Geophysical modeling of Valle de Banderas graben and its structural relation to Bahía de Banderas, Mexico

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ABSTRACT

A gravimetric survey consisting of five lines and 483 stations, as well as a magnetotelluric (MT) survey consisting of 17 observation sites, were made in the Valle de Banderas region for the determination of the structural characteristics of the valley. Additionally, data from a previous aeromagnetic survey were analyzed to correlate them with our geophysical measurements. The gravimetric and MT models confirm that the valley corresponds to a graben structure with slumped blocks that vary from ~2000 m deep close to Bahía de Banderas to shallow burial depths (~100 m) toward the NE end of the valley. Faults flanking the valley, inferred from the gravity and magnetic models, trend toward offshore faults in Bahía de Banderas, indicating a structural connection between land and sea. From the MT measurements we conclude that a 2-D resistivity behavior is observed within the graben whereas outside of the graben the behavior is 1-D, in spite of the rough topography of this region. Our gravimetric models also indicate the occurrence of basin-like structures within the graben, coinciding with similar structures reported offshore in the Bahía de Banderas, suggesting that such structures may be typical erosional features of the graben. The aeromagnetic analysis correlates with the gravimetric and MT models, and suggests that the graben structure is an extensional zone on granitic crust; it also indicates that the extensional zone continues to the NE, beyond the topographic limits of Valle de Banderas on land and towards Bahía de Banderas seawards. We propose that this region belongs to the same tectonic structure in spite of an approximate change in orientation of 30° between the bay and the valley, and strengthen the idea that this graben constitutes part of the NW limit of the Jalisco Block. A tectonic model for the region is presented at various stages, from around 100–75 Ma to the Present. We propose that initiation of the Bahía de Banderas structure started at ~14 Ma along an E-W trend, and that at ~5 Ma the graben axis was reoriented to a SW-NE direction, that induced the formation of Valle de Banderas.

Key words: geophysical modeling, gravity, magnetotellurics, Valle de Banderas, Jalisco Block, Mexico.

RESUMEN

Un levantamiento gravimétrico que incluye 483 estaciones distribuidas en 5 líneas, así como un levantamiento magnetotelúrico (MT) que incluye 17 sondeos se efectuaron en la región del Valle de Banderas con el propósito de determinar las características estructurales del valle. Además, se

analizaron los datos aeromagnéticos existentes de la zona y se correlacionaron con los datos geofísicos medidos. Los modelos gravimétricos y de MT obtenidos a partir de ellos confirman que, en general, el valle corresponde a una estructura de graben, con bloques caídos, cuyas profundidades varían desde aproximadamente 2000 m cerca de la costa hasta unos 100 m, en el extremo NE del valle. Las fallas que limitan el valle, inferidas a partir de los modelos gravimétricos y los datos magnéticos, se pueden conectar con fallas ubicadas en el mar, indicando una conexión estructural entre la bahía y el valle de Banderas. A partir de las mediciones MT se deduce que dentro del graben prevalece una estructura de resistividad 2-D, en tanto que fuera del graben se observa un comportamiento 1-D a pesar del carácter montañoso de la región. Los modelos gravimétricos sugieren la ocurrencia de subcuencas dentro del graben, entendidas como hundimientos locales rellenos de sedimentos, que coinciden morfológicamente con estructuras similares reportadas anteriormente en la bahía, indicando que éstas pueden ser un rasgo erosivo típico del graben. El análisis aeromagnético se correlaciona con los modelos gravimétricos y MT y sugiere que la estructura del graben es una zona de extensión que separa bloques de granito con una firma magnética similar; también sugiere que la zona de extensión continúa hacia el NE, más allá de los límites del valle. Estos resultados tienden a confirmar que tanto la Bahía de Banderas como el Valle de Banderas pertenecen a la misma estructura tectónica a pesar de que la orientación de sus ejes difiere 30°, y apoyan la idea de que estas estructuras constituyen parte del límite NW del Bloque de Jalisco Proponemos que la estructura de Bahía de Banderas inició hace ~14 Ma a lo largo de una tendencia E-W y que a ~5 Ma el eje del graben se reorientó en una dirección SW-NE, lo que indujo la formación del Valle de Banderas.

Palabras clave: modelado geofísico, gravedad, estudios magnetotelúricos, Valle de Banderas, bloque Jalisco, México.

INTRODUCTION

The limits between the Jalisco Block (JB) in western Mexico and the North American (NAM) plate are graben structures (Figure 1); to the northeast, the JB is bounded by the Tepic-Zacoalco graben (Luhr *et al.*, 1985; Ferrari *et al.*, 1994), and to the east by the Colima graben (Allan, 1986; Bandy *et al.*, 1995). The northwestern limit of the Jalisco Block may also be a graben; Johnson and Harrison (1990) proposed that a major branching of the Tepic-Zacoalco graben, 90 km in length, trending W-SW along the Río Ameca, starting south of Volcán Ceboruco and ending in Valle de Banderas, in the limits between Jalisco and Nayarit states, could represent such a boundary. Using new and available echo sounding data, Alvarez (2002) constructed a digital elevation model of Bahía de Banderas, which is the offshore continuation of Valle de Banderas, and suggested that this region is also a graben and that together with the above structure represents a 150 km long graben that may constitute the northwestern limit of the JB. More recently Álvarez-Béjar (2005) suggested that the faults defining Bahía de Banderas canyon extend down to the trench, near the north end of the Middle American Trench (MAT), in a way similar to that observed in the Colima graben, in which its offshore continuation, the Manzanillo graben, extends beyond the MAT, ending in El Gordo graben (Bourgois *et al.*, 1988; Khutorskoy *et al.*, 1994). The southwestern limit of the JB may consist of a fault, the Barra de Navidad fault proposed by Bourgois *et al.* (1988), that extends from the Tres Marías Escarpment (TME) to El Gordo graben

(EGG) running subparallel to, and crossing the MAT in that region.

The bathymetry of Bahía de Banderas was reconstructed with depth echo soundings that led to a digital terrain model of the area. In Bahía de Banderas, a series of closed depressions, or basins, were observed within the graben (Alvarez, 2002; Álvarez-Béjar, 2004) (see Figure 2). Up to now it was not known whether similar structures extended under the sedimentary filling. Another intriguing question is the change in trend between the bay's main structure and the valley's graben, which is of about 30°. To help clarify these questions, in this work we build cross-sectional models of the valley's sediment thicknesses based on gravimetric and magnetotelluric surveys, supported by the analysis of an aeromagnetic survey of the area.

GEOLOGICAL BACKGROUND

The opening of Bahía de Banderas has been associated with the separation of Baja California from mainland Mexico in the middle Miocene (Lyle and Ness, 1991). Ferrari and Rosas-Elguera (2000) placed the origin of the Valle de Banderas graben in late-Miocene to early-Pliocene times, and associated it with the same extensional tectonic framework of the Tepic-Zacoalco graben zone. Álvarez-Béjar (2005) suggested that the change in canyon's direction was associated with a regional tectonic episode occurring ~5 Ma. Bönhel *et al.* (1992) showed that the age and the isotopic composition of the Los Cabos and the Puerto
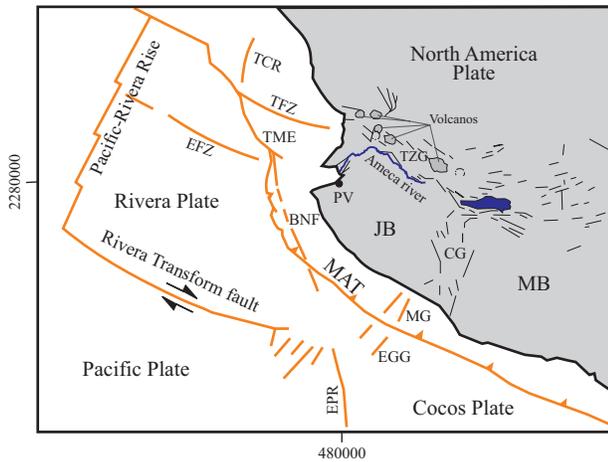
Figure 1. Tectonic setting in the vicinity of the study area (after Ferrari and Rosas-Elguera, 2000). According with their interpretation, the Jalisco Block (JB) is limited to the north by the Tepic-Zacoalco graben (TZG), and to the east by the Colima Graben zone (CG). BNF: Barra de Navidad Fault Zone; EFZ: Esplandian Fault Zone; EGG: El Gordo Graben; EPR: East Pacific Rise; MAT: Middle American Trench; MB: Michoacán Block; MG: Manzanillo graben; PV: Puerto Vallarta; TCR: Tamayo Canyon Rift; TFZ: Tamayo Fault Zone; TME: Tres Marías Escarpment.

Vallarta batholiths are quite similar, which suggest that they were close together before the separation of the peninsula took place. The Jalisco Block has also been identified with a structural uplifted domain constituted by exposed crystalline basement (Fenby and Gastil, 1991).

The granitic basement in the Jalisco Block has been dated around 100–75 Ma (Zimmerman *et al.*, 1988; Schaaf *et al.*, 1995). Moore *et al.* (1994) studied the San Cristóbal plateau basalts near Guadalajara City, which filled a pre-existing extensional basin in the area, at around 10 Ma; they speculated that this may be one of the first indications of separation of the Jalisco Block from NAM. Rosas-Elguera *et al.* (1996) reported that the mid-crustal rock assemblage of the Puerto Vallarta batholith is presently exposed at 1,000 to 2,500 m of elevation, indicating that it has undergone a significant uplift since its emplacement. The lack of ash flow tuffs from the Sierra Madre Occidental in the Jalisco Block (Ferrari *et al.*, 1994) was considered by Rosas-Elguera *et al.* (1996) as an indication that most of the uplift occurred in the Paleogene; the fission track findings of Calmus *et al.* (1995) indicate that the batholith was at a depth greater than 1,000 m by Eocene times, supporting the above statement.

The Valle de Banderas graben was called "Puerto Vallarta graben" by Ferrari and Rosas-Elguera (2000); we think the name used herein corresponds better with the geographic location and connects intuitively with Bahía de Banderas. In their description of the graben they reported that it is bounded by two main 25°– 45° striking fault systems, with vertical offset of around 600 m; furthermore, they also identified a northeast trending extension direction. Based on the existence of a faulted conglomerate in the eastern part of the graben, they assumed that this extensional pattern has continued until Recent times.

Bahía de Banderas bathymetry

The first contour representation of the bay's depths was probably that of Fisher (1961); he proposed the existence of a fault along the canyon. After gathering additional bathymetry data Alvarez (2002, 2005) elaborated a digital elevation model (DEM) of the bay. The northern portion of the bay corresponds to a wide platform (Figure 2), while the south flank attains depths of 1,200 to 1,500 m close to the shoreline. Erosional processes induced by faulting affect the northern flank of the canyon, and occur mainly as landslides. Several basins have been identified in and around the canyon, which suggests that the graben development is accompanied by the formation of such structures.

Of particular interest to the present paper is the observation that Banderas canyon changes from an E-W trend along the southern flank of the bay to a NE trending portion close to the eastern shore of the bay, which coincides with the trend of the axis of Valle de Banderas. The change in trend initiates within the bay, as observed above, and continues into the valley (Figure 2). This change in trend can be interpreted as linked to a major tectonic activation; the change is probably contemporaneous with the beginning of the northwestward drifting of Baja California, at about 6–5 Ma. Lyle and Ness (1991) suggested that the formation of Banderas canyon was induced by the opening of the Gulf of California, at ~14 Ma, and associated it with slow rifting in the NW-SE direction. If these models are correct, the
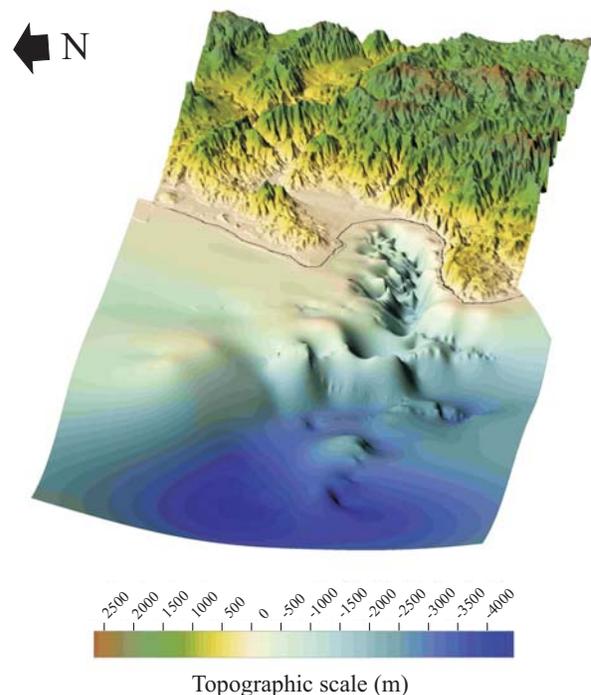

Topographic scale (m)

Figure 2. Digital elevation model of Bahía de Banderas canyon merged with the inland DEM, suggesting its continuation towards the Valle de Banderas graben after a NE change in trend toward the E end of the canyon (after Álvarez, 2005b).

formation of the canyon probably began around 14 Ma and the change in trend initiated around 5 Ma. A more detailed discussion about the origin of Banderas canyon will be made ahead, in connection with a tectonic model of the area.

GRAVITY SURVEY

A gravity survey was carried out in the Valle de Banderas area with the purpose of modeling the basement and tracking any possible inland continuation of the faults observed offshore (Figure 3). The extent of the surveyed lines is about 150 km with 483 gravity stations. The elevation of the stations was measured with a total station with subcentimeter accuracy; the gravity meter used was a Scintrex CG-3, measuring to an accuracy of 0.01 mGal. The location of stations were determined with a GPS, with an estimated horizontal accuracy of 7 m. Drift and tidal corrections to the data were done automatically by the instrument using appropriate base station measurements and preprogrammed tidal variations. Other corrections to the data set included: standard latitude, free air, and Bouguer slab compensations. Figure 4 shows the complete Bouguer anomaly map of the zone, which includes also terrain corrections applied to each station using an automated Hammer (1939) type approach. A low reaching -90 mGals is revealed in the vicinity of the coast, at the southwestern portion of the valley.

A second-degree polynomial fitting was used to find out the suitable regional field prevailing in the study area. Then, the residual field was obtained (Figure 5) from the difference between the complete Bouguer anomaly map and the fitted regional field. The resulting residual field shows a rather well defined elongated minimum along an axis whose azimuth is about 30 degrees (letters B and C), coinciding with the Valle de Banderas axis. Its absolute amplitude ranges from 8 to 10 mGals, and although the data set has limited coverage, it appears that, instead of a continuous elongated basin, there are separated basin-like structures (letters A, E and D); the residual field probably reflects the distribution of fluvial deposits. The northernmost portion of the surveyed area also discloses a negative anomaly, apparently interrupted from the main gravity low by locally high values. In general, a series of gravity highs with maximum amplitudes of up to 20 mGals are observed surrounding the main elongated negative anomaly, particularly in the W-NW region. A steep gravity gradient is observed along the NW portion of the surveyed area, which extends from MT Station 12 (see Figure 6) to the shoreline with a SW trend. Cross-sectional models based on these gravity charts will be discussed further ahead.

2-D gravity sections

Three gravity profiles L-1, L-2, and L-3 were selected for two-dimensional modeling across the Valle de Banderas. The profiles were extracted from the complete Bouguer anomaly chart and are located close to the roads along which the gravity measurements were done (Figure 3). The resulting models obtained are shown in Figure 7. Inverted triangles indicate the location of the Ameca and
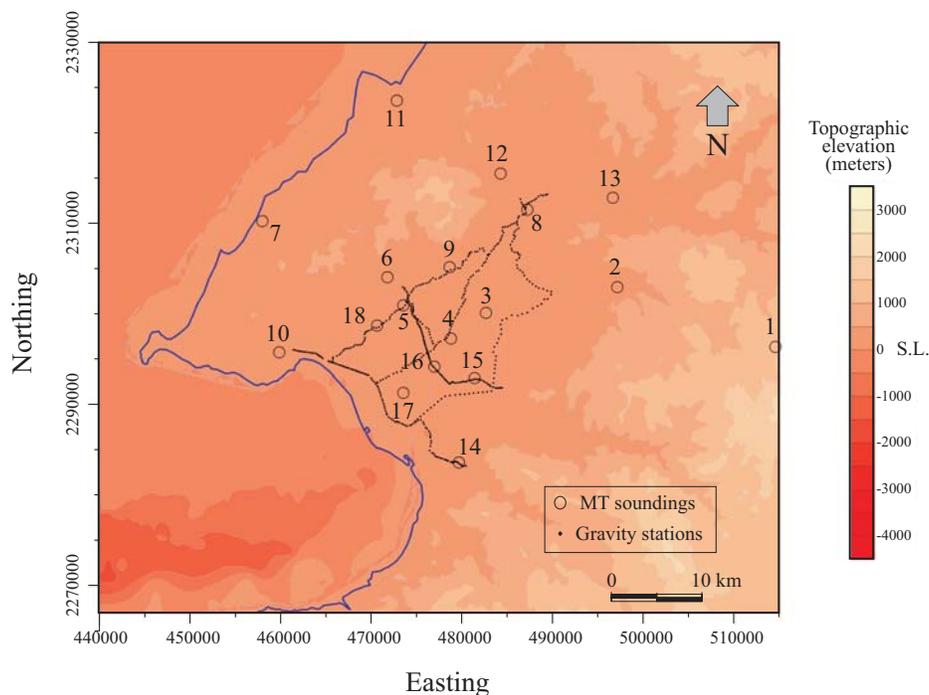

Figure 3. Gravimetric (dots) and magnetotelluric stations (circles) measured in Valle de Banderas.
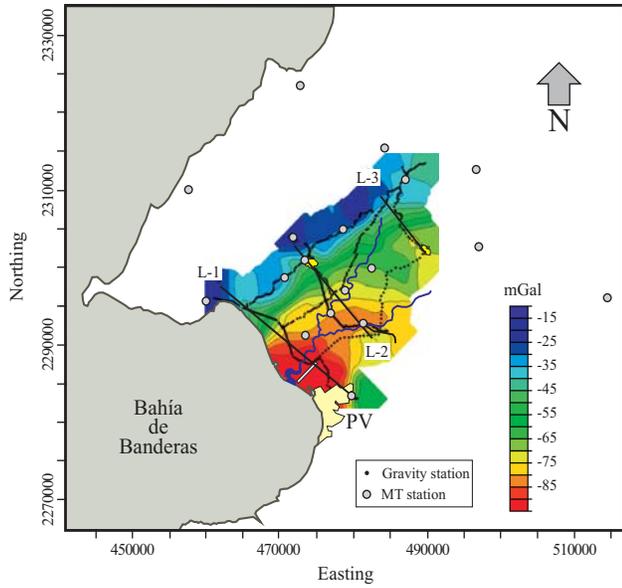
Figure 4. Complete Bouguer anomaly map of the zone, with terrain corrections. Black dots are gravity stations, white circles are MT locations, wandering blue line indicates the trace of the Ameca river within the valley, and L-1, L-2, and L-3 are the modeled gravity profiles.
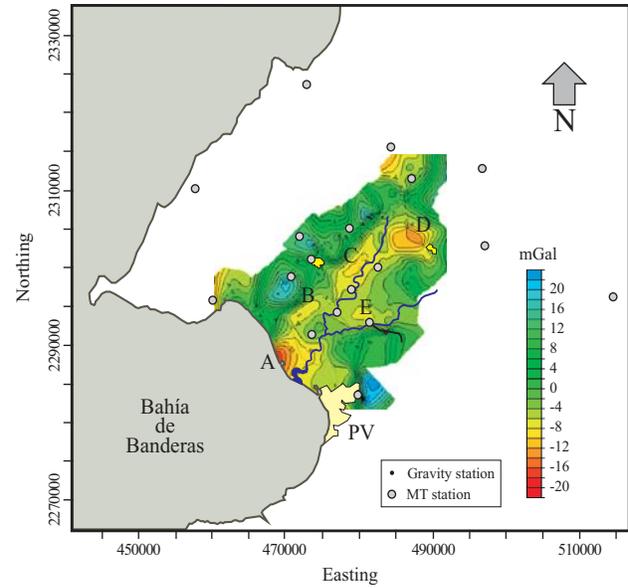

Figure 5. Residual gravity field obtained from the difference between the complete Bouguer anomaly chart and second degree fitted regional field. Five basin-like structures are suggested along the axis of Valle de Banderas and identified as A, B, C, D, and E.
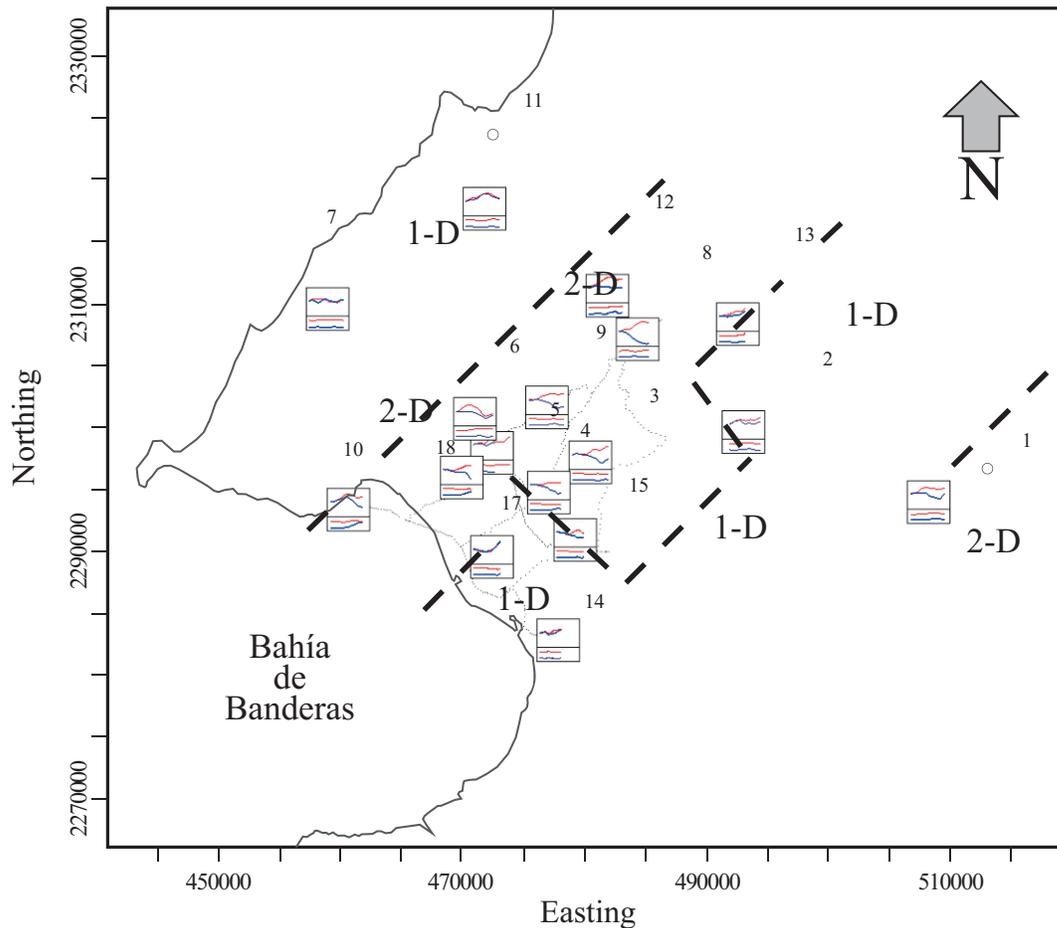

Figure 6. Sounding curves of apparent resistivities $\rho_\parallel$ and $\rho_\perp$ and the impedance phases $\phi_\parallel$ and $\phi_\perp$. There are several sites (six out of seventeen), mainly off the valley area, that have a 1-D behavior.

Mascota rivers. In general, gravity profile L-1 is smoother than profiles L-2 and L-3 (Figures 7a, 7b and 7c, respectively) and has a higher total amplitude (close to 75 mGals) than the other two profiles. The horizontal gradients of the respective Bouguer anomaly profiles are located on top of each profile. Local maximum values of the gradient are interpreted as major vertical displacements in basal rocks. We assume that the observed gravity anomalies are due mainly to the contrast between the granitic basement of average density 2.8 g/cm³ and the sedimentary filling of the graben. We speculate that such sedimentary filling is composed by talus, marine, and fluvial sedimentary deposits to the top, having a combined average density of 2.0 g/cm³. Shallow deposits are expected to be mostly non consolidated, and therefore to have a lower density than the average, whereas deeper deposits are expected to have densities above this

average value. Gravity profile L-1, which is the closest to the mouth of Bahía de Banderas, shows a wide-basin geometry according to the resulting model cross-section from a 2-D Talwani type of inversion (Talwani *et al.*, 1959). The model assumes relatively shallow shoulders at the NW and SE extremes, close to the places where granite outcrops. We have extended the models beyond the measured lines in order to show the approximate location of the main faults, whose position was not reached owing to the steep topography. The maximum thickness estimated for the sedimentary layer at the mouth of the valley is about 2.5 km. Variations of up to 0.3 g/cm³ in the density of the sedimentary filling does not change significantly the maximum thickness nor the shape of the basement rocks. A difference of about 100 m in total sedimentary thickness is found for a density contrast of $\Delta\delta = 1.1$ g/cm³ in contrast with $\Delta\delta = 0.8$ g/cm³ used in
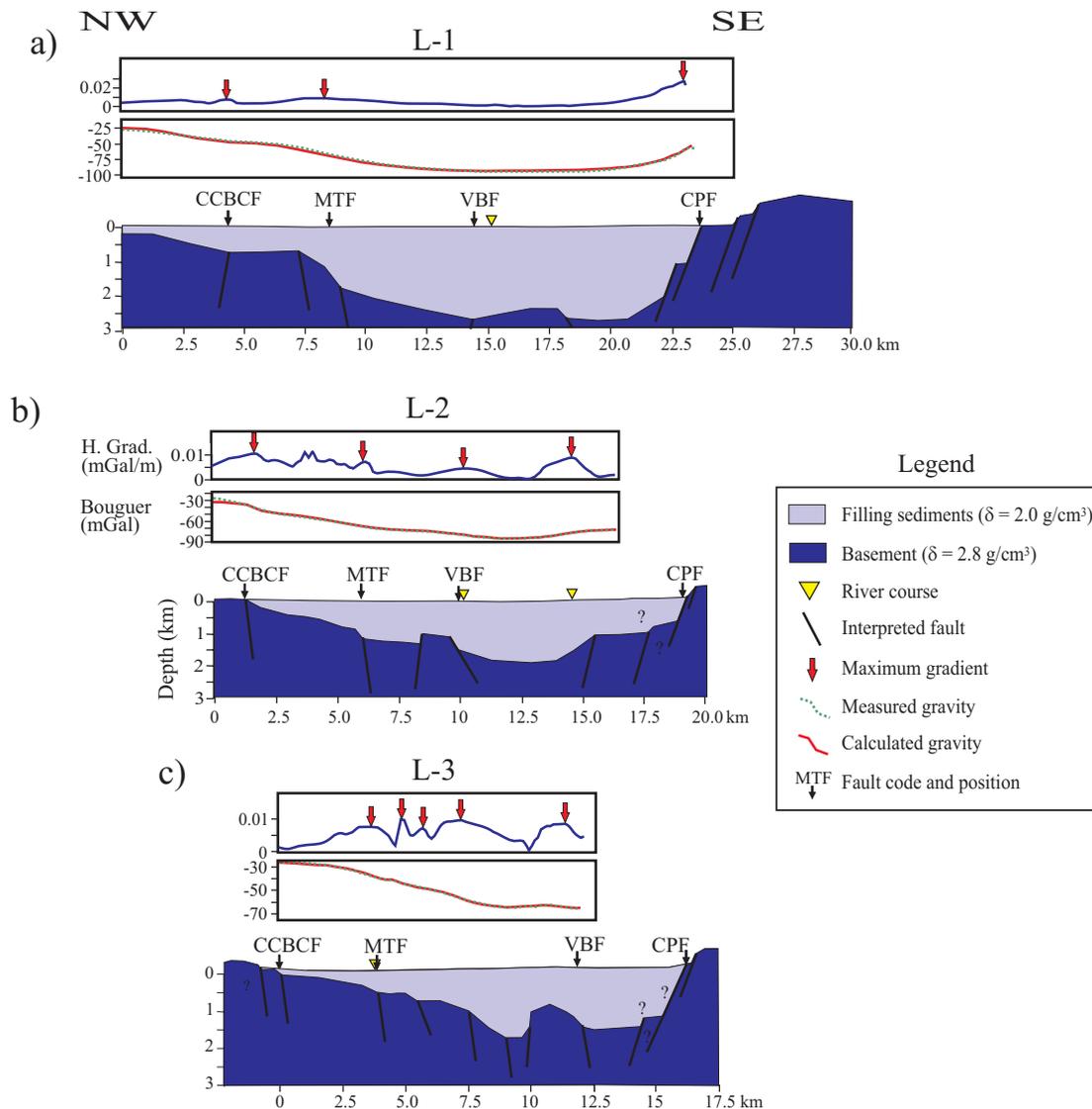

Figure 7. Two-dimensional gravity models of the complete Bouguer anomaly obtained using two rock types: i) sedimentary filling of average density of 2.0 g/cm³, and ii) the basement rocks with 2.8 gr/cm³. Inverted triangles indicate the location of the Ameca and Mascota rivers. The deepest portion of the graben is to the SE. The position of the inferred faults is shown; for abbreviations see Figure 11.

our models. The curve fitting accuracy seems to be more sensitive to the shape of the basement (*i.e.*, the positions of topographic highs and lows) than to variations of the density contrast. The same observations are valid for profile L-2 where the estimated maximum depth to the basement is close to 2 km and the graben width is about 17 km. In essence, the Valle de Banderas graben is about 23 km wide at the shoreline and narrows toward the NE down to about 12 km at the location of profile L-3, where the sedimentary thickness drops to about 1.5 km. A common feature of the three profiles is a horst type structure about 2.5 km width at the bottom of the sedimentary filling. On the basis of these models and the resulting basement topography, a series of faults are associated with these cross sections. Faults designated CCBCF (Cabo Corrientes-Bucerías-El Colomo Fault), VBF (Valle de Banderas Fault), and CPF (Cucharitas-Pitillal Fault) correspond to faults previously identified in the bay (Álvarez-Béjar, 2005) whose trace can now be extended into the valley. Fault MTF (Mezcales-Tebelchía Fault) is inferred in this work and appears to be concealed by the valley sediments. A joint representation of the bay and valley faults is presented ahead.

MAGNETOTELLURIC SURVEY

A total of 18 magnetotelluric soundings were measured in Valle de Banderas with the purpose of finding out possible anomalous conductors related to faulted basement. Fifteen MT soundings were carried out within the valley and three in the surroundings. One of the sites (16) in the valley was too noisy to be useful, for this reason it was not included in the interpretation process. The location of sites (Figure 3) was chosen according to accessibility and space availability to spread out the electrode arrays, always trying to have a good coverage of the valley. A full MT sounding measurement took between 8 to 14 hours. The survey was carried out in two stages; in the first fieldwork campaign we used two Phoenix V5, while in the second campaign we used two Phoenix MTU-2000, both five channel systems. MT soundings from 1 to 11 were measured with the V5 systems, whereas the last 7 were acquired with the MTU-2000. The resistivity data of the first measuring campaign is of varying quality whereas the data of the second campaign is generally better.

The five channel systems recorded two horizontal components of the electric and two horizontal components of the magnetic fields (E_x, E_y, H_x, and H_y) as well as the vertical component of the magnetic field H_z, in the period range from 0.0025 to 100 seconds. However, H_z is not analyzed in this work. Standard processing of the data included FFT of the acquired time series and robust estimation of the impedance tensor Z (r,ω). The impedance tensor, often termed the Transfer Function, reflects the earth's conductivity distribution. When rotated to the principal axis (*i.e.*, to the axis of the main geologic structure), and in the absence

of local current scatters, the magnetic (H_x, H_y) and the electric fields (E_x, E_y) are related to Z, through the linear equation system

$$\begin{pmatrix} s_1 E_x \\ s_2 E_y \end{pmatrix} = \begin{pmatrix} 0 & Z_{xy} \\ Z_{yx} & 0 \end{pmatrix} \begin{pmatrix} H_x \\ H_y \end{pmatrix} \tag{1}$$

where Z_{xy} and Z_{yx} are the off diagonal components of Z, a rank-two, complex tensor, and s_1, s_2 are real multipliers representing near-surface galvanic shift. Here it is assumed that, to the scale of the Valle de Banderas graben, three-dimensional structures are all inductively weak, so that they do not distort significantly the measured electric and magnetic fields. In the studied area, major field scatterers can be sharp coastal lines, and conducting intrusives. Although local faults diagonal to the graben strike can also behave as scatterers, special attention was paid to locate MT stations away from such features when there was surface evidence of its presence. In addition, the coastal line only affects sites located within a skin depth (Vozoff, 1989) distance of 5 km, which corresponds to sampling field periods larger than 1 Hz for a ground average resistivity of 100 ohm·m. Figure 6 shows that only soundings 7, 10, and 11 are within this distance, and of these only site 10 is located within this distance to the Bahía de Banderas sharp coastal line. Sites 7 and 11 are located over a marine platform that extends tens of kilometers west of the shoreline (see Fig. 2). Thus, the coastal effect is regarded negligible for most of the MT soundings at least down to about 1 Hz.

Resistivity maps

The principal impedances Z_{xy} and Z_{yx} are either perpendicular ($Z_\perp$) or parallel ($Z_\parallel$) to the strike of the two dimensional structure. $Z_\perp$ is the impedance associated with the two dimensional mode containing only currents perpendicular to the strike, and $Z_\parallel$ is the impedance associated with the mode containing only current parallel to the strike. Accordingly, the apparent resistivities $\rho_\parallel$ and $\rho_\perp$ and the impedance phases $\varphi_\parallel$ and $\varphi_\perp$, as a function of frequency, are calculated from the complex elements Z_{xy} and Z_{yx} respectively using (*e.g.*, Vozoff, 1989)

$$\rho_{ij}(\omega) = \frac{1}{\omega \mu_0} \left| Z_{ij}(\omega) \right|^2 \tag{2}$$

and

$$\phi_{ij}(\omega) = \tan^{-1} \frac{\mathrm{Im} Z_{ij}(\omega)}{\mathrm{Re} Z_{ij}(\omega)} \quad , \tag{3}$$

where *ij* are either *xy* or *yx*; μ_0 is the permeability of free space and ω the angular frequency. From these expressions, the sounding curves were obtained for the principal axes. The apparent resistivity curves were corrected by static shift, which consisted of shifting the curves by factors s_1, s_2 at those sites where vertical displacements were off the 100 ohm·m level. This value is regarded as the normal resistivity level at the near surface in the studied area, because 13 out of 17 sites showed sounding curves starting at this resistivity.

In some cases, the orthogonal apparent resistivities curves of $\rho_\parallel$ and $\rho_\perp$ are equal, which reflects the one-dimensional (1-D) character of the ground for the measured frequency band. Theoretically, when both resistivity curves overlap and are invariant under any rotation of Z, then we say that the site is 1-D. On the other hand, typical 2-D sites are characterized by having unequal apparent resistivity curves in part, or for all the sampling frequency bands. Figure 6 shows that there are several sites (six out of seventeen), mainly off the valley area, having one-dimensional behavior, except sounding 1 which is outside the valley and has a 2-D response. In this figure, $\rho_\parallel$, also known as transverse magnetic or TM resistivity, is plotted in blue while $\rho_\perp$, also known as transverse electric or TE resistivity, is plotted in red. The stations 14 and 17 to the SE, 2 and 13 to the NE, and 7 and 11 to the NW of the valley are 1-D sites. The rest of the stations, predominantly located within the valley, are clearly affected by the graben structure and reflect a 2-D earth at least. This behavior appears contrary to what might be expected, however deep rooted massive granite units flanking a highly faulted graben can explain the observed behavior. The granites are apparently quite homogeneous for a wide frequency band (down to 0.1 Hz), hence the 1-D response, while the fault structures within the graben promote current polarization at frequencies below 10 Hz. Figure 8 shows the resistivity distributions at depths of 1 km, 2.5 km, and 10 km (a, b, and c charts respectively) calculated by using Bostick transfom (Bostick, 1977), which produces smoothly varying resistivity-depth profiles. The plots give an idea about the distribution of the conductive filling sediments and the resistive granite at different depths. For example, in Figure 8a it is observed that the conductor has the same SW-NE trend as the graben. This trend seems to prevail down to 2.5 km as shown in Figure 8b, however at this depth and down to 10 km (Figure 8c) the background resistivity is higher. To this depth, the high conductivity distribution appears to change from a SW-NE direction (Figures 8a and 8b) to a more NW-SE orientation (Figure 8c) although the central part of the valley remains as a good conductor at depth.

2-D magnetotelluric models

Three magnetotelluric cross sections were modeled (inset Figure 9) by using 2-D Rodi and Mackie (2001) smooth inversion algorithm. The three magnetotelluric electrical sections are formed by stations in some cases separated far apart. Even though, the section provides an idea of the electric structure down to about 10 km deep into the ground. The MT profiles comprising a total of 13 stations were rotated to the structural axis of the graben using a mean rotation angle of 40 degrees in the induction band of 10^2–10^{-1} Hz. The resistivity and phases of the TE and TM modes were simultaneously inverted using a mesh that incorporated topography, extending laterally and down-

wards beyond the end site locations. The obtained resistivity sections after 25 iterations are shown in Figure 9 and were named MT-1, MT-2, and MT-3 respectively. The misfits between observed and calculated apparent resistivities and phases are presented graphically in Figure 10 for all the sites and profiles. In general both the TE and TM curve fittings are in reasonably good agreement for most of the sites and for the resistivity and phase. The horizontal scale of plots range from 10^3 to 10^{-2} Hz and the resistivity ranges from 10^0 to 10^4 ohm·m.

Section MT-1 comprises six MT sites covering a total length of about 40 km and having an orientation roughly S50E. Except at the location of station 18, the profile is characterized by a shallow flat conductor that suggests a constant sediment thickness, that would be expected as the profile is approximately parallel to the northern edge of the graben. The wide conductivity anomaly observed at site 18 is an artifact of the interpolation algorithm, which is emphasized by the ample separation between contiguous sites. However, the anomalous conductor appears to be real and it is probably associated to the presence of a fault (LQ) just bellow the site location.

Section MT-2 comprises four sites, cuts diagonally the graben basin, and extends for a total distance of about 30 km with an approximate S20E orientation. Site 14 is located in the southern extreme of the profile, close to Puerto Vallarta, and suggests a thicker sedimentary layer than at the location of site 8. In the central part of the profile, sites 15 and 3 reveal a thicker sedimentary layer than at the other sites. However, at the station 15, the basement appears deeper than at site 3 implying that this difference in depth to the basement has been induced by faulting.

Section MT-3 comprises five stations and has a total length of about 50 km; it cuts the graben to the east of gravity profile L-3, close to the zone where it becomes narrower. The electrical structure along this section reveals a relatively shallow resistive basement, particularly at sites 11 and 1, located at the extremes of the profile. The high conductivity layer associated with the sedimentary filling of the valley was detected only at the location of site 8, which evidences that at this latitude the graben becomes shallower. The vertical displacements within the graben along the interpreted faults seem to be negligible in this zone, in contrast with what is observed towards the coastal plain, where according to gravity results they can be larger than 1 km. Observed differences in depth to the basement between the three inverted MT sections at site 8 are due to differences in curve fitting. In sections MT-1 and MT-3, the calculated TE and TM resistivity curves are shifted downwards the measured resistivity curves producing an artificially thicker conductive layer. In section MT-2, no curve shifting is observed at station 8 and the match between the measured and calculated resistivity curves is better, which suggests that the electrical structure bellow this site is better defined here.

There is not a direct way to define with accuracy the depth to the interface between the sedimentary filling and
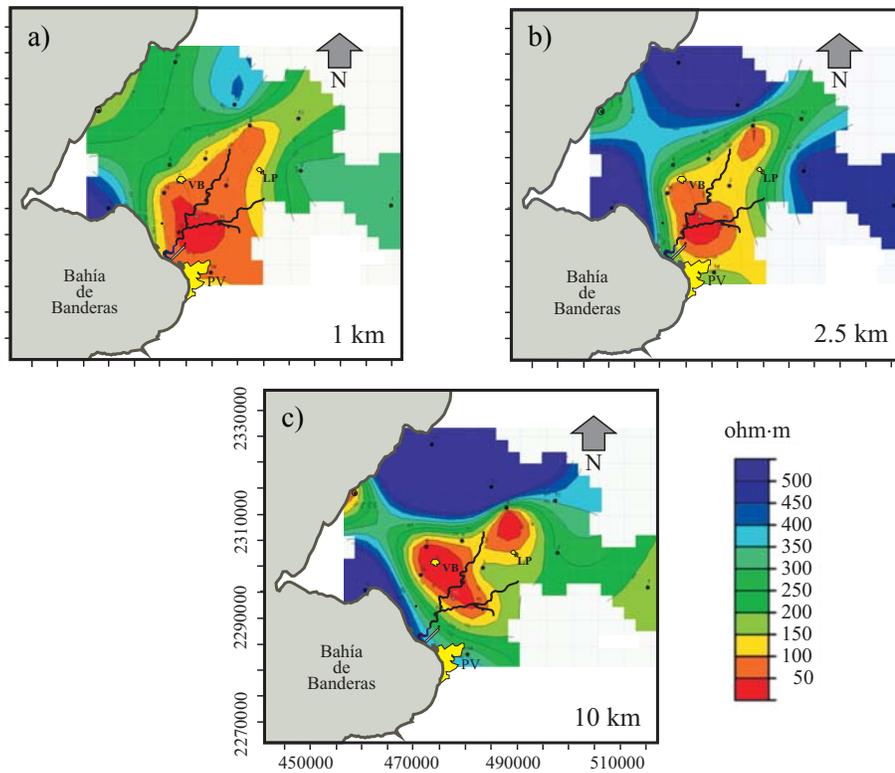
Figure 8. Resistivity maps of Valle de Banderas at 1, 2.5, and 10 km depth. Conductors along a NE direction dominate the response at 1 and 2.5 km, whereas an apparent change in the conductor direction towards the NW is observed at larger depths (10km).
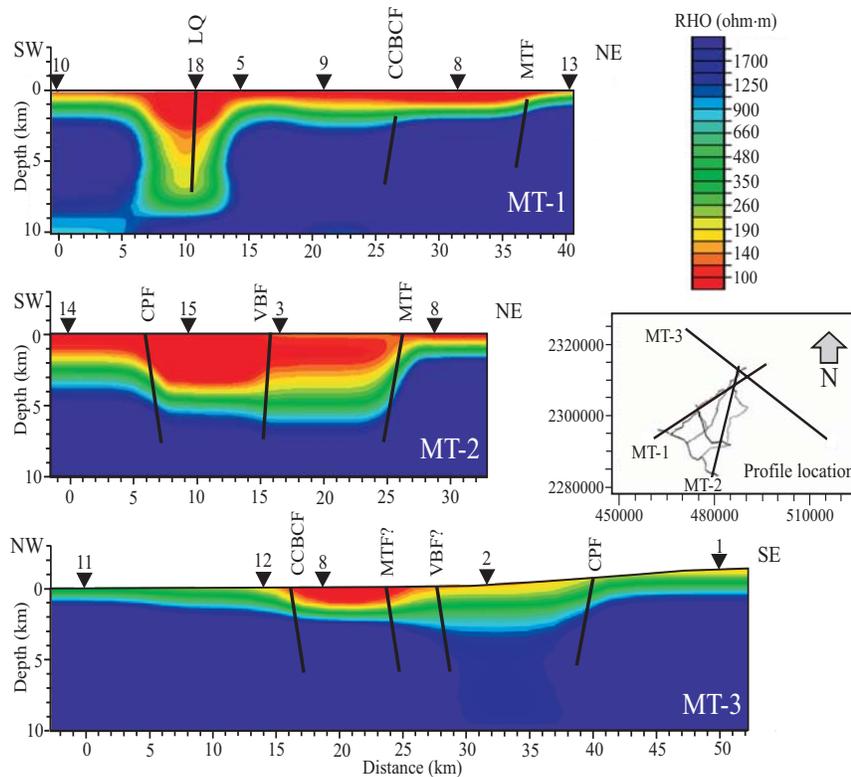

Figure 9. Two-dimensional magnetotelluric models along profiles MT-1, MT-2, and MT-3. Red color is associated with the sedimentary filling of the graben, except at site 18 where the conductor appears to be related to the presence of a fault (La Quebrada Fault or LQF) just below the measuring site probably in a different direction that CCBCF fault. Blue and green tones are associated to the presence of the granitic resistive basement. Black lines are interpreted faults; although their position is not accurate, their existence is assured by differences in depth to a common conductive horizon. For faults abbreviations see Figure 11.
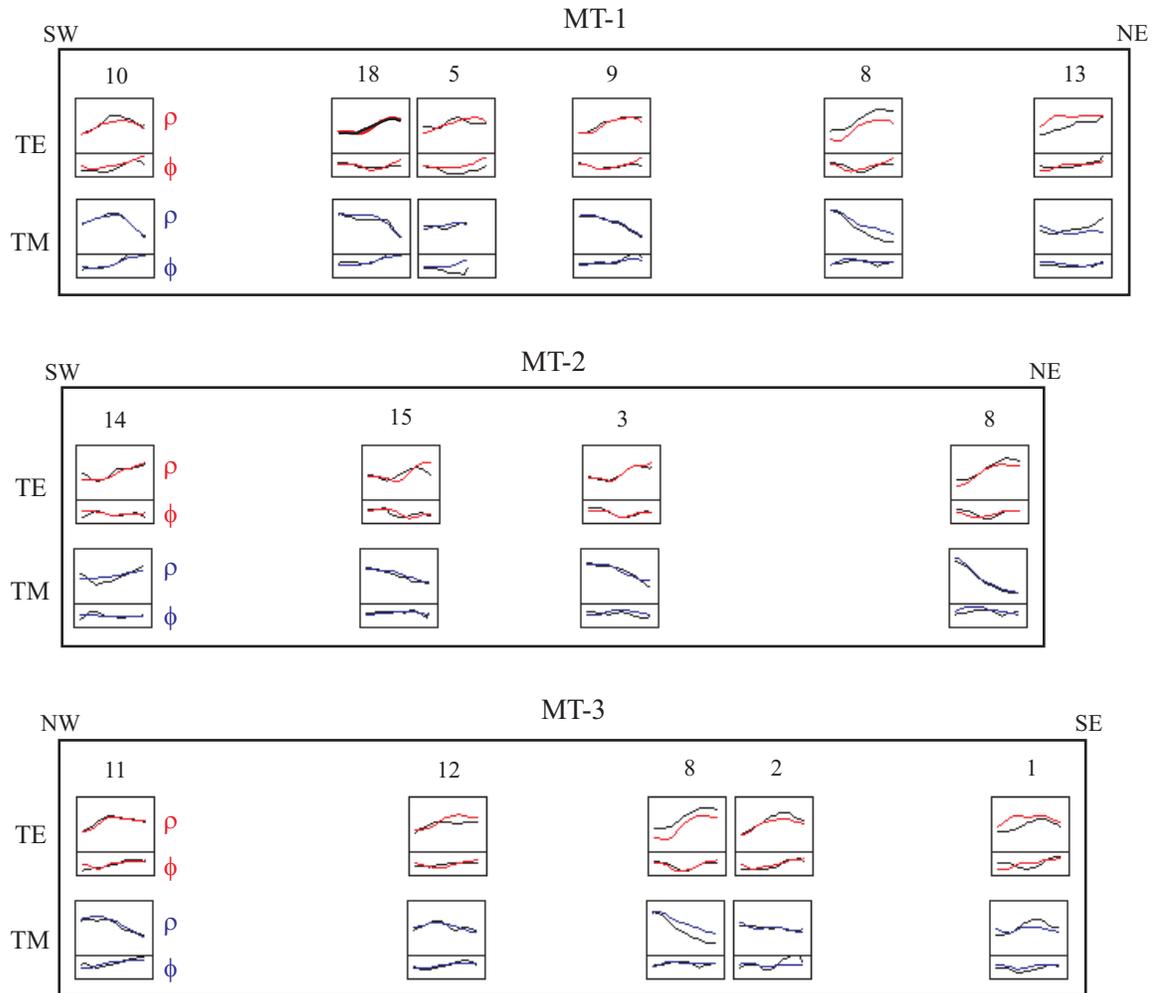
Figure 10. Curve fitting obtained from the 2-D inversion of the three magnetotelluric profiles using an average strike angle of 40 degrees. Red curves correspond to the TE polarization mode whereas the blue ones correspond to the TM polarization. Black curves are the observed resistivities (upper frame) and phases (lower smaller frame).

the granitic basement unless we have knowledge of the actual resistivity ranges of these units, perhaps from geophysical well logs. However, as the ground water is very close to the surface, there is no much lithologic information available from deep wells in the area and still less of well logs to calibrate our electrical sections. Nevertheless, the information provided by the MT soundings is quite useful because it allows to observe lateral relative changes in depth of similar electrical values. On the basis of observed changes in the relative thickness of the conductive unit, a number of faults have been interpreted along the three MT sections. Although their precise location is not possible from the MT sections alone, differences in depth to a conductivity level allow to constrain them between contiguous sites. Figure 11 shows the distribution of faults in the bay and the valley area; those in the valley were derived mainly from the correlation of deduced gravity and MT models, while those in the bay and its vicinity were incorporated from Álvarez-Béjar (2005).

MAGNETIC FIELD MAP

Total-field aeromagnetic data of the study area were collected by the Consejo de Recusos Minerales, (COREMI, today Mexican Geologic Service) in 1983 with a nuclear precession Geometrics G-803 magnetometer installed in an Islander BN2-B27 aircraft; positioning was visual. The flight lines were in a NE 30° orientation, with a terrain clearance of 300 m and line spacing of 1,000 m. The initial data were corrected by COREMI and we performed further data processing by using the Geosoft software (Oasis Assembly Dates Processing and Analysis System). The International Geomagnetic Reference Field from 1980 was subtracted to the total magnetic field data, obtaining the magnetic residual field. Subsequently, the residual magnetic field was reduced to the magnetic pole (Baranov and Naudy, 1964). The reduced to the pole magnetic map (Figure 12) is the result of transforming the dipolar magnetic field into a polar (vertical) magnetic field, therefore the observed anomalies
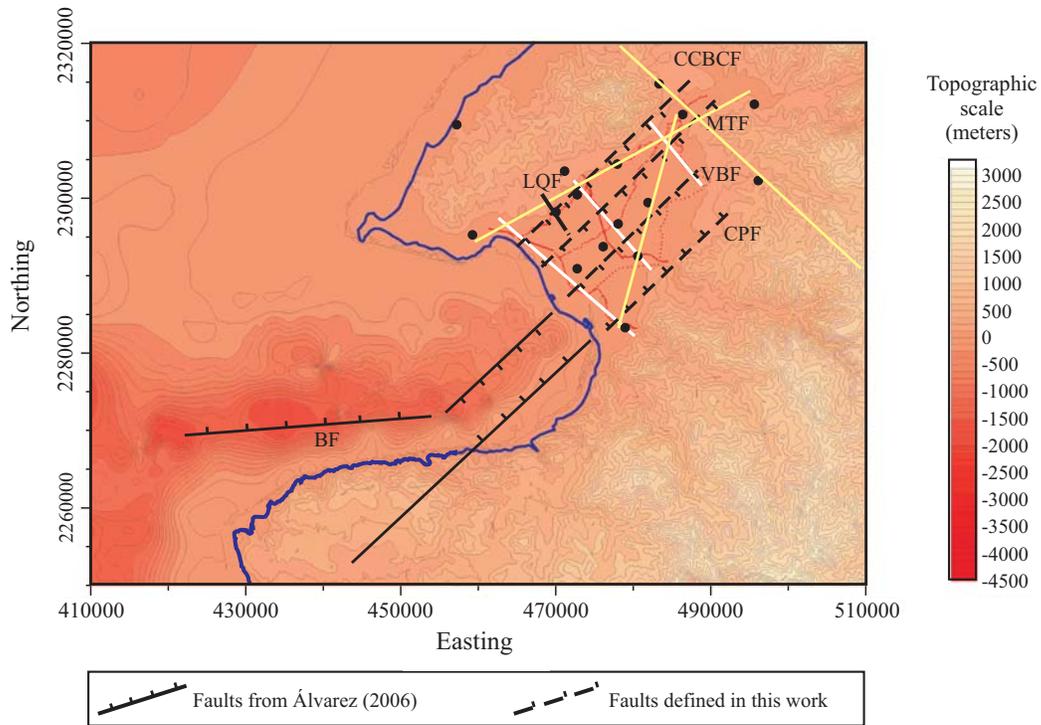
Figure 11. Fault distribution in Valle de Banderas as obtained in this study. The faults shown in the bay were taken from Álvarez (2005b); there is a good correlation between the faults that are located in the bay and the valley. Mezcales-Tebelchía fault (MTF), Valle de Banderas fault (VBF), Pitillal-Cucharitas fault (PCF), Cabo Corrientes-Bucerías-El Colomo fault (CCBCF), Banderas fault (BF), and La Quebrada fault (LQF).
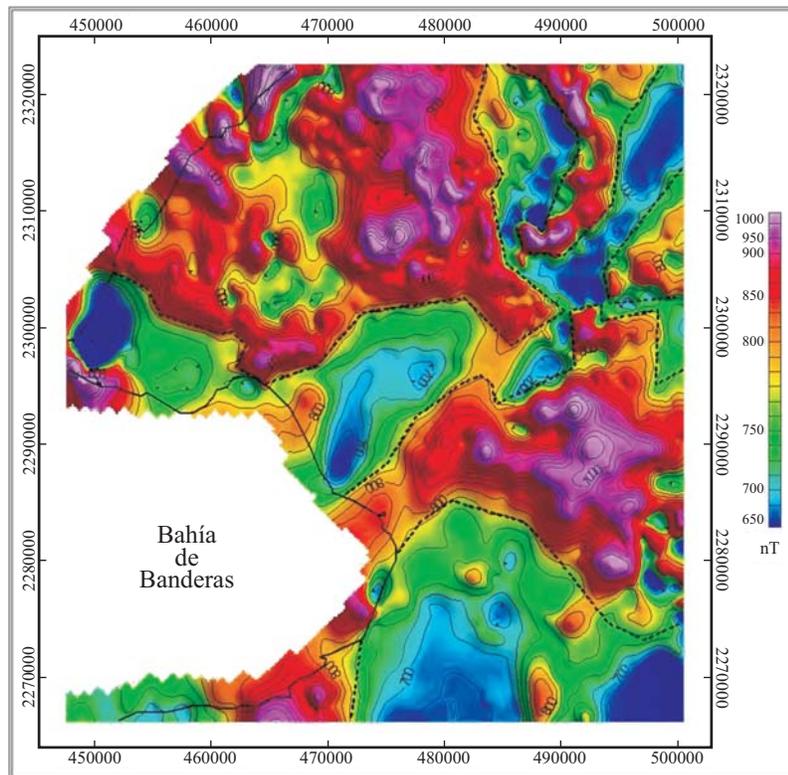

Figure 12. Magnetic anomaly map reduced to the pole of the study area deduced from the total field aeromagnetic map. The region of Valle de Banderas corresponds to a magnetic NE trending low. Dashed line within the valley suggests that the granite unit, showing high magnetization values, can be matched together implying that segmentation has occurred in the past.

can be directly associated to the geological features in the ground. Blue tones represent areas of low magnetic susceptibility ($<10^{-6}$ cgs), while red colors are associated with areas of higher magnetic susceptibility ($>10^{-5}$ cgs). In particular, the sedimentary filling of the Valle de Banderas graben can be associated to a magnetic low in the range of 650–750 nT. In contrast, the surrounding high magnetic values (>850 nT) are correlated with granitic rocks, mostly outcropping around the valley. The separation in a NW and a SE granite blocks of similar magnetic signature suggests that these formed once a single block before fragmentation and separation of the granite unit throughout the Valle de Banderas fault system occurred. The doted line in Figure 12 show the surface limits of the two blocks separated by the graben and suggests a way they could possible match together. Other elongated low to the northeastern corner of the figure may indicated the possible continuation of the extensional regime further north beyond the limits of Valle de Banderas, and into the canyon that confines the Ameca river.

DISCUSSION OF RESULTS

In Figure 11 we have located the Cabo Corrientes-Bucerías-El Colomo fault (CCBCF), which was originally mapped by Lyle and Ness (1991), and recently confirmed in the work of Álvarez-Béjar (2005). The Pitillal-Cucharitas fault (PCF) runs along the southwestern boundary of the valley and, together with the CCBCF, limits its extent in the NW-SE direction. Another set of faults between CCBCF and PCF was also suggested by Álvarez -Béjar (2005), based on the epicentral location of seismic activity in the area (Núñez-Cornú *et al.*, 2002). The CCBCF and VBF continue offshore in Bahía de Banderas, where apparently they have been inducing erosion on the northern flank of the canyon. These results support the idea that Valle de Banderas represents the inland continuation of an extensional zone offshore. The Bahía de Banderas basin (Figure 2) is also inferred to continue into the Valle de Banderas trough modeled with the gravimetric data. A general description of the valley basement derived from the total field (Figure 5), and three cross-sections of the valley (L1, L2, and L3) extracted from the topography-corrected Bouguer anomaly field (Figure 4) show that there are several basin-like regions also observed in the Banderas canyon, which suggests that these structures might represent a typical form of erosion in the zone. Regarding the region from the Banderas canyon up to the northeastern end of Valle de Banderas, it is evident that the graben narrows, which suggests that its development proceeds in this direction. The magnetotelluric model sections also provide evidence of a narrower graben structure to the NE (section MT-3, Figure 9) and strengthen the previous observation that the basement is shallow towards the NE of the Valle de Banderas (sections MT-2 and MT-3, Figure 9). Interpreted faults are quite consistent

between the gravity and MT modeled sections, and can be extrapolated to coincide with the proposed fault system in Bahía de Banderas (Álvarez -Béjar, 2005).

Although it is not possible to conclude directly from the magnetic field map that extension perpendicular to the graben has occurred, it is possible to deduce from the dashed contours limiting the valley that the surrounding granite units can be matched back together by shifting the blocks towards each other in a SE-NW direction (Figure 12). The observation made by Alvarez (2005) regarding the markedly different slopes in the south and north flanks of Bahía de Banderas appears to hold in Valle de Banderas graben, because similar topographic features are present between the SW and NE flanks of the valley, which however were out of the modeled gravity sections (Figure 8).

TECTONIC EVOLUTION MODEL

A simplified model is presented to help understand the development of the Bahía-Valle de Banderas graben. The model mostly represents a compilation of descriptions and ideas already found in the literature and the link to the present results. Figure 13 shows in six steps the tectonic evolution of the study area. Parts (a) and (b) as well as (d) through (f) have been proposed and discussed by various authors, whose references are given along the discussion of the model. We propose part (c) as speculative, inasmuch as we link the first stages of the Banderas graben structure to the extensional deformation along the Magdalena-Cocos plate boundary. This does not affect the previous, or the subsequent stages of the model.

Emplacement of granitic batholiths in the area took place around the Cretaceous-Tertiary boundary (Zimmermann *et al.*, 1988; Schaaf *et al.*, 1995), which we take as the initiation time for our model. According to Calmus *et al.* (1995), the batholith was at a depth of ~1 km in the Eocene (Figure 13a). Rosas-Elguera *et al.* (1996) proposed that the batholith was uplifted in pre-Neogene times (Figure 13b), and concluded that the JB is presently 1 to 2.5 km above its original emplacement level. The limit of the Pacific-Farallon plates at 20 Ma was the Molokai fracture zone, which entered the continent at the location of the Banderas canyon (Larson, 1972) extending it into the continent. Consequently, a fractured limiting zone developed at that time between the uplifted and the static neighboring blocks. The uplifted structure already defined the extent of the Jalisco Block (Rosas-Elguera et al., 1996), making this region its NW limit.

Initiation of rifting and E-SE motion of the JB took place at 14 Ma; the Magdalena microplate began to stagnate, and the decreased subduction rate induced left-lateral and extensional deformation along the Magdalena-Cocos plate boundary that propagated to the continental crust (Ferrari, 1995). We speculate that this deformation propagated along the already weakened region of the NW limit
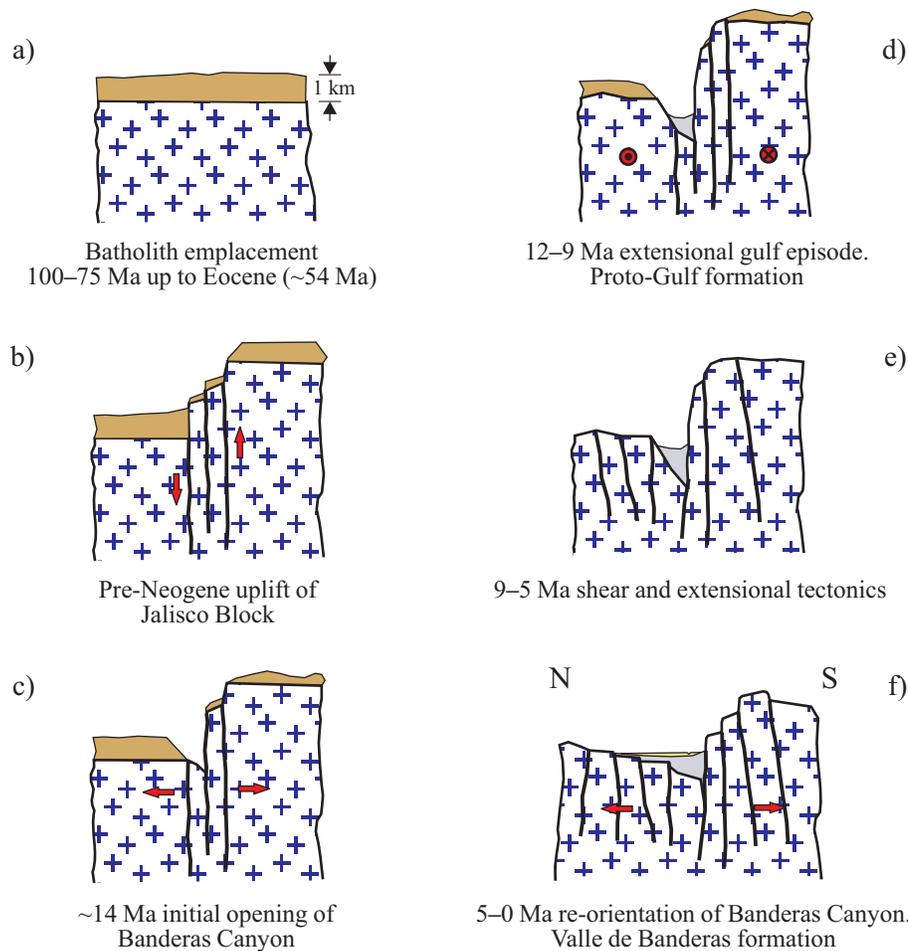
Figure 13. Model of the tectonic evolution of Bahía and Valle de Banderas structures from the Eocene to the Present. The initial formation stages of the bay probably started at ~14 Ma, while those of the valley probably started ~5 Ma.

of the Jalisco Block, probably inducing the first stages of the graben structure of Banderas canyon (Figure 13c). The proto-Gulf of California was formed in the 12–9 Ma period (Karig and Jensky, 1972) by an E-W extensional zone, whose southern limit was Bahía de Banderas (Stock and Hodges, 1989) (Figure 13d). This started the process of separation of Baja California from mainland Mexico; however, it did not induced drifting of the peninsula at this time. Simultaneously, extensional episodes took place inland in the neighborhood of the JB; in the Guadalajara area, an extensional episode (Moore *et al.* 1994) produced extensive basalt flows, and the Jalisco Block-Sierra Madre Occidental boundary acted as a right-lateral transtensional zone, linking E-W extension in the Tepic area with that of the Guadalajara area (Ferrari, 1995).

Thus, the late-Miocene to early-Pliocene period was characterised by major tectonic activity around the area of Bahía de Banderas (Figure 13e); Ferrari and Rosas-Elguera (2000) speculated that it was in this period that the Valle de Banderas graben originated. At ~5 Ma another major tectonic episode took place in the area: the initiation of the

northwestward drifting of Baja California and the beginning of the opening of the Gulf. The sediments in Valle de Banderas were mapped as marine sediments of 5–0 Ma by Fenby and Gastil (1991); this deposition time frame led us to propose that, associated with the initiation of drifting of Baja California, the axis of Banderas canyon changed from an E-W to a NE–SW direction, and that a NE trending family of faults in the valley probably accompanied such a direction change (Figure 13f). The presence of marine sediments in the valley indicates that its floor was under the ocean level, probably in its early stages of development.

CONCLUSIONS

The geophysical data shows that the Valle de Banderas has an irregular basement that deepens to 2.5 km close to the shoreline. Towards the NE, the graben becomes narrower and the basement shallower. Cabo Corrientes-Bucerías-El Colomo Fault (CCBCF), and Cucharitas-Pitillal Fault (CPF) flank the valley in the NW and SE regions, respectively;

the SE flank of the valley rapidly drops to 2 km, while towards the NW it raises more gently; a similar behavior has been observed in the Banderas canyon (Alvarez, 2005; Álvarez-Béjar, 2005). A possible explanation for the origin of the asymmetry is the uplift of the Jalisco Block, which created a sharp drop at the uplifted flank versus the flank that apparently was not uplifted. This structure evokes that of a half-graben. The classification of the valley materials as marine sediments (Gastil *et al.*, 1979; Fenby and Gastil, 1991) suggests that the valley was below sea level, probably at the early stages of its formation.

The 2-D resistivity distribution at different depths suggests that the observed anomalous conductivity at shallow and deeper depths respond to different causes. The shallow conductor is associated to the sedimentary filling the graben, part of which may be of marine origin. The deep conductor (10 km) might be related to the dehydration process (Jödicke *et al.*, in press) of the Rivera Plate under the Jalisco Block. However, at this point this argument is regarded as a hypothesis that has to be further analyzed. The magnetic data suggest that the graben structure corresponds to an extensional zone, which continues to the NE of the valley. This extensional zone apparently divides a granitic formation that constituted a single unit before extension started. Major branching to the SW from the Tepic-Zacoalco graben zone suggested by Johnson and Harrison (1990) may effectively connect with the Valle de Banderas and Bahía de Banderas fault zone hinted by the results shown here.

The structural results obtained in this work support (1) the graben structure of Valle de Banderas, (2) the strike change of Banderas canyon in the direction of the valley axis, and (3) the continuation of Banderas canyon inland into Valle de Banderas.

ACKNOWLEDGEMENTS

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