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Crustal structure of the Colima rift, western Mexico: gravity models revisited

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RESUMEN

Se reportan resultados del análisis de la estructura del rift de Colima a partir del modelado de dos perfiles de gravedad orientados ESE-WNW con longitudes de 250 km y 280 km, localizados en el sector sur (SCR) y central (CCR) del graben. Estimaciones estadísticas de la profundidad de las interfaces se obtienen del análisis espectral. Las anomalías se modelan a partir de dos tipos distintos de modelos: un grupo asume que la anomalía es debida a fuentes profundas en la interface corteza-manto y el otro grupo considera una combinación de fuentes profundas y someras en un arreglo estratificado en la corteza. Para estimar el espesor cortical, se usan dos métodos iterativos que incluyen arreglos de prismas verticales o de polígonos para representar la interface y un contraste fijo de densidades. Las estimaciones estadísticas espectrales de profundidades y la topografía del Moho se usan para la construcción de modelos poligonales de corteza tipo Talwani. Los resultados del modelado indican una estructura para el sector sur del rift en la región costera que consiste en un graben 80-90 km de ancho y unos 7-9 km de profundidad. Este graben forma una continuación de la depresión que se extiende al NW del puerto de Manzanillo al SE del poblado de Tecomán. El Moho es más somero en la zona, donde tiene una profundidad de 17-18 km. Estos modelos difieren de interpretaciones previas en las cuales se propuso un modelo para el SCR con dos grábenes separados por un 'ridge'. El graben al NE tiene un ancho de 35 km y una profundidad de 8 km y el otro graben al SE es 60 km de ancho y 6 km de profundidad. La estructura somera en el sector central CCR se caracteriza por una depresión asimétrica de 9-10 km de profundidad con el límite NW abrupto e intrusiones graníticas en esta zona. El espesor cortical disminuye en el sector occidental del graben de Colima hasta unos 22 km y es alrededor de 28-30 km en el perfil CCR.

PALABRAS CLAVE: Gravedad, graben de Colima, estructura cortical, occidente de México.

ABSTRACT

Two 250 km and 280 km long gravity transects, across the southern (SCR) and central (CCR) sectors of the Colima rift are reinterpreted. Spectral analysis is used to estimate statistical depths to major interfaces. Gravity anomalies are reinterpreted assuming: (1) that the gravity signal arises solely from deep sources at the crust-mantle boundary, and (2) that the signal arises from a combination of deep and shallow sources. We use vertical prisms or a polygon to model the Moho interface. The spectral depths and the Moho topography are combined with available seismic data to construct layered crustal models with Talwani-type polygonal source bodies. The crustal structure along the coast consists of an 80-90 km wide and 7-9 km deep graben, which constitutes the offshore continuation of a 100 km wide graben, extending from just NW of Manzanillo to SE of Tecoman. The Moho shoals under the graben to about 17-18 km depth. Previous interpretations proposed an offshore profile of two grabens. The shallow crustal structure inland features a 9-10 km deep asymmetric depression with a steep NW boundary. Granitic intrusions thicken towards the SE. The crust is 28-30 km thick along the CCR transect, and thins to 22 km beneath the western sector of the Colima graben.

KEY WORDS: Gravity, Colima graben, crustal structure, western Mexico.

INTRODUCTION

The Colima rift in western Mexico (Figure 1) has been studied mostly from satellite images (Johnson and Harrison, 1990; Michaud *et al*., 1994), fault striations (Garduño and Tibaldi, 1991; Rosas-Elguera *et al*., 1996), surface stratigraphy and structure (Allan, 1986; Michaud *et al*., 1994), and land and marine geological and geophysical data (Serpa *et al*., 1992; Urrutia-Fucugauchi and Molina-Garza, 1992; Bourgois *et al*., 1988; Mercier de Lepinay *et al*., 1997). Serpa *et al*. (1992) have questioned the southern extension of the rift south of Colima volcano. Their preferred interpretation is in terms of a half-graben structure. These studies have led to three main proposals regarding the origin of the rift. The first proposes that the rift formed in response to relative motion between the Rivera and Cocos plates along their mutual boundary located roughly below the rift (e.g., Bandy *et al*., 1995). The second proposes that the Colima rift is part of a regional rift system formed in response to an incipient eastward jump of a segment of the East Pacific Rise (Luhr *et al*., 1985; Allan, 1986; Allan *et al*., 1991). According to this proposal, the Jalisco block, defined to the E and NE by the

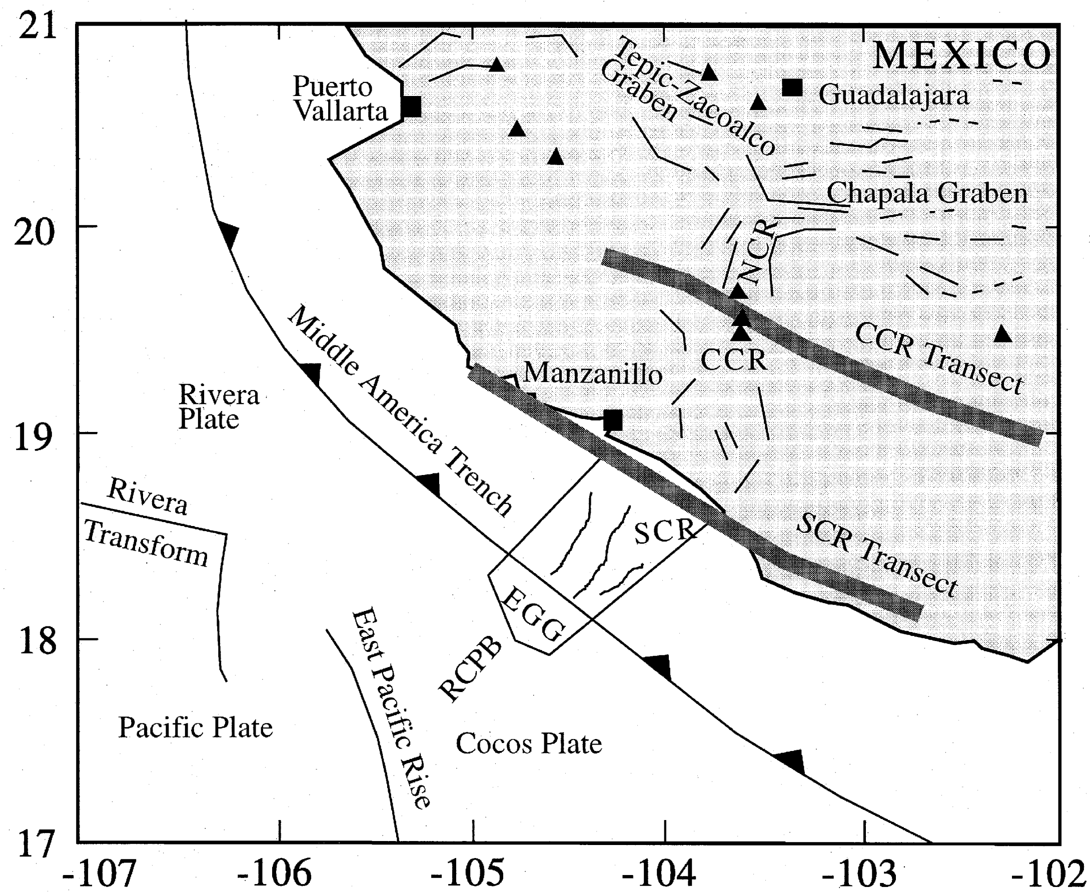

Fig. 1. Tectonic map of western Mexico showing the Jalisco block, Colima graben, Middle America trench and major offshore and landward structures. The location of the two gravity transects along the southern Colima graben (SCR) and central Colima graben (CCR) are indicated by solid lines.

Colima and Tepic-Zacoalco rifts, is in the process of being rifted away from the North American plate. The third proposes that the Colima rift is formed in response to SE movement of the Michoacan block, located to the SE of the rift (Johnson and Harrison, 1990; DeMets and Stein, 1990; Ferrari, 1995; Rosas-Elguera *et al.*, 1996).

Gravity studies have been extensively used in investigating the subsurface structure of the Colima graben (e.g., Allan, 1985; Serpa *et al.*, 1992; Urrutia-Fucugauchi and Molina-Garza, 1992; Bandy *et al.*, 1993, 1995; Medina *et al.*, 1996). One of the limitations in these studies is the non-uniqueness inherent in gravity modeling (García-Abdeslem, 1996; Bandy *et al.*, 1996). To better constrain the interpretation of the gravity data, we propose to reinterpret gravity anomalies over the southern (SCR) and central (CCR) Colima transects in the frequency domain, and to estimate statistical depths to major interfaces derived from power spectra. Spectral analysis has the advantage of not requiring a priori assumptions on the geometry and density contrast of source bodies. The gravity anomalies will be interpreted using two extreme types of models: (1) assuming the anomaly is due to deep sources at the crust-mantle boundary, assuming shallow and deep sources (layered Talwani-type models). The crustal thickness was found from two iterative methods that model the crust-mantle interface with a series of vertical prisms and with polygons. Crustal structure was found from a layered model initially constrained from the spectral analysis and available seismic data.

GRAVITY DATA

The gravity data used in this study consist of two E-W profiles across the southern and central sectors of the Colima graben (Figure 1). The Colima graben is characterized by two distinct trends, being N-S north of Colima volcano and NE-SW between Colima volcano and the coast (Allan *et al.*, 1991). The CCR is 50-60 km wide, with steep normal faults along the western side and a gradual eastward rise into granitic highland terrains. The SCR is much wider, up to 100 km between NW of Manzanillo and of Tecoman, characterized by an extensive alluvial plain.

Data for the SCR gravity profile have been presented in Bandy *et al*. (1993). The survey includes 137 stations between Barra de Navidad and Playa Azul in the coastal plain of the graben, along a 280 km long transect. Land and marine gravity data from the US Defense Mapping Agency and the National Geophysical Data Center were used to supplement the data set. Bandy *et al*. (1993) proposed a crustal 2-D model derived with the Talwani algorithm (Talwani *et al.*, 1959). In this model, the Colima graben is formed by two grabens, one 35 km wide and 8 km deep and the other 60 km wide and 6 km deep respectively. The SCR is over 100 km wide between NW of Manzanillo and SE of Tecoman. This model was subsequently commented by García-Abdeslem (1996) and Bandy *et al*. (1996). The sediment thickness within the grabens and the shoaling of the Moho are uncertain because of the non-uniqueness inherent in gravity modeling (Bandy *et al*., 1993).

Data for the CCR gravity profile have been presented in Bandy *et al*. (1995). The gravity data consist of 79 stations along a 250 km transect oriented NW-SE that crosses the CCR just north of Colima volcano (Figure 1). Bouguer anomalies were calculated with a standard density of 2.67 g/cc. A residual anomaly was refered to a 2-D model, assuming isostatic equilibrium and a depth to the top of the subducting plate to within +10 km of the Wadati-Benioff zone. The residual Bouguer anomaly was computed with a 2.5-D modeling algorithm (Ramarao and Radhakrishna Murthy, 1989). The densities for the subducting plate, upper mantle and bulk crust are 3.38 g/cc, 3.27 g/cc and 2.67 g/cc, respectively. The model assumes a thermal anomaly affecting the subducting plate and the upper mantle, with densities of 3.34 g/cc and 3.11 g/cc, respectively. The Bouguer anomaly features two lows of some 50 mGals below the values on either side, extending over a distance of 100 km. The depression of the Colima graben lies towards the NW flank of this feature. The SE flank of the anomaly is aligned with the SE flank of the SCR and the offshore El Gordo graben (Bandy *et al*., 1995).

SPECTRAL ANALYSIS

The spectral method allows the estimation of depths to the top of assemblages of source bodies from the wavelengths of gravity and magnetic fields (Spector and Grant, 1970; Bhattacharyya and Leu, 1975, 1977; Pal *et al*., 1979; Escanero-Figueroa, 1986). It does not require a priori knowledge of the geometry and density contrasts of the source bodies. The depth to the top of source bodies is related to the slope of the logarithm of the power spectrum as a function of the logarithm of the wave number. The power spectrum is smoothed by applying a low-pass filter. The depths represent statistical estimates of the interfaces, to estimate average crustal structure models.

The power spectrum for the SCR transect is shown in Figure 2. Statistical uncertainties are calculated from the linear least-squares fit. The depths of 22.4 km and 14.9 km are associated with the Moho and the lower/upper crust boundary. The depths of 6.6 km and 3.6 km may correspond to the thickness of the sedimentary sequence within the offshore Colima graben (Bandy *et al*., 1993).

The corresponding power spectrum for the CCR transect is given in Figure 3. The depth of 27 km is interpreted as the Moho. The crustal thickness increases landward away from the margin as expected from the gravity anomalies. It agrees with the thickness estimated previously in Bandy *et al*. (1995). The shallow depths of 5.8 and 2.4 km may correspond with the volcano-sedimentary sequence and the granitic intrusive bodies.

CRUSTAL MODELS

The crustal thickness was investigated with two iterative methods based on vertical prisms and polygons, assuming the gravity anomaly to be due to the Moho vertical variations (e.g., Bott, 1960; Cordell and Henderson, 1968;

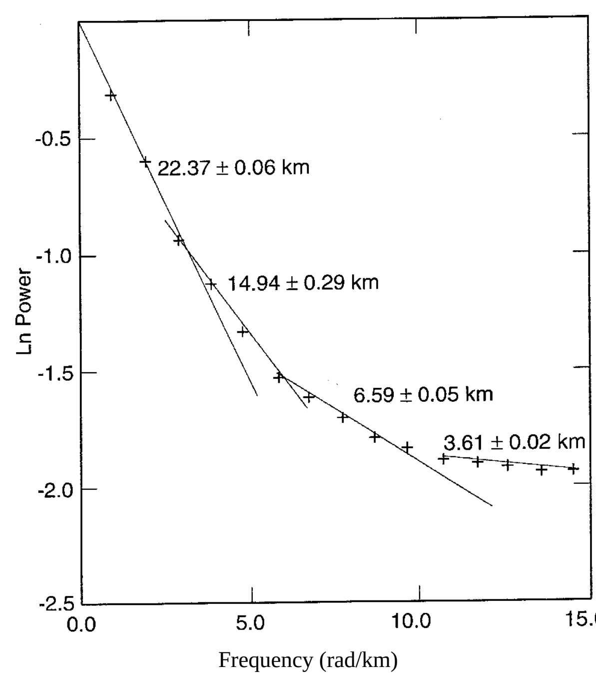

Fig. 2. Spectral depth estimates for the southern Colima rift from the logarithmic power spectrum as a function of frequency. Estimated depths to the top of source body assemblages are given in kilometers. The uncertainties are derived from the linear regression.

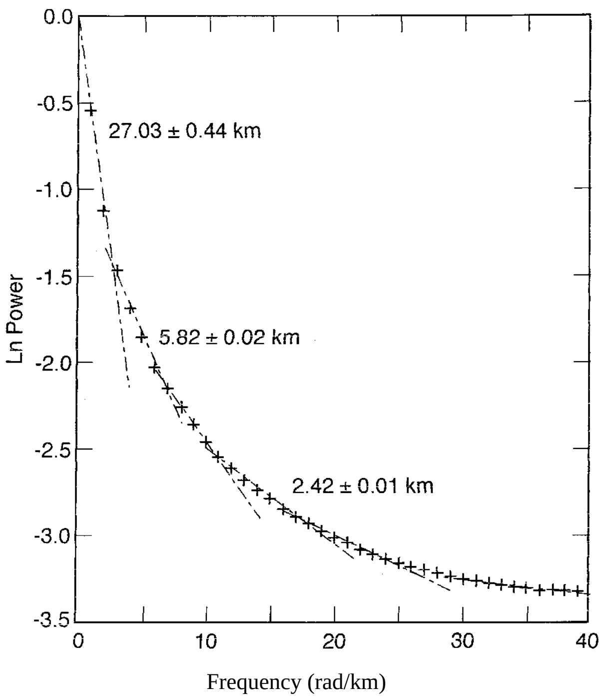

Fig. 3. Spectral depth estimates for the central Colima rift from the logarithmic power spectrum as a function of frequency (as in Figure 2).

Quereshy and Mula, 1971; Radhakrishna Murthy and Rao, 1979; Urrutia-Fucugauchi and Flores-Ruiz, 1996).

First, we use an iterative method based on the gravity response of vertical dikes and the Marquardt non-linear optimization procedure (Radhakrishna Murthy and Jagannadha Rao, 1989). The interface is approximated by a series of prisms. The vertical gradient is assumed constant over the prisms. The gravity anomaly is calculated at regular spacing assuming one prism below each measurement point. We move the position of the prisms up or down about a depth Z to match the observed anomaly. Marquardt's (1963) least-squares non-linear optimization method is used to determine when the iteration procedure ends, by using a damping factor of 15 (Radhakrishna Murthy and Jagannadha Rao, 1989). The gravity anomaly is considered to cover the complete structure, i.e., the depth to the modeled interface beyond the first and last prism is Z.

The crust-mantle boundary was estimated with the iterative procedure of Radhakrishna Murthy *et al*. (1990) which uses the gravity response of a polygon (Talwani *et al*., 1959). The iteration starts with a flat boundary polygonal model and modifies the vertices of the polygon to fit the observed anomaly. The procedure is terminated when the sum of squares of differences between observed and calculated anomalies falls below a pre-defined value, or when the sum of squares of differences shows a tendency to increase or when the number of iterations reaches 60.

Results for the SCR gravity profile are given in Figures 4 and 5. The initial average depth in the two models is assumed as 20 km. The depth obtained from the spectral analysis of 22.4 km was optimized from the number of iterations needed for convergence, which agrees with shallower depths. The two procedures give similar results. The vertical prism model shows a closer fit between observed and calculated anomalies and a smoother crust-mantle topography (Figure 4) than the polygonal model (Figure 5).

Results for the CCR gravity profile are given in Figures 6 and 7. The initial depth derived from the spectral analysis of 27 km increases to 30 km. The two procedures give similar results indicating a deeper crust-mantle interface in the central sector of the gravity transect. The fit between observed and calculated anomalies is better in the vertical prism model (Figure 6). The fit near the ends of the transect in both models is not satisfactory and convergence was not reached. This may be due to the boundary conditions in the modeling and to effects of shallower interfaces within the crust.

Layered models were investigated for the two profiles using the polygonal method (Talwani *et al*., 1959). For the SCR profile we use three and four layers constrained from the spectral analysis and both model results (Figure 2). As expected, the effects of the crust-mantle interface and of the shallow structures corresponding to the Colima graben were dominant (Figure 8). The crust-mantle boundary was constrained by the spectral depth estimates of 22 km and 15 km, and the shallow interface was left to fluctuate around the 6.6 km spectral depth estimate. The crust-mantle boundary is 17-18 km deep beneath the SCR and deepens towards the east (Figure 8). The shallow structure is dominated by a graben about 80-90 km wide and 7-9 km deep, extending under Manzanillo and the coastline. This structure agrees with Bandy *et al*. (1993) where it is referred to as TOGL, with a width of 60 km and a depth of 6 km. The adjacent structure MOGL also modeled in Bandy *et al*. (1993), which is 35 km wide and 8 km deep, is not required in our model. The Moho was kept at a constant depth, and a minor variation may account for the anomaly. We concluded that a two-graben structure was not required for the gravity modeling. A single wide and deep graben structure corresponding to the offshore extension of the Colima graben is a viable interpretation of the gravity low between Manzanillo and the coastline (Figure 8).

For the CCR gravity profile we examined layered Talwani-type models with four layers constrained initially by the spectral depth estimates and by the two iterative crustal models. The density contrasts for the four layers, from the

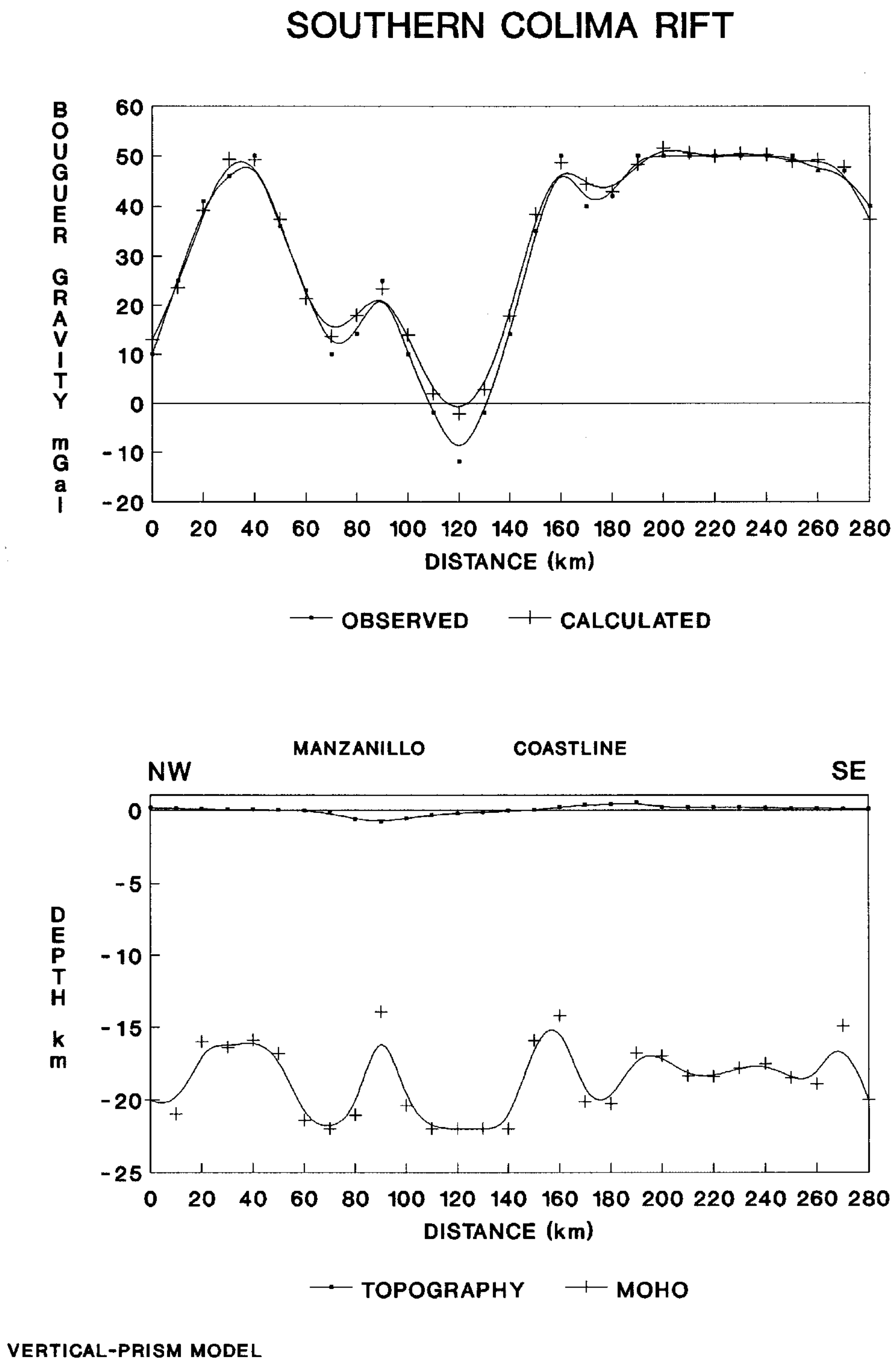

Fig. 4. Vertical-prisms model for the southern Colima rift. Top diagram shows the observed and calculated gravity anomalies. Bottom diagram shows the depths estimated for the Moho. The fitted curve to the data points is a smoothed estimate of the interface. The topography and bathymetry along the profile is also shown.

surface to the lower crust, are -0.20, 0.05, 0.08 and 0.35 g/cc (Figure 9). The effects of the crust-mantle interface and of the shallower structures were dominant (Figure 9). The crust-mantle interface shows a smooth pattern with depths between 28 and 30 km. The crust thins to 22 km beneath the western sector of the Colima graben (Figure 9), as for the polygonal

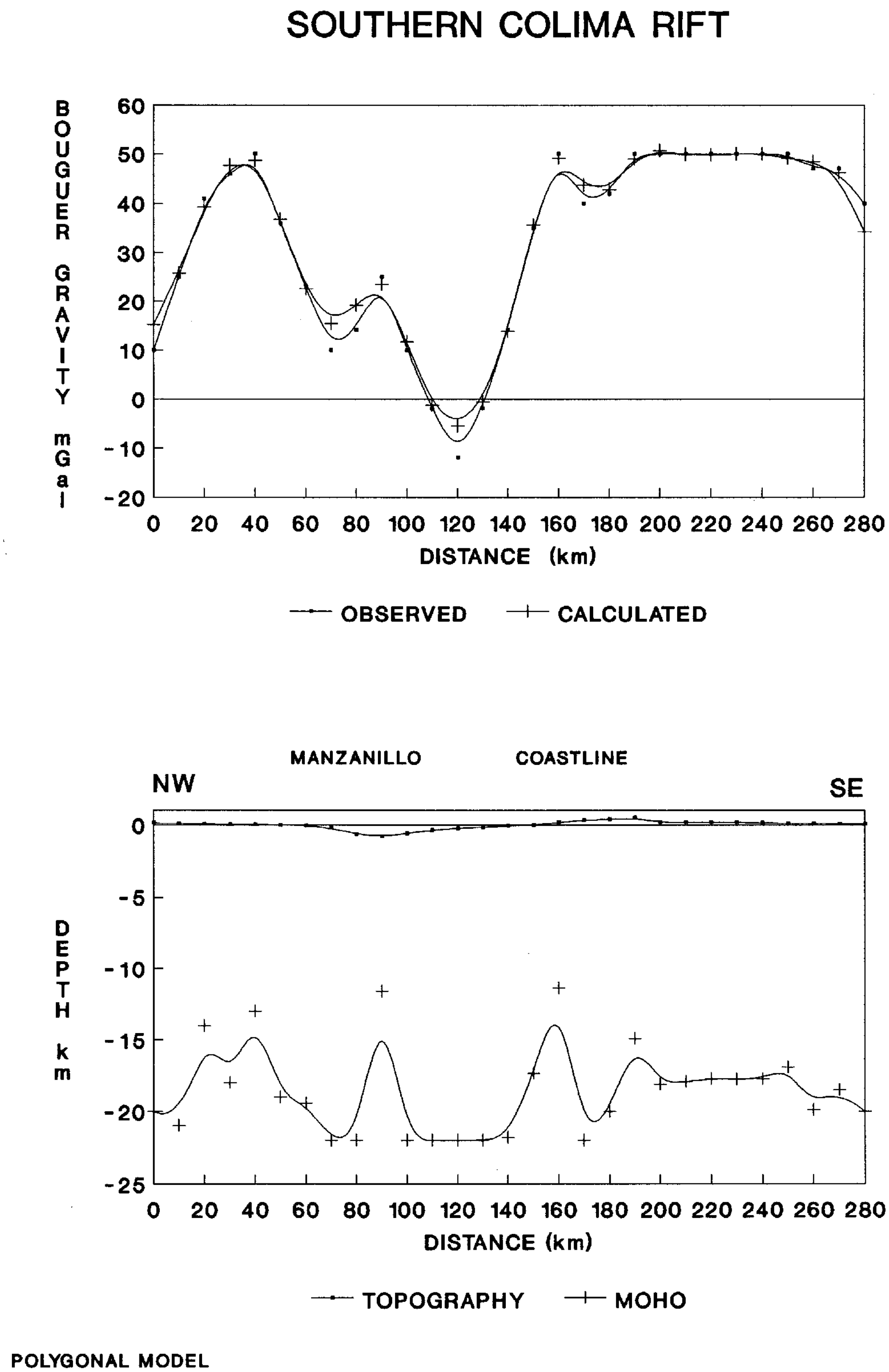

Fig. 5. Polygonal model for the southern Colima rift (as in Figure 4).

model (Figure 7). In both iterative models the fit to observed and gravity was unsatisfactory (Figures 6 and 7). In the layered model the fit is improved (Figure 9). The shallow interface shows several structures that present a surface expression. From west to east they correspond to the Colima graben, which is asymmetrical as in Bandy *et al.* (1995), with a

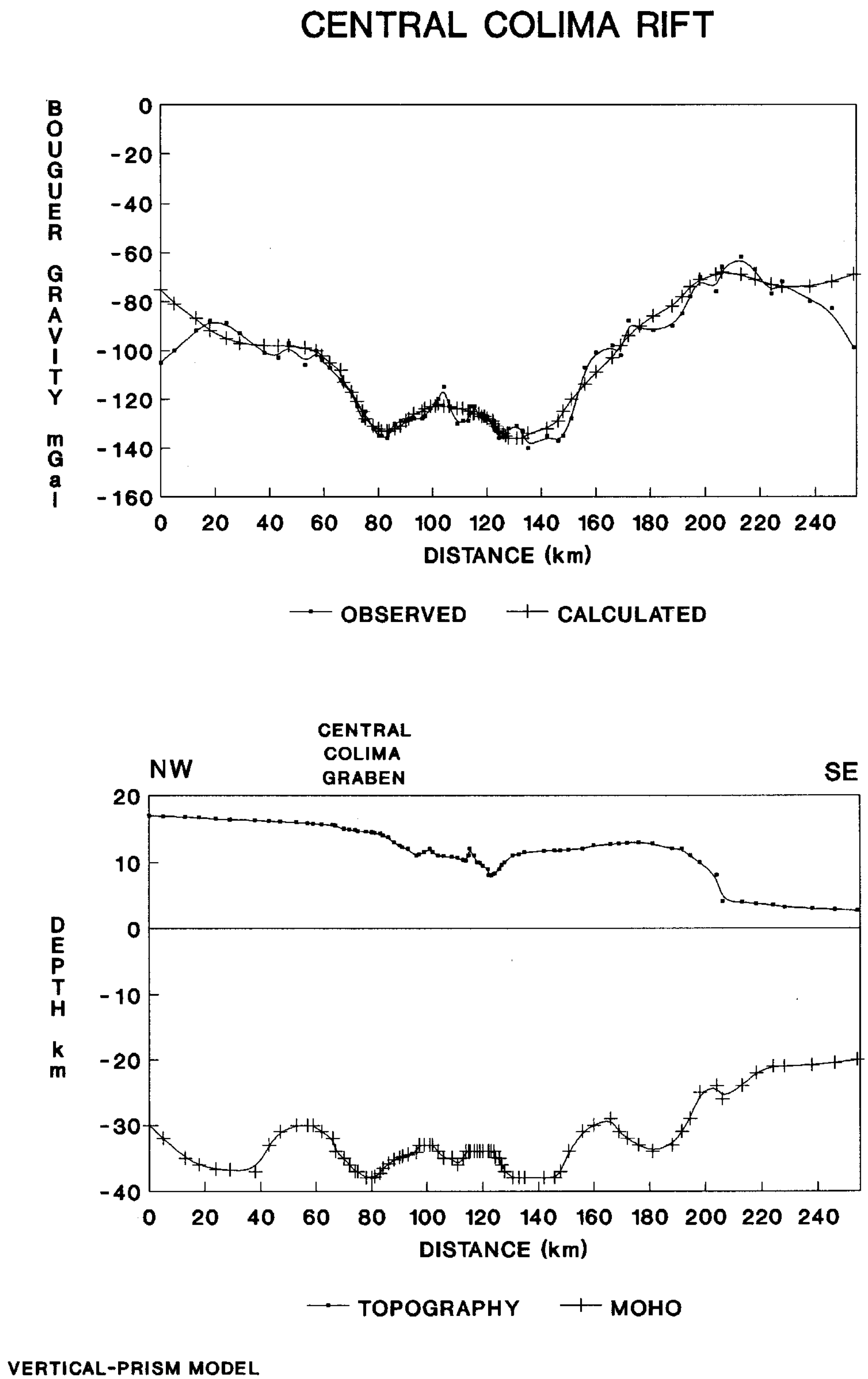

Fig. 6. Vertical-prisms model for the central Colima rift (as in Figures 4 and 5).

steep NW boundary. There is another depression, about 10 km deep, to the west 125 to 175 km along the transect, where a low-density mantle wedge was proposed by Bandy *et al.* (1995). At the eastern end of the transect, between 220 km and 250 km, there is a zone corresponding to the granitic intrusive terrain.

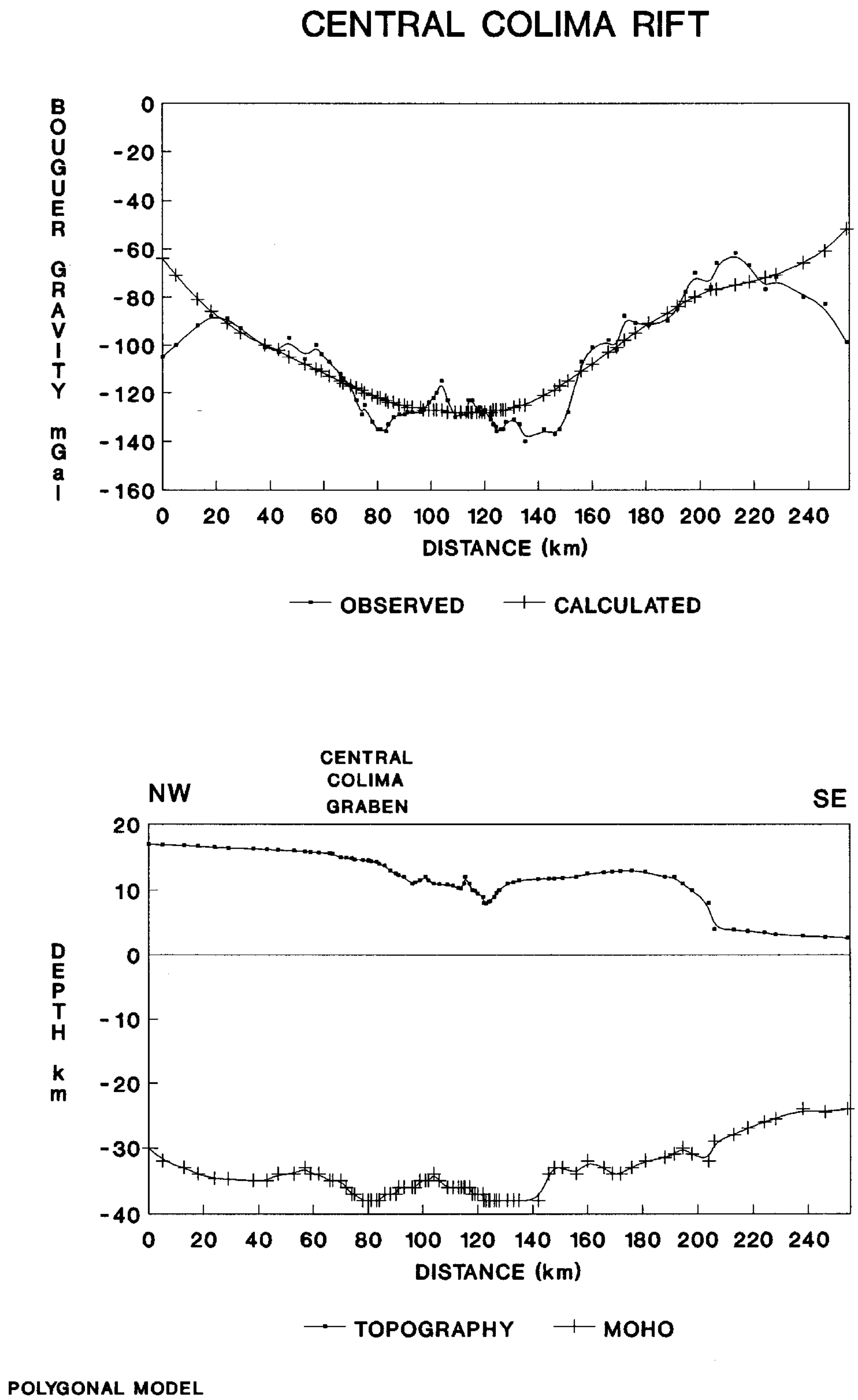

Fig. 7. Polygonal model for the central Colima rift (as in Figures 4 to 6).

DISCUSSION

Gravity studies have been successfully applied to investigate crustal structure in a variety of tectonic environments (e.g., Talwani *et al*., 1959; Simpson *et al*., 1986). They can provide valuable information on isostatic equilibrium and

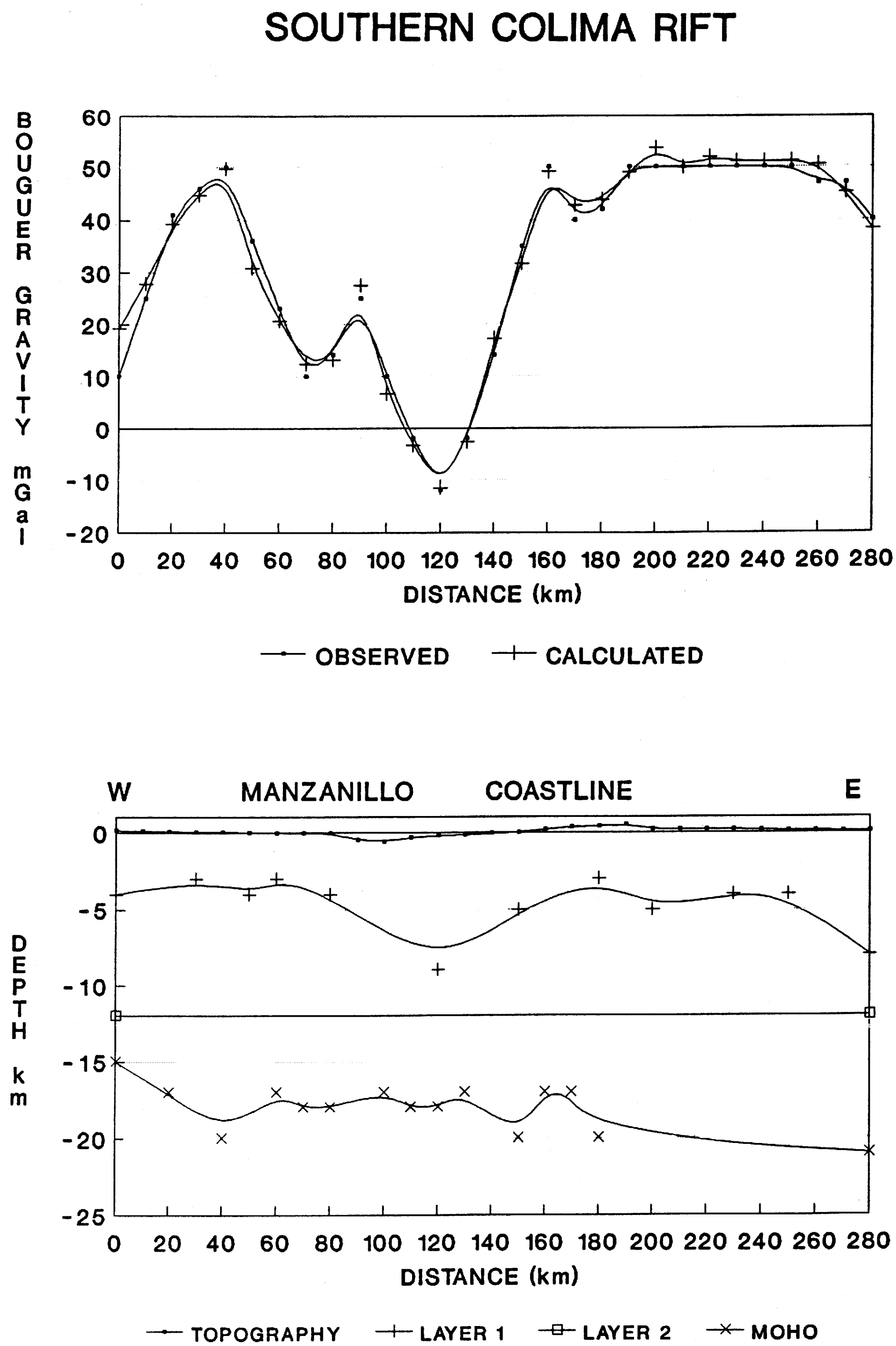

Fig. 8. Talwani-type layered crustal model for the southern Colima rift (as in Figures 4 to 7).

deep mantle and core processes (e.g., Marsh and Marsh, 1976; Simpson *et al*., 1986). Gravity studies have previously been used to investigate the crustal and lithospheric structure of the Colima graben, a major tectonic feature of western Mexico (e.g., Allan, 1985, 1986; Serpa *et al*., 1992; Urrutia-Fucugauchi and Molina-Garza, 1992; Bandy *et al*., 1993,

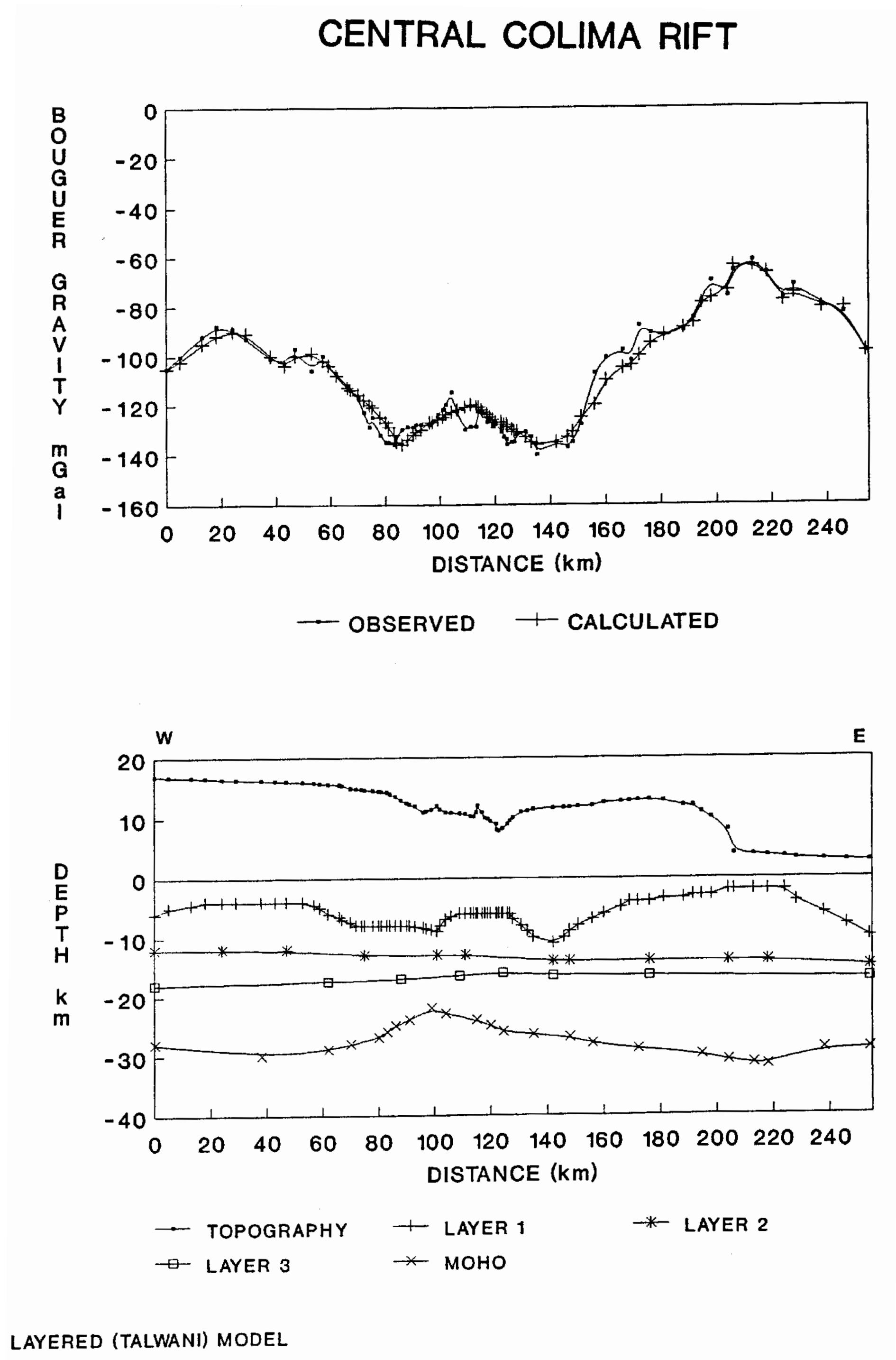

Fig. 9. Talwani-type layered crustal model for the central Colima rift (as in Figures 4 to 8).

1995; Medina *et al*., 1996). In the absence of additional data such as deep drilling, seismic reflection and refraction profiling or other geophysical studies, modeling of gravity anomalies has a limitation of non uniqueness. In this study we reinterpret the crustal models derived from earlier modeling of the gravity anomalies by using spectral analysis, iterative methods for estimating the crust-mantle boundary, and the Talwani method for a layered crustal model. The spectral analysis assumes that the frequency of the anomaly contains statistical depth information, so that no a priori inferences need to be made on density contrast or geometry of sources (Spector and Grant, 1970; Pal *et al*., 1979). In the iterative methods, the Talwani-type modeling was used to distinguish between deep and shallow contributions to the gravity signal.

Bandy *et al*. (1993) had proposed that the offshore extension of the SCR is formed by two grabens, one 35 km wide and 8 km deep and an adjacent one 60 km wide and 6 km deep. They also proposed that the Moho shoals, particularly under the NW graben. Our layered model constructed with Talwani-type polygons also finds shoaling of the crust - mantle boundary beneath the SCR. The crustal thickness is 16-17 km and increases towards the SE to 21 km. The offshore extension of the SCR can be modeled by a single graben about 80-90 km wide and 7-9 km deep (Figure 8). This correlates with the landward depression, which is about 100 km wide and extends from NW of Manzanillo to SE of Tecoman (Figure 1). The bathymetric expression of the SCR offshore extension is a broad depression with several submarine canyons. Burgois *et al*. (1988) have found one kilometer vertical offsets along the major faults limiting the canyons, from single channel seismic reflection profiling. Further evidence for the offshore graben has been reported by Michaud *et al*. (1990). Near surface reflectors at the NW and SE boundaries of the SCR were found to dip inwards. Evidence for normal faulting at the NW boundary was also found in the Nautimat survey (Mercier de Lepinay *et al*., 1997).

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