Shallow crustal structure of the junction of the grabens of Chapala, Tepic-Zacoalco and Colima, Mexico

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RESUMEN

Con base en un estudio gravimétrico se ha inferido la estructura cortical del graben de Tepic, en su área adyacente a la ciudad de Guadalajara. Esta depresión, delimitada al norte por la Sierra Madre Occidental y al sur por las sierras graníticas del Bloque de Jalisco, no constituye un graben simétrico con fallas maestras bien definidas, sino más bien una zona de transición compleja. Bloques disgregados de las sierras graníticas están afallados y basculados hacia el noreste a lo largo del frente de estas sierras. Estos bloques forman una depresión tipo semigraben casi continua al pie del batolito levantado. Más al norte, el basamento granítico profundiza gradualmente. Sin embargo, profundiza abruptamente en lo que es interpretado como el límite entre la Sierra Madre Occidental y el Bloque de Jalisco. En la porción noroeste de nuestra zona en estudio, el límite se encuentra un poco al norte de la falla Plan de Barrancas. En la porción este de nuestra zona de estudio, el límite se localiza más próximo a la prolongación sur de la falla Plan de Barrancas (cerca de la Cadena Volcánica del Sur de Guadalajara). El cambio en posición ocurre cerca de la caldera de La Primavera. La caldera de La Primavera, el volcán Tequila y los conductos de erupción de conos de lava y de ceniza están emplazados a lo largo de zonas de debilidad NW-SE que afectan a la corteza batolítica o al contacto difuso imbricado entre estos dominios regionales. La corteza de la Sierra Madre Occidental adyacente al límite está caracterizada por lineamientos NE-SW perpendiculares a aquellos del vecino Bloque de Jalisco.

PALABRAS CLAVE: Sierra Madre Occidental, Bloque de Jalisco, límite, estructura cortical somera, punto triple, graben de Tepic.

ABSTRACT

Gravity data is used to infer the shallow crustal structure of the Tepic graben adjacent to the City of Guadalajara. This depression does not constitute a symmetric graben with steep master faults but rather a complex transition zone. Blocks detached from the granitic sierras are downfaulted and tilted to the northeast along the front of these sierras. Farther to the north, the granitic basement deepens gradually. However, it steepens at the limit between the Sierra Madre Occidental and the Jalisco Block. Northwest of our study area, the limit is located north of the Plan de Barrancas fault. At the east the limit is located closer to the southward prolongation of the Plan de Barrancas fault. The change in position occurs near La Primavera caldera. The La Primavera caldera, Tequila volcano, and vents of cinder and lava cones are emplaced along NW-SE weakness zones in the batholith. The crust of the Sierra Madre Occidental adjacent to the limit features NE-SW lineaments perpendicular to those of the neighbouring Jalisco Block (JB).

KEY WORDS: Sierra Madre Occidental, Jalisco Block, limit, shallow crustal structure, triple junction area, Tepic graben.

INTRODUCTION

In westernmost central Mexico the Sierra Madre Occidental (SMOc) and the Trans-Mexican Volcanic Belt (TMVB) intersect (Figure 1). The SMOc is a vast plateau, 1300 km in length, capped by an approximately 2-km volcanic section composed predominantly of Oligocene rhyolitic ignimbrites (tuffs and domes) and lesser amounts of lava flows and alkali basalts (McDowell and Clabaugh, 1979; Cameron *et al.*, 1980). The SMOc is related to subduction of the Farallon plate. The major volcanic activity of the SMOc occurred between 38 and 26 Ma and ejected a great abundance of ignimbrites (Ferrari *et al.*, 1994). Miocenic andesites can also be observed in a 500 m sequence forming the walls of the Cañon del Río Grande de Santiago (CRGS) (Rosas-Elguera *et al.*, 1997).

The TMVB extends E-W across central Mexico; it contains intermediate to silicic rocks of Recent to Late Oligocene age. Although the trend of the TMVB is not parallel to the
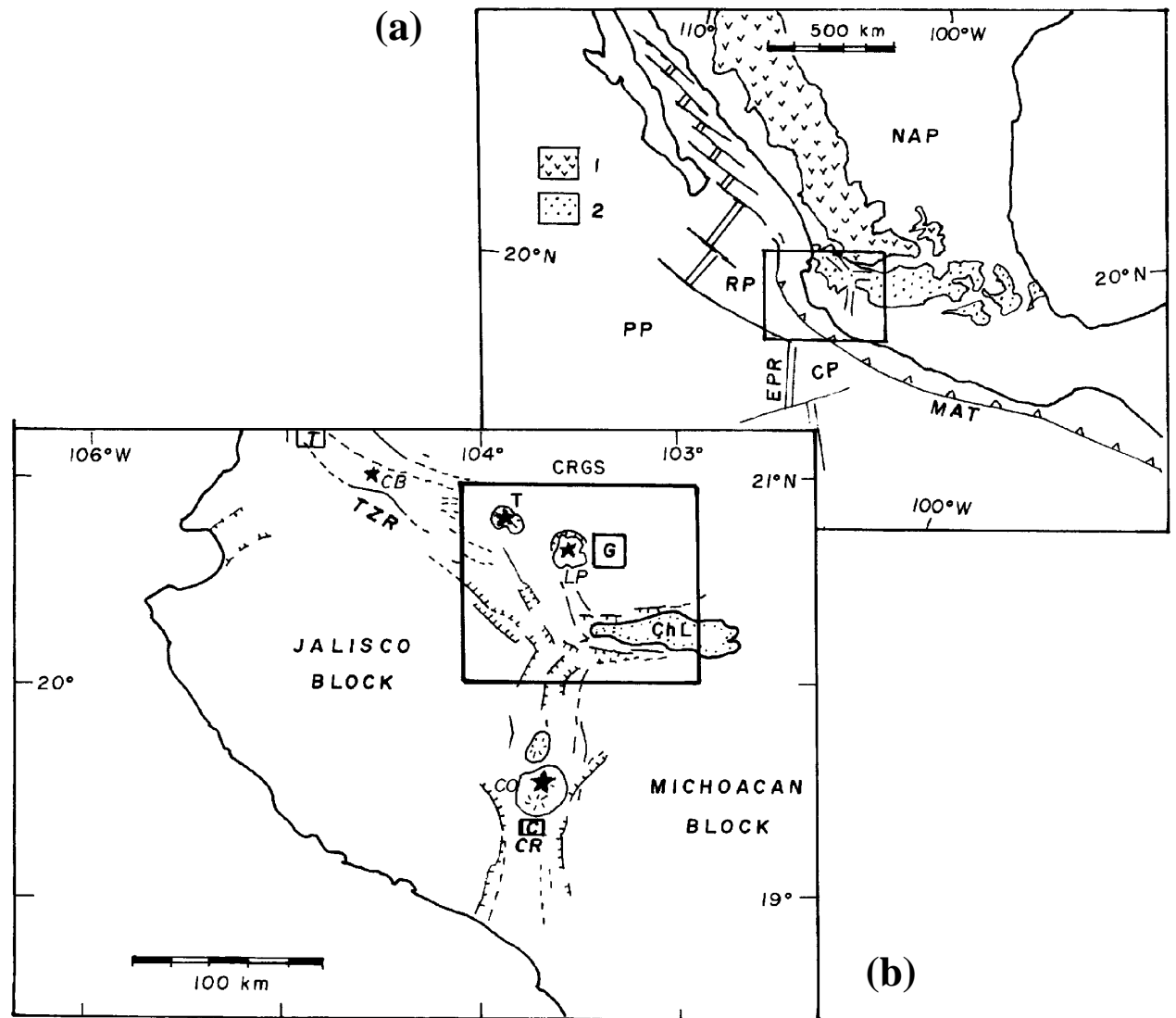
Fig. 1. a) Main physiographical provinces of central Mexico and the study area. NAP: North American Plate: PP: Pacific Plate; RP: Rivera Plate; CP: Cocos Plate; EPR: East Pacific Rise; MAT: Middle American Trench; 1: Sierra Madre Occidental; 2: Trans-Mexican Volcanic Belt; b) Simplified tectonic setting of the Jalisco Block and location of grabens. Open boxes represent main cities (G-Guadalajara, C-Colima, T-Tepic); closed stars represent main volcanoes (CO-Colima, LP-La Primavera Caldera, T-Tequila, CB-Ceboruco); ChL: Lake Chapala; CRGS: Canyon del Río Grande de Santiago; CR: Colima graben; TZR: Tepic-Zacoalco graben.

Middle America Trench, the origin of this volcanic province has been commonly related to subduction of the Cocos plate beneath the North American plate (Demant, 1978; Nixon, 1982). The limits between the SMOc and the neighbouring JB and Michoacán Block, covered by the products of the TMVB, were recently suggested to be located in the Tequila volcano area and at the northern limit of the Chapala rift (Rosas-Elguera *et al.,* 1997). Deep wells drilled at La Primavera and San Marcos geothermal areas cut the Mesozoic basement directly below the TMVB volcanics (Venegas *et al.,* 1985).

The controversy over the onset of volcanic activity in the TMVB may be resolved by new geologic mapping and isotopic age determinations. The new information indicates that an older andesitic sequence appearing at the CRGS and below the La Primavera silicic caldera could not be part of the SMOc volcanic sequences (Rosas-Elguera *et al*., 1997).

Various authors believe that between the SMOc and the TMVB there exists a different volcanic sequence of Miocene age. Because the chronological and structural characteristics of this volcanic sequence are different from those of

the SMOc and/or the TMVB, it is considered to be the sub-basement of either the TMVB or a proto-TMVB (e.g., Pasquarè and Zanchi, 1985; Venegas *et al.*, 1985; Pasquarè *et al.*, 1988).

According to the general distribution of fault systems, Pasquarè *et al.* (1986) subdivided the TMVB into three sectors: 1) a western sector, from the Pacific Ocean coast up to Guadalajara; 2) a central sector extending from Guadalajara to the Queretaro-Taxco fault system; and 3) an eastern sector extending from the Querétaro-Taxco fault system to the coast of the Gulf of Mexico.

The western sector of the TMVB is characterized by three long fault systems, with roughly N-S, E-W and NW-SE orientations, intersecting about 50 km SSW from Guadalajara City at a triple point (Demant, 1981). They roughly define three elongated depressions that have been called the Colima, Chapala and Tepic-Zacoalco grabens (Luhr *et al.*, 1985). It has been proposed that the Colima and Tepic-Zacoalco grabens bound an incipient microplate, the Jalisco Block, which is rifting away from the North America plate in response to an eastward jump of a segment of the East Pacific Rise (Luhr *et al.*, 1985; Allan *et al.*, 1991).

Studies in this area have established its volcanic evolution (e.g., Demant, 1979; Allan, 1986). Recent geodynamic models of the JB try to account for its origin and mechanism of deformation. The simpler models postulate a rigid microplate with right lateral movements at its northern boundary (Luhr *et al.*, 1985; Bourgois *et al.*, 1988; Barrier *et al.*, 1990; Allan *et al.*, 1991; Bourgois and Michaud, 1991; Garduño and Tibaldi, 1991) and active extension at its eastern border. These models imply that the separation of the JB from the North American plate occurs along the Colima and Tepic - Zacoalco rifts (Luhr *et al.*, 1985; Wallace *et al.*, 1992), that the motion of the JB is towards the west or the northwest, that pure normal faulting should occur in the Colima rift, and that a combination of normal and right-lateral faulting should occur in the Tepic-Zacoalco rift (Allan *et al.*, 1991; Bourgois and Michaud, 1991).

Other models include intraplate deformation due to plate boundary forces (Ferrari *et al.*, 1994), and a propagation of rifting southward from the triple junction area (Barrier *et al.*, 1990; Bandy, 1992; Delgado-Granados, 1993; Ferrari and Rosas-Elguera, 1995). Furthermore, it has been proposed that the oblique subduction of the Cocos plate induces an east-southeastward displacement of continental blocks of western Mexico (DeMets and Stein, 1990). Recent studies indicate that the Colima rift is a response to tensional stresses in the overriding plate induced by the subduction of the Rivera-Cocos plate boundary (Bandy *et al.*, 1995). Seismological studies (Eissler and McNally, 1984; Singh *et al.*, 1985;

Pardo and Suárez, 1993; Bandy *et al.*, 1997) suggest that subduction is still active along a considerable length of the Rivera subduction zone.

The JB has undergone recent internal deformation (Wallace *et al.*, 1992; Righter and Carmichael, 1992) produced by either a relocation of the subduction-related arc volcanism (Pardo and Suárez, 1993) or by trench-parallel extension due to a northwestward progressive increase in the obliquity of convergence between the Rivera and North American plates (Bandy, 1992). This deformation has given rise to several tectonic basins inside the JB, which contain young (< 6 my) alkaline lavas (Luhr *et al.*, 1989; Lang and Carmichael, 1990; Righter and Carmichael, 1992). These basins are bounded by normal and dextral strike slip faults. Palaeomagnetic data from Talpa and Mascota grabens do not show a significant northward motion for these grabens; however, recent local tilting may have occurred (Nieto-Obregon *et al.*, 1992; Maillol and Bandy, 1994; Maillol *et al.*, 1997). Note also that palaeomagnetic data for La Primavera caldera show no significant rotation or northern motion (Campos-Enríquez *et al.*, 1987; Urrutia-Fucugauchi *et al.*, 1988).

The continental boundaries of the JB remain to be established, although some recent works have attempted to define these frontiers. Rosas-Elguera *et al.* (1996), based on structural and aeromagnetic data, locate the boundary at the central part of the Tepic - Zacoalco rift, and at the western limit of the Colima rift. Most recently, Rosas-Elguera *et al.* (1997) suggested that the northern boundary of the JB, near Guadalajara, is located at the Tequila volcano area and is prolonged in a NW-SE orientation along the volcanic chain south of Guadalajara.

Few studies report results about the deep or shallow crustal structure. Some exceptions are Allan (1985) (shallow structure across northernmost Colima graben), Serpa *et al.* (1992) (shallow structure of southern Colima graben), and Bandy *et al.* (1993, 1995) (deep structure of southern portion of Colima graben, including a simple shear evolution model). Campos-Enríquez *et al.* (1990) discussed the regional shallow crustal structure of western TMVB. Urrutia-Fucugauchi and Molina-Garza (1992) infer the crustal structure of southern Colima graben. Michaud *et al.* (1994) based on processing of SPOT-DEM images of an area located north of central Colima proposed the development of the Zacoalco graben in association with a detachment fault dipping to the NE.

The crustal structure surrounding the triple junction is not known. Alatorre-Zamora and Campos-Enríquez (1991) and Yokoyama and Mena (1991) establish the crustal structure of La Primavera caldera. Campos-Enríquez (1986) and Alatorre-Zamora and Campos-Enríquez (1991) infer the ex-

istence of a regional NW-SE lineament that crosses the La Primavera caldera. This lineament belongs to the Tepic-Za-coalco system. Further study of the crustal structure of this area is needed to understand the relationship between the SMOc and the TMVB, as well as the evolution of the Tepic-Zacoalco graben, and to define the northern limit of the JB.

In this work we infer the shallow crustal structure of the area using gravity data. We propose the limits between the SMOc and JB.

GEOLOGY AND TECTONIC SETTING

Location

The study area lies roughly between 20º 25' N and 21º N and between 103º 50' W and 102º 40' W (Figure 1). It is located at the northern boundary of the Jalisco Block and it comprises the triple junction formed by the Tepic-Zacoalco, Chapala and Colima grabens. The study area is bounded, to the north and east by the CRGS; to the west, northwest and southwest by the Tequila volcano and the Sierra de Tapalpa; and to the south by Lake Chapala.

REGIONAL GEOLOGIC FRAMEWORK

In the study area we find rocks from the SMOc, the TMVB, and the Jalisco Block (i.e., the Sierra Madre del Sur; SMS).

The study area is covered mainly by Tertiary and Quaternary igneous rocks (Figure 2). The basement of the Neogene volcanic rocks is constituted by plutonic and Cretaceous marine rocks that build up the SMS and constitute most of the JB. The plutonic rocks are exposed at Sierra de Tapalpa and Sierra Ameca located in the southwestern and western central parts of the study area; whereas the limestones main-
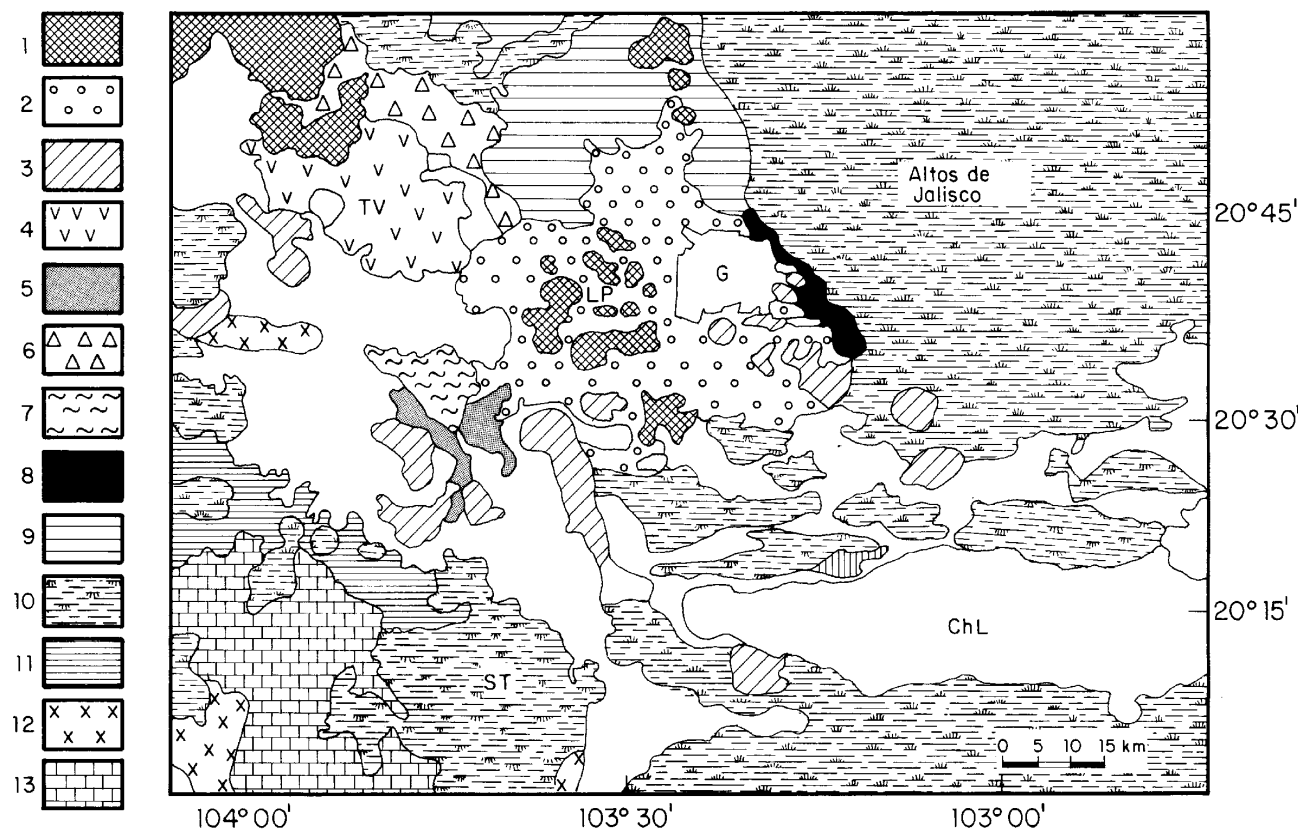

Fig. 2. Geology of the study area and surroundings. 1) Rhyolitic domes of La Primavera caldera (LP) and Quaternary silicic domes; 2) Pyroclastic deposits of La Primavera caldera (LP); 3) Quaternary lava and cinder cones; 4) Tequila volcano (TV) late Pleistocene andesites; 5) Acatlan ignimbrites (middle Pleistocene); 6) Santa Rosa basalts; 7) Ash flow tuffs; 8) Basalts; 9) Silicic domes and pyroclastics; 10) Pliocenic andesites and basaltic andesites; 11) Cretacic rhyolites; 12) Cretacic intrusive rocks; 13) Limestones and sandstone. G: Guadalajara; TV: Tequila volcano; ChL Chapala Lake; ST: Sierra de Tapalpa.

ly crop out in the central Sierra de Tapalpa. In the Sierra Ameca a horst structure of Cretaceous granitic rock rises to 2600 m a.s.l. This horst is bounded toward the south by the 34 km long normal Ameca fault. The motion along this 80° to 110° oriented fault is dominantly strip-slip with a small right-lateral component (Rosas-Elguera *et al*., 1997). Drill-holes by the Federal Commission of Electricity (Comisión Federal de Electricidad) at La Primavera and San Marcos bottom out in granitic and arkosic rocks (Venegas *et al*., 1985).

Tertiary rocks belonging to the SMOc outcrop north of the area. According to new radiometric data, the southernmost outcrop occurs at the bottom of the CRGS in Santa Rosa area (Rosas-Elguera *et al.*, 1997). They are rhyolitic ignimbrites of Oligocene age. For our gravity study, it is important to emphasize the existence in the study area of large quantities of low density volcanic silicic rocks.

Miocene rhyolitic rocks crop out towards the northern zone of the study area and at Sierra de Tapalpa. They comprise rhyolitic flows, tuffs and breccias. Miocenic andesites are also distributed to the south of the study area.

In the study area the most common outcrops are Plio-Quaternary basaltic-andesitic rocks of the TMVB, including basaltic breccias and basaltic andesites exposed toward the northeastern part of the CRGS (Figure 2). These rocks also border the Chapala graben and form the eastern segment of Sierra de Tapalpa. The more recent rocks are represented by Quaternary pyroclastic flows and rhyolitic tuffs of the Guadalajara urban and La Primavera suburban areas, and the recent alluvial and lacustrine deposits filling the geomorphic and tectonic depressions.

The TMVB volcanism in this region began with large basaltic emissions that gave rise to "mesas" (e.g., Mesa de Santa Rosa; Figures 2 and 3) of late Pliocene to Pleistocene age (Demant, 1979). Based on the northward tilt of this plateau, Demant (1979) inferred its origin to lie in a sector now covered by the Tequila volcano. Its origin could be a small volcanic center or a fissure (Demant, 1979).

The Tequila volcano is a prominent cone with a height of 1300 m, open on its northeast side. Large volumes of volcanic rocks were emplaced from Pliocene to Recent times along NW-SE lineaments. At the southern flank of the Tequila volcano there exists a series of vents of cinder and lava cones aligned in a NW-SE direction which have emitted andesitic lavas.

One of the main volcanic structures located in the center of the study area is the caldera complex of La Primavera.

It is of a comenditic composition, and is aligned with the Tequila volcano and with the cinder and lava cones. The Guadalajara plains is limited to the north by ignimbritic relief of the CRGS, and to the south by andesitic cones which are aligned NW-SE along the southern Guadalajara volcanic chain system. In this plain we find dacitic and rhyolitic domes of Plio-Quaternary age that belong to the TMVB (Rosas-Elguera *et al*., 1997).

South of La Primavera, there are also silicic domes, cinder cones and ignimbrites of Quaternary age (Rosas-Elguera *et al*., 1997), cut probably by N30°W vertical faults (Demant, 1979). There is basaltic-andesitic volcanism, particularly north of Lake Chapala where a sequence of volcanic cones show an E-W orientation.

TECTONIC EVOLUTION OF THE TRIPLE JUNCTION AREA

Recent field studies of the triple junction area suggest that the three grabens developed at different times, beginning in the late Miocene (Barrier *et al*., 1990; Michaud *et al*., 1991, 1992). The E-W Chapala graben formed between late Miocene and early Pliocene (Delgado, 1992) along N90°E lineaments originally left-lateral and subsequently normal (Garduño-Monroy *et al.*, 1993). At present the extension seems to be active 20 km to the south, at the Citala graben (Garduño and Tibaldi, 1991). Urrutia-Fucugauchi and Rosas-Elguera (1994) report a counterclockwise rotation of the Chapala graben. The tectonic control of the volcano-sedimentary sequence was recently re-appraised by Rosas-Elguera and Urrutia-Fucugauchi (submitted).

In the northern part, the Colima rifting started in early Pliocene (Allan, 1986). Suárez *et al*. (1991) found it to be active today . This is supported by absence of alluvial piedmont deposits and by the frequent rupture of the Guadalajara-Colima highway where it crosses a normal fault as observed by us during a field trip. The Tepic-Zacoalco graben is either a broad graben or rift (Demant, 1981; Luhr *et al*., 1985) or a combination of extensional and rigth-lateral strike-slip structures (Barrier *et al*., 1990; Allan *et al*., 1991). Recently, Rosas-Elguera *et al*. (1997) proposed its southern sector to be a half-graben.

Since the late Miocene no major strike-slip deformation has occurred along the northern boundary of the JB (Ferrari *et al*., 1994). The Quaternary extension, and thus the possible displacement of the JB, is trenchward (southwestward). Thus, the rifting in western Mexico could be explained by the subduction of the Rivera plate (Ferrari *et al*., 1994).

GRAVITY DATA

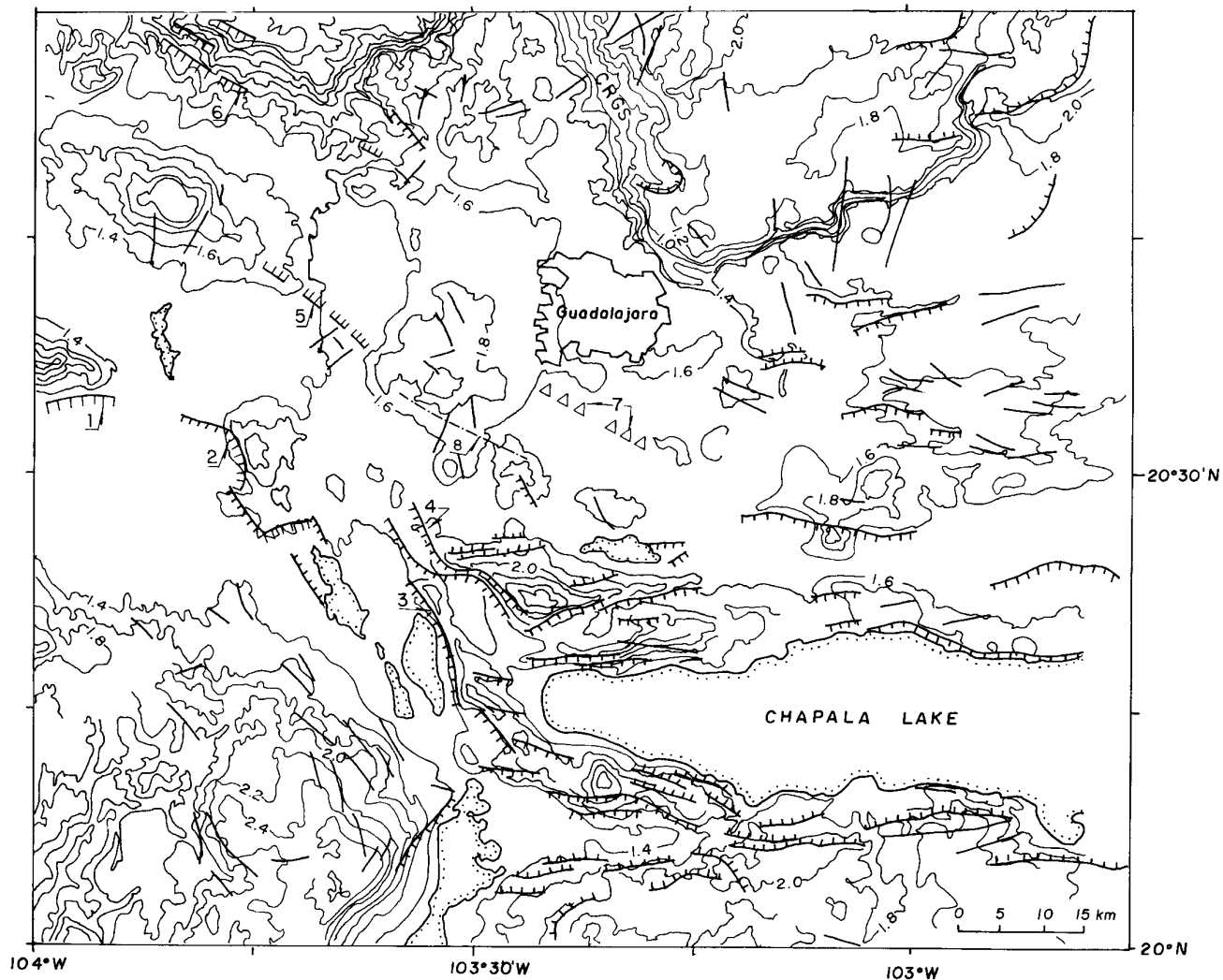The gravity data were obtained during a cooperative

Fig. 3. Topography and structural setting of the study area. Contours are given in km. Main normal faults are indicated by continuous hatchured lines. 1: Ameca fault; 2: Ahuisculco fault; 3: San Marcos fault; 4: Bola de Viejo fault; 5: southward prolongation of Plan de Barrancas fault; 6: Santa Rosa fault; 7: southern Guadalajara volcanic chain system; 8: fault inferred by Alatorre-Zamora and Campos-Enríquez (1991).

geophysical study sponsored by the Japanese International Cooperation Agency (J.I.C.A.) and the Federal Commission of Electricity (Comisión Federal de Electricidad). The data consist of 462 measurements made with a Lacoste & Romberg type G gravimeter at intervals of 500 m, covering approximately 14 000 km^2. The data were corrected for tidal, terrain, Bouguer, latitude, altitude and free-air effects. Details of the processing are given in JICA (1986) and Alatorre-Zamora and Campos-Enríquez (1991).

The density values used for modeling were obtained from field samples. Density values from cores of deep drill-holes at La Primavera and San Marcos, and density values reported in the literature were also used in addition to our field data.

RESULTS

Bouguer gravity anomaly

Figure 4 shows the Bouguer anomaly and the location of the modeled profiles. At the western sector of the study area we observe an alignment of gravity highs trending first E-W and then NW-SE. These gravity highs are located above Mesozoic granitic rocks (see Figures 2 and 3 for geology) or above basaltic andesites. There are other major gravity highs associated with the Tequila volcano and with the Sierra de Tapalpa. The sierras, between lakes Cajititlan and Chapala (Figure 3), are also marked by gravity highs. Conspicuous gravity lows are associated with the grabens of Colima,

Fig. 4. Bouguer anomaly map. Location of the modeled profiles is given. Contour interval is 2 mGal. The city of Guadalajara, and main water bodies are indicated.

Chapala-Citala, Tepic-Zacoalco and Ameca, as well as with the caldera of La Primavera.

The gravity highs and lows are correlated with basement rocks, or with valleys and lacustrine areas.

RESIDUAL ANOMALY

A regional-residual separation was obtained by fitting a second-degree surface to the Bouguer anomaly data. The resulting residual field (Figure 5) presents a similar pattern to the Bouguer gravity anomaly (Figure 4). There are several gravity highs, mainly over the Sierra de Tapalpa, and some pronounced gravity lows bordering it. These gravity anomaly lows cover the lacustrine basins of the San Marcos-Zacoalco and Tepic grabens.

The gravity highs located over the ranges bordering the northern portion of Lake Chapala merge into a roughly E-W trending, broad anomaly. The gravity low associated with Lake Chapala turns into an E-W, broad low open to the south. The wide gravity low associated with La Primavera caldera is well resolved. Two gravity lows were also detected to the NNW and to the east of the La Primavera gravity low. A broader composite high is observed at the northern portion of the study area. Between the two major gravity highs located at the southwestern and eastern portions of our study area, the anomalies are arranged approximately in three belts. The first belt lies N and E of the gravity high associated with Sierra de Tapalpa. It includes three NW-SE trending gravity lows. To the south, this belt merges with the E-W broad, open gravity low associated with Lake Chapala. In this intersection zone we also observe N-S lineaments of the northern Colima graben (the Sayula graben). The presence of these three systems of regional gravity lineaments confirms the location of the triple junction area.

The second belt, located immediately to the north of the first belt, consists of a series of elongated gravity highs with a mean NW-SE orientation. South of La Primavera they become broader and exhibit an E-W orientation. The western branch of this belt is associated with ranges exposing
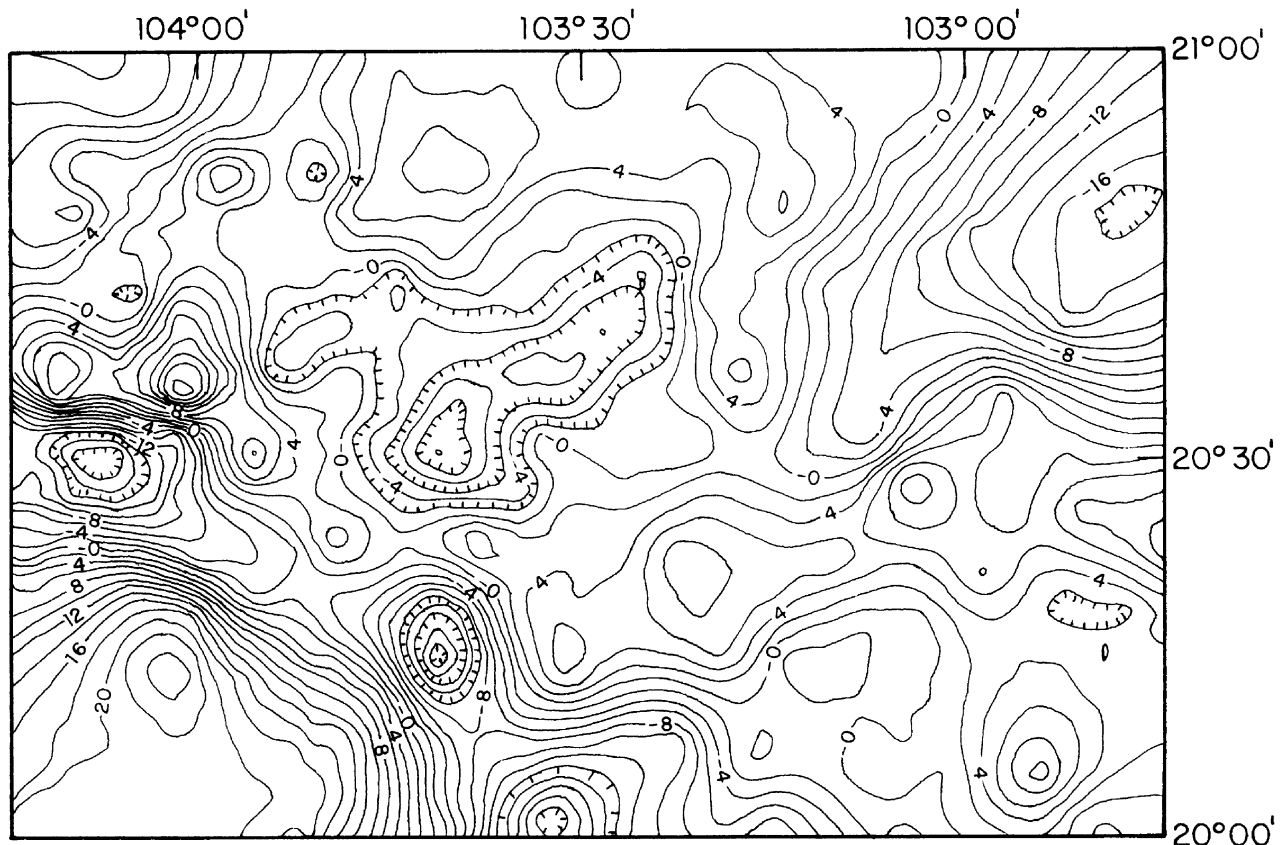
Fig. 5. Second order residual gravity anomaly of the study area. Contour interval is 2 mGal.

basement rocks (e.g., the granitic Sierra Ameca). The eastern branch is associated with sierras located between the lakes of Cajititlan and Chapala.

The third belt, located north of the second belt, consists of a minor gravity low and two major composite gravity lows forming a broad, more or less continuous series of gravity lows. North of the study area lies a broad major composite gravity high associated with the region of the Altos de Jalisco and the SMOc.

In the southwestern quarter of the study area the anomalies present a clear NW-SE trend. The orientations are mainly E-W at the southeastern portion. In contrast, lineaments with a NE-SW orientation can be observed in the northeastern portion of the study area.

The presence of a belt of gravity highs between two belts of gravity lows implies that the structure of the depression between the Sierra de Tapalpa and the SMOc is not a symmetrical graben. The belt of gravity lows associated with the lacustrine basins of Ameca, San Marcos and Zacoalco

features steep gravity gradients resulting from the sharp contacts between the sedimentary infill of the basins and the basement. North-northeast of the intra-basin gravity high the gradients are gentler. In its central portion, the third belt of anomalies is featured by a broad gravity low associated with the La Primavera caldera. Tectonically this is a very complex area. Campos-Enríquez (1986), based on aeromagnetic data, inferred a NW-SE fault cutting through the La Primavera caldera. This fault joins a regional NW-SE structure running from the Tequila volcano to La Primavera caldera. Southeast of the caldera eight small Plio-Pleistocene lava and cinder cones (the southern Guadalajara volcanic chain system) are also aligned in a northwest-southeast orientation.

The belt of gravity highs divides the regional depression into two minor depressions, the northern one being wider and irregular. The contact of this second, broad, depression with the SMOc is not as clear as between the Ameca-San Marcos-Zacoalco depression and the Sierra de Tapalpa. We can infer some imbrication between the SMOc and the nearby depression.

In conclusion, the depression of the Tepic graben in

the Ameca-San Marcos-Zacoalco segment is bounded to the southwest by the Sierra de Tapalpa, and by the SMOc to the northeast. The structure of this depression features major tilted basement blocks forming two half-grabens. The contact between these two half-grabens corresponds to the intra-basin gravity highs, which represents the structural high of a southward tilted block detached from the Sierra de Tapalpa. The contact of the southern half-graben with the Sierra de Tapalpa is well defined, but the contact of the northern half-graben with the SMOc is less clear. The imbricated contact of the SMOc with the JB lies in the second half-graben. This is a suture zone with faults affecting large portions of the crust. La Primavera caldera, the Tequila volcano, and several others cinder and lava cones were emplaced along such crustal weakness zones.

VERTICAL DERIVATIVES AND UPWARD CONTINUATIONS

The first and second vertical derivatives of the residual anomaly enable us to enhance the limits between the sources of anomalies and to delineate the gravity belts.

The half-graben of Ameca stands out conspicuously in the first vertical derivative map (Figure 6). We observe several gravity lows associated with La Primavera caldera minimum. Some lineaments correspond perfectly to large mapped faults, e.g., the Ameca, Ahuisculco, San Marcos, and Bola de Viejo faults (Figure 3). There are NE-SW lineaments near the SW part of La Primavera caldera, that corresponds to surficial structures inferred previously by Campos-Enríquez (1986) and Alatorre-Zamora and Campos-Enríquez (1991).

In the SW portion of the study area, NE-SW lineaments seems to divide the Sierra de Tapalpa near its western border with the Sierra de Quila.

The upward continuation similarly helps to delineate the belts of gravity anomalies (Figure 7).

SHALLOW CRUSTAL STRUCTURE

We modeled 10 profiles across the most important anomalies (Figure 4). The profiles satisfy common requirements of orthogonality over bi-dimensional anomalies (Figures 4, 5, 6 and 7). A first-order regional was computed
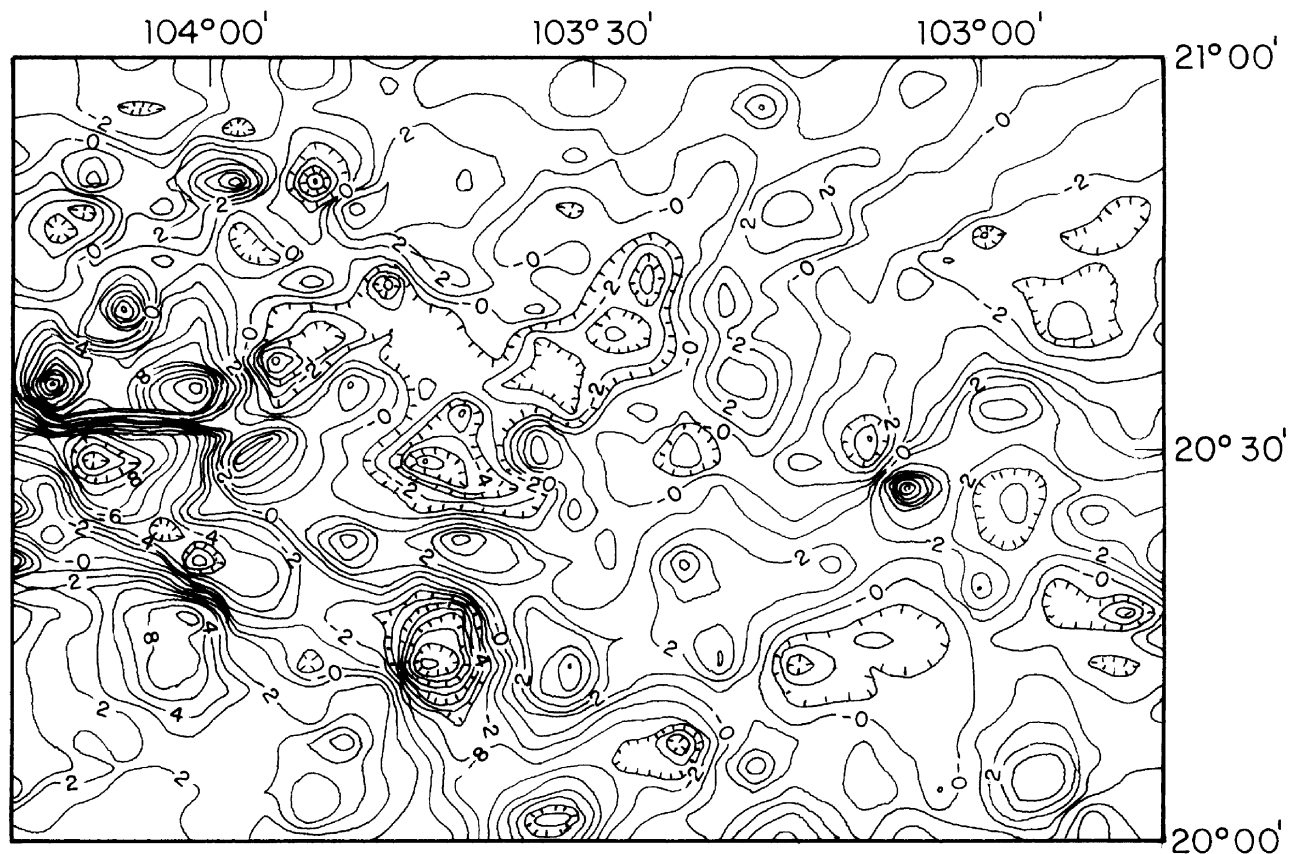

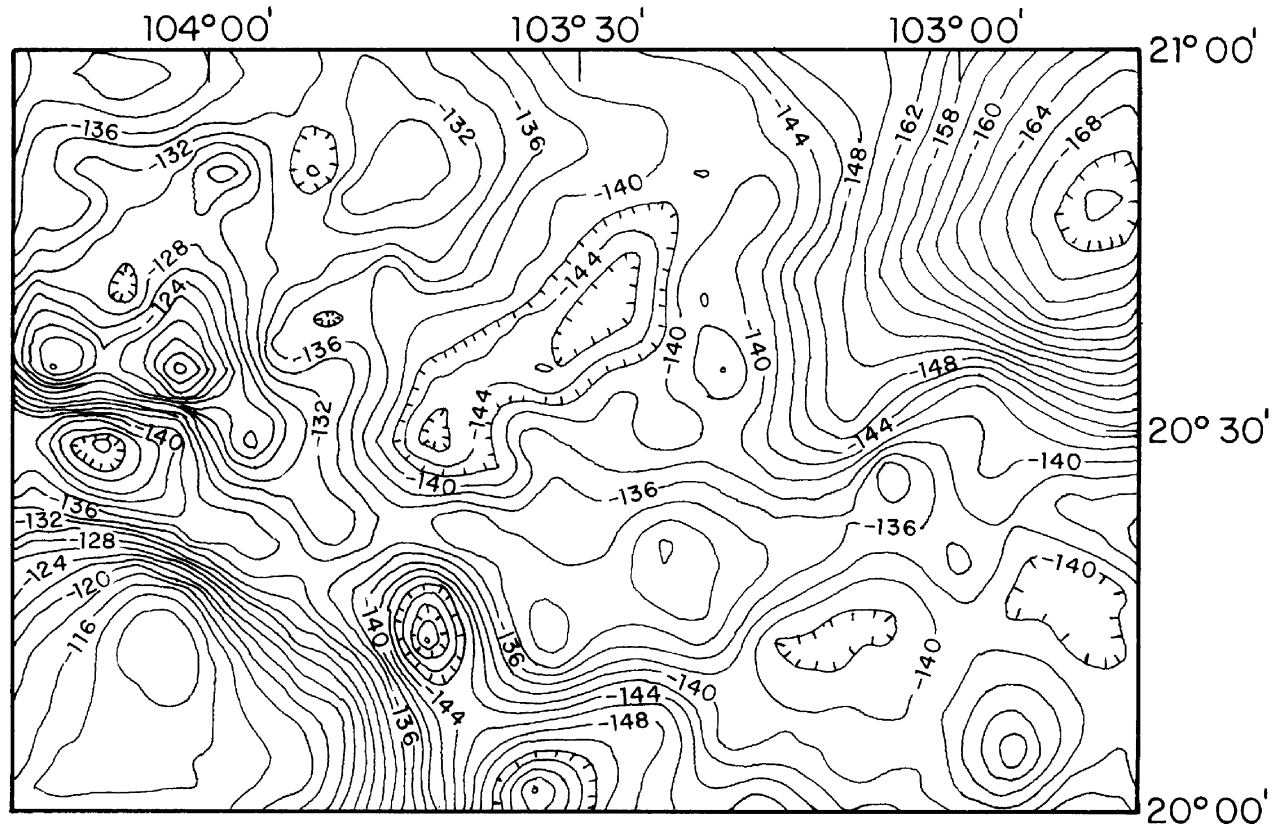Fig. 6. First vertical derivative of the residual anomaly. Contour interval is 2 mGal/km.

Fig. 7. Upward continuation to 250 m of the Bouguer anomaly. Contour interval is 2 mGal.

and substracted (not shown) from the Bouguer anomaly profiles to obtain the residual anomaly.

All profiles were modeled using the algorithm of Talwani (Talwani *et al.*, 1959). Information used to constrain the models was derived from surficial geology and density measurements as well as from available geological studies of the area (see Table 1). Studies by Demant (1979), Venegas *et al*. (1985), Garduño *et al*. (1993) and the geologic map by DETENAL (1975) were crucial for this purpose.

It was possible to obtain surficial samples, and to measure densities, in the Mesozoic granitic area of Sierra Ameca, between Ameca and Guadalajara cities, and in some other areas.

A description of the interpreted profiles follows:

a) Profile A-A' (Figure 8a) has a length of 55 km. It is oriented with an azimuth of 10º, from Sierra de Quila (northwestern continuation of Sierra de Tapalpa), through the Ameca lacustrine valley, through Sierra Ameca, and up to the Tequila volcano. The basement is granitic, and is shallower at the Sierra de Quila and Sierra de Tapalpa. Ac-

cording to the gravity model, the lacustrine valley of Ameca is an asymmetric basin (half-graben). To the south, this half-graben is delimited from the Sierra de Quila by a gently dipping fault. The northern limit corresponds to the relatively steeper Ameca fault. The depocenter is located closer to the Ameca fault.

b) Profile B-B' (Figure 8b) has a length of 52 km and an azimuth of 20º. It runs from the Sierra de Tapalpa, across the Ahuisculco fault and the Sierra de Ahuisculco, up to the Tala Valley west of La Primavera caldera. According to the gravity model, the granitic basement is shallower under Sierra de Tapalpa and under Sierra de Ahuisculco. Here the granitic basement is covered by about 600 m of tuffs. Between these points the basement constitutes a slightly asymmetric basin. However, the basin here has an opposite polarity; the depocenter is located at the foot of Sierra de Tapalpa. Clearly, the fault delimiting this basin from the Sierra de Tapalpa is steeper in relation to the Ahuisculco fault (northern limit).

c) Profile C-C' (Figure 8c) runs from Sierra de Tapalpa up to the south of La Primavera caldera with an azimuth of 60º. It has a length of 55 km. According to the model, the gra-
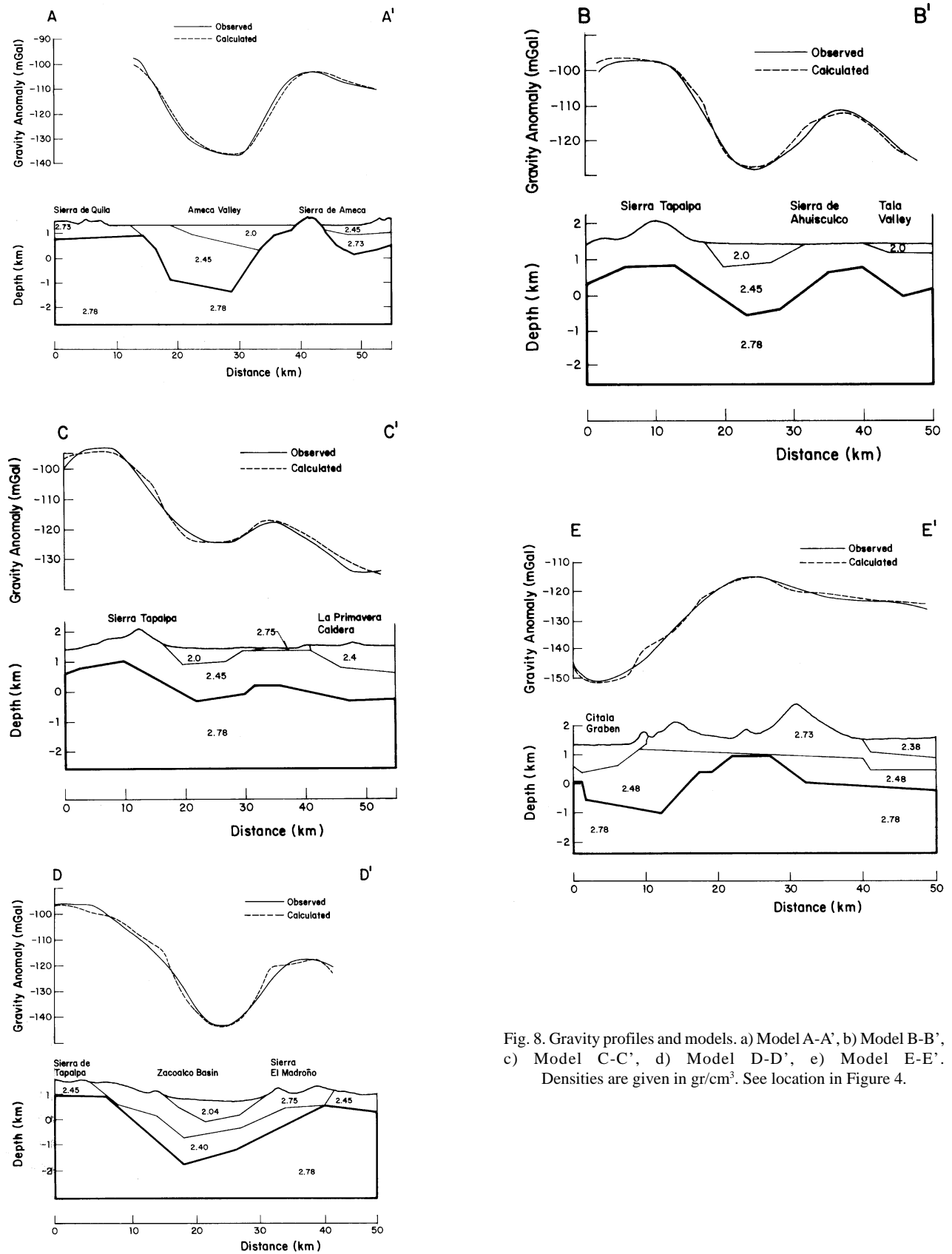
Fig. 8. Gravity profiles and models. a) Model A-A', b) Model B-B', c) Model C-C', d) Model D-D', e) Model E-E'. Densities are given in gr/cm³. See location in Figure 4.

Table 1

Core and field sample density values used in this study

Rock-type	Density (gr/cm³)
Limestone[5]	1.93 - 2.90
Sand-Lime-Clay[1]	1.44
Andesite[2]	2.746
Tala tuff[3]	2.165
Tuff[3]	2.21
Vitreous Rhyolite[3]	2.06
Diabase[1]	2.965
Diabase[2]	2.746
Granodiorite[2]	2.671
Granodiorite[2]	2.594
Granite[1]	2.667
Granite[2]	2.733
Rhyolite[4]	2.51

[1] Dobrin (1960)   [4] Ward (1990)
[2] This study   [5] Telford *et al*. (1990)
[3] JICA (1986)

nitic rocks are covered by about 500 m of tuffs at Sierra de Tapalpa. The basement deepens under the Tala - Ameca basin (about 1500 m). It is relatively shallow (about 1000 m) immediately to the north. Further to the north it deepens smoothly. Under the valley of Tala - Ameca the basement constitutes a more symmetric basin. The depocenter remains closer to the Sierra de Tapalpa. The eastern segment of the Ahuisculco fault (northern limit) has an intermediate to sub-horizontal dip. The fault separating the basin from the Sierra de Tapalpa is relatively steep.

d) Profile D-D' (Figure 8d) has a length of 50 km and crosses the Zacoalco basin at an azimuth of 50°. It runs parallel to the western limit of the Chapala graben, and ends to the SE of La Primavera caldera. According to the gravity model, the granitic rocks approach the surface at both ends, 500 m below the surface approximately. The southwestern end corresponds to the Sierra de Tapalpa. Here the granite is capped by about 500 m of basalts. The northeastern end is located in the westward portion of Sierra el Madroño constituted of basalts, where it crosses the Bola de Viejo fault. The basement granitic rocks form a slightly asymmetric basin, filled with up to 700 m of limestones, basalts, and lacustrine sediments. To the south, the basin is delimited by a slightly steeper fault. The depocenter is slightly offset to the south of the basin axis. To the north, the basin is bounded by the western part of the San Marcos fault, which presents an intermediate dip. Further to

the north, the Bola de Viejo fault appears as a gently dipping fault of a listric nature that intersects at depth its conjugate antithetic fault. Finally, in the northernmost portion of the profile the basement deepens beneath Guadalajara City.

e) Profile E-E' (Figure 8e) has a length of 50 km and a N9°E trend. In its southern portion it crosses the Citala graben, and it runs parallel to the western limit of the Chapala graben. It crosses the Bola de Viejo fault and ends to the SE of La Primavera caldera. According to the gravity model, the Citala graben in this sector corresponds to a half-graben. The basement is shallow under the volcanic ranges delimiting the southern boundary of the Lake Chapala. Finally, the basement deepens under the northern portion of this profile below Guadalajara.

f) Profile F-F' (Figure 9a) crosses the Guadalajara plain at an azimuth of 120° and has a length of 70 km. According to the gravity model the granitic basement is deeper than in the preceding profiles. It is located at a depth of 2000 m, with a depression beneath the Guadalajara metropolitan area. A sequence of basaltic-andesites and rhyolites overlies the basement. There are small basaltic bodies at the surface such as that located at the northwestern end of the profile. This basaltic body is 200 m thick and corresponds to the basaltic plateau of Mesa de Santa Rosa.

g) Profile G-G' (Figure 9b) has a length of 50 km. It is oriented with an azimuth of 110°, nearly parallel to profile F-F' to the south. It crosses the northern limit of the Guadalajara urban area. According to the gravity model the basement deepens gently toward its southeastern end. A gentle depression is also observed beneath the Guadalajara urban area.

h) Profile H-H' (Figure 9c) has a length of 65 km. It runs nearly parallel to the two former profiles with an azimuth of 70°. According to the gravity model, the granitic basement deepens toward the SE. The basement is covered with a 2000 m thick sequence of basaltic-andesites, rhyolites and two basaltic flows around Río Grande de Santiago and Río Verde. The depression present in the two former profiles beneath the Guadalajara metropolitan area is again observed.

The granitic basement in the last three profiles is deeper than in the first five profiles. The depression observed beneath the Guadalajara metropolitan area was independently inferred by Rosas-Elguera *et al*. (1997) based on geologic and borehole information. Here we establish its NE-SW orientation. The basement deepens towards the northeastern quarter of the study area, i.e., north of the Chapala graben. It
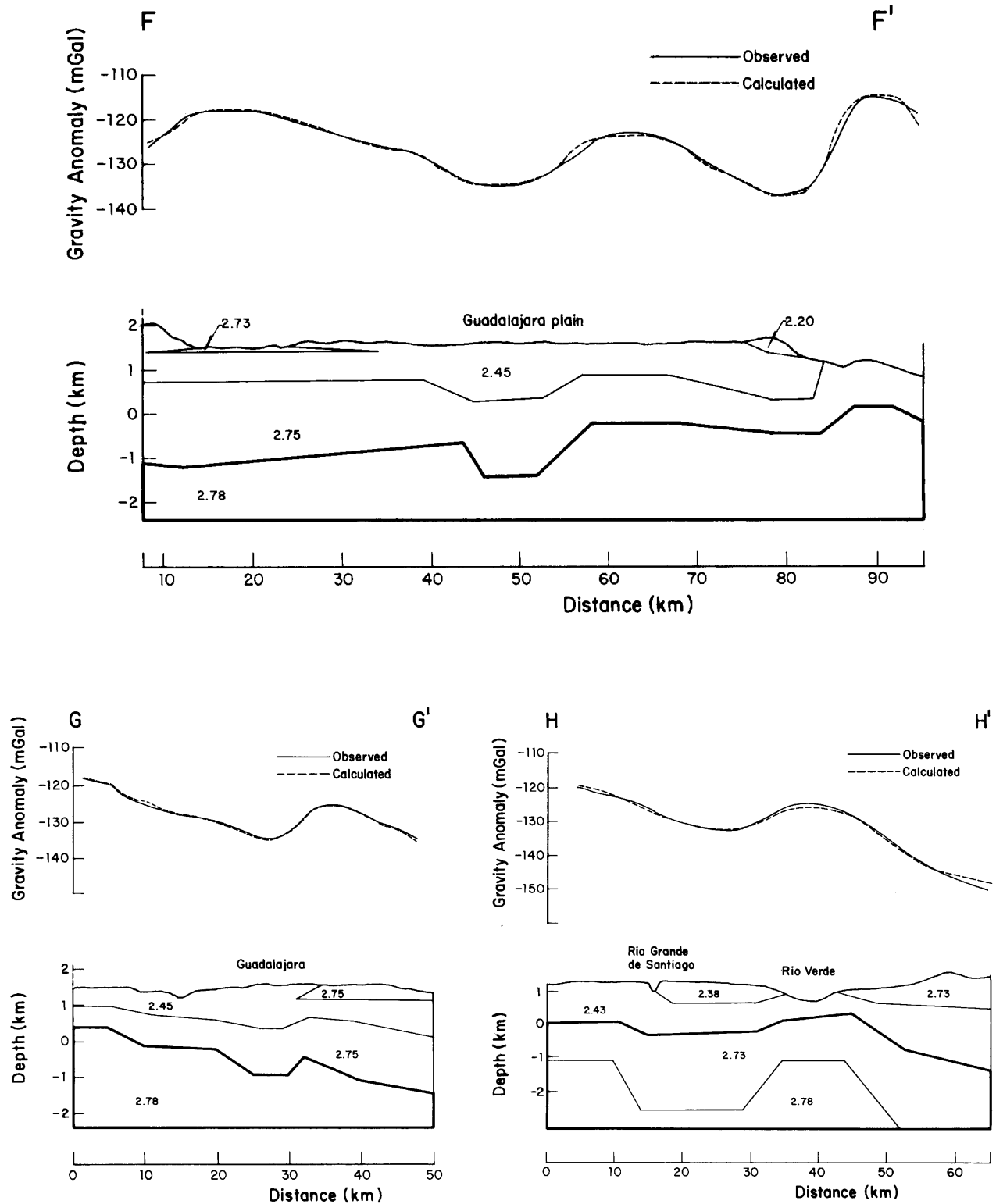
Fig. 9. Gravity profiles and models. a) Model F-F', b) Model G-G', c) Model H-H'. Density values are given in gr/cm³. See location profiles in Figure 4.

disappears below 4000 m in profile H-H'. We interpret this as the limit between the SMOc and the northeastern border of the Jalisco Block.

DISCUSSION

We observe different shallow-crustal-structure styles in the two groups of profiles. In the first group the granitic basement is relatively shallow. We note an almost continuous NW-

SE basin, asymmetric in places next to the Sierra de Tapalpa. This half-graben merges at the triple junction area with the half-graben of Citala and northern Colima graben (Figure 10).

The second group of profiles (Figure 11) is located near the boundary between the SMOc and the JB. In this area the trend of the gravity anomalies changes from NW-SE to N-S and NE-SW. The depression observed beneath the Guadalajara metropolitan area presents a NE-SW orientation, per-
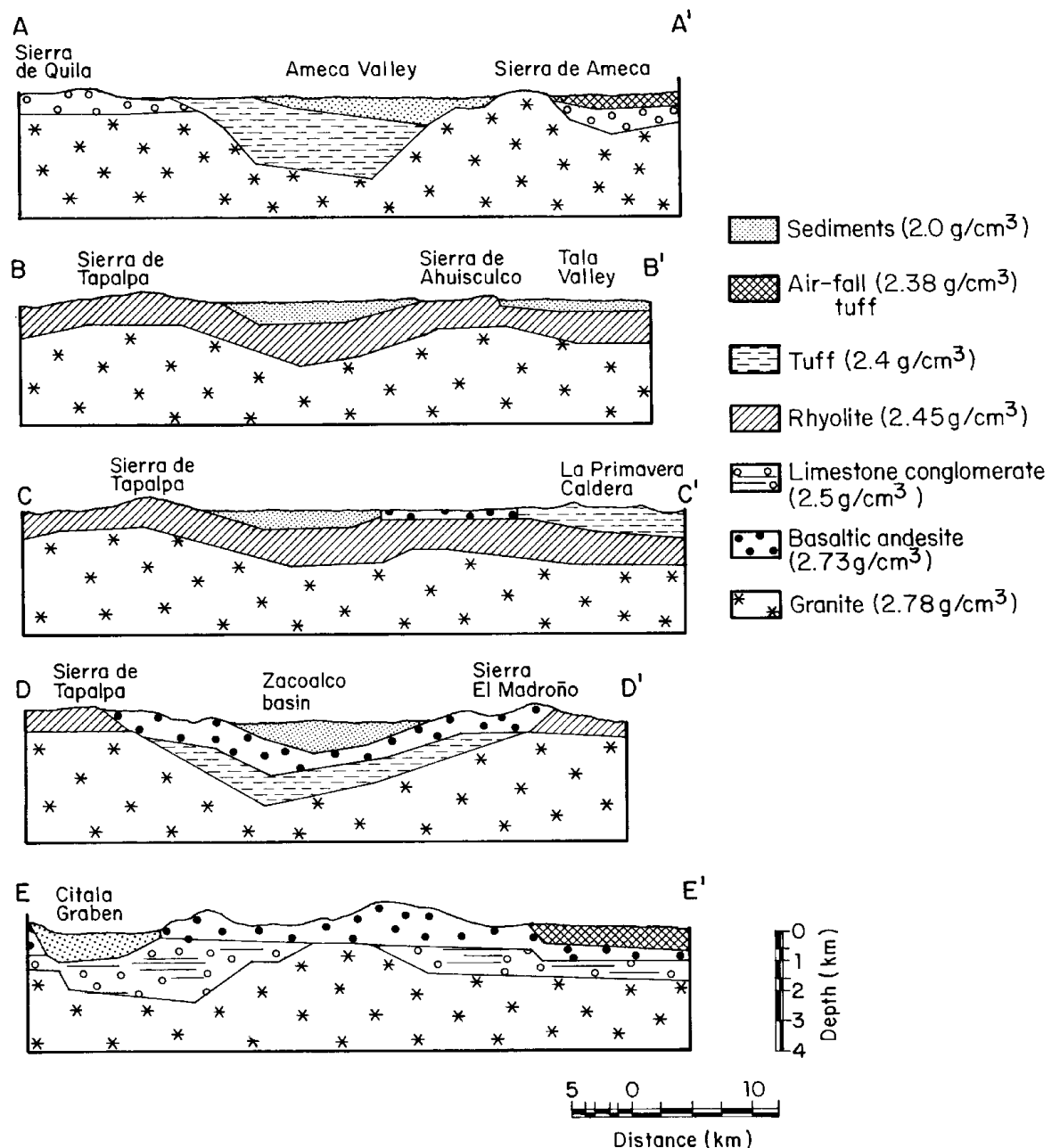

Fig. 10. The shallow crustal structure in the southern portion of the study area.
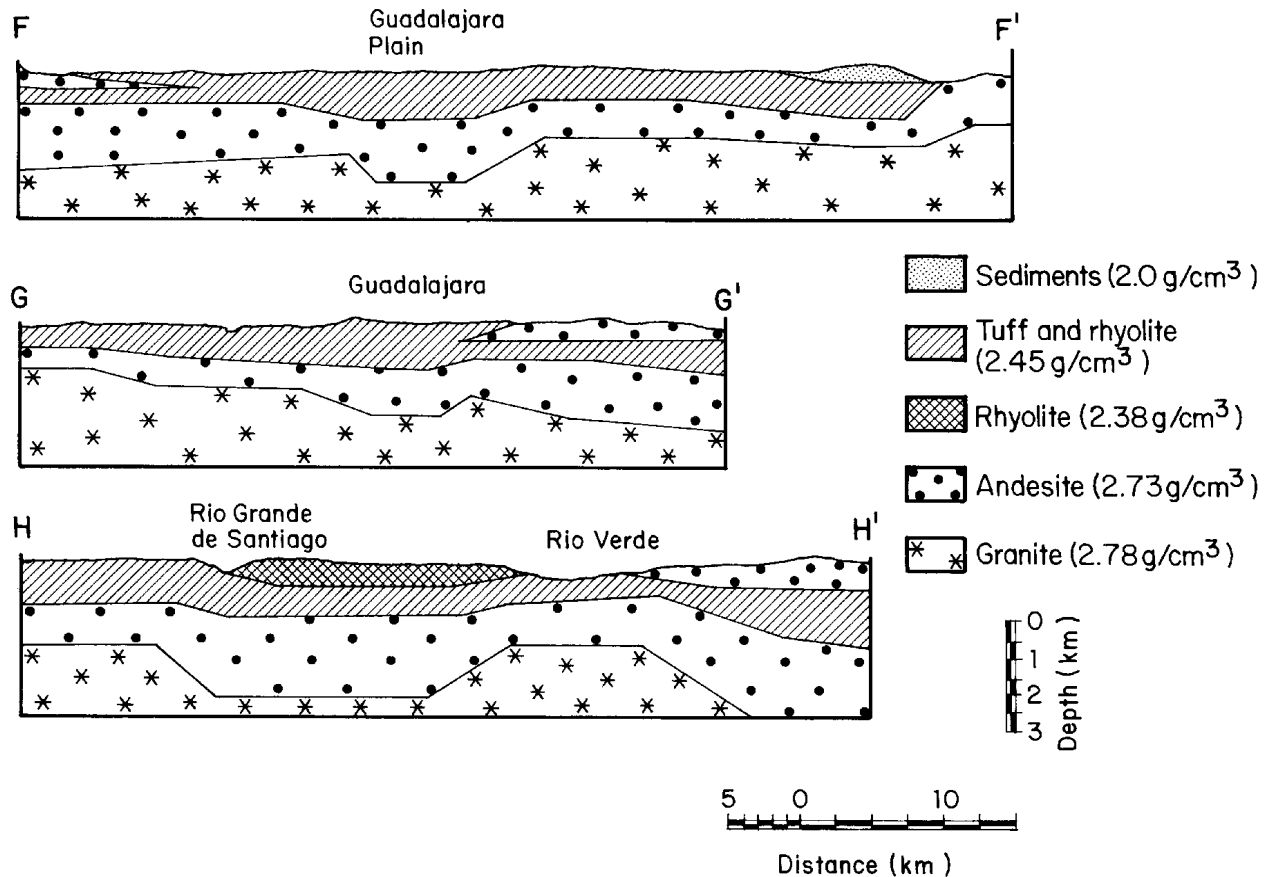
Fig. 11. The shallow crustal structure in the northern portion of the study area.

pendicular to the half-graben depression at the foot of Sierra de Tapalpa. Here the granitic basement deepens gently towards the N, and abruptly in the northeastern portion of the study area (Figure 12).

Figure 12 shows the basement deepening towards the N-NE. Along with the presence of the belts of gravity highs and lows and the regional geological and structural features in our study area, we propose a shallow crustal model in which the regional depression of the Tepic graben represents a complex transition zone between the SMOc and the JB. Granitic basement blocks from the Sierra de Tapalpa and Sierra de Quila are of batholitic nature. They are downfaulted and tilted in such a way as to form half-graben depressions beneath the San Marcos and Zacoalco lacustrine basins. These two depressions are somewhat shallower at their merging area, where the Zacoalco graben is conspicuously wider than the Ameca graben. This last feature may be due: 1) to differential movement between the granitic basement blocks from the Sierra de Tapalpa and Sierra de Quila underlying these two lacustrine basins, or 2) or to a NE-SW left lateral strike slip movement. The first interpretation is sup-

ported by tectonic studies showing pure extension for the study area since the upper Miocene. The structural highs of the tilted blocks constitute the granitic core of the belt of NW-SE ranges which crosses the Tepic graben. Northward of this belt of structural highs the granitic basement tends to deepen toward the NE, eventually disappearing in the northeastern portion of our study area.

The northern plain contains the volcanic complex of La Primavera caldera, the Tequila volcano, and other minor cinder cones. These volcanic edifices were emplaced along NW-SE lineaments.

In the northwestern sector of our study area, the limit between the SMOc and the JB corresponds with the Plan de Barrancas-Santa Rosa graben. North of the Santa Rosa fault we have SMOc basement, while south of the Plan de Barrancas fault we find JB basement. Our gravity data do not cover all the Plan de Barrancas-Santa Rosa graben; thus we cannot locate the limit between the SMOc and the JB. However, the alignment of the Tequila volcano with cinder and lava cones in a NW-SE direction implies a major crustal frac-

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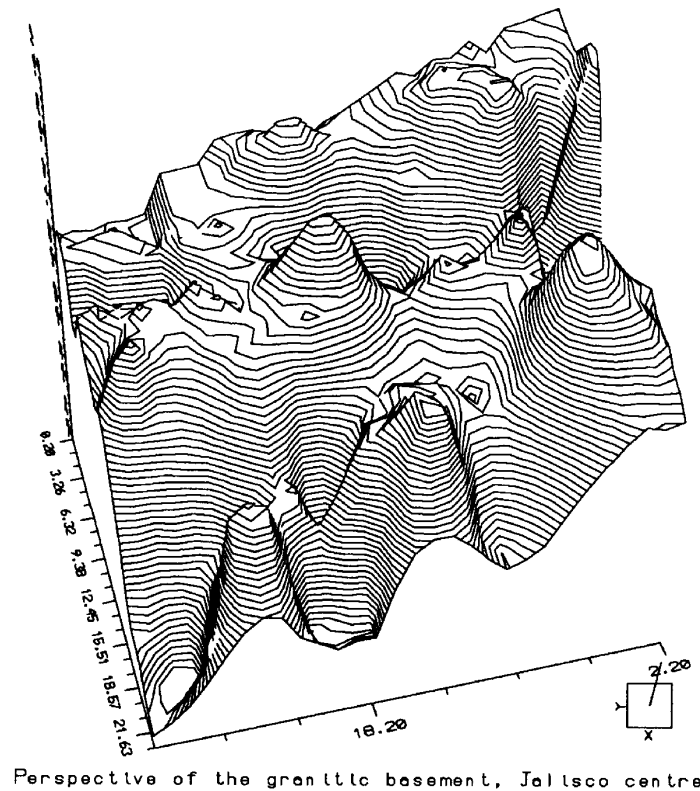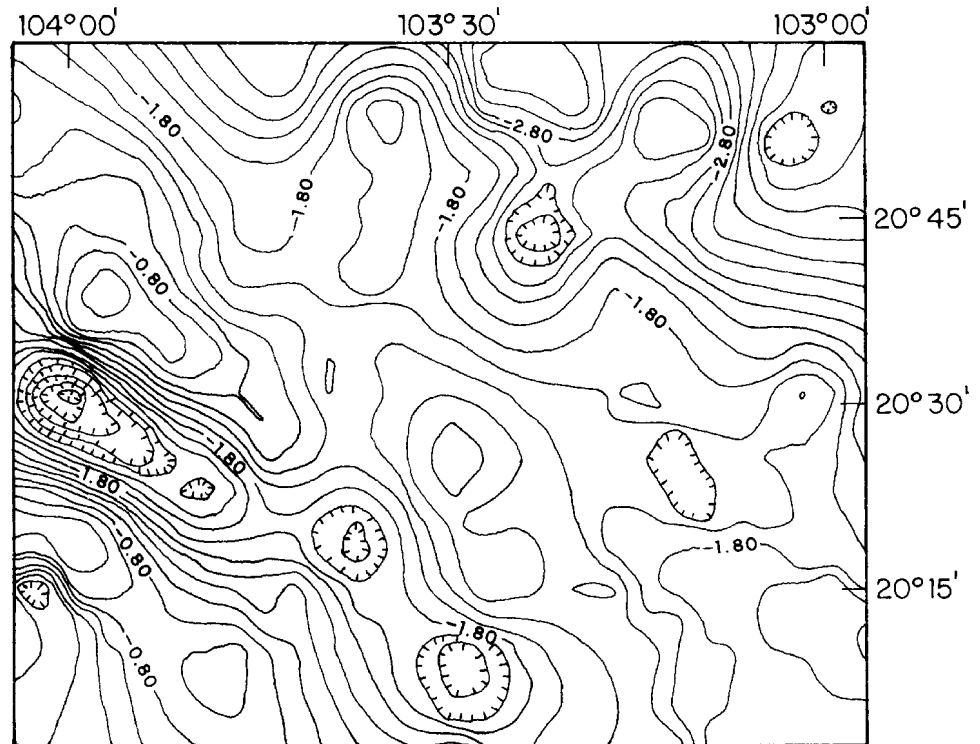Perspective of the granitic basement, Jalisco centre.

Fig. 12. a) Basement topography in the study area. Contours are given in km, b) Three-dimensional view of the basement topography.

ture (e.g., Alatorre-Zamora and Campos-Enríquez,1991; Rosas-Elguera *et al*., 1997). The northward prolongation of this regional fracture suggests that the SMOc-JB limit may be located slightly north of the Plan de Barrancas fault. This agrees with recent subsurface data identifying Plan de Barrancas fault as the boundary between the SMOc and JB, rather than the Santa Rosa fault (e.g., Rosas-Elguera *et al*., 1997). The Santa Rosa fault may be an old boundary between these two domains (Michaud *et al*., 1992). In the area of Guadalajara the basement constitutes a depression elongated NE-SW perpendicular to the general tectonic fabric of the southern portion of the study area (i.e., Ameca and Zacoalco half-grabens). This change in the tectonic fabric suggests that here the basement has affinity to that of the SMOc. The front of the SMOc should be closer to the southern Guadalajara volcanic chain system. According to our model, the granitic basement deepens to the east of Guadalajara. Since the gravity anomaly in this part features NE-SW lineaments, we interpret this area to be underlain with SMOc basement. Thus the limit between the SMOc and the JB would be the NW-SE trending Plan de Barrancas fault. In the eastern sector, the limit is located closer to the southeastward prolongation of the Plan de Barrancas fault around the southern Guadalajara volcanic chain system. In the area around La Primavera caldera, the limit changes between these two locations. In the eastern part of the study area, the boundary should be E-W as suggested by the tectonic fabric of Lake Chapala. It is located to the north of the Chapala graben, as inferred by Rosas-Elguera *et al*. (1997). Summarizing, the basement of the JB and the SMOc may be differentiated by their distinct tectonic fabrics (NW-SE to E-W, and NE-SW, respectively). The basement on both sides of the boundary is highly fractured. The JB is affected by a series of NW-SE lineaments as inferred from geology (i.e., Rosas-Elguera *et al*., 1997) and geophysical information (i.e., Campos-Enríquez, 1986; Alatorre-Zamora and Campos-Enríquez, 1991). These lineaments define the last portions of the JB crust. In contrast, the basement of the SMOc is fractured along NE-SW directions (e.g., the NE-SW elongated depression beneath Guadalajara City).

ACKNOWLEDGMENTS

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