Gravity modelling of regional crustal and upper mantle structure of the Guerrero terrane - 1. Colima graben and southern Sierra Madre Occidental, western Mexico.

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RESUMEN

La estructura de la corteza y el manto superior en la región centro-occidental del país se ha investigado por análisis detallados de las anomalías de Bouguer y Aire Libre (mapas regionales y un perfil de 400 km de longitud). El espesor cortical se incrementa del margen continental Pacífico hacia el interior, con los valores mayores bajo las provincias volcánicas de la Faja Trans-Mexicana (TMVB) y la Sierra Madre Occidental (SMO) (en el rango de 40 a 46 km). La región se encuentra en equilibrio isostático regional, con anomalías locales de cortas longitudes de onda. Los resultados del estudio gravimétrico no parecen apoyar los modelos en términos de secuencias de arcos de isla construídos sobre litosfera oceánica ya que el arreglo de densidades y espesores derivado sugiere una corteza inferior gruesa y de naturaleza continental o sub-continental. Estas observaciones aplican al sector occidental del terreno Guerrero, hacia el sur en Colima y sur de Jalisco la corteza se adelgaza y las secuencias volcano-sedimentarias corresponden a ambientes tipo arco. La corteza inferior hacia el norte podría corresponder a una corteza granulítica probablemente compuesta de líquidos máficos, cumulos o residuos y meta-sedimentos ricos en granate, o bien a una corteza de carácter ígneo (diorítica o gabro-diorítica). Los modelos corticales bi-dimensionales son compatibles con la ocurrencia de una capa de densidad baja a intermedia en la base de la corteza, la cual podría representar una zona de fusión parcial que estaría relacionada a mecanismos de levantamiento regional. Modelos de geotermas construídos de tiempos de viaje para ondas superficiales Raleigh y Love en el centro y altiplano indican un alto régimen térmico y una zona de fusión parcial. Si esta interpretación es correcta, ello provee un mecanismo simple para la generación de actividad volcánica cercana a la trinchera y levantamiento regional, asociado a la subducción de bajo ángulo y rápida de litosfera muy joven como es el caso en el segmento de la zona de subducción de Jalisco y Colima.

PALABRAS CLAVE: Estructura cortical, gravedad, tectónica, terreno Guerrero, Graben de Colima, Occidente de México.

ABSTRACT

Quantitative modelling of the Bouguer and Free-Air composite gravity anomaly map for western-central Mexico and of a long, ~400 km north-south, gravity profile is used to investigate the crust and upper mantle structure beneath the region. Crustal thickness increases from the Pacific ocean margin towards the continental interior, presenting higher values beneath the plateaus of the Trans-Mexican volcanic belt (TMVB) and the Sierra Madre Occidental (SMO) (in the range of ~40-46 km thick). The region appears to be under regional isostatic equilibrium with shorth wavelength local departures. Results of the gravity study do not support interpretations of an igneous Mesozoic island-arc assemblage over oceanic lithosphere for the western Guerrero terrane. Instead, gravity modelling suggests a crust of continental (or transitional) character, with a thick lower crust of metamorphic or igneous nature. This may correspond to a high density granulitic lower crust, probably consisting of crystallized mafic liquids, cumulates and/or residues from removal of a partial melt, and garnet-rich metasediments, or alternatively, an igneous (dioritic or gabbroic) crust. Two-dimensional crustal models are compatible with the occurrence of a low-to intermediate-density layer at the base of the crust which has been proposed as responsible for the uplift mechanism of the volcanic plateaus. Geotherms constructed from travel time analysis of surface Raleigh and Love waves for central Mexico indicate a high thermal regime with partial molten material at the base of the crust. If this interpretation is correct, it provides a simple mechanism for close-to-trench volcanic activity and regional plateau uplift that incorporates a high thermal regime associated with low angle rapid subduction of a very young lithospheric plate.

KEY WORDS: Crustal structure, gravity, tectonics, Guerrero terrane, Colima Graben, Western Mexico.

1. INTRODUCTION

The Cocos plate subducts the southern Mexico margin along the Middle American trench. The proximity of the corresponding Cocos-North America pole of rotation (27.9 N, 120.7 W) and high angular velocity (ω = 1.42 degrees/Ma, DeMets *et al.*, 1990), results in increasing convergence rates from the transform-ridge-trench (TRT) triple junction toward the southeast. The north-south orientation of the East Pacific rise and its proximity to the Jalisco continental margin also gives rise to a rapid variation of the age of the plate being subducted along the trench (Figure 1). In contrast, convergence of the smaller Rivera plate is less clear, with no developed trench along its northern sector (e.g. Eissler and McNally, 1984). Thus, subduction angle and kinematics show a complex pattern

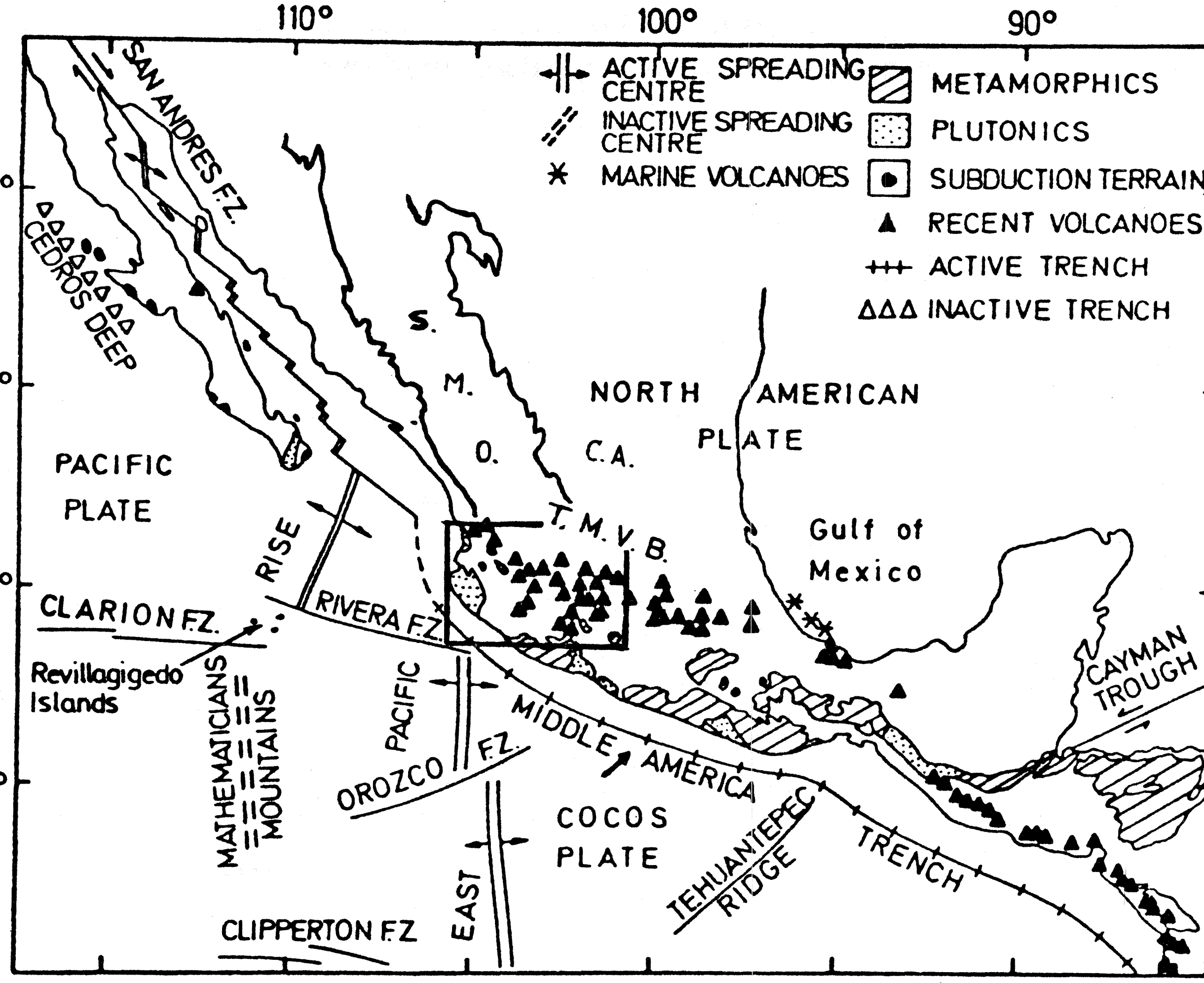

Fig. 1. Schematic tectonic map of Mexico showing location of study area (rectangle) in western-central Trans-Mexican Volcanic Belt.

for the interactions of the Pacific, North America, Cocos and Rivera plates in this portion of central and southern Mexico.

Active arc magmatism in the continental margin also shows a peculiar pattern, with stratovolcanoes concentrated along two narrow belts at oblique angles with respect to the trend of the trench and plate convergence directions (Figure 1). Historic volcanism occurs in the Colima Graben, the Tepic-Chapala Graben and the region around the City of Guadalajara and Chapala lake. Volcanic activity displays an apparent tectonic control, as it is concentrated within the structural depressions at odd positions with respect to generalized subduction zone models. The large Colima stratovolcano complex is near the Middle American trench. Activity appears to have migrated trenchward as suggested by the Cantaro-Nevado de Colima-Volcán de Colima chain. The association between activity along the Tepic-Chapala Graben (e.g. Ceboruco, Tequila, and La Primavera) and Rivera plate subduction is less clear. To complicate matters further, there is contemporaneous bimodal volcanism of calc-alkaline and alkaline character occurring in the region (Luhr and Carmichael, 1985; Allan, 1986).

The past evolution of the area seems also rather complex. The Jalisco and Colima segments of the continental margin have been interpreted as part of the composite Guerrero terrane (Campa and Coney, 1983) with island arc and continental arc affinities. The terrane also contains many large batholithic complexes of Late Cretaceous and younger ages (Böhnel *et al.*, 1989). The granitic bodies are dominantly magnetite-bearing or I-type (Alva-Valdivia *et al.*, 1991); thus display an apparent age progression, becoming younger towards the southeast along the terrane margin (Köhler *et al.*, 1988; Schaaf, 1990).

Critical to the tectonic evolution of the region is the crustal and upper mantle structure along the continental margin and interior. Unfortunately, there are relatively few studies concerning the deep crustal and upper mantle structure beneath most of Mexico (e.g. Urrutia-Fucugauchi, 1986). In this paper we report preliminary results of gravity modelling of the crustal and upper mantle structure of the Guerrero terrane in the Jalisco-Colima region including the Trans-Mexican volcanic belt (TMVB) and Sierra Madre Occidental (SMO) igneous provinces.

2. GRAVITY DATA

A regional Bouguer gravity anomaly map for the west-central part, approximately between 18.5 N and 20.5 N and 101 W and 105.5 W, and a north-south profile across the Colima Graben and southern Sierra Madre Occidental were used (Figure 2).

The Bouguer gravity map for central Mexico (Woollard *et al.*, 1969; Monges-Caldera and Mena, 1973) was supplemented with Free-Air gravity data for the Pacific Ocean (Sánchez-Zamora, 1981). The mapped measurements on land were made with LaCoste and Romberg G- gravimeters No. 96, 130 and 247 (Monges-Caldera and Mena, 1973). The measurements on sea were made with a LaCoste and Romberg S-42 gravimeter (Sánchez-Zamora, 1981). Bouguer gravity values were computed with a standard density of 2.67 g/cc. The resulting composite (Free-Air and Bouguer) gravity anomaly map is shown in Figure 3.

Our profile was measured with a Worden gravimeter No. 33. The data, including the computed Free-Air and Bouguer anomalies and the topography, are shown in Figure 4. The density for the Bouguer corrections was 2.67 g/cc. The entire profile is some 400 km long and crosses an abrupt topography. The profile starts at an altitude of about 400 m above sea level at Colima City and climbs up to 1500 m in Ciudad Guzmán. About 150 km of the profile run along the depression of the Colima Graben, mainly on pyroclastic and lava flows and Quaternary to Recent sediments. Near Guzman City, the graben joins two major structures: the Chapala graben (trending almost E-W) and the Tepic-Chapala graben (at about 120 degrees in a NW-SE trend). Between 160 and 230 km from Colima, then we cross the Madroño Sierra at elevations of up to 1300 m. North of Guadalajara the profile crosses the Rio Grande depression, which is 500 m lower than the surrounding volcanic plain. Between 320 and 370 km from Colima the relief rises to 1750 m in the Guajolote Sierra, and gradually drops again across the rhyolitic deposits of the Sierra Madre Occidental (SMO). The limit between the Trans-Mexican volcanic belt (TMVB) and the SMO is not well established. The SMO volcanic products may represent the local basement of the TMVB as observed in several 1.5 to 2.5 km deep borings (Venegas-Salgado *et al*,, 1985). The Bouguer gravity anomaly shows a negative correlation with topography, with several superimposed short wavelength anomalies. Near Ciudad Guzmán and Guadalajara some anomalies of 20-30 mgal and 50 km wavelength are not correlated with surface effects.

Samples collected from some outcrops included limestones, mafic and acid volcanics, intrusive bodies and recent river and lake sediments. Sampling was mainly along the profile. Weight was estimated by using a mechanical balance and volumes and effective porosity were estimated by submerging samples in distilled water. For the interpretation of the deep subsurface structure, densities were estimated from P-wave velocities reported in seismicity studies, by using density-seismic velocity relationships (Grant and West, 1973).

3. GRAVITY MODELLING OF LITHOSPHERIC STRUCTURE

3.1 Regional Structures and Trends

The composite gravity anomaly map (Figure 3) displays a relatively simple regional pattern characterized by large wavelength negative anomalies of some -200 to -250 mgal over the central portion, in the TMVB province. Smooth gradients of some 2 mgals/km towards the west and south trend parallel to the coastline. Superimposed on this regional pattern, there are high frequency anomalies with wave lengths of about 20 to 50 km, which are related to major exposed tectonic features. Negative anomalies are associated with the N-S Colima graben, E-W Chapala graben, N-S La Piedad graben and Cuitzeo and Yuriria lakes. The Middle America trench (MAT) features an elongated, well developed gravity anomaly. The zero mgal contour approximately follows the coastline.

Upward analytical continuations to 16 km and 32 km enhance the overall regional features (Figure 3b, c). The regional trend of anomalies is clearly to the continental margin. The first and second vertical derivatives of gravity are shown in Figure 5a, b. Offshore anomalies follow the trend of the trench. Anomalies on land display an E-W trend from the Chapala region to the east. Anomalies to the west are dominantly oriented N-S.

3.2 Isostasy

The Free-Air anomaly along the profile shows a good overall correlation with the topography (Figure 4). The Bouguer anomalies also correlate with the elevations (Figure 6a): Values for the northern sector of the SMO volcanic province are shown as filled symbols. They seem to show a different trend to the rest of the profile. Least-square linear regression of the Bouguer anomalies yields.

$$BA = -0.111\, H + 5.23 \qquad r = 0.80 \qquad (1)$$

where BA is the Bouguer value and H is elevation in meters.

Wollard *et al.*, (1969) reported the following relation, from a regional study with 1 x 1 degrees grid:

$$BA = -0.79\, H - 35 \qquad (2)$$

for elevations between about 750 m and 2500 m, and

$$BA = -0.111\, H + 1 \qquad (3)$$

for elevations between about 0 m and 1250 m.

Relation (3) is similar to our values in Eq (1). Airy-type isostatic anomalies were estimated for the profile. Several density contrasts and crustal thicknesses were tested. The model for a 30 km crust with a density contrast of 0.45 g/cc is shown in Fig. 6b. Comparison with the

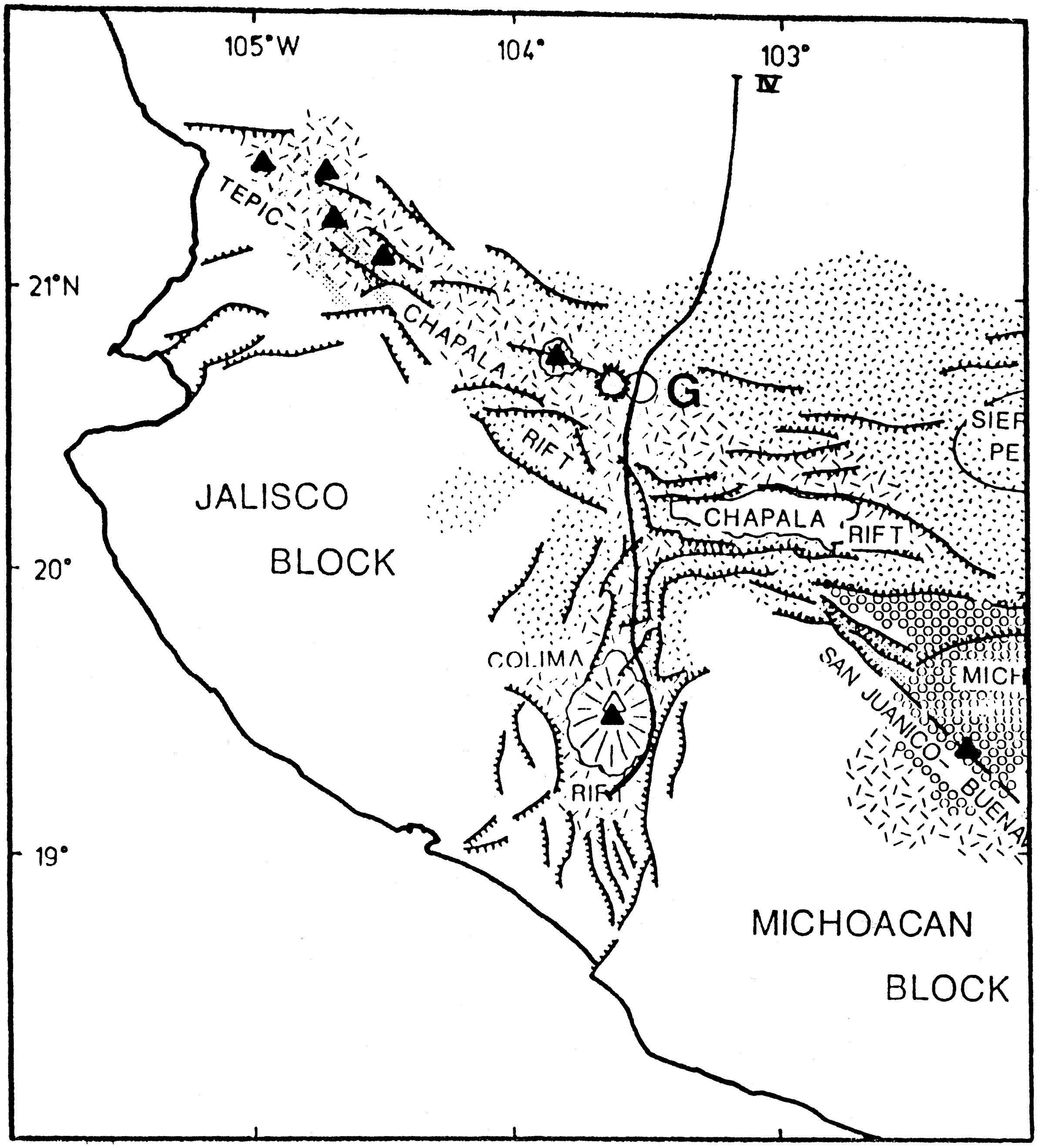

Fig. 2(a). Schematic neotectonic map for western central Mexico showing approximate location of gravity profile. The profile lies along the Colima graben and accross the Trans-Mexican Volcanic Belt (TMVB) and the Sierra Madre Occidental (SMO) volcanic provinces.

observed profile shows some positive and negative departures of the order of 20 mgals. The departure in the north, within the SMO province, shows a distinct trend. The Bouguer vs elevation data also lie consistently below the least-square fit to the overall profile data (Figure 6a).

3.3 Spectral Analysis

Spectral analysis using a fast Fourier transform (FFT) algorithm may provide a statistical estimation of the top elevation of assemblages of bodies when no previous assumptions on the geometry and density contrast of subsurface units are required. It may supply useful constraints on the quantitative modelling of gravity anomalies, following methods as proposed by Talwani *et al.*, (1959, 1965). This is useful when constraints from deep drilling or geophysical methods are not available.

The spectral method is widely used in aeromagnetics (e.g. Spector and Grant, 1970; Shuey *et al.*, 1977; Campos-Enríquez *et al.*, 1990). We followed the methods

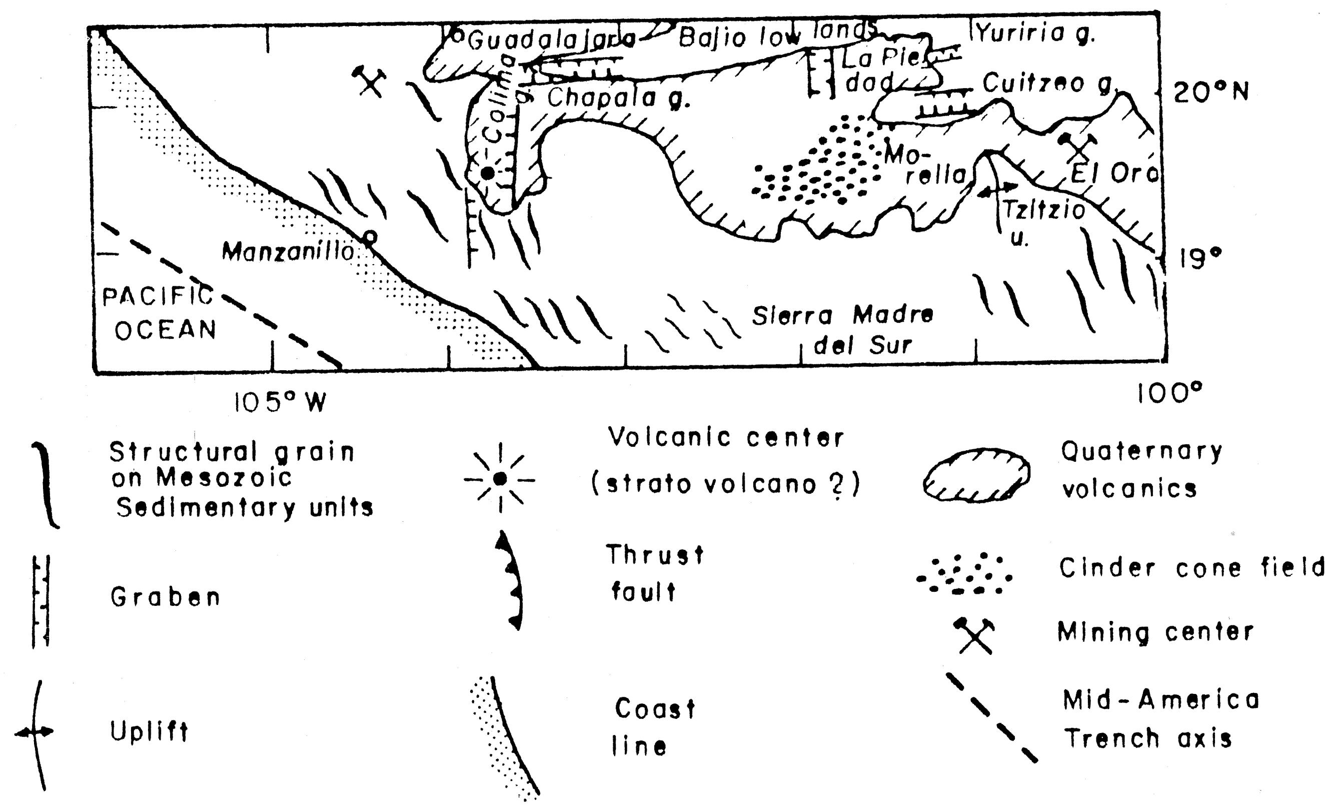

Fig. 2 (b). Sketch geologic and structural map for central - western Mexico showing some of the major structural tectonic features. methods are not available.

developed by Bhattacharyya and Leu (1975, 1977) and Escanero-Figueroa (1986). Results for the profile in terms of the logarithmic plot of the smoothed amplitude spectrum as a function of the logarithm of the wave number are shown in Figure 7. Three deep interfaces are estimated as follows: 43 km, 24 km and 16 km. The deepest interface is interpreted as the crust-mantle boundary; it seems to correlate well with the seismic data and with results of the modelling of the gravity profile. On the other hand, the two intermediate depth interfaces do not seem to match any interface in the gravity or seismic models.

3.4 Crustal Models

Gravity effects of crustal models were calculated using a Talwani-type algorithm for two-dimensional prismatic bodies (Talwani *et al.*, 1959). Isostatic models suggest a crust thicker than some 30 km and a density contrast of -0.5 g/cc. For the construction of the crustal structure in the models we used the available seismic data. P-wave velocities were converted into equivalent densities (Grant and West, 1973), and we used the thickness of the layers to construct the polygonal models. The geometric model was modified until the gravity effects fitted the observed Bouguer anomaly values. Density values were also modified during modelling: values below were derived from the P-wave velocities. An anomalous layer of intermediate density at the base of the crust in two of the model groups had been suggested from surface Raleigh and Love waves modelling (Fix, 1975) and from geochemical data from the volcanic units of the TMVB (Urrutia-Fucugauchi, 1978, 1982). It was interpreted as due to partial melting within a high thermal regime associated with plate subduction, regional plateau uplift and volcanism (Fix, 1975; Urrutia-Fucugauchi, 1978, 1982).

An initial model (Model A) assumes a single layer of equivalent density contrast of -0.5 g/cc. The crust was assigned a mean density of 2.85 g/cc and the upper mantle a density of 3.35 g/cc. The Bouguer anomaly is modelled by varying the topography of the crust-mantle boundary (Figure 8). The model shows an average crustal thickness of 35 km, but thicker regions, of some 40 km, are found between Colima and Guzman, Guzman and Guadalajara, and Guadalajara and Juchipila.

A second model (Model B) uses surface wave models reported by Fix (1975), and Rivera-Hernández and Ponce-Mori (1986). The crust is modelled by two thin surface layers of average densities of 2.33 and 2.63 g/cc and a thicker layer with density of 3.08 g/cc. Changing the density and keeping the same density contrast has no effect on the modelling. The relatively high density for the lower crust was adopted as equal to the average density of granulites. Amphibolites and gabbros may also contribute in minor amounts. The upper mantle is assigned a standard

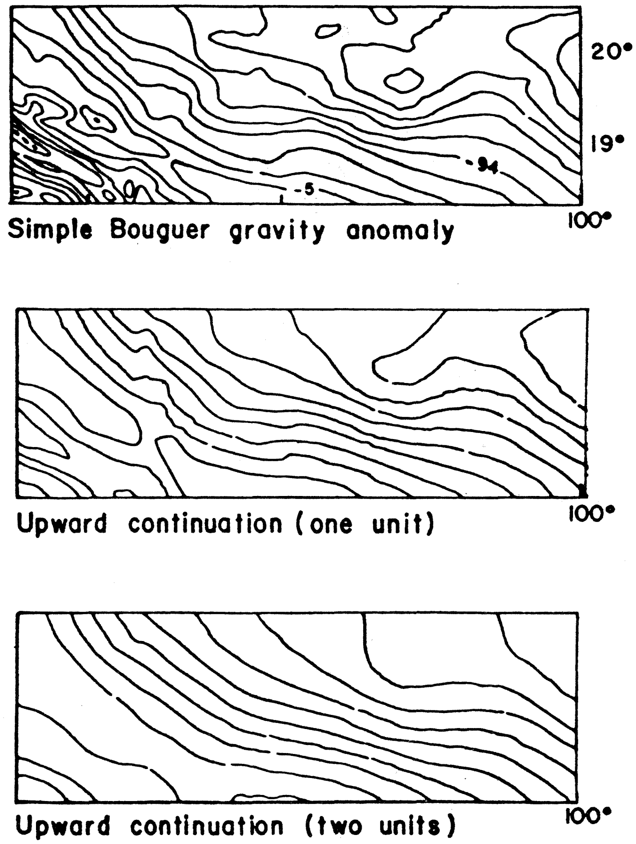

Fig. 3 (a). Simplified Bouguer gravity anomaly map for western Mexico (b). Upward analytical continuation (one grid unit) of gravity map (c). Upward analytical continuation (two grid units) of gravity map (refer to Fig. 2b for geographic and geologic information).

density of 3.3 g/cc. The layer of intermediate density, of 3.25 g/cc, had been interpreted as a partial melt in the analysis of surface waves by Fix (1975); its relief is similar to that in model A. Results are shown in Figure 9. The maximum crustal thickness is in the order of 45 km, in the north beneath the TMVB and SMO.

A third group of models (referred to as model C) was constructed from the seismic model used by RESMAC (Nava and Toledo, 1982). It features two surface layers with densities of 2.3 and 2.63 g/cc and a thicker layer with density of 2.95 g/cc. This last density may correspond to metamorphic rocks in the facies of granulites (hornblende or piroxene granulites). The upper mantle density is assumed to be 3.4 g/cc. A layer of intermediate density (3.29 g/cc) at the base of the crust is also included. Results are shown in Figure 10. In this model, the topography of the lower crust boundary smoothly dips to the north beneath the TMVB and SMO provinces. The maximum crustal thickness is in the order of 46 km.

4. DISCUSSION

4.1 Crustal Structure

The gravity anomaly map and our preliminary two-dimensional modelling of crustal structure suggest that crustal thickness increases from the Pacific continental margin to the continental interior, with maximum thicknesses beneath the volcanic provinces of the TMVB and SMO (in the order of 40-46 km). The entire region appears to be under regional isostatic equilibrium. Qualitative evaluation of the Free-Air and Bouguer anomalies, topography, and Airy-type two-dimensional isostatic models agree with isostatic equilibrium, with only short-wavelength departures beneath the volcano-capped plateaus. Density contrast is of the order of -0.5 g/cc and crustal thickness is close to but greater than 30 km.

Spectral analysis of the two-dimensional data for the 400 km profile provide a statistical regional estimate of the crustal structure. This analysis constrains the gravity models for crustal and upper mantle structure. It suggests an average crustal thickness of 43 km. Two shallower interfaces are at about 24 km and 16 km; further modelling is required to evaluate the significance of these two interfaces.

Gravity modelling alone cannot discriminate between the crustal and upper mantle models from seismicity studies. Different gravity models derived from the available seismic models (with equivalent density estimates from P-wave velocities) all reasonably fit the observed anomalies. Three different groups of gravity models may provide preliminary information on crustal and upper mantle structure beneath western-central Mexico. Additional constraints are required for interpreting the crustal structure. In this work, we used seismic data, regional geology and spectral analysis of gravity data. Models B and C incorporate three crustal layers and a layer of intermediate density at the base of the crust. They are to be preferred for the lithospheric structure in this area of Mexico. The thick lower crust may represent metamorphic rocks in the granulite facies and intrusive bodies of probable gabbroic composition. Evidence for granulites in this region is lacking, but gabbroic xenoliths have been reported in the Tepic-Chapala graben (e.g. at Sanganguey volcano; cf. Giosa and Nelson, 1985).

Long and intermediate wavelength gravity anomalies may result from several factors such as crust-mantle topography, lateral density variations within the lower and/or upper crust, local structure and density variations of surface layers, sedimentary basins, large magmatic bodies, etc. Lateral as well as vertical variations and inhomogeneities are found in the lower as well as the upper crust (e.g. Smithson and Brown, 1977), and modelling only gravity anomalies might produce an oversimplified view.

4.2 Basement of Guerrero Terrane

Unfortunately, very little is known about the nature and age of the lower crust in the region, due to the absence of basement exposures. Available information comes from geochemical and petrologic studies of lower crustal and upper mantle xenoliths in localities to the northeast in the central plateau or Altiplano (e.g. Roberts and Ruiz, 1989; Pier *et al.*, 1989; Ruiz *et al.*, 1988), and from isotopic

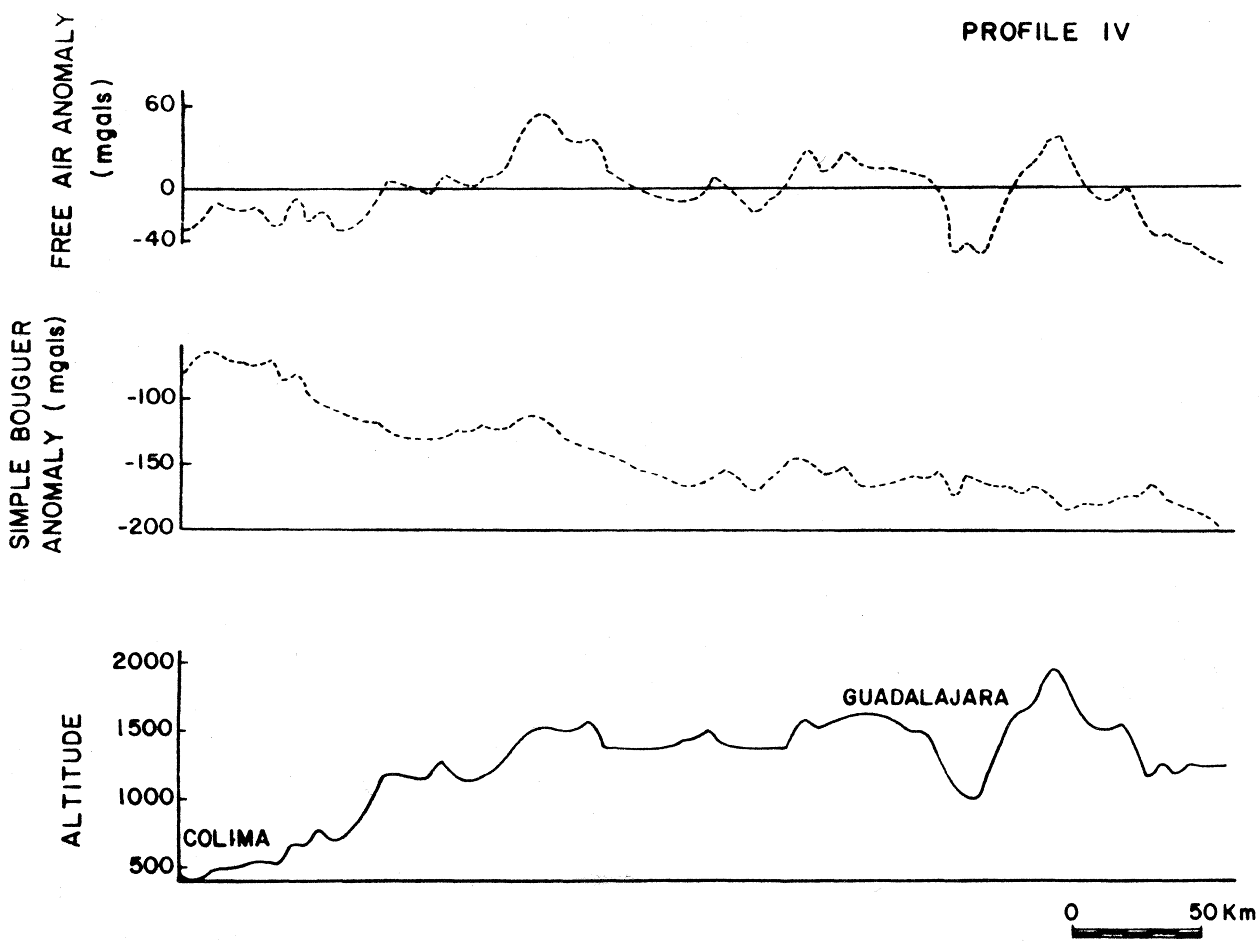

Fig. 4. Gravity and topographic data for profile analysed (location in Fig. 2a). (top) Free-air anomaly, (middle) Bouguer gravity anomaly, and (bottom) topographic relief.

studies in the TMVB. The gravity modelling does not appear to support that the basement of the Guerrero terrane would consist mainly of igneous rocks of Mesozoic island-arc assemblages (Campa and Coney, 1983). Rather, the models suggest a thick lower crust of high density and metamorphic composition. The gravity models seem compatible with interpretations such as that of Roberts and Ruiz (1989), who suggest that the Mexican lowermost crust consists of a zoned granulitic layer of crystallized basaltic liquids, cumulates and/or residues from removal of a partial melt, and garnet-rich metasediments. Extensive outcrops of the crystalline basement are only found farther to the east, in the Paleozoic Acatlan and Precambrian Oaxaca complexes. The Zihuatanejo sub-terrane contains many large intrusive bodies of batholithic dimensions, like those in the Xolapa terrane. Recent isotopic studies by Morán-Zenteno (1992) suggest that the Cretaceous intrusives of magmatic arc association in the Xolapa complex may have intruded continental crust and/or the accretionary sedimentary prism near the Acatlan terrane. Elías-Herrera and Sánchez-Zavala (1992) have discussed the pre-Tertiary units in the Zacazonapan area which is in the Tierra Caliente Complex. They studied a mylonitic granite that constitutes the basement to the Mesozoic metasedimentary sequence.

The composite nature of the Guerrero terrane was recognized since it was first defined. It points to a heterogeneous basement (Campa and Coney, 1983). The large area under the TMVB and SMO may likely include a continental lower crust as indicated in some models, in order to generate the huge ignimbrite flows of the SMO. Oceanic-type basement has been suggested elsewhere in the terrane and several tectonic models involve closure of a marine basin within the terrane (e.g. Urrutia-Fucugauchi and Valencio, 1986).

Metamorphic 'basement' outcrops are rare and of limited extent in most of the terrane; they have received relatively little attention (e.g. Pantoja Alor, 1959; Elías-Herrera and Sánchez-Zavala, 1992). The largest is the Tierra Caliente complex in the elongated region south of Tejupilco and between Teloloapan and Arcelia. Other metamorphic exposures include the Arteaga Schist (Barba-López *et al.*, 1988) and the core of theTzitzio anticline. These units may have lower Paleozoic (?) or early Mesozoic (?) protoliths and metamorphic ages from middle Paleozoic to late Jurassic.

Further constraints on the nature of the crust come from the maar volcanic field of Valle de Santiago in the northern part of the Michoacan-Guanajuato volcanic field.

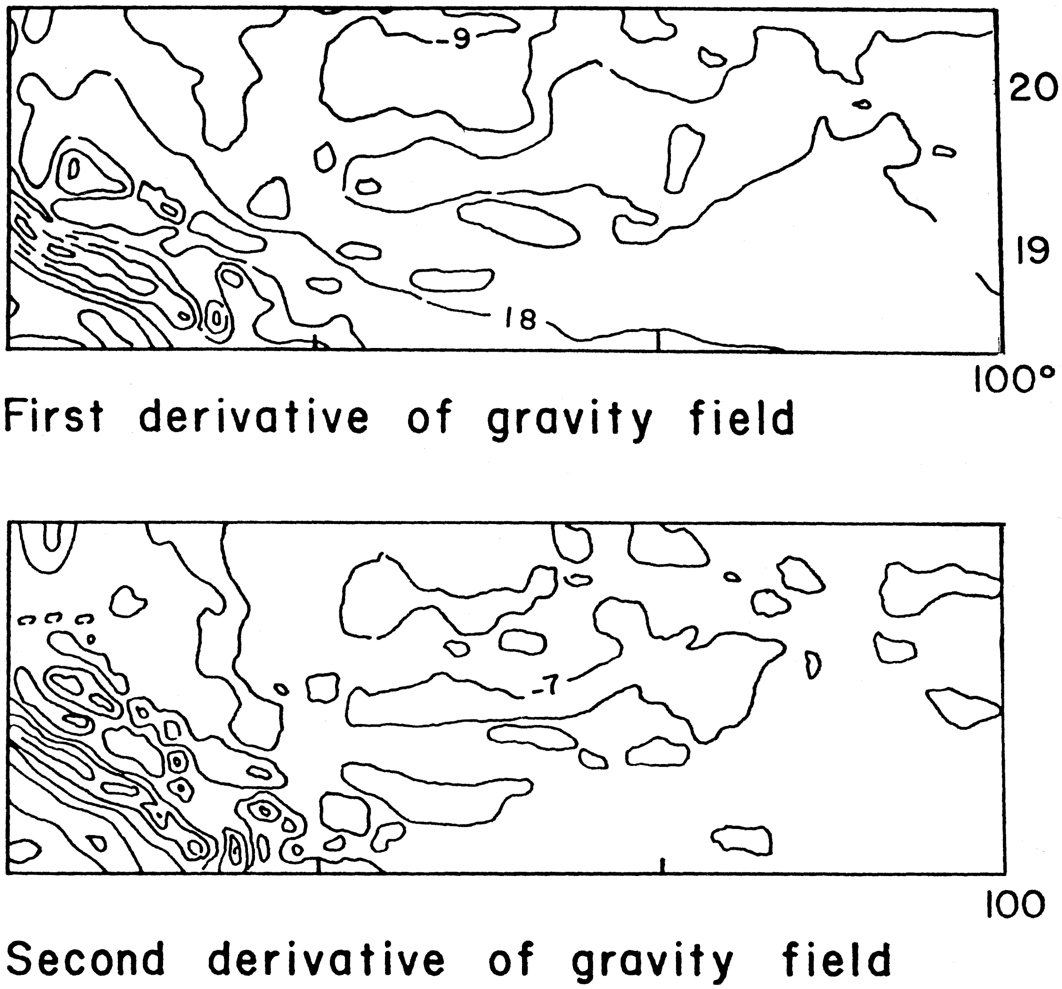

Fig. 5 (a) First vertical derivative of Bouguer anomaly gravity field (b). Second vertical derivative of Bouguer gravity field (refer to Fig. 2 (b) or geographic and topographic details).

Granulitic xenoliths recovered from the Rincón de Parangueo maar suggest a granulitic lower crust under this area (Uribe-Cifuentes, 1992; Uribe-Cifuentes and Urrutia-Fucugauchi, 1992).

The volcano-sedimentary sequences of island-arc association in the Zihuatanejo sub-terrane may have been emplaced north of the margin (from Colima City northwards) and into continental crust. The situation closer to the margin is not investigated here. Results of gravity modelling of a profile parallel to the margin near Manzanillo is reported in a companion paper briefly discussed below. Preliminary results were presented in Bandy *et al*, (1991). Three wells drilled by PEMEX near Colima City (Colima-1, Tepames-1 and Jalisco-1) traverse a sequence of volcanic and carbonate units up to depths of about 3.5 km. They end in a sequence of tuffs and andesites identified as the Tecalitlán Formation (Grajales-Nishimura and López-Infanzón, 1983).

4.3 Neotectonics of Western-Central Mexico

Considerable attention has been recently given to the regional graben structures of Colima and Tepic-Chapala in west-central Mexico, as a result of propositions that consider the structures as incipient divergent plate margins (Luhr *et al.*, 1985).

The Colima Graben is interpreted in terms of a continental rift undergoing active extension and lithospheric thinning. The rifting process is linked to an eastward jump of a segment of the East Pacific rise into the western Mexico mainland. The Jalisco block would be eventually separated from the continent (Luhr *et al.*, 1985). Observations in support of this hypothesis are mainly from petrography and geochemistry, showing contemporaneous alkaline and calc-alkaline volcanism the grabens (e.g. Luhr and Carmichael, 1985; Nelson and Liviers, 1986).

The gravity data suggest a crustal thickness in the order of 30 to 46 km with no apparent indication of significant crustal thinning as compared to adjacent regions in southern Mexico (Molina-Garza, 1984; Molina-Garza and Urrutia-Fucugauchi, 1984 and in press). The two-dimensional models that include a layer of partial melt at the base of the crust also suggest a high thermal regime

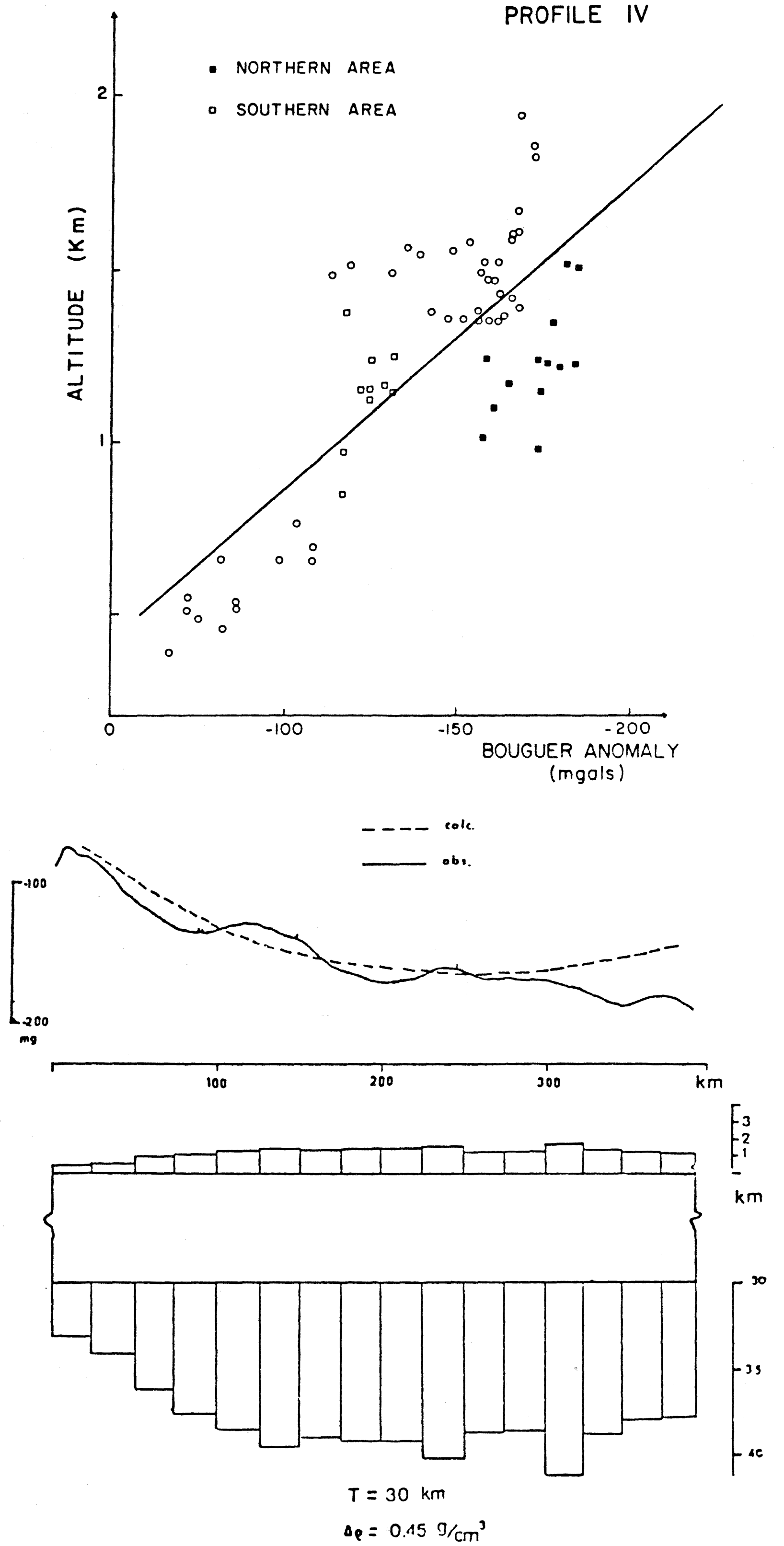

Fig. 6. Isostatic data for Colima-Juchipila profile. (a) Bouguer anomaly-altitude above sea level graph (left) and (b) Airy type isostatic compensation model. Reference depth is 30 km and density contrast is 0.45 g/cc.

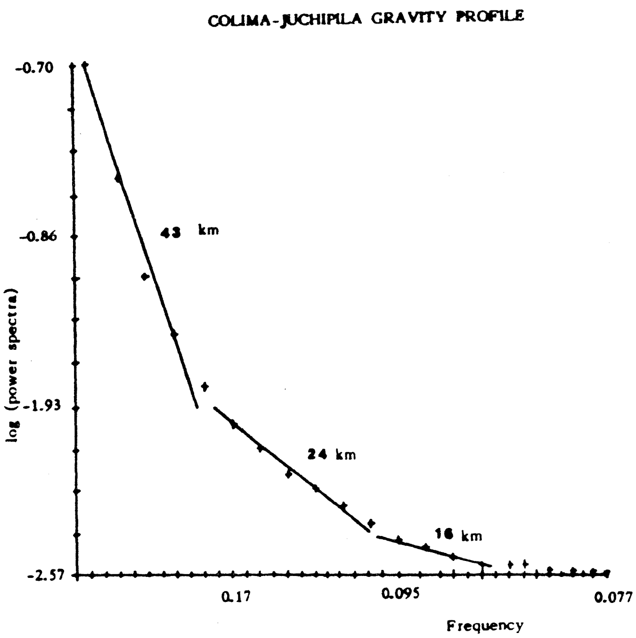

Fig. 7. Spectral estimation of average depths for Colima-Juchipila profile. The depths correspond to 43 km, 24 km and 16 km.

beneath the region, in agreement with expectations for a continental rift structure. However, similar conditions may prevail in other areas beneath central Mexico (Fix, 1975, Urrutia-Fucugauchi, 1978, 1982). If active rifting due to jumping inland of a segment of the spreading ridge is taken place, it must be in an incipient stage as there is no significant thinning of the crust along the Colima Graben.

Another observation of interest for the structure of the Colima Graben comes from a gravity profile along the coast nearby Manzanillo, which is discussed in a companion paper (Bandy *et al.*, 1991, in press). The model suggests that the Colima structure may be displaced to the west in relation to the orientation inland. This interpretation agrees with the offshore bathymetry of the Manzanillo canyons and marine geophysical surveys in the trench area (Bourgois *et al.*, 1988).

Serpa *et al.*, (in press) conclude from geology and ground magnetics and gravity surveys south of the Colima Graben that little or no tectonic extension has occurred. Features previously interpreted as evidence of tension are actually erosional landforms related to earlier deformation events. Their gravity models do not support the presence of a graben structure in the area from Colima volcano to the coast.

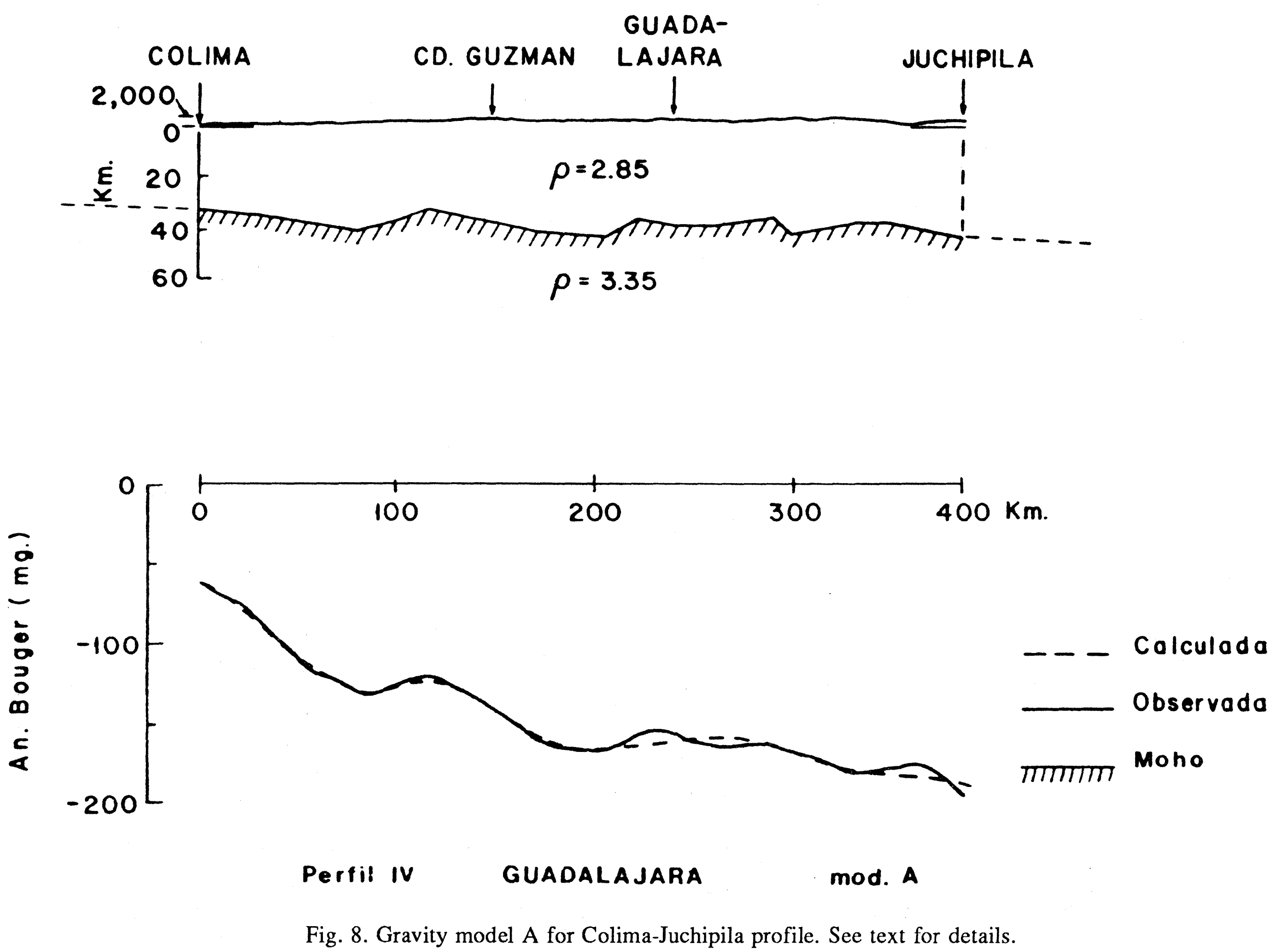

Fig. 8. Gravity model A for Colima-Juchipila profile. See text for details.

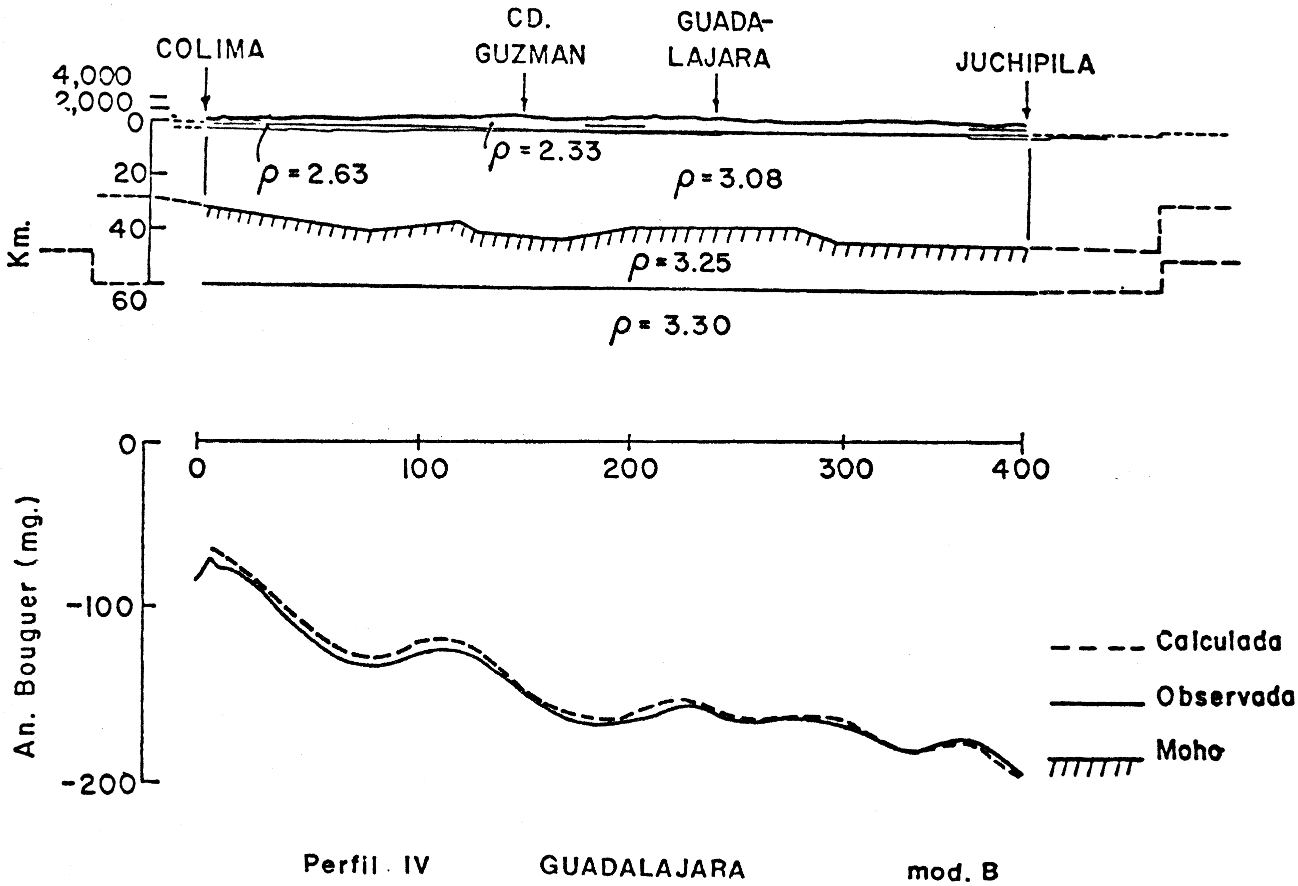

Fig. 9. Gravity model B for Colima-Juchipila profile. See text for details. Compare with Fig. 8.

Alternative tectonic interpretations for western Mexico, and in particular for the Colima and Tepic-Chapala grabens, are given in Urrutia-Fucugauchi (1989), Johnson and Harrison (1990), Nixon *et al.*, (1987), Nieto Obregón *et al*, (1992), and Bandy (1992).

4.4 Shallow Crustal Structure

The available gravity data do not allow firm inferences concerning the shallow crustal structure of the area. The information is important for constrainting the density contrasts and the modelling of the intermediate and deep structures. Some data around Guadalajara come from regional geologic surveys and geothermal exploration drilling (by the Federal Commission of Electricity, CFE), local gravity study (Allan, 1985) and aeromagnetic surveys (Campos-Enríquez *et al.*, 1990). Detailed geophysical data from the area just south of the Colima volcano is reported by Serpa *et al.*, (in press).

Deep drilling for geothermal exploration in the Sierra de la Primavera (west of Guadalajara City) and in the San Marcos area (southeast of Guadalajara City) documents a thick sequence of volcanic and volcanic-sedimentary rocks (Venegas-Salgado *et al.*, 1985). In La Primavera, the wells cross sequences of ignimbrites, rhyolites, tuffs and andesites, up to depths of 200 m. In San Marcos, lake sediments and volcanoclastics make a thick cover of some 750 m. This is underlain by a sequence of andesites, tuffs, basaltic-andesites and riodacites with a thickness of about 1000 m. The San Marcos SM-1 well bottomed in an arkosic sandstone unit at a depth of 1950 m.

Allan (1985) reported a local gravity survey in the northern portion of the Colima Graben. He interpreted a 20 mgal anomaly relative to the flanks of the graben, in terms of a sediment thickness of about 900 m. From the relief, the vertical fault offset is about 2.5 km. A K-Ar date from the capping horizontal lava flows on the flanking scarp of 4.5 Ma provides an estimate of the maximum tectonic subsidence rate (Allan, 1985), of some 0.5 km/Ma, i. e. rapid subsidence over the past 4.5 Ma.

5. CONCLUSIONS

Crustal thickness in western Mexico increases from the Pacific ocean margin towards the continental interior, with thicker crust in the order of 40-46 km beneath the plateaus of the TMVB and SMO. The entire region appears to be under regional isostatic equilibrium, with some short-wavelength local departures in the TMVB and SMO.

Gravity models do not support previous interpretations which consider the Guerrero terrane as a Mesozoic island-

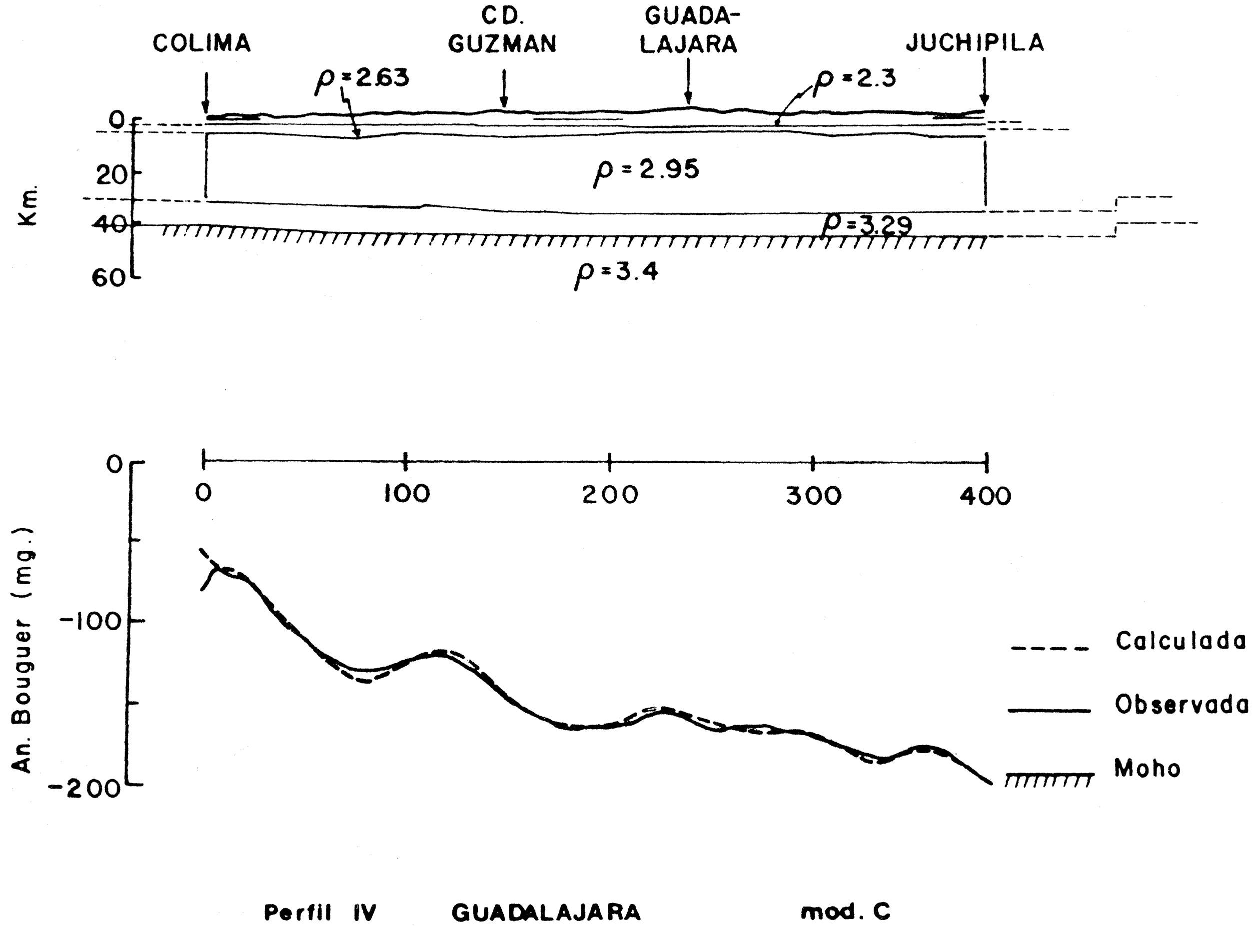

Fig. 10. Gravity model C for Colima-Juchipila profile. See text for details. Compare with Figs. 8 and 9.

arc assemblage constructed over oceanic lithosphere 'sensu stricto' accreted during the Laramide orogeny (e.g. Campa and Coney, 1983). Instead, a crust of continental or transitional character, with rather thick lower crust of metamorphic and/or igneous nature, is suggested. The lower crust may contain granulites and gabbroic intrusions. The lowermost crustal layer may be composed of crystallized mafic liquids, cumulates and/or residues from removal of a partial melt, and garnet-rich metasediments (Roberts and Ruiz, 1989). An alternative interpretation might consist of a relatively old and thick oceanic lithosphere that has been subsequently thickened by the emplacement of island arc magmatism and tectonic processes.

In any event, it seems difficult to accept an homogeneous oceanic lithosphere 'lower crust' for the entire Guerrero terrane. The composite nature of the terrane recognized earlier (Campa and Coney, 1983) clearly precludes large-scale generalizations for the lower crust. The ignimbritic volcanism of the Sierra Madre Occidental, where large-scale involvement of the continental lower crust should have occurred, points to a continental crust for a significant part of the terrane. The evidence for an oceanic basement in other areas, with closure of a marine basin, discussed for the eastern sector of the Guerrero terrane, also suggests the composite nature of the terrane (e.g. Campa and Coney, 1983; Urrutia-Fucugauchi and Valencio, 1986; Tolson, in press).

Our two-dimensional preliminary crustal models are compatible with a low to intermediate density layer at the base of the crust, which has been proposed as responsible for the uplift of the volcanic capped plateaus (Fix, 1975; Urrutia-Fucugauchi, 1978, 1982). Geotherms constructed from travel time analysis of surface Raleigh and Love waves for central Mexico suggest a high thermal regime, with partial molten material at the base of the crust (see also Gomberg *et al.*, 1988). If these interpretations are correct, a simple efficient mechanism for close-to-trench volcanic activity and regional plateau uplift would incorporate a high thermal regime associated with low angle, very rapid subduction of a young buoyant and hot lithospheric plate.

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