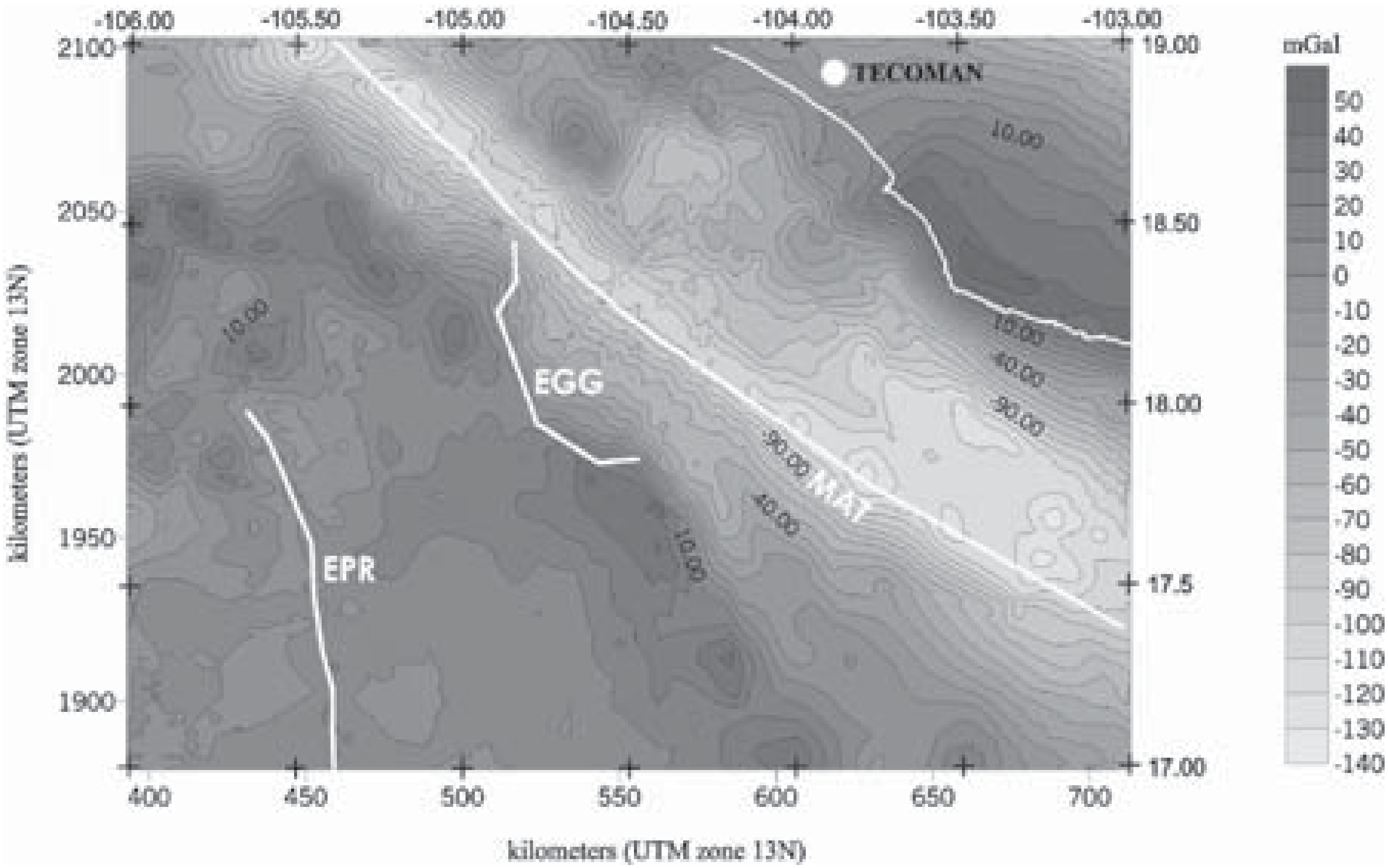

Fig. 4. Free-air anomaly map constructed from sea-surface gravity measurements. Gravity values have been adjusted for crossover errors. Contour interval equals 10 mGal.

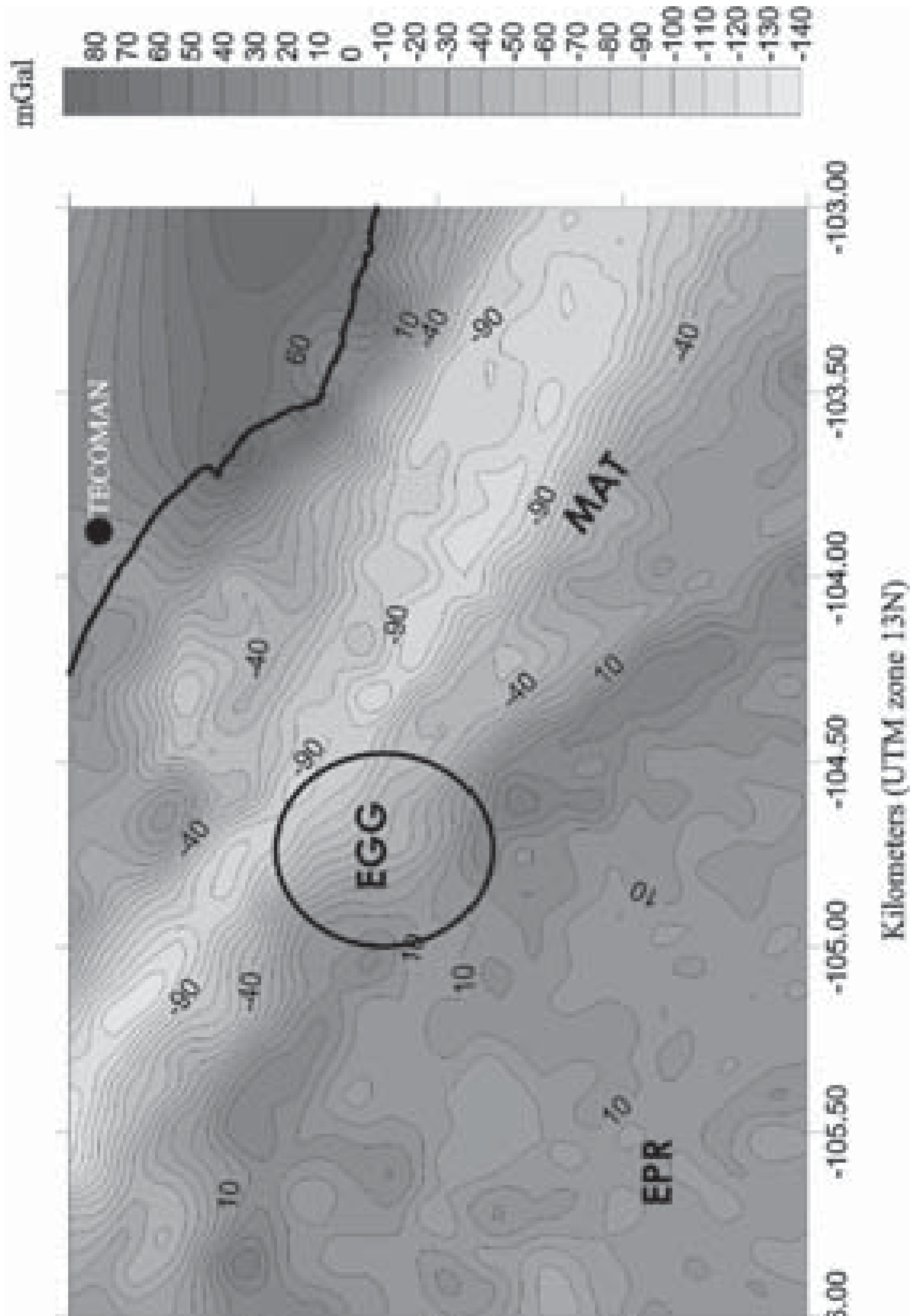

Fig. 5. Marine gravity anomaly map derived from satellite altimetry data (after Smith and Sandwell (1997)). Contour interval equals 10 mGal.

DATA AND METHODS

The data used in this study consists of (1) marine gravity data obtained from the National Geophysical Data Center (NGDC), Boulder Colorado, (2) previously published land gravity data (Skidmore, 1988; Serpa *et al*., 1992; Bandy *et al*., 1993), (3) previously unpublished land gravity data collected from 1992 to 1999, and (4) bathymetric data from Bandy (1992) and more recent marine data presently available from the NGDC. All of the land gravity data are referenced to the absolute gravity base station located at the Oceanographic Institute, Manzanillo, Mexico (location = 19°03'45.545"N, 104°18'08.800"W; elevation with respect to the WGS-77 ellipsoid = -11.15 m; absolute gravity = 978581.46 mGal) (Ness, 1984), and are reduced to complete Bouguer Anomaly values using the Mexico terrain correction data base of Aiken *et al*. (1997). In all, a total of 25 989 gravity measurements (Figure 6) were used to construct a new Free-Air/Bouguer Anomaly map used in this study. The bathymetric coverage is illustrated in Figure 7.

The maps of the data coverage illustrate that the area of the El Gordo graben is well covered by both gravity and bathymetric data. In contrast, both gravity and bathymetric data are sparse in the area between the graben and the East Pacific rise.

Free-Air Gravity Map

The marine gravity data contained in the NGDC database was collected from the 1960's until the present. Various gravity meters and navigational systems were employed during the collection of these data, the observed values were referenced to either the Potsdam or IGSN71 datums, and the FAA values were calculated using several theoretical gravity formulas. Thus, the first step in the construction of the Free-Air anomaly map used in this study was to recalculate the FAA values using a common theoretical gravity formula (WGS-84; Defense Mapping Agency, 1987a) and a common datum (IGSN71). The equations used in the calculations are found in Table 3 of the internal report of the Defense Mapping Agency (1987b). The second step was to remove from the database all data collected while the ships were changing course as such changes produce anomalous accelerations.

The third step was to correct the remaining data for crossover errors, i.e. differences in the gravity values recorded at the position where one ship track crosses over another ship track. The corrections were calculated using the methods of Bandy *et al*. (1990) and Prince and Forsyth (1984). Both methods determine constant corrections (DC shifts) to be applied to individual cruise segments such that, after these corrections are applied, the crossover errors are minimized in the least squares sense. As the data quality is variable, and the data comes both from detailed surveys within the area and ship transits through the area, the complete data set was not corrected as a whole, instead the following sequence of corrections were applied. First, the two detailed surveys conducted within the area (i.e., those of the CERE02WT cruise of Mammerickx (1984) and the SEAMAT cruise of Bourgois *et al*. (1988)) where each corrected for internal crossover errors. Next, the means of crossover error between the data from the two detailed surveys and data collected during transits which both employed a GPS navigation systems and which tied their gravity meter directly to the gravity base station located in Manzanillo Mexico were calculated. This was done to tie the marine and land data to a common absolute gravity base station. The mean crossovers were -9 mGal and -7 mGal for the SEAMAT and CERE02WT data, respectively. The data from the two cruises were adjusted by subtracting the respective mean crossover error. Next, the two detailed surveys were each treated as a single line and combined with the data collected during all GPS navigated transits. These data were then corrected for crossover errors. Lastly, these data were combined with the data collected during transit satellite navigated transits and crossover corrections were determined and applied to the data. During this last correction, the GPS navigated data and the data from the two detailed surveys were fixed (i.e. the correction to be applied to these data in this step were fixed at zero).

Prior to the correction procedure, the crossover errors (456 crossings) averaged -0.66 mGal with a standard deviation of 9.12 mGal (see Table 1 for more details). After the corrections were applied, the crossover errors averaged 0.01 mGal with a standard deviation of 4.84 mGal. The large improvement in the FAA map resulting from the correction procedure is clear by comparing the maps presented in Figures 4 and 8.

Table 1

Statistics of the Crossover errors

	Entire Data Set	Data with GPS	Data with Satellite
<u>Original Data</u>			
Number of Crossovers	456	111	190
Average	-0.660	-0.073	-2.000
Standard Deviation	9.12	5.55	12.50
Minimum Difference	-48	-13	-48
Maximum Difference	46	15	46
<u>Corrected Data</u>			
Number of Crossovers	456	111	190
Average	-0.008	-0.030	-0.010
Standard Deviation	4.84	4.40	6.15
Minimum Difference	-32	-13	-32
Maximum Difference	17	13	17

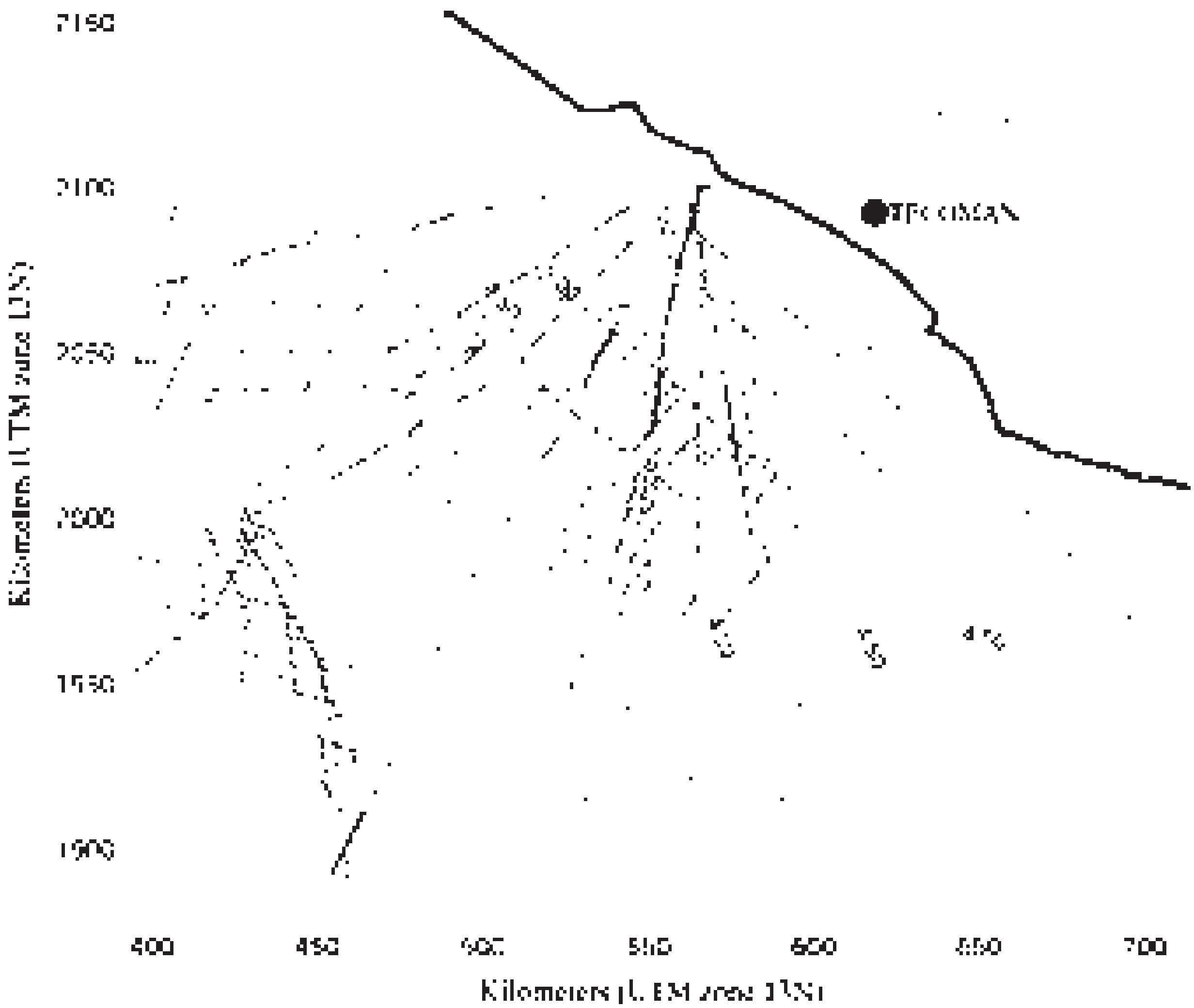

Fig. 6. Location map of the gravity data used in this study.

Mantle Bouguer Anomaly Map

The reduction of Free-Air anomalies to Mantle Bouguer anomalies has proven to be a useful tool in the investigation of the internal structure of oceanic rifts (e.g. Prince and Forsyth, 1998; Kuo and Forsyth, 1988; Rommevaux *et al*., 1994; Detrick *et al*., 1995; Pariso *et al*., 1995; Cormier *et al*., 1995; Weiland and Macdonald, 1996). The Mantle Bouguer Anomaly (MBA) is calculated by subtracting from the FAA values the gravitational attraction of a reference model; typically a three-layer model consisting of the water, oceanic crust, and upper mantle is used as the reference model. The resulting anomalies thus reflect departures of the real earth structure from that of the reference model. High MBA have generally been assumed to reflect crustal thinning or the presence of anomalously high density zones within the crust/upper mantle; whereas low MBA values reflect crustal thickening or anomalously low density zones within the crust/upper mantle related to the presence of high temperatures and/or the presence of partial melts (Cormier *et al*., 1995).

Three reference models are employed herein to test the effects of different reference models on the calculation of the MBA. These models differ from those normally used to calculate Mantle Bouguer anomalies in that, herein, we must include, to the east, a layer representing the continental crust.

The first model consists of a water layer (ρ=1.03 g\cm^3), a continental crust layer (ρ=2.67 g\cm^3), a constant

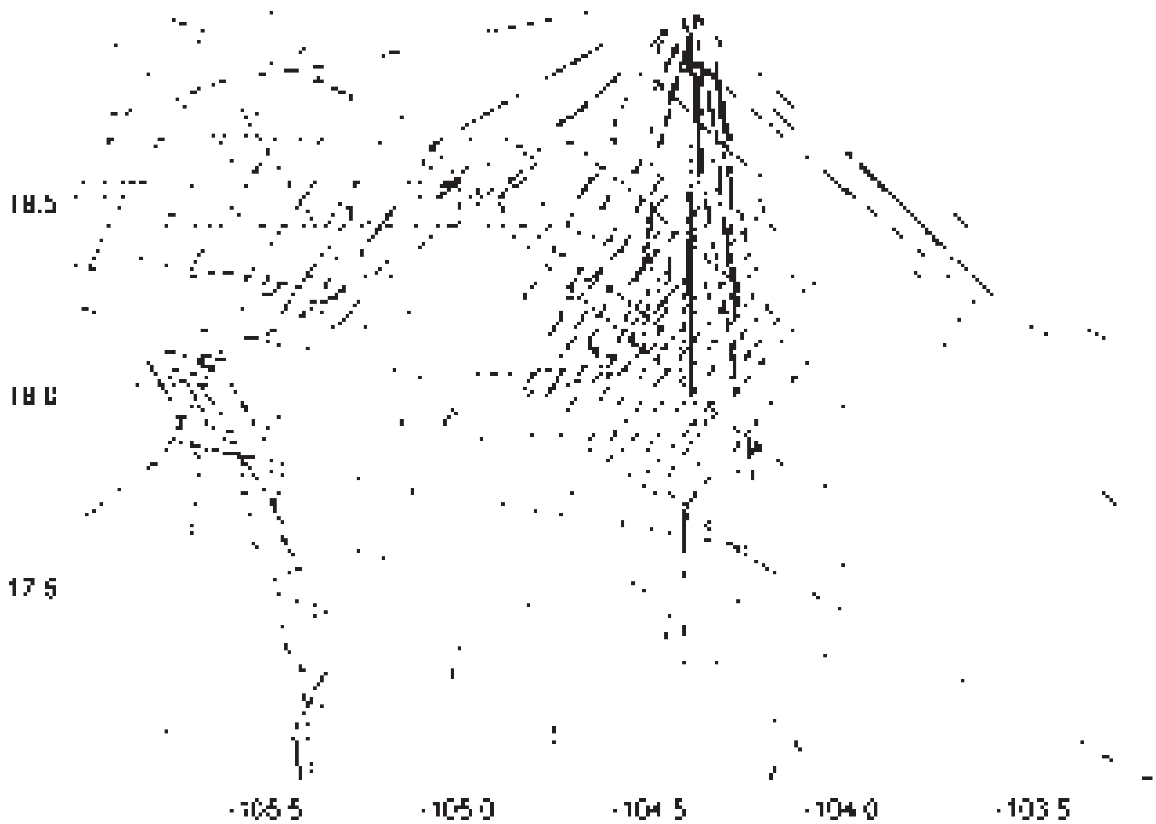

Fig. 7. Location map of the bathymetry data used in this study.

(6 km) thickness oceanic crust layer (ρ=2.7 g\cm^3), and an upper mantle layer (ρ=3.3 g\cm^3) extending to a depth of 30 km.

The second model consists of a water layer (ρ=1.03 g\cm^3), a continental crust layer (ρ=2.67 g\cm^3), a constant (2 km) thickness upper oceanic crust layer (ρ=2.73 g\cm^3), a constant (4 km) thickness lower oceanic crust layer (ρ=2.93 g\cm^3), and an upper mantle layer (ρ=3.33 g\cm^3) extending to a depth of 30 km.

The third model consists of a water layer (ρ=1.03 g\cm^3), a continental crust layer (ρ=2.67 g\cm^3), a constant (0.5 km) thickness upper oceanic crust layer (ρ=2.6 g\cm^3), a constant (5.5 km) thickness lower oceanic crust layer (ρ=2.90 g\cm^3), and an upper mantle layer (ρ=3.33 g\cm^3) extending to a depth of 30 km.

The attractions of the model layers were calculated using the 3-D Fourier algorithm of Parker (1973). This algorithm uses the Fast Fourier Transform to calculate the attraction of a layer bounded by two 3-D surfaces (grids). The density of the material lying between these grids is specified as a grid of density values; the density may vary horizontally but not vertically. The dimensions of all grids used in the algorithm must be identical, and the gravitational attraction of the layer is output for each grid node. In the present study the locations of the data were first converted to UTM coordinates and then gridded into a 1 km x 1 km grid between 103°W to 106°W and 17°N to 19°N. The resulting grids all consist of 225 rows and 321 columns. The FAA data was also gridded into the exact same grid. The seafloor grid was constructed from the bathymetric data. The depth to the top of the subducted oceanic lithosphere was obtained from Pardo and Suárez (1995).

Lastly, the Mantle Bouguer Anomaly map was band pass filtered to eliminate spatial wavelengths less than 12 km.

Two-dimensional gravity models

To better define the geometry of the sources of the Mantle Bouguer Anomalies, two 2-D models were con-

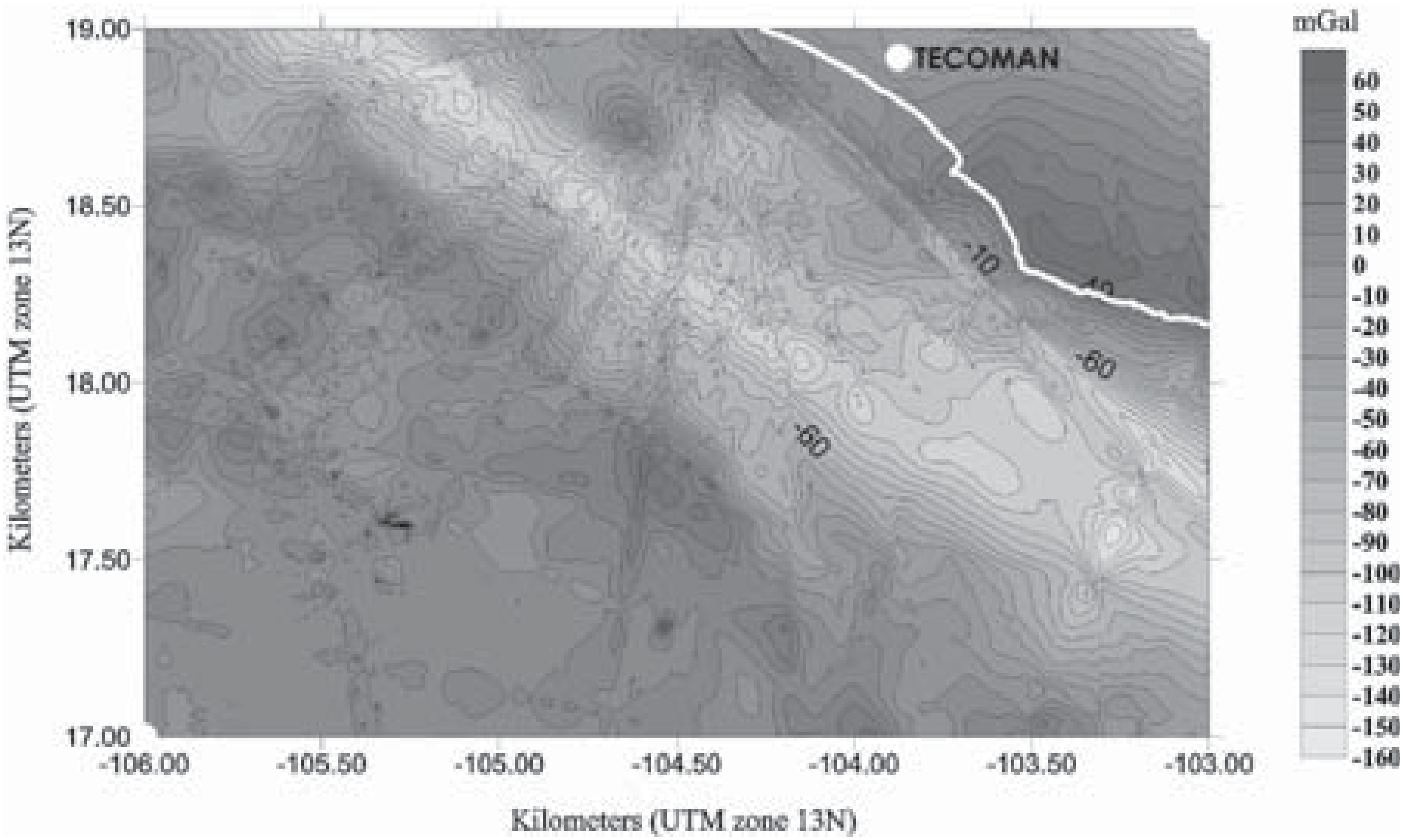

Fig. 8. Free-air anomaly map constructed from sea-surface gravity measurements. Gravity values have not been adjusted for crossover errors. Contour interval equals 10 mGal.

structed using the algorithm of Talwani *et al*. (1959). The first model was oriented NW-SE, crossing the El Gordo graben. The second model, also oriented NW-SE, was constructed to better define the source of the anomaly that extends from the El Gordo graben to the East Pacific Rise.

RESULTS

Choice of Reference Model

The Mantle Bouguer Anomalies calculated from the three reference models are presented in Figures 9a, b, and c. In the area of the interest (i.e. the El Gordo graben and the region located between the El Gordo graben and the East Pacific Rise) the differences both between model 1 and model 2, and model 2 and model 3 are less than 5 mGal, (Figures 10a, b). Since the standard deviation of the adjusted crossover errors is approximately 5 mGal, we conclude that all of the three reference modals are equally acceptable in our particular case. Thus, in the following analysis we will use the Mantle Bouguer Anomaly map produced using reference model 2 (Figures 9b and 11).

Mantle Bouguer Anomaly

The Mantle Bouguer Anomaly map (Figures 9b and 11) exhibits several trends west of the trench axis. The first trend coincides with the Michoacán trough. This anomaly is oriented NW–SE and exhibits values ranging from –5 mGal to 60 mGal. The trend appears to terminate to the north at about 18.75°N. The high MBA values indicate that either the crust in the area of the trough is anomalously thin (which we prefer) or a zone of anomalously high density exists within the crust and\or upper mantle.

The second trend is superimposed on the first trend. Specifically, a prominent decrease (15 to 30 mGal) in the MBA values associated with the Michoacán trough is observed in the area of the El Gordo graben. The maximum decrease is located over the El Gordo volcanic complex. Since the Mantle Bouguer Anomaly method removes the effects of bathymetry variations from the data, the decreased values are not due to bathymetric fluctuations, but instead indicate either that the crust is thicker in the graben or that there is a low-density zone within either the crust or upper mantle.

The third trend, located east of the East Pacific Rise at -105.25°W, is a NE-SW oriented area of slightly positive MBA values (up to about 8 mGal) bounded to the north and south by areas of low MBA values. This anomaly trends toward the El Gordo graben but terminates prior to reaching the graben. Like in the Michoacán trough area, the high values are suggestive of thin crust or an anomalously high crust/upper mantle density in this area.

2-D Models

Two-dimensional gravity models were constructed to better define the source of the MBA anomalies in the area of the El Gordo graben and the area of the MBA high east of the East Pacific Rise. The anomaly associated with the Michoacán trough was not modeled as this lies outside the scope of the present study.

The first model (Figure 12) is oriented NW-SE and crosses perpendicular to the MBA high located east of the East Pacific Rise. In this area the MBA values can be modeled as a broad zone (about 100 km) of crustal thinning with two narrow (about 6 km), low density, zones in the upper mantle. The amount of crustal thinning increases to the NW.

The second model (Figure 13) is oriented NW-SE and runs along the crest of the MBA high associated with the Michoacán trough, perpendicular to the El Gordo graben. The pronounced MBA low associated with the El Gordo volcanic complex (i.e. the southern half of the graben) is modeled as being produced by two, fairly broad, low-density zones in the crust. Another narrow, low-density zone within the crust is found to the NW, and coincides with the northern boundary escarpment of the El Gordo graben.

DISCUSSION

The geometry and motion of the various lithospheric plates and blocks comprising western Mexico, both onshore and offshore, has recently received much attention (e.g., Mammerickx, 1984; Luhr *et al*., 1985; Bourgois *et al*., 1988; Allan *et al*., 1991; Bandy, 1992; Serpa *et al*., 1992; Bandy and Pardo, 1994; Bandy *et al*., 1995, 1998a,b; Lonsdale, 1995; DeMets and Wilson, 1997; Suárez *et al*., 1999; Michaud *et al*., 2000, 2001; Bourgois and Michaud, 2002). Of particular interest to the present study, is the current debate concerning the location and nature of the boundary between the Rivera and Cocos plates.

Early proposals as to nature of the Rivera-Cocos plate boundary suggested that the boundary is a NE to NNE trending left-lateral transform, extending from the EPR to the Middle America Trench at, or just north of, its intersection with the Colima graben (Molnar, 1973; Nixon, 1982; Eissler and McNally, 1984; Lonsdale, 1995; DeMets and Wilson, 1997). However, high resolution, multibeam bathymetric and seafloor image data collected in this area (Bourgois *et al*., 1988; Michaud *et al*., 2000, 2001; K.C. Macdonald, unpublished data; W.L. Bandy, unpublished data) clearly rule out the possibility that the boundary is a well defined, discrete, transform. To circumvent these results, DeMets and Wilson (1997) proposed that instead of being a discrete transform, left-lateral motion was being taken up across a diffuse zone of deformation (Figure 1). Further, they proposed that the El

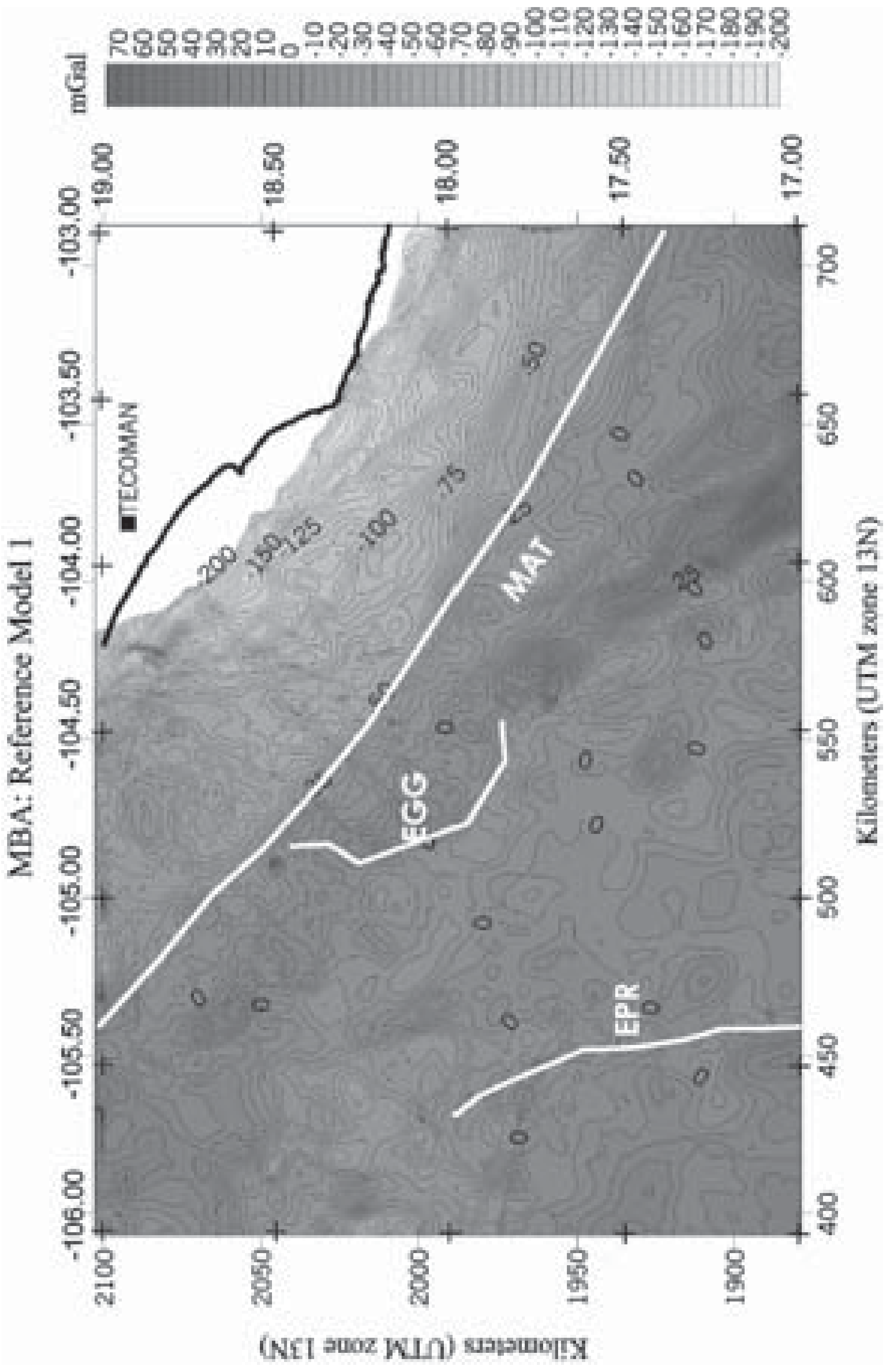

Fig. 9a. Mantle Bouguer Anomaly map constructed employing reference model 1. Contour interval equals 5 mGal.

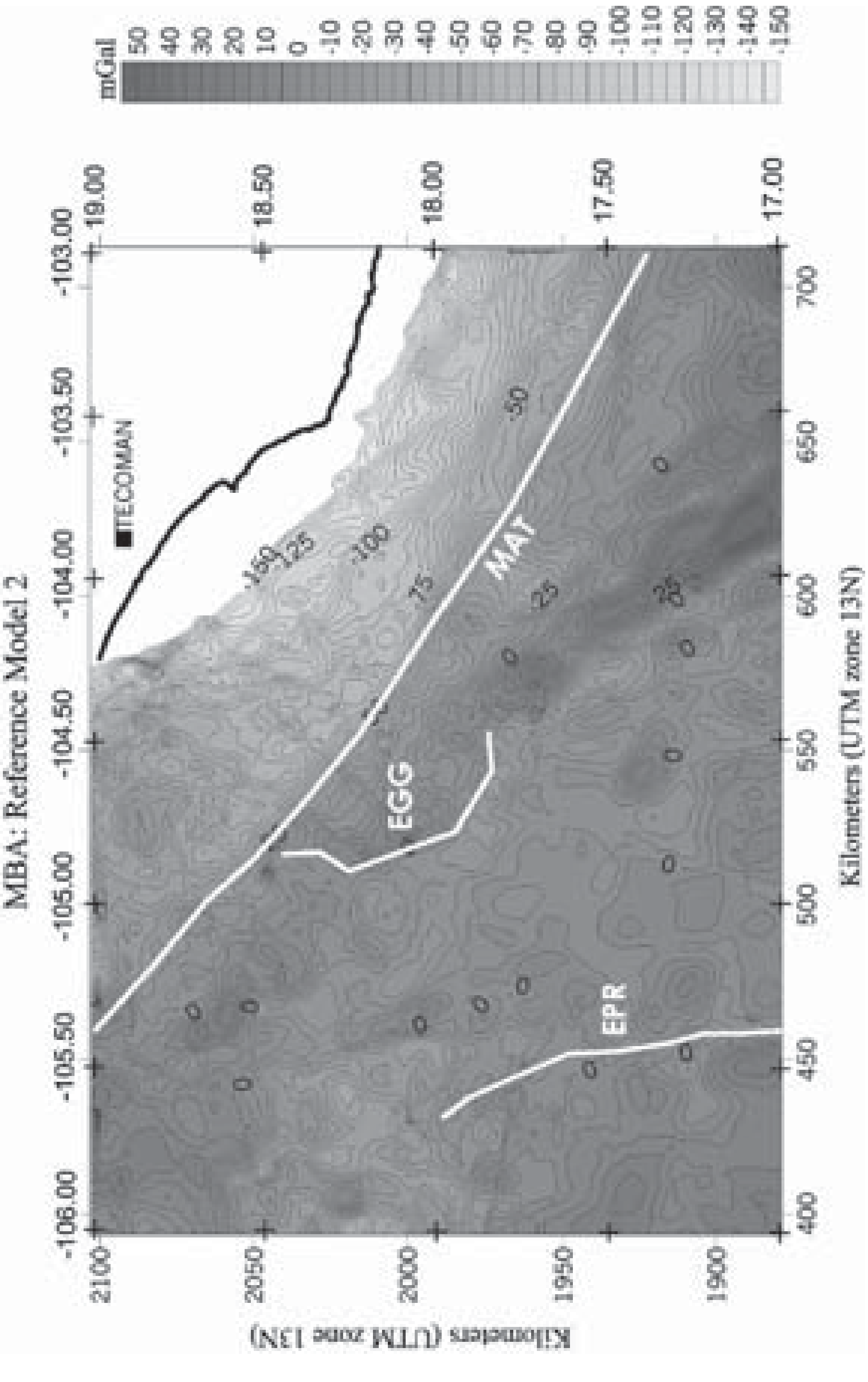

Fig. 9b. Mantle Bouguer Anomaly map constructed employing reference model 2. Contour interval equals 5 mGal.

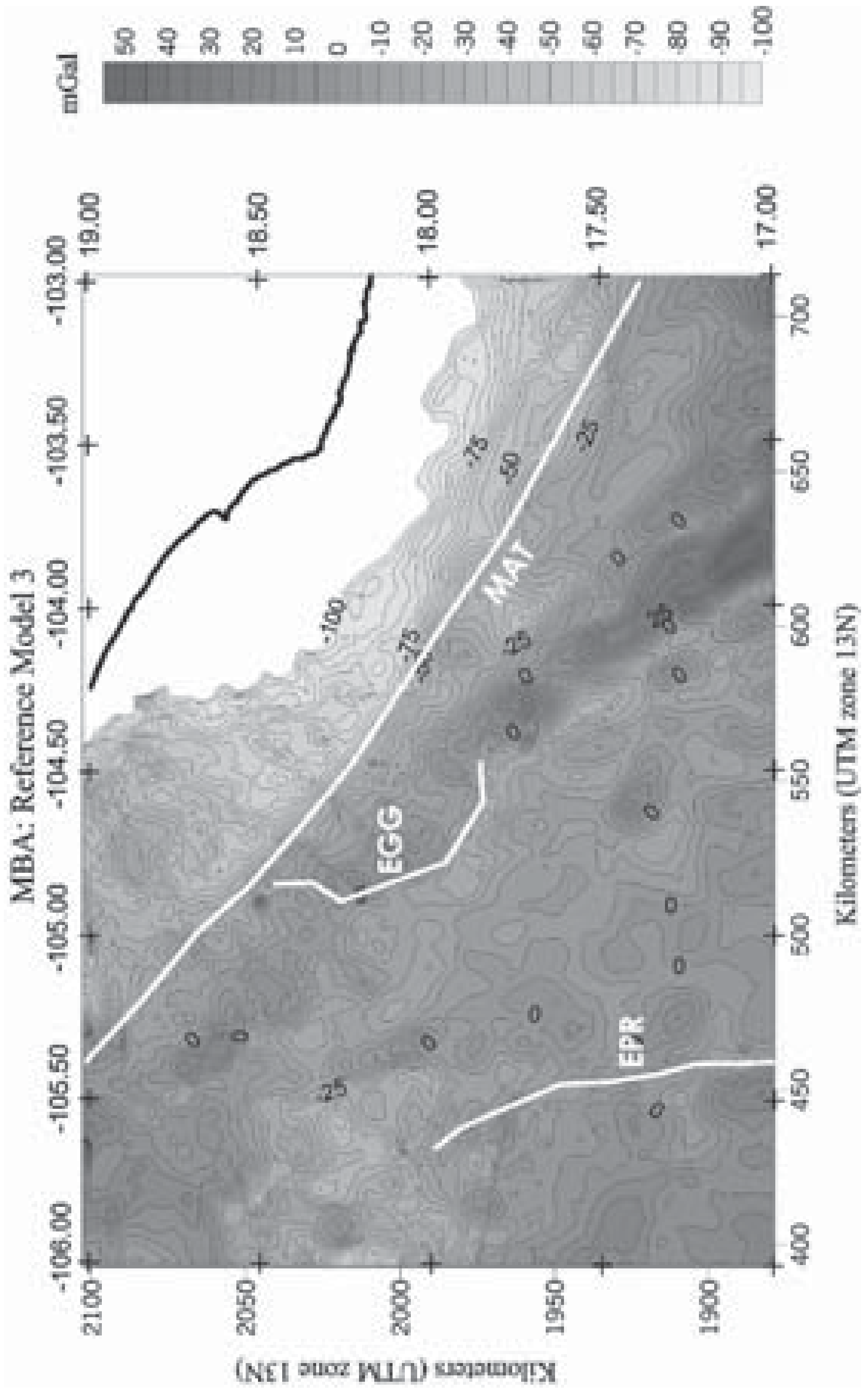

Fig. 9c. Mantle Bouguer Anomaly map constructed employing reference model 3. Contour interval equals 5 mGal.

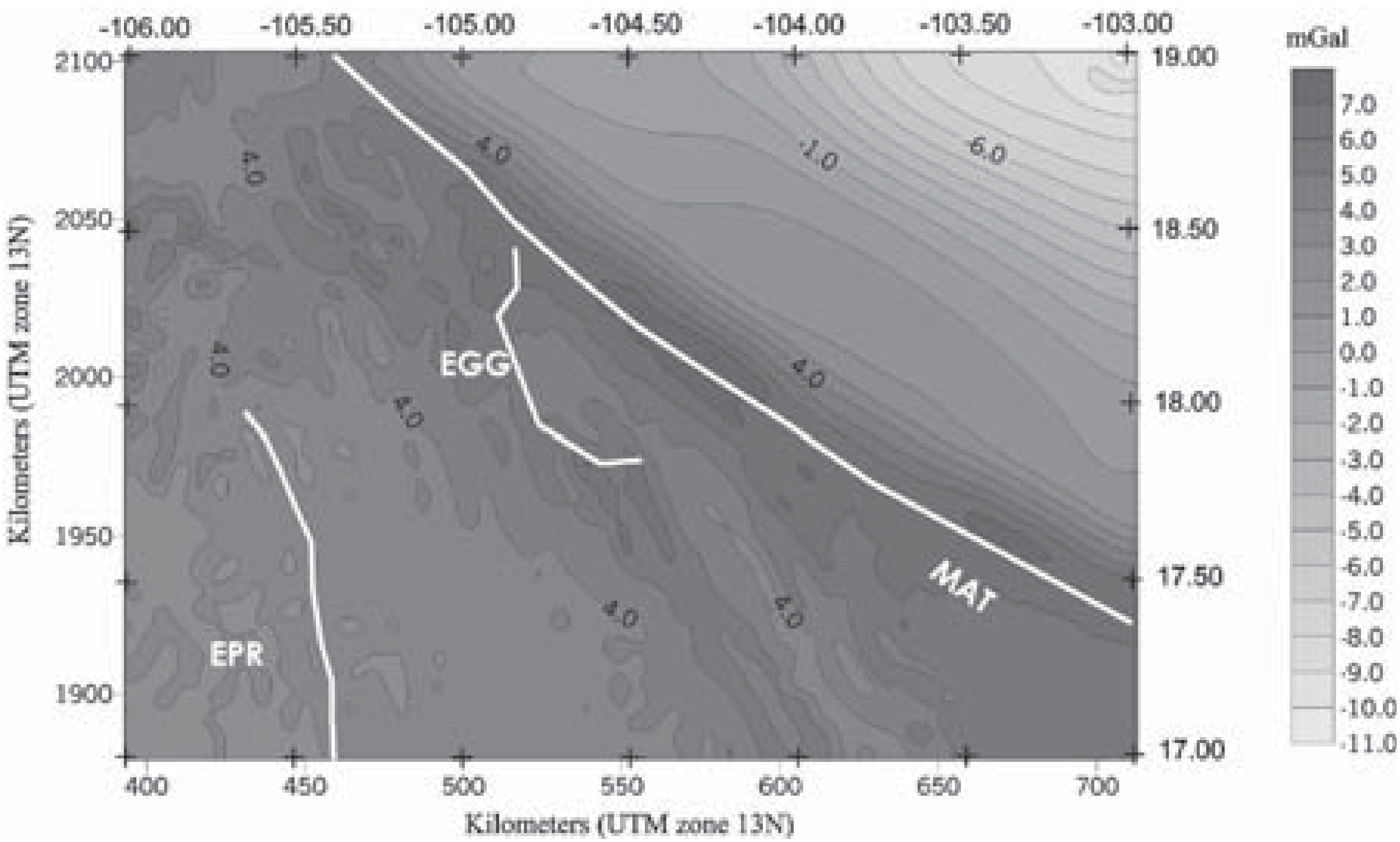

Fig. 10a. Difference between MBA anomalies calculated using reference model 1 and reference model 2. Contour interval equals 1 mGal.

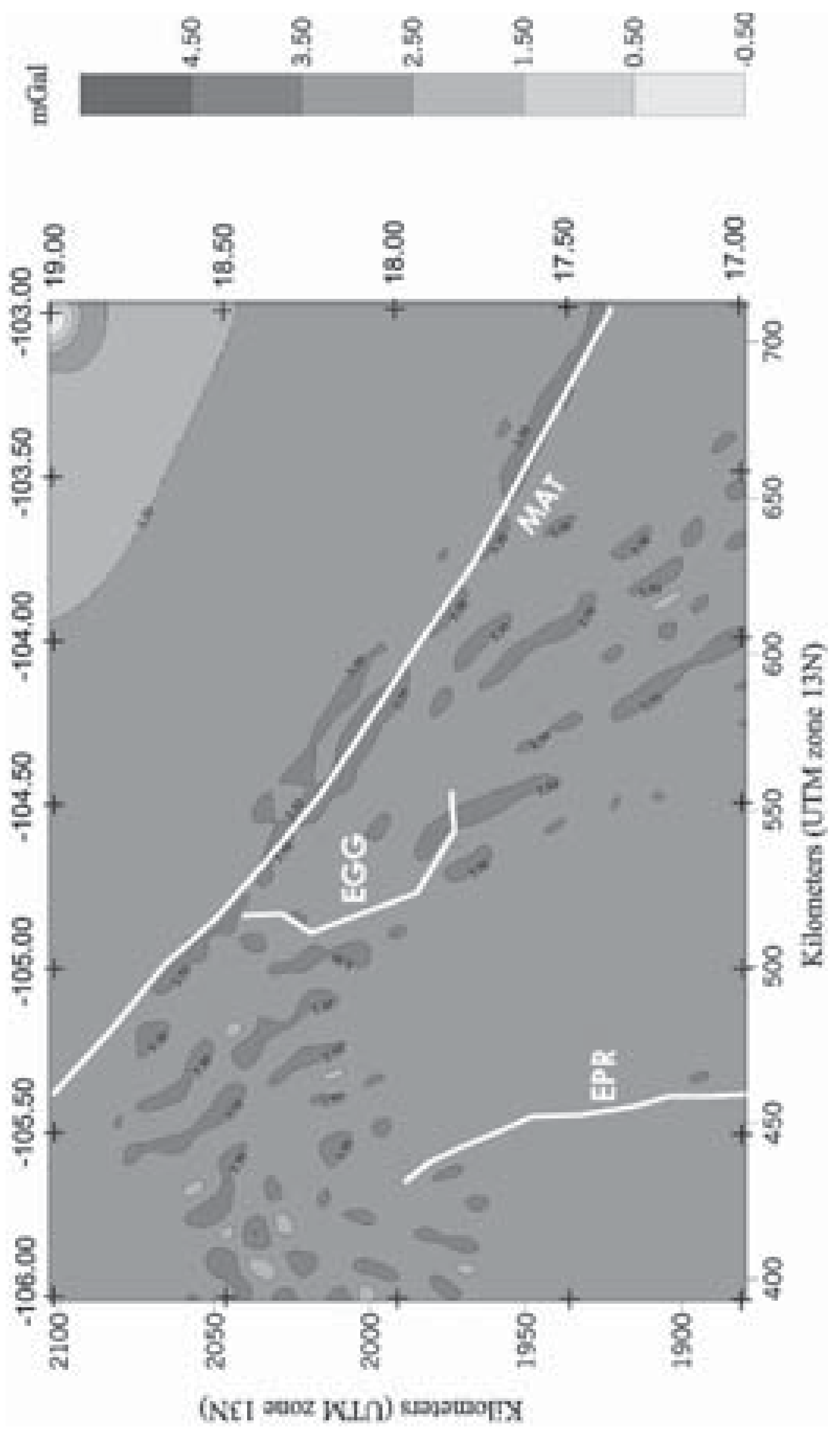

Fig. 10b. Difference between MBA anomalies calculated using reference model 3 and reference model 2. Contour interval equals 1 mGal.

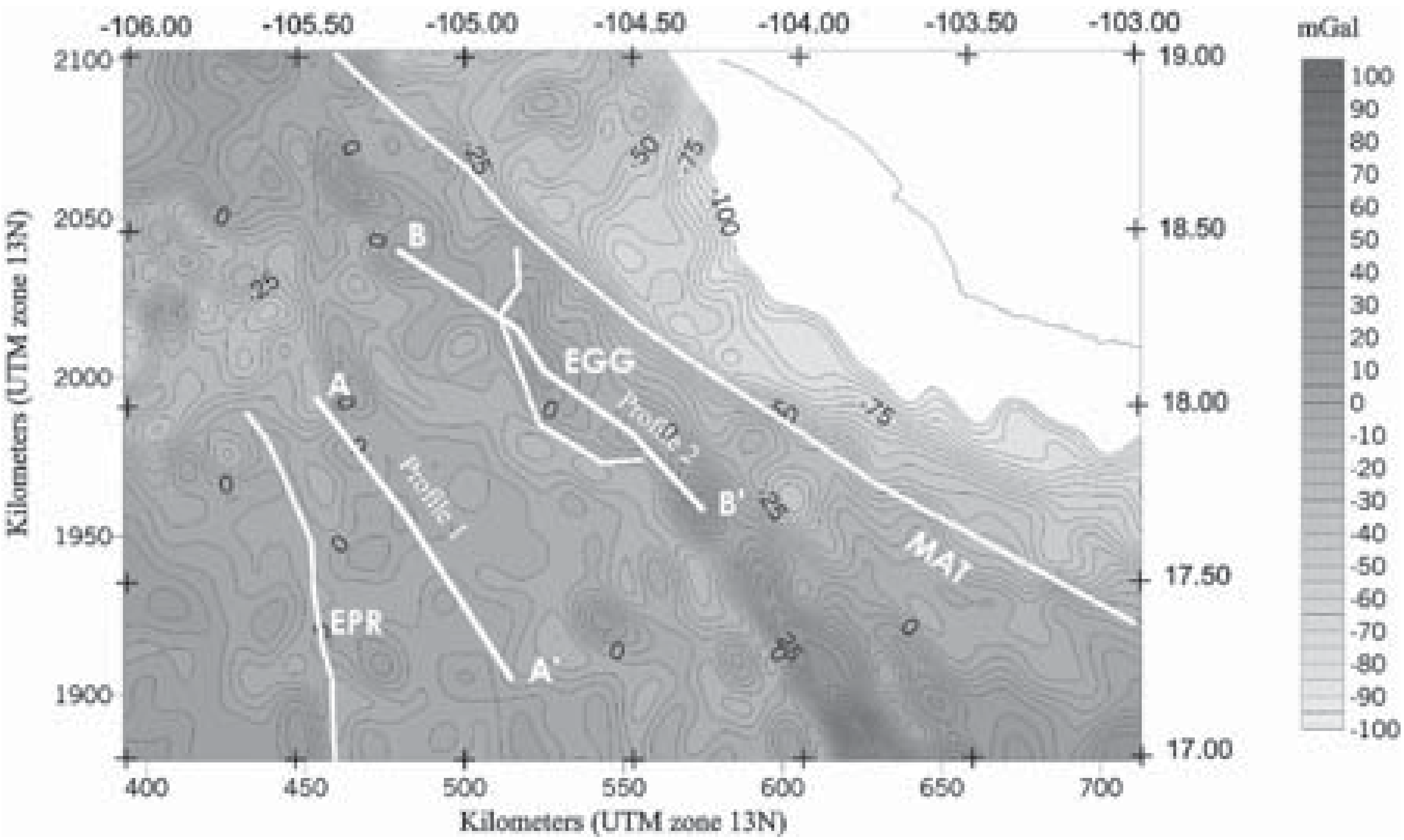

Fig. 11. Band pass filtered MBA anomaly map constructed using reference model 2. Also illustrated are the locations of the gravity models shown in Figures 12 and 13.

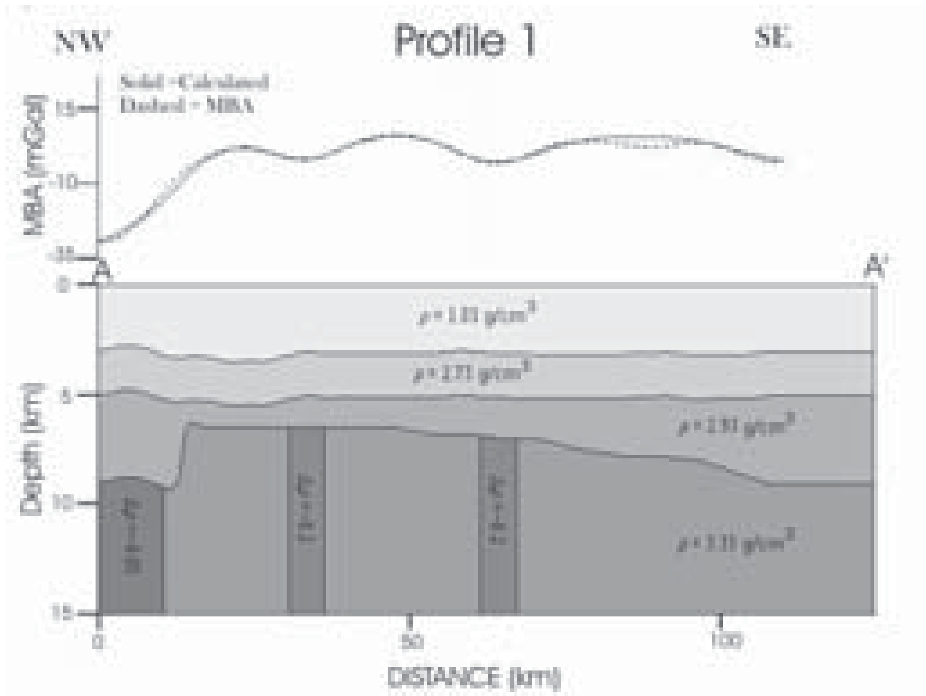

Fig. 12. 2-D geologic model derived from the MBA along profile 1 (See Figure 11 for profile location). The densities shown in the model are the sum of densities of reference model 2 and the anomalous densities. The anomalous densities are the departures from the densities of the reference model needed to reproduce the MBA anomaly.

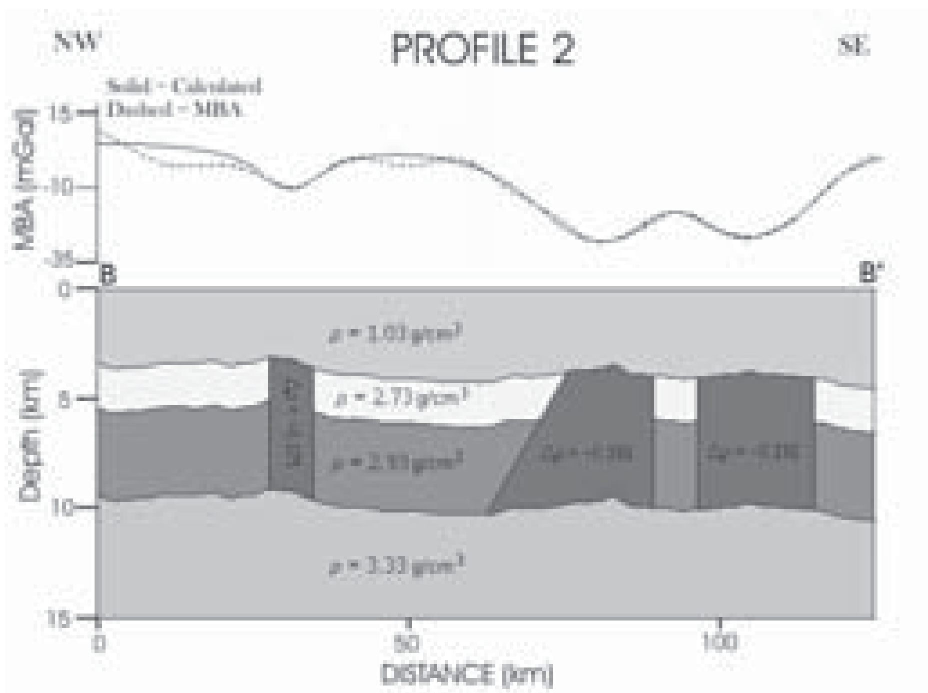

Fig. 13. 2-D geologic model derived from the MBA along profile 2 (See Figure 11 for profile location). The Δρ's shown on the model are the anomalous densities derived from modeling of the MBA. The ρ's are the densities of reference model 2.

Gordo graben, at least for the most part, was not part of this boundary. Implicit in their proposal is that the pronounced bend in the Wadati-Benioff zone observed beneath western Mexico does not mark the contact between the subducted Rivera and Cocos plates as proposed by other investigators (Pardo and Suárez, 1995; Bandy *et al*., 1995).

Alternatively, Bandy (1992) proposed that the Rivera-Cocos plate boundary is a divergent boundary which is presently propagating southwestward toward the East Pacific Rise and that the El Gordo graben marks the southwest tip of this propagation (Figure 1). This situation is viewed as being analogous to the Galápagos triple junction, between the Nazca, Pacific and Cocos plates, where the Cocos-Nazca spreading center does not presently extend completely to the triple junction (Lonsdale, 1988). In this proposal the bend in the Wadati-Benioff zone lies along the boundary between the subducted Rivera and Cocos plates.

The results of the present study are consistent with the proposal of Bandy (1992). The decrease in the MBA high associated with the Michoacán trough in the area of the El Gordo graben is consistent with recent magmatic activity within the graben, the activity being centered under the El Gordo volcanic complex. These results are supported by the high surface heat flow measured within the El Gordo graben, the highest values being measured in the area of the El Gordo volcanic complex (Khutoskoy *et al*., 1994). Also, the NE-SW oriented MBA high east of the East Pacific Rise is consistent with crustal thinning associated with the southwest propagation of rifting along the Rivera-Cocos plate boundary. However, unlike the area of the El Gordo graben, gravity and bathymetric data is sparse in this area just east of the East Pacific Rise, so this result should be considered with caution.

CONCLUSIONS

The MBA map exhibits the following characteristics west of the Middle America Trench.

(1) A NW-SE oriented trend of high MBA values is associated with the Michoacán trough, indicating that either the crust in the area of the trough is anomalously thin (which we prefer) or a zone of anomalously high density exists within the crust and\or upper mantle.

(2) A prominent decrease in the MBA values occurs in the area of the El Gordo graben, the maximum decrease being centered over the El Gordo volcanic complex. This decrease can be modeled as being the result of magma intrusion within the oceanic crust of the graben centered under the El Gordo Volcanic complex. This model is supported by the high surface heat flow measurements in the area of this complex.

(3) A NE-SW free-air gravity high is observed to extend from the El Gordo graben to the East Pacific Rise. Only the western part of this anomaly is observed in the MBA map. Modeling of the MBA values indicate that this anomaly may be due to crustal thinning in this region. However, unlike the area of the El Gordo graben, gravity and bathymetric data is sparse in this area, so this result should be considered with caution.

(4) The results of the present study are consistent with the proposal that the El Gordo graben marks the westward extent of a zone of present day divergence between the Rivera and Cocos plates, and that this zone of divergence may presently be in the process of propagating southwestward toward the East Pacific Rise.

ACKNOWLEDGMENTS

We thank the two anonymous reviewers for their helpful comments and suggestions. Financial support was provided by CONACyT grant #27823T and the Instituto de Geofísica, UNAM, grant #B111.

BIBLIOGRAPHY

AIKEN, C. L. V., M. BALDE, X. XU, M. G. ABDEL-SALAM, M. F. DE LA FUENTE and M. MENA, 1997. Integrated studies of Mexico with gravity, magnetic, and GIS database. *The Leading Edge 16,* 1779-1785.

ALLAN, J. F., S. A. NELSON, J. F. LUHR, I. S. E. CARMICHAEL, M. WOPAT and P. J. WALLACE, 1991. Pliocene-Holocene rifting and associated volcanism in southwest Mexico: An exotic terrain in the making. *In:* J.P. Dauphin, J.P., Simoneit, B.R.T., (Eds.), The Gulf and Peninsular Province of the Californias, AAPG Mem., 47, 425-445.

BANDY, W. L., A. F. GANGI and F. D. MORGAN, 1990. Direct method for determining constant corrections to geophysical survey lines for reducing mis-ties. *Geophysics 55,* 885 896.

BANDY, W. L., 1992. Geological and geophysical investigation of the Rivera-Cocos plate boundary: Implications for plate fragmentation, Ph.D. thesis, Texas A&M Univ., College Station.

BANDY, W., C. MORTERA-GUTIÉRREZ and J. URRUTIA-FUCUGAUCHI, 1993. Gravity field of the southern Colima graben, Mexico. *Geofís. Int., 32*, 561-567.

BANDY, W. and M. PARDO, 1994. Statistical examination of the existence and relative motion of the Jalisco and southern Mexico blocks. *Tectonics, 13,* 755-768.

BANDY, W., C. MORTERA-GUTIÉRREZ, J. URRUTIA-FUCUGAUCHI and T. W. C. HILDE, 1995. The subducted Rivera-Cocos plate boundary: Where is it, what is it, and what is its relationship to the Colima rift? *Geophys. Res. Lett. 22,* 3075-3078.

BANDY, W. L., V. KOSTOGLODOV and C. A. MORTERA-GUTIÉRREZ, 1998a. Southwest migration of the instantaneous Rivera-Pacific Euler pole since 0.78 Ma. *Geofís. Int. 37,* 153-169.

BANDY, W. L., V. V. KOSTOGLODOV, C. A. MORTERA-GUTIÉRREZ and J. URRUTIA-FUCUGAUCHI, 1998b. Comment on "Relative motions of the Pacific, Rivera, North American, and Cocos plates since 0.78 Ma" by Charles DeMets and Douglas S. Wilson. *J. Geophys. Res., 103*, 24,245-24,250.

BANDY, W. L. and T. W. C. HILDE, 2000. Morphology and recent history of the ridge propagator system located at 18°N, 106°W. *In:* Delgado-Granados, H., Aguirre-Díaz, G. J., Stock, J. M., (Eds.), Cenozoic tectonics and Volcanism of Mexico: Boulder, Colorado, Geological Society of America Special Paper 334, 29-40.

BANDY, W. L., T. W. C. HILDE and C.-Y. YAN, 2000. The Rivera-Cocos plate boundary: Implications for Rivera-Cocos relative motion and plate fragmentation. *In:* Delgado Granados, H., Aguirre-Díaz, G. J., Stock, J. M., (Eds.), Cenozoic tectonics and Volcanism of Mexico: Boulder, Colorado, Geological Society of America Special Paper 334, 1-28.

BOURGOIS, J. and F. MICHAUD, 1991. Active fragmentation of the North American plate at the Mexican triple junction area off Manzanillo. *Geo-Marine Letters, 11,* 59-65.

BOURGOIS, J. and F. MICHAUD, 2002. Comparison between the Chile and Mexico triple junction areas substantiates slab window development beneath northwestern Mexico during the past 12-10 Myr. *Earth Plant. Sci, Letts., 201,* 35-44.

BOURGOIS, J. and 11 others, 1988. Active fragmentation of the North American plate: Offshore boundary of the Jalisco Block off Manzanillo. *C. R. Acad. Sci. Paris Serie II 307,* 1121-1130.

CORMIER, M.-H., K. C. MACDONALD and D. S. WILSON, 1995. A three-dimensional gravity analysis of the East Pacific Rise from 18° to 21°30' S. *J. Geophys. Res. 100,* 8063 8020.

DEFENSE MAPPING AGENCY, 1987a. Department of Defense World Geodetic System 1984: Its definition and relationships with local geodetic systems. DMA Technical Report # TR 8350.2.

DEFENSE MAPPING AGENCY, 1987b. WGS 84 ellipsoidal gravity formula and gravity anomaly conversion equations. Intenal report of the DMA Aerospace Center, St. Louis, Mo.

DEMETS, C. and D. S. WILSON, 1997. relative motions of the Pacific, Rivera, North American, and Cocos plates since 0.78 Ma. *J. Geophys. Res., 102,* 2789-2806.

DETRICK, R. S., D. H. NEEDHAM and V. RENARD, 1995. Gravity anomalies and crustal thickness variations along the Mid-Atlantic Ridge between 33°N and 40°N. *J. Geophys. Res. 100,* 3767-3787.

EISSLER, H. K. and K. C. MCNALLY, 1984. Seismicity and tectonics of the Rivera plate and implications for the 1932 Jalisco, Mexico, earthquake. *J. Geophys. Res., 89,* 4520-4530.

KHUTORSKOY, M. D., L. A. DELGADO-ARGOTE, R. FERNÁNDEZ, V. I. KONONOV and B. G. POLYAK, 1994. Tectonics of the offshore Manzanillo and Tecpan basins, Mexican Pacific, from heat flow, bathymetric and seismic data. *Geofís. Int. 33,* 161-185.

KOSTOGLODOV, V. and W. BANDY, 1995. Seismotectonic constraints on the convergence rate between the Rivera and North American plates. *J. Geophys. Res. 100,* 17,977-17,989.

KUO, B.-Y. and D. W. FORSYTH, 1988. Gravity anomalies of the ridge-transform system in the South Atlantic between 31 and 34.5° S: Upwelling centers and variations in crustal thickness. Mar. *Geophys. Res. 10,* 205-232.

LONSDALE, P., 1988. Structural pattern of the Galapagos Microplate and evolution of the Galapagos triple junction. *J. Geophys. Res., 93*, 13,551-13,574.

LONSDALE, P., 1995. Segmentation and disruption of the East Pacific Rise in the mouth of the Gulf of California. Mar. *Geophys. Res., 17,* 323-359.

LUHR, J. F., S. A. NELSON, J. F. ALLAN and I. S. E. CARMICHAEL, 1985. Active rifting in southwestern Mexico: manifestations of an incipient eastward spreading-ridge jump. *Geology, 13,* 54-57.

MAMMERICKX, J., 1984. The morphology of propagating spreading ridges. *J. Geophys. Res. 89,* 1817-1828.

MICHAUD, F., J. J. DAÑOBIETIA, R. CARBONELL, R. BARTOLOMÉ, D. CÓRDOBA, L. DELGADO, F.

NÚÑEZ-CORNÚ and T. MONFRET, 2000. New insights into the subducting oceanic crust in the Middle American Trench off western Mexico (17-19°N). *Tectonophysics, 318,* 187-200.

MICHAUD, F., J. J. DAÑOBIETIA, R. BARTOLOMÉ, R. CARBONELL, L. DELGADO ARGOTE, D. CORDOBA and T. MONFRET, 2001. Did the East Pacific Rise subduct beneath the North American plate (western Mexico)? *Geo-Mar. Lett., 20,* 169-173.

MOLNAR, P., 1973. Fault plane solutions of earthquakes and direction of motion in the Gulf of California and on the Rivera fracture zone. *Geol. Soc. Am. Bull., 84,* 1651-1658.

MOOSER, F., 1972. The Mexican volcanic belt: structure and tectonics. *Geofís. Int., 12,* 55-70.

NESS, G., 1984. Georeceiver position and gravity tie at the Instituto Oceanográfico, Manzanillo, Mexico. Oregon State Internal Memo.

NIXON, G. T., 1982. The relationship between Quaternary volcanism in central Mexico and the seismicity and structure of subducted ocean lithosphere. *Geol. Soc. Am. Bull., 93*, 514 523.

PARDO, M. and G. SUÁREZ, 1995. Shape of the subducted Rivera and Cocos plates in southern Mexico: Seismic and tectonic implications. *J. Geophys. Res. 100,* 12,357-12,373.

PARISO, J. E., J.-C. SEMPÉRÉ and C. ROMMEVAUX, 1995. Temporal and spatial variations in crustal accretion along the Mid-Atlantic Ridge (29°-31°30' N) over the last 10 m.y: Implications from a three-dimensional gravity study. *J. Geophys. Res. 100,* 17,781-17,794.

PARKER, R. L., 1973. The rapid calculation of potential anomalies. *Geophys. J. R. astr. Soc. 31,* 447-455.

PRINCE, R. A. and D. W. FORSYTH, 1984. A simple objective method for minimizing crossover errors in marine gravity data. *Geophysics 49,* 1070-1083.

PRINCE, R. A. and D. W. FORSYTH, 1988. Horizontal extent of anomalously thin crust near the Vema fracture zone from the three-dimensional analysis of gravity anomalies. *J. Geophys. Res. 93,* 8051-8063.

PROL-LEDESMA, R. M., V. M. SUGROBOV, E. L. FLORES, M. G. JUÁREZ, Ya. B. SMIRNOV, A. P. GORSHKOV, V. G. BONDARENKO, V. A. RASHIDOV, L. N. NEDOPEKIN and V. A. GARRILOV, 1989. Heat flow variations along the Middle America Trench. Mar. *Geophys. Res. 11,* 69-76.

ROMMEVAUX, C., C. DEPLUS and P. PATRIAT, 1994. Three-dimensional gravity study of the Mid-Atlantic Ridge: Evolution of the segmentation between 28° and 29° N during the last 10 m.y. *J. Geophys. Res. 99,* 3015-3029.

SMITH, W. H. F. and D. T. SANDWELL, 1997. Marine gravity anomaly from GEOSAT and ERS-1 satellite altimetry. *J. Geophy. Res. 102,* 10,039-10,054.

SERPA, L., S. SMITH, C. KATZ, C. SKIDMORE, R. SLOAN and T. PAVLIS, 1992. A geophysical investigation of the southern Jalisco block in the state of Colima, Mexico. *Geofís. Int. 31,* 475-492.

SKIDMORE, C. M., 1988. A geophysical and tectonic study of the Colima graben, Mexico, M.S. Thesis, University of New Orleans.

SUÁREZ, G., D. ESCOBEDO, W. BANDY and J. F. PACHECO, 1999. The 11 December, 1995 earthquake (Mw=6.4): implications for the present-day relative motion on the Rivera Cocos plate boundary. *Geophys. Res. Lett., 26,* 1957-1960.

TALWANI, M., J. L. WORZEL and M. LANDISMAN, 1959. Rapid gravity computations for two-dimensional bodies with application to the Mendocino submarine fracture zone. *J. Geophys. Res. 64,* 49-59.

VAQUIER, V., J. G. SCLATER and C. E. CORRY, 1967. Studies of the thermal state of the earth. *Bull. Earth. Res. Inst., 45,* 375-393.

WEILAND, C. M. and K. C. MACDONALD, 1996. Geophysical study of the East Pacific Rise 15°N-17°N: An unusually robust segment. *J. Geophys. Res. 101,* 20,257-20,273.

Gloria S. Serrato-Díaz, William L. Bandy and Carlos A. Mortera Gutiérrez
Instituto de Geofísica, Universidad Nacional Autónoma de México, México, D. F., México
Email: selenesd@igeofcu.unam.mx