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Bahía de Banderas, Mexico: Morphology, Magnetic Anomalies and Shallow Structure

CARLOS A. MORTERA GUTIÉRREZ,[1] WILLIAM L. BANDY,[1] FRANCISCO PONCE NÚÑEZ,[2] and DANIEL A. PÉREZ CALDERÓN[1]

Abstract—The Bahía de Banderas lies within a tectonically complex area at the northern end of the Middle America Trench. The structure, morphology, subsurface geology and tectonic history of the bay are essential for unraveling the complex tectonic processes occurring in this area. With this focus, marine geophysical data (multi-beam bathymetry, high resolution seismic reflection and total field magnetic data) were collected within the bay and adjacent areas during four campaigns aboard the B.O. EL PUMA conducted in 2006 and 2009. These data image the detailed morphology of, and sedimentation patterns within, the Banderas Canyon (a prominent submarine canyon situated on the south side of the bay) as well as the shallow subsurface structure of the northern part of the bay and the submarine Marietas Ridge, which bounds the bay to the west. We find that the Marietas Ridge is presently a transtensional feature; the course of the Banderas Canyon is controlled by extensive turbidite fan sedimentation in its eastern extremity and by structural lineaments to the west; the canyon floor is filled by sediments and exhibits almost no evidence for recent tectonic movements; the southern canyon wall is quite steep and a few sediments are deposited as submarine fans at the base of the southern wall; and extensive turbidite fans form the lower part of the northern canyon wall, producing a gently sloping lower northern wall. We find no evidence for a regional east–west striking lineament between the bay and the Middle America Trench, which casts doubts on the previous assertion that the Banderas Canyon is unequivocally related to the presence of a regional half-graben. Finally, a N71°E oriented normal fault offsets the seafloor reflector by 15 m within the central part of the bay, suggesting that the bay is currently being subjected to NNW–SSE extension.

Key words: Bahía de Banderas, Banderas Canyon, marine geophysics, Canyon morphology, subsurface structure, multi-beam bathymetry.

1. Introduction

The Bahía de Banderas is a broad, tectonically active, coastal embayment located on the Pacific margin of Mexico offshore of Puerto Vallarta, Jalisco (Fig. 1). Geologically, the bay is important because it is the offshore extension of the tectonically active Rio Ameca Rift (e.g., Johnson and Harrison 1989, 1990; Núñez-Cornú et al. 2000, 2002; Arzate et al. 2006), which has been proposed to be the northern boundary of the Jalisco Block (e.g., Johnson and Harrison 1989); a small crustal block which may be in the process of slowly rifting away from the rest of North America (Luhr et al. 1985; Bandy and Pardo 1994; Selvans et al. 2011).

Given its tectonic importance, surprisingly few detailed marine geological and geophysical studies have been carried out within the bay and in the offshore area between the bay and the Middle America Trench (MAT). Existing studies include (1) several cursory bathymetric surveys using conventional wide-beam echo-sounders and satellite altimetry data (Fisher 1961; Dauphin and Ness 1991; Alvarez 2007) and a bathymetry map (Núñez-Cornú et al. 2016) constructed from multibeam data collected during the CORTES 96 and TsuJal projects (Dañobeitia et al. 1997; Córdoba et al. 2014), (2) geological and geochemical studies related to observations of present day submarine hydrothermal activity within the bay (Núñez-Cornú et al. 2000; Taran et al. 2002), and one cursory total field magnetic survey (Alvarez et al. 2010). In addition to these studies, several earthquake studies have been conducted in the area of the Bahía de Banderas (e.g., Núñez-Cornú et al. 2002; Rutz López 2007; Núñez-Cornù 2011; Rutz López et al. 2013) and presently the bay is covered by a local seismic network (Red Sísmica y Acelerométrica Telemétrica de Jalisco, RESAJ) (Núñez-Cornù et al. 2011) operated by the Universidad de Guadalajara,

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[1] Instituto de Geofísica, Universidad Nacional Autónoma de México, Ciudad Universitaria, Delegación Coyoacan, 04510 Mexico, DF, Mexico. E-mail: cmortera@geofisica.unam.mx

[2] Instituto de Ciencias del Mar y Limnología, Universidad Nacional Autónoma de México, Ciudad Universitaria, Delegación Coyoacan, 04510 Mexico, DF, Mexico.

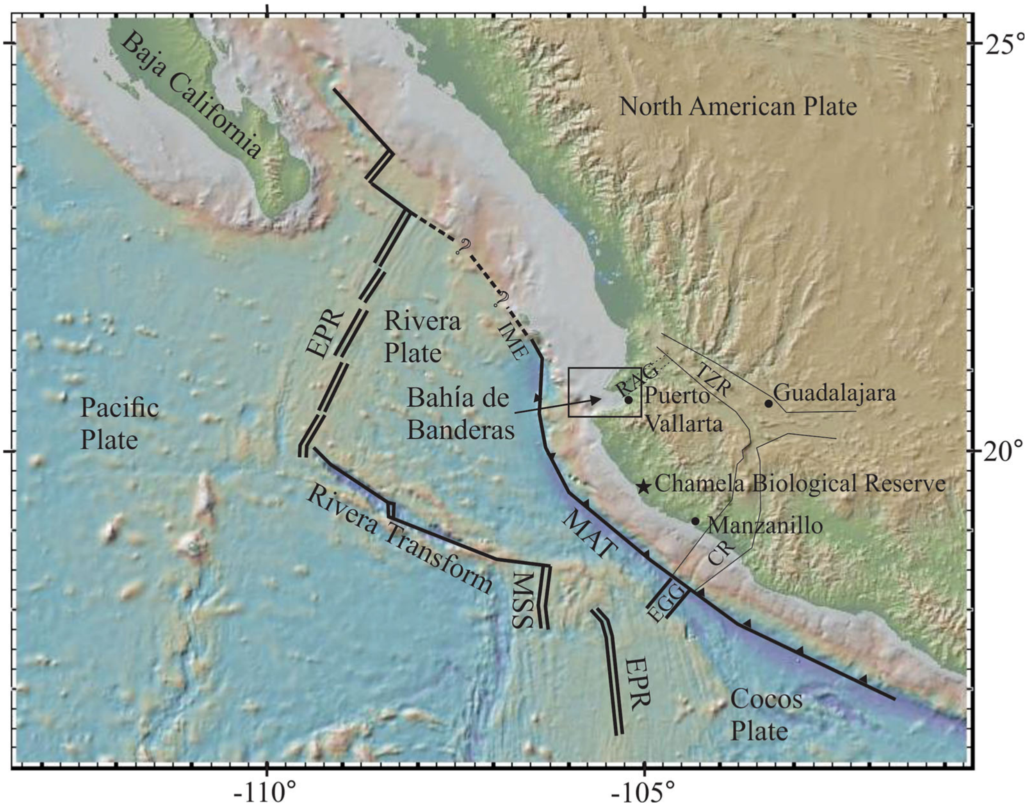

Figure 1

Location of study area (*rectangle*). *CR* Colima Rift, *EGG* El Gordo Graben, *EPR* East Pacific Rise, *IME* Islas Marias Escarpment, *MAT* Middle America Trench, *MSS* Moctezuma Spreading Segment, *RAG* Rio Ameca Graben, *TZR* Tepic Zacoalco Rift. Background map from http://www.geomapapp.org which was constructed with elevation data from http://ned.usgs.gov, http://asterweb.jpl.nasa.gov, and http://topex.ucsd.edu/WWW_html/mar_topo.html

Puerto Vallarta (SisVoc). These studies found many interesting features within the bay worthy of further investigation; for example, active hydrothermal vents along the northern margin of the bay, and a very prominent submarine canyon along the bay's southern margin, and seismic activity within the bay.

The initial formation of the bay has been proposed to be related to the opening of the Gulf of California (e.g., Ferrari 1995) in the middle to late Miocene. Since that time the bay has been subjected to several distinct tectonic environments. Thus, one might reasonably expect to observe a complex array of morphotectonic structures in this area and unraveling their development history will most likely require very detailed datasets.

With the aim of better defining the morphology, subsurface geology and tectonic history of the Bahía de Banderas and surrounding area, detailed total field marine magnetic data, conventional and multibeam bathymetric data and sub-bottom seismic reflection data were collected from 2006 to 2009 during four marine geophysical campaigns of the B.O. EL PUMA which is owned and operated by the Universidad Nacional Autónoma de México (UNAM); these campaigns are the PMITA01, BABRIP06 and MORTTIC06 campaigns conducted in 2006 and the MORTIC08 campaign conducted in January 2009. Herein we present a detailed analysis of these previously unpublished data.

2. *Tectonic and Geologic Setting*

The Bahía de Banderas is situated in a tectonically complex region near the northern terminus of the Middle America Trench off Puerto Vallarta, Jalisco, Mexico (Fig. 1). No clear evidence exists to determine the age of the initial formation of the bay. However, the orientation of the bay, roughly perpendicular to the transform faults of the southern Gulf of California, is consistent with the proposals that it initially formed in association with the opening of the southern Gulf of California in the middle Miocene, between 12 and 14 Ma (e.g., Lyle and Ness 1991; Ferrari 1995; Arzate et al. 2006). Since its initial formation, the area has been affected by a variety of stress regimes; these include: (1) stresses arising from the separation of the Jalisco Block from the rest of the North American Plate, most likely initiated during the early Pliocene (Luhr et al. 1985; Allan 1986; Allan et al. 1991), (2) stresses arising from plate motion changes associated with ridge-trench collisions and the resulting separation of the Rivera Plate from the Cocos Plate which appears to have been initiated in the mid to upper Miocene (Lonsdale 1991; DeMets and Traylen 2000), and (3) stresses arising from the highly oblique subduction between the Rivera Plate and the Jalisco Block along the northernmost part of the Middle America Trench (Kostoglodov and Bandy 1995). Further, Maillol et al. (1997) proposed that the Valle de Banderas graben has been subjected to stresses arising from a regional right-lateral shear couple affecting the NW part of the Jalisco Block. Additionally, there is growing evidence (e.g., Couch et al. 1991; Brown et al. 2009; Bartolomé et al. 2011) that subduction along the Middle America Trench is presently progressing to the northwest along the Islas Marias Escarpment (i.e. a new trench may be in the process of developing along the escarpment). If so, then the area of Bahía de Banderas presently may be subjected to stresses related to the bending of the Rivera Plate as it begins to subduct beneath the escarpment. This could explain the observed deepening of the trench as it approaches the escarpment (Bartolomé et al. 2011).

Structurally, the bay appears to be the offshore extension of the Rio Ameca Rift (Fig. 2) (the Rio Ameca Graben of Johnson and Harrison 1989) which is a regional, NE–SW zone of crustal extension located between the Tepic-Zacoalco Rift to the NE and the Pacific coast, NW of Puerto Vallarta, Jalisco, Mexico, where it is delineated by a broad alluvial plain. This alluvial filled valley has been called the Puerto Vallarta Graben (Ferrari and Rosas-Elguera 2000) or, alternatively, the Valle de Banderas Graben (Arzate et al. 2006). Herein, we will refer to the combination of the onshore, sediment filled, topographic depression and the Bahía de Banderas as the "Puerto Vallarta Graben". We will use the term "Rio Ameca Rift" to refer to the regional extensional zone identified by Johnson and Harrison (1989). Thus, the Puerto Vallarta Graben is the western part of the Rio Ameca rift. Several previous authors have made a distinction between the offshore and onshore parts of the Puerto Vallarta Graben (Arzate et al. 2006; Alvarez 2007). We will refer to the onshore part of the Puerto Vallarta Graben as the "Valle de Banderas", and the offshore part of the Puerto Vallarta Graben will be referred to as the "Bahía de Banderas". Note that, unless otherwise specified, we use the term "graben" in a generic sense, without regards to whether or not it is a half- or full-graben.

The Rio Ameca Rift has been proposed based on structural geology to mark the NW boundary of the Jalisco Block (e.g., Johnson and Harrison 1989; Alvarez 2002; Rutz-López and Núñez-Cornú 2004). However, other investigators, based on petrologic, lithologic and magnetic characteristics, place the limit somewhat further to the north within the Tepic-Zacoalco rift (e.g., Ferrari 1995; Rosas-Elguera et al. 1996; Ferrari and Rosas-Elguera 2000; Urrutia-Fucugauchi and González-Morán 2006). Young fault scarps, thermal springs and seismicity indicate that the western part of the rift (i.e. the Puerto Vallarta Graben) is tectonically active at present (Ferrari et al. 1994; Dañobeitia et al. 1997; Ferrari and Rosas-Elguera 2000; Núñez-Cornú et al. 2000; Alfonso et al. 2003; Taran et al. 2002, 2013; Canet and Prol-Ledesma 2007). However, it is noteworthy that, even with the installation of a local seismic red (RESJAL) in the area of the bay, the bounding faults of this proposed graben are not well defined by presently recorded seismicity (e.g., Núñez-Cornú et al. 2000, 2002; Rutz-López and Núñez-Cornú 2004; Rutz López et al. 2013).

Overall, the study area lies within the granitic Puerto Vallarta Batholith (e.g., Böhnel and Negendank 1988; Schaaf et al. 1993) (Fig. 2) and can be subdivided into six distinct physiographic provinces. Within the confines of the Bahía de Banderas, two

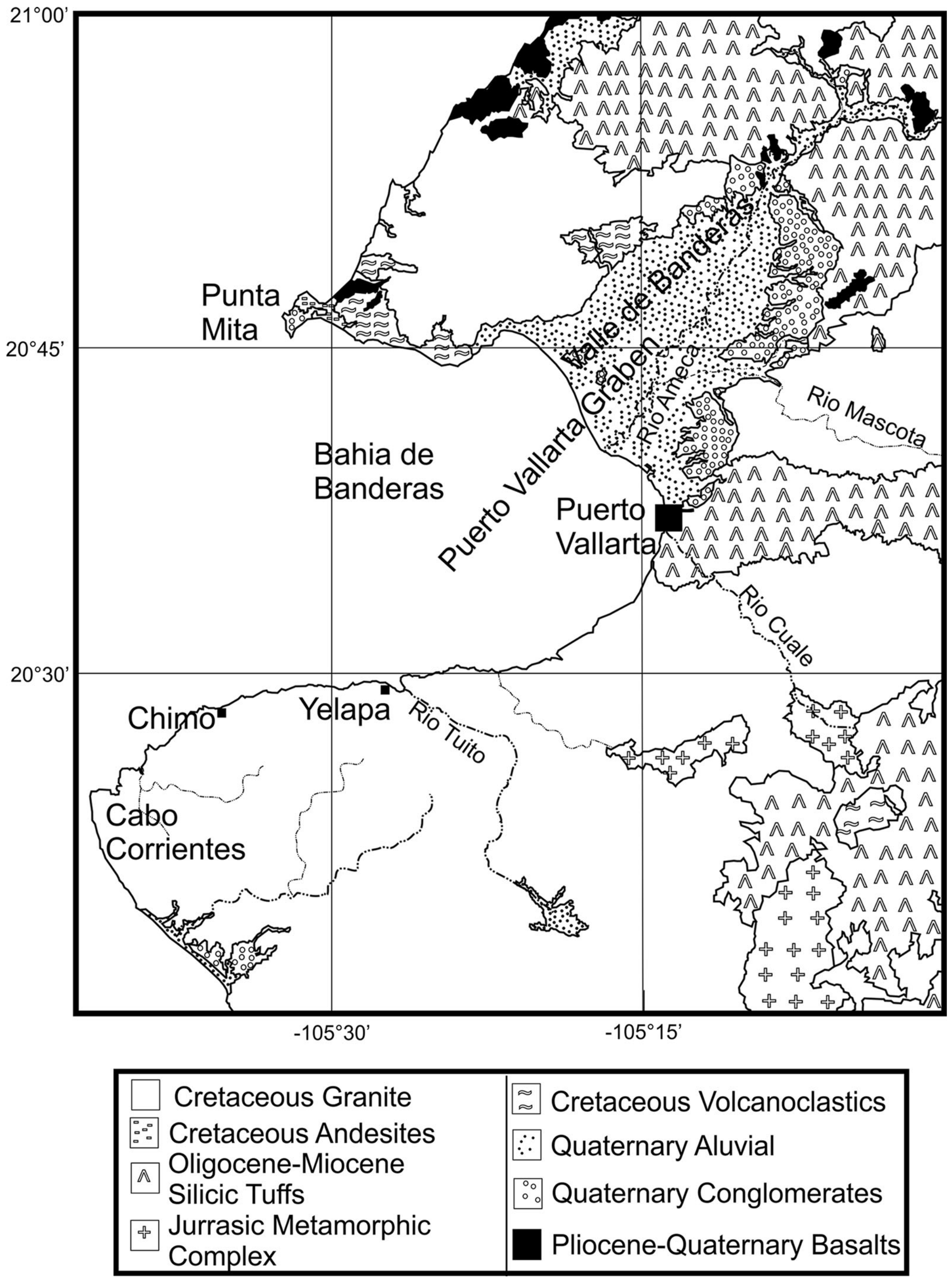

Figure 2
Geologic map of the study area Modified from INEGI (1988)

provinces are observed; herein referred to as the Northern and Southern Bay provinces. The Southern Bay Province is delineated by the presence of a deep submarine canyon, which we refer to as the Banderas Canyon (Fig. 3) (e.g., Fisher 1961), within which depths reach in excess of 1.5 km at the mouth of the bay just north of Cabo Corrientes. The Banderas Canyon has been proposed, based on bathymetry and magnetic data (Alvarez 2007; Alvarez et al. 2010), to lie within a half-graben structure, the main fault located along the southern margin of the bay. However, no direct evidence (such as seismicity) for such faulting has been presented in the literature and if present, the main fault does not extend onshore where one could easily confirm its existence. In contrast to the Southern Bay Province, the Northern Bay Province is distinguished by a shallow platform (for the most part <100 m). The "Fisura de la Coronas" and associated hydrothermal springs are located within this province (Núñez-Cornú et al. 2000). Taran et al. (2013) found low $^3He/^4He$ isotope ratio values (0.4 Ra) in this area. The Northern Bay Province is bounded to the west by the Marietas Ridge. Very little is known about the subsurface geology of these marine provinces including the Marietas Ridge.

The third province, the Granitic Highlands Province, bounds the bay to the south and consists almost exclusively of surface exposures of Cretaceous granitic rocks. However, an extensive, east–west trending band of Oligocene–Miocene volcanic tuffs is observed (Fig. 2) at 20°37′N; the tuffs being flanked on the north and south by the granites. No faults have been recognized at the contacts between the tuffs and granites, thus, these tuffs most likely infilled a topographic depression present at the time when the tuffs were deposited. These tuffs intersect the coastline

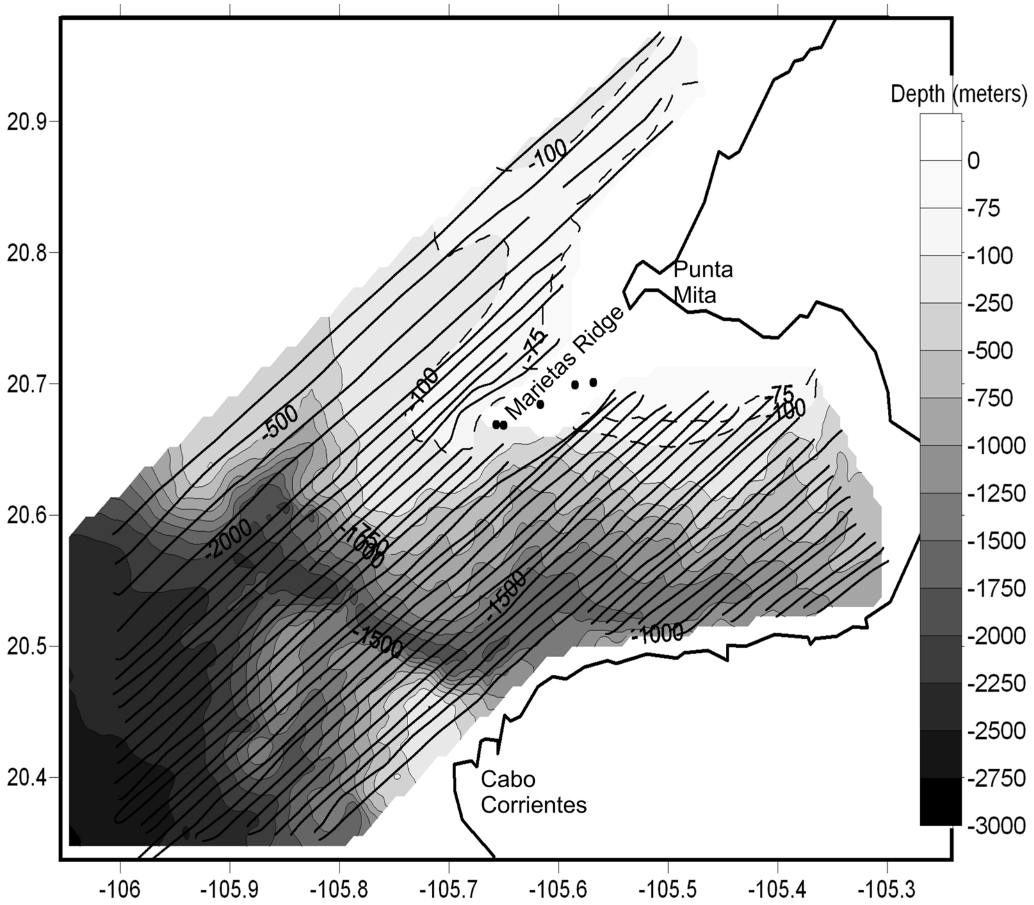

Figure 3

Ship tracks along which magnetic and single beam bathymetric data were collected during the 2006 PMITA campaign. The survey consisted of *41 lines* with an average spacing of 1.5 km. Background bathymetric map (contour interval = 250 m) was constructed using only the single beam echo sounder bathymetric data collected during the PMITA campaign near the town of Puerto Vallarta, in the vicinity of the mouth of the Banderas Canyon, and, therefore, may be important to the development of the submarine canyon within the bay since the tuffs are more easily eroded than the surrounding granites. This province has undergone several episodes of uplift. Based on the lack of the Sierra Madre Occidental ignimbrites in the Puerto Vallarta Batholith, Rosas-Elguera et al. (1996) proposed that the batholith was uplifted and the ignimbrites eroded prior to the Neogene. Based on the geomorphology (wave-cut terraces, notches, etc.) along the Jalisco coast, Ramírez-Herrera et al. (2011) proposed that the Puerto Vallarta Batholith has been uplifted since at least the Pliestocene to the present, the rates of uplift being 0.7–0.9 m/ka during the Pliestocene and increasing to 3 m/ka during the Holocene. Taran et al. (2013) found high ^{3}He/^{4}He isotope ratio values (2.3 Ra) in the El Tuito Springs (20°22.2′N, 105°26.4′W) indicating a high concentration of mantle helium. This is typically thought to be due to deep crustal fractures, which makes the crust permeable to the mantle helium.

The fourth province is the Valle de Banderas Province located east of the bay. This province is readily delineated by the Quaternary alluvial surface deposits found within the valley. Although no deep wells have been drilled within the Puerto Vallarta Graben to directly determine the types and thicknesses of the sediments infilling the graben, its subsurface structure has been inferred from gravity, magnetic and MT data (Arzate et al. 2006; Alvarez et al. 2010). These data have been interpreted to indicate a graben/half-graben structure filled by up to 2.5 km of sediments near the coast, with the sediment thickness decreasing northeastward. Clearly, our knowledge of the area would greatly benefit from a drilling/coring program. Taran et al. (2013) found high ^{3}He/^{4}He isotope ratio values (up to 4.5 Ra) within the valley indicating a high concentration of mantle helium.

The fifth province is the Punta Mita Province, which bounds the bay to the north. The most distinguishing feature of the Punta Mita Province is the great variation in the types of rocks outcropping within the province. In addition to outcrops of the granitic rocks typical of the Granitic Highlands Province to the south, outcrops of Paleozoic metamorphics, marbles and silicic tuffs, and Miocene (approximately 10 Ma) basalts and basaltic dikes are observed (INEGI 1988; Fernández de la Vega-Márquez and Prol-Ledesma 2011). The basalts are reported to have “erupted in submarine conditions forming massive lava, pillow lava and pillow breccias intercalated with repetitiously and thinly bedded mudstone (turbidite deposits) and ash beds” (Jensky 1974; Sawlan 1991). K–Ar ages for these basalts range from 7.5 to 12.5 Ma (Sawlan 1991). The geology of the Marietas Ridge is poorly studied, however, there are reports that the Islas Marietas, which lie along the Marietas Ridge, are predominantly of volcanic origin (e.g., Cano Sánchez 2004). Given this and the location of the ridge near Punta Mita, we tentatively propose that the ridge is the offshore extension of the Punta Mita Province. If correct, then the age of the volcanics comprising the islands would most likely correspond to that of the volcanic episodes noted within the onshore part of the province (7.5–12.5 my). Taran et al. (2013) found low ^{3}He/^{4}He isotope ratio values (0.6 Ra) in this area.

Almost immediately outside the confines of the bay, the seafloor depths increase abruptly to greater than 3 km, and a broad flat terrace forms the majority of the continental slope in this area. This area is the sixth province, herein called the Slope Terrace Province.

3. *Data and Methods*

The data used in this study consists of previously unpublished total field magnetic data, single beam and multibeam bathymetric data, seafloor backscatter strength data and sub-bottom seismic reflection data. These data were collected during four campaigns of the B.O. EL PUMA conducted since 2006, namely, the PMITA01, BABRIP06 and the MORTIC06 campaigns in 2006 and the MORTIC08 campaign in January 2009. For all campaigns, the ship’s location was determined using non-differential GPS navigation.

3.1. *Magnetic Data*

The total field magnetic data presented herein were collected along 41 profiles during a single cruise, PMITA01, conducted during 12–18 January 2006, using a GEOMETRICS G877 marine proton precession magnetometer. The data coverage is illustrated in (Fig. 3). The magnetic sensor was towed 250 m behind the ship to minimize the effects of the ship (a 50 m long, steel hulled vessel) on the measurements. Measurements were taken every 2 s. The location of the sensor behind the ship was calculated as the data were recorded using GEOMETRICS MAGLOG LITE software.

The recorded total field magnetic measurements were reduced to magnetic anomalies by first subtracting the reference value of the Earth's magnetic field, and then correcting for diurnal variations and the effects of the ship's heading. The IGRF11 model (IAGA, working Group V-MOD 2010) was used to calculate the reference value for each measurement. The calculated magnetic field values are definitive for dates prior to 2010 (i.e. for all our data).

To correct for diurnal variations, a permanent base station was installed onshore within the UNAM Biological Reserve located near Chamela, Jalisco (19°29′56.1″N, 105°02′32.1″W; ~120 km southeast of the bay). A site-selection magnetic survey was run to find a location where the local horizontal magnetic gradient was <0.1 nT/m. Measurements of the total field were made with a GEOMETRICS G856AX proton precession magnetometer at 1 min intervals. The diurnal variations (Fig. 4) for the survey dates were fairly regular with variations being for the most part less than ±20 nT. According to the Dst-Indice of the WDC for Geomagnetism, Kyoto, Japan, no magnetic storms occurred during the survey period.

After correcting for diurnal variations, the data were then corrected for ship's heading following the methods of Bullard and Mason (1961), Whitmarsh and Jones (1969) and Buchanan et al. (1996). Finally, the anomaly data were gridded (100 m × 100 m grid

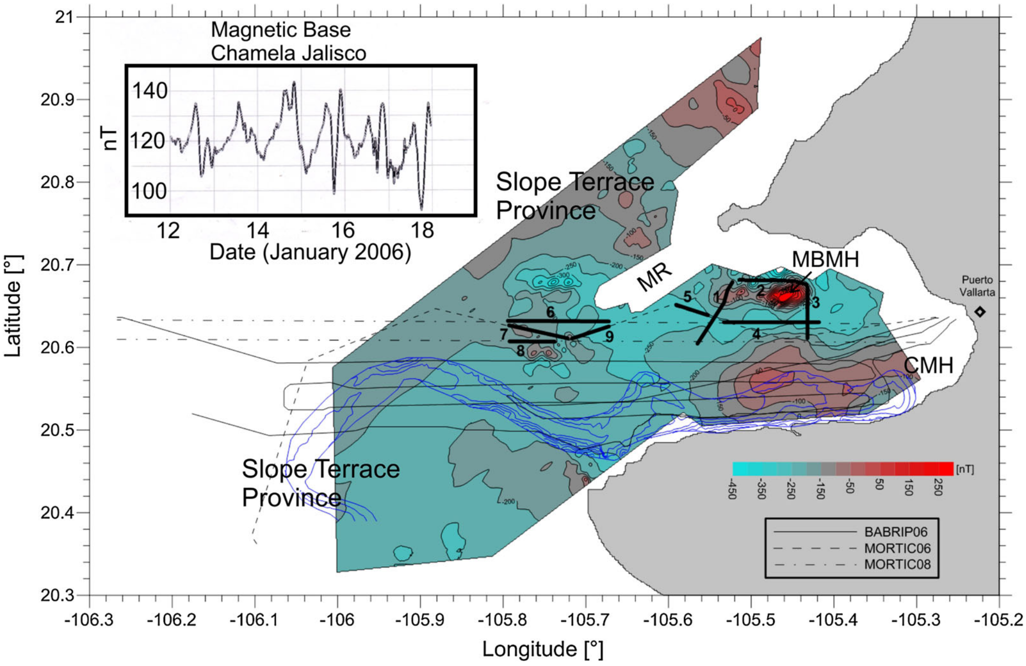

Figure 4

Map showing location of ship tracks along which multibeam bathymetric and subbottom seismic reflection data was collected during the BABRIP06, MORTIC06 and MORTIC08 campaigns of the B.O. EL PUMA superimposed on the magnetic anomaly contour map (contour interval = 50 nT) constructed from the data collected during the PMITA campaign. *Numbered bold lines* locate the seismic reflection profiles illustrated in the various *figures* of this article. The *solid line* contours (from the multibeam data) reveal the canyon floor. The *inset* is a plot of the diurnal variations recorded at the Chamela base for 12–18 January 2006. *CMH* canyon magnetic high, *MBMH* Mid-Bay magnetic high, *MR* Marietas Ridge node spacing) and contour maps of the data were constructed.

3.2. *Bathymetric and Seafloor Backscatter Strength Data*

Depth measurements were also collected during the PMITA campaign using the Kongsberg ES60 (with a 38 kHz transducer) single beam echosounder. These data were also collected along the ship tracks shown in Fig. 3: however, only the data collected in the areas not covered by the multibeam data are used in the construction of the final bathymetry map of the bay.

Multibeam bathymetry and seafloor backscatter data were recorded during the MORTIC06 (12–13 October 2006), BABRIP06 (5–11 October 2006) and the MORTIC08 (3–23 March 2009) campaigns of the B.O. EL PUMA. The locations of the ship tracks along which these data were obtained are illustrated in Fig. 4. These data were obtained using the KONGSBERG EM300 multibeam system, which is permanently installed on the B.O. EL PUMA. Post-processing of these data was done at the Marine Geophysics Lab of the Instituto de Geofísica, Universidad Nacional Autonoma de Mexico, using IFREMER's CARAIBES software package. Processing included editing of ambient noise, gain adjustments to the backscatter data and, if needed, adjustments for inaccurate water velocity profiles and inaccurate ship's motion calibration parameters. After cleaning and adjustments had been made, the data was gridded (grid node spacing of 30 m) and contour and shaded relief maps were generated for both the bathymetry and backscatter strength (Fig. 5).

3.3. *Sub-bottom Seismic Reflection Data*

Single channel seismic reflection data (sub-bottom profiles) were also recorded during the MORTIC06, BABRIP06 and the MORTIC08 campaigns of the B.O. EL PUMA, concurrent with the collection of the multibeam bathymetric data (see Fig. 4 for profile locations). The sub-bottom seismic reflection data were collected using the Kongsberg TOPAS-PS18 Parametric Sub-bottom Profiler, which is also permanently installed aboard the B.O. EL PUMA. The source pulse was a 1.5–5.5 kHz chirp waveform, 15 ms sweep. The sample rate for recording the returning signal was 33 µs. Although the p-wave velocity within the sediments is unknown, we estimate that the vertical resolution is less than 1 m (more details of the system specifications can be found at the Kongsberg web page). The data were processed during their collection (application of match filter, time varying gain and instantaneous amplitude processing) and analog (gif-files) displays of the resulting profiles were made and stored along with the raw field data. Post-cruise processing was limited to gain adjustment and redisplay using the TOPAS-REPLAY software. Depth sections were made using a constant velocity of 1450 m/s.

4. *Results*

4.1. *Magnetic Signature of the Bahía de Banderas*

The map of the magnetic data illustrates a very simple magnetic character within the confines of the Bahía de Banderas (Fig. 4); the majority of the area exhibiting negative values. In the Southern Bay Province magnetic anomalies are greater than −200 nT and form a broad, magnetically high area (herein called the "Canyon Magnetic High") elongated S84°E. The Canyon Magnetic High contains two isolated highs; one located at 20.56°, −105.48° with maximum value of −25 nT, and the other located at 20.54°, −105.38° with a maximum value of −47 nT. Of particular importance is that the Canyon Magnetic High is confined to the bay and the submarine canyon lies for the most part within the anomaly (Fig. 4). Thus, the canyon location is clearly not being controlled by any regional east–west striking structure that crosses the forearc from the bay to the MAT, such as the previously proposed Banderas Fault (e.g., Fisher 1961; Lyle and Ness 1991; Alvarez 2007; Alvarez et al. 2010). We interpret the Northern Bay Province to be an overall magnetically low area, with values lower than those of the Southern Bay Province, however, given the shallow depth in the northernmost part of the bay, we were unable to collect magnetic data in that area during the BABRIP06 campaign. This overall

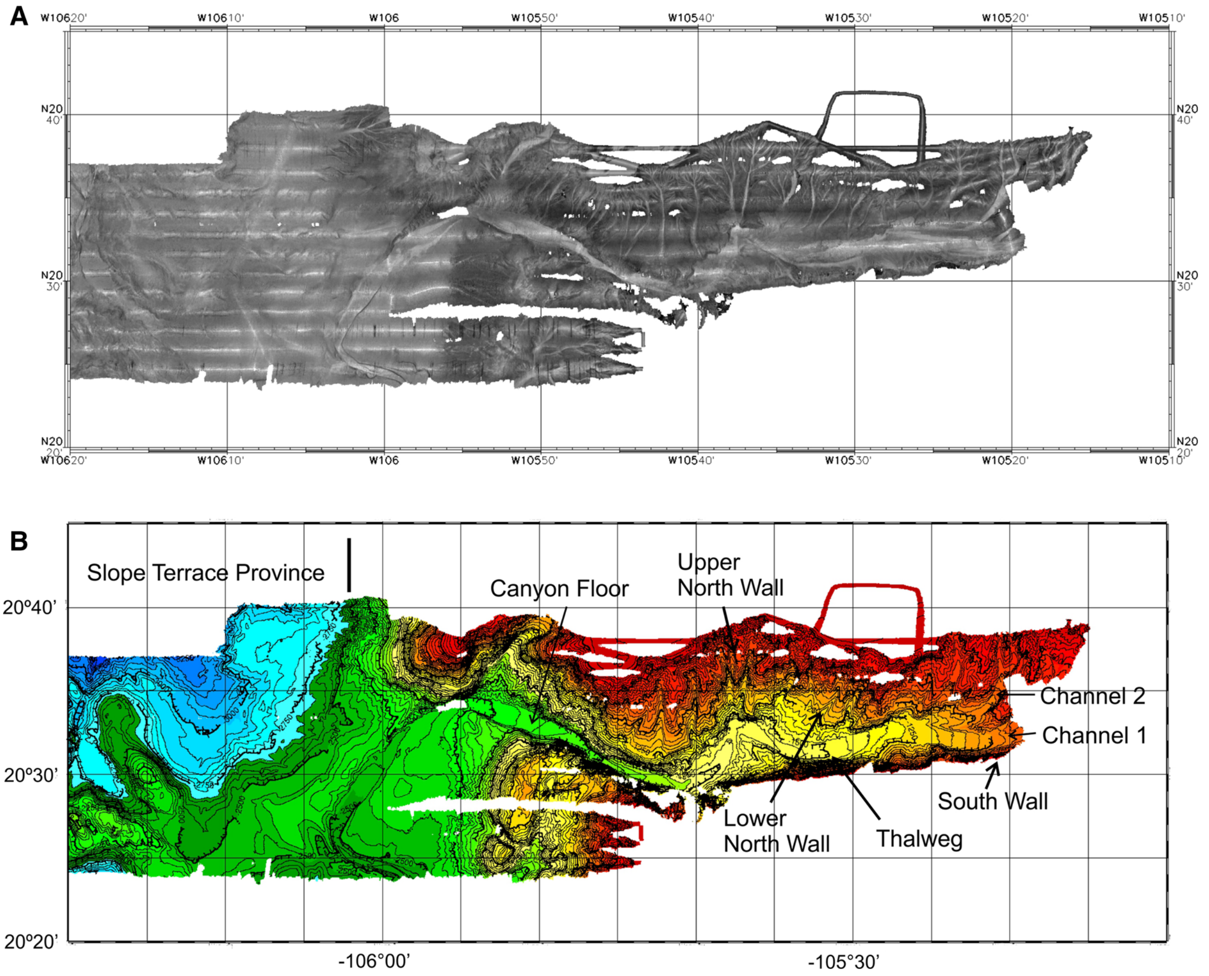

Figure 5
Seafloor backscatter strength image (*top*) and bathymetric contour map (*bottom*) constructed from the new multibeam data (contour interval for the bathymetry map is 50 m)

negative region is disrupted in its western half by a prominent east–west trending magnetic high (herein called the Mid-Bay Magnetic High) where amplitudes reach up to 413 nT. The Mid-Bay Magnetic High appears to extend northwestward across the Marietas Ridge and into the Slope Terrace Province where it may connect with a weak, NNW-SSE orientated, magnetic-high.

Between the Mid-Bay Magnetic High and the Canyon Magnetic High, one observes a magnetic low elongated east–west. Within the bay south of the Mid-Bay Magnetic High, this low magnetic anomaly extends along the boundary between the Southern and Northern Bay Province (i.e. along the upper part of the northern flank of the canyon). This magnetic low appears to extend across the Marietas Ridge and into the Slope Terrace Province where a similar east–west oriented magnetic low is observed. However, the magnetic low in the Slope Terrace Province is shifted by about 2 km to the north relative to its counterpart within the bay. This is consistent with a small amount of northward translation of the continental slope region relative to onshore area noted to the south (Bandy et al. 2005; Urías Espinosa et al. 2016), as well as with a slight northward translation of a forearc block due to the highly oblique convergence of the Rivera plate with respect to the North American plate in this region (e.g., Kostoglodov and Bandy 1995). It is important to note that this prominent elongated magnetic low in the Slope

Terrace Province does not cut across the entire survey area, suggesting that this anomaly also does not correspond to a major regional fault which extends from the bay to the MAT.

In the Slope Terrace Province south of 20.5°N the magnetic contours are quite smooth exhibiting long wavelengths (>10 km) and fairly small variations in amplitudes (<200 nT) (note: some artifacts of the acquisition geometry are observed on this map in this region; specifically, heading errors, and perhaps an incomplete diurnal correction, were not fully removed from the data as is indicated by the small deflections, zig-zag pattern, of the contours). Here, no anomalies are observed to completely cross the survey area in a general east–west direction. In contrast, in the Slope Terrace Province north of 20.5°N (i.e. west of the Marietas Ridge), anomalies are observed with shorter wavelengths (<5 km) and larger amplitude variations (up to 400 nT) compared with those to the south. This also suggests that the geology in Slope Terrace Province changes seaward of the bay, most likely due to faulting and associated volcanism in the Slope Terrace Province north of the bay.

Of particular interest are the very small, circular, short period wavelength anomalies present along the southwest prolongation of the Marietas Ridge. We propose that these anomalies are most likely the SW continuation of the volcanic centers observed along the Marietas Ridge and in the onshore area near Punta Mita. Thus, we consider that the Marietas Ridge is part of the Punta Mita Province and that these small anomalies mark the southwest extent of the ridge.

4.2. Geomorphology and Shallow Subsurface Structure

4.2.1 South Bay Province (Banderas Submarine Canyon)

The geomorphology of the South Bay Province is dominated by the upper reaches of the Banderas Canyon (Fig. 6), which follows the southern shoreline of the Bahía de Banderas until Cabo Corrientes where it abruptly shifts to a WNW orientation, an orientation nearly perpendicular to the coast. The survey covers 100 % of the canyon between

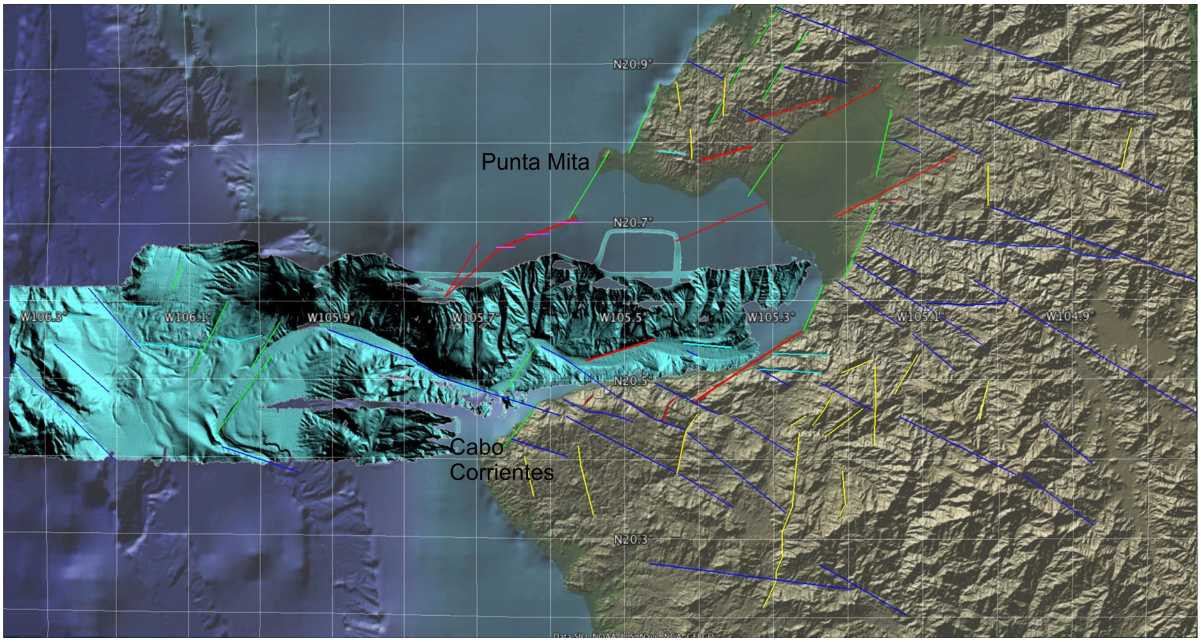

Figure 6
Shaded relief bathymetric map of the Bahia de Banderas Canyon constructed from the multibeam data of the EL PUMA campaigns. Background map, constructed from Google Earth and GeomapApp (http://www.geomapapp.org) illustrates the onshore structural lineaments of the area

105°20′W and 106°03′W (within the Slope Terrace province). The south side of the canyon has a single steep wall whose overall orientation is N85°E from 105°20′W to 105°50′W at which point the southern wall of the canyon abruptly changes to N110°E and continues along this azimuth until 106°05′W, the beginning of the flatter Slope Terrace Province. Relief of the south wall exceeds 1 km within the bay west of 105°20′W. In contrast, the northern wall of the canyon (Figs. 7, 8) has a steep upper wall that is cut by numerous dendritic channels, and a relatively gentle lower wall where the dendritic drainage pattern changes to a series of parallel linear channels, which empty into a flat canyon floor. Given the fan morphology of the gently dipping lower northern wall, it is most likely made up of unconsolidated turbidite fan deposits. This gross morphology is best illustrated in the 3D image of the seafloor backscatter strength image draped on the bathymetry (Fig. 8).

4.2.1.1 Deflections in Canyon Orientation The canyon exhibits sharp deviations in its course at several locations. To the east the deviations appear to be controlled by the presence of turbidite fans, whereas to the west they are structurally controlled (Figs. 6, 7, 9). These deviations can be divided into two groups based on the changing azimuths of the canyon segments: namely, those where the canyon is oriented N45E (canyon segments 3 and 5 have this orientation) and those where the canyon is oriented N110E (canyon segments 4, 6 and the western part of segment 2 have this orientation). The N110E trending segments have been previously noted to be aligned parallel to major lineaments observed on the satellite images of the adjacent onshore area south of the canyon (Núñez-Cornú et al. 2016). The N110E lineaments dominate south of the bay, whereas the N45E lineaments are mainly found in the Punta Mita Province. Thus, it appears that these two groups of lineaments intersect in the western part of the canyon and that they control the canyons course. A more detailed analysis of these trends and their relation to the canyon can be found in Núñez-Cornú et al. (2016) who reported on the multibeam data collected in the Bahía de Banderas during the 2014 TsuJal project.

4.2.1.2 Canyon Floor The canyon floor is broad (up to 2 km wide) with a very gentle down-canyon dip. This, along with the low backscatter strength (Fig. 5a), indicates that the canyon floor is most likely formed by sediments ponded in the canyon axis. Between 105°20′W and 105°41′W, the canyon is made up of three arcuate segments, the eastern two segments being concave to the north and the western most being concave to the NW (Fig. 9). The floor of the canyon here gradually flattens from 1.8° in the east to 0.8° to the west. With the exception of the marked change in slope (from 3.7° to 1.8°) at the east end of the survey area, no reversals in slope nor

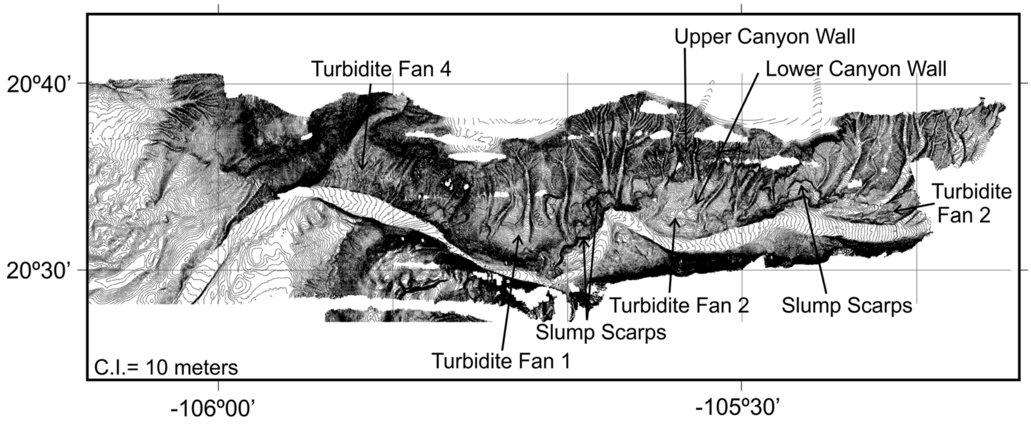

Figure 7

Detailed bathymetric map of the Banderas Canyon (contour interval 10 m) illustrating the extensive turbidite fans and slumps on the northern canyon wall

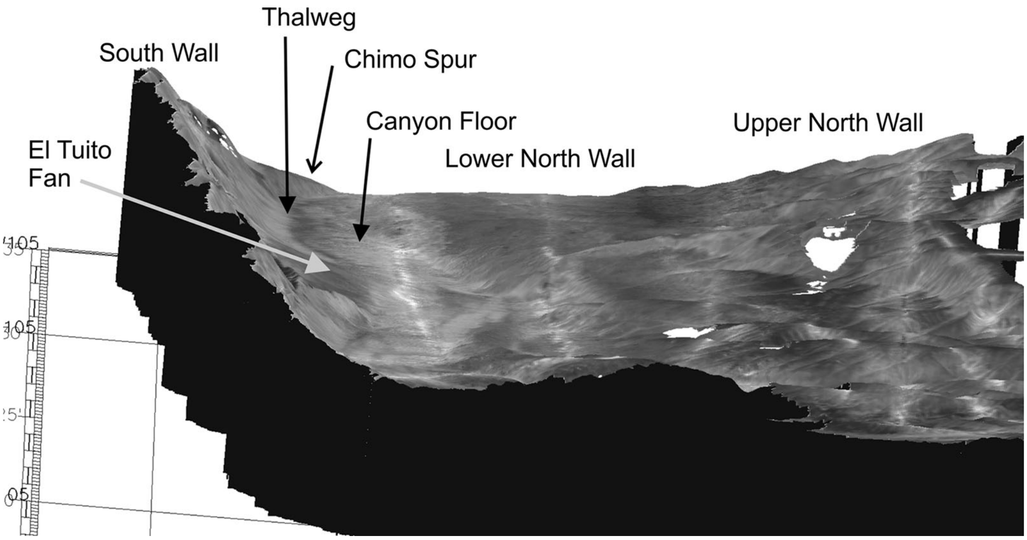

Figure 8

3-D image of the seafloor backscatter mosaic draped on bathymetry; view looking to the west from the east end of the survey area. Note that the present day active channel cuts into the sediments on the south side of the broad canyon floor. Note also that the northern canyon wall is made up of a steep highly eroded upper canyon wall and a gentle sloping, smoother, lower canyon wall

knickpoints [areas of anomalously steep slope (Mitchell 2006)] are noted, suggesting the lack of recent tectonic movements in this area of the canyon.

Two spurs in the canyon floor are located between the three arcuate segments. The easternmost of which (at 105°27′W) is due to a deflection of the channel by a submarine fan (herein called the El Tuito Fan) located within the canyon; the sediments of the fan originate from the El Tuito River, which intersects the coast near the town of Yelapa (Fig. 2). The second spur (located at 105°37′W offshore of the town of Chimo) is most likely not the result of a deflection due solely to a small sediment fan. As illustrated in Fig. 6, the east side of this spur is aligned with a major NW–SE lineament observed south of the canyon onshore, whereas the west side of the spur is aligned with the system of NE–SW lineaments found in the Punta Mita area. Thus, we propose that the western spur is formed by the intersection of these two systems of lineaments. Finally, the Majagua Basin proposed in Alvarez (2002) to be present along the canyon floor in this area is not observed in the new multibeam bathymetric map.

West of 105°41′W the canyon segments are more linear. The canyon floor exhibits a continuous gentle dip ranging from 1° along segment 4 (located between 105°41′W and 105°55′W) to 0.7° along canyon segment 5 (located between 105°55′W and 106°03′W). The Yalapa and Cabo Corrientes basins proposed in Alvarez (2002) to be present along the canyon floor in this area are not observed in the new multibeam bathymetric map. Segment 4 again has an orientation parallel to the southern system of lineaments and we propose that the course of the canyon along segment 4 is being controlled by this fracture system. Recent tectonic activity is evidenced by a narrow, low relief (<10 m) ridge, which cuts across the canyon floor at the intersection of canyon segments 3 and 4. This might be considered as a small knickpoint as the canyon floor also steepens from 0.8° to the east to about 1° to the west of this point. This is the only place along the canyon where the canyon floor exhibits any sign of recent tectonic activity, and implies some recent dip-slip movement. The canyon floor narrows considerably along the eastern half of segment 4, which we propose is due to debris flow deposits on top of the canyon floor sediments.

At 105°55′W, the course of the canyon is deflected sharply (almost 90°), taking on the NE–SW orientation that is parallel to the system of lineaments of the Punta Mita area. Thus, we propose

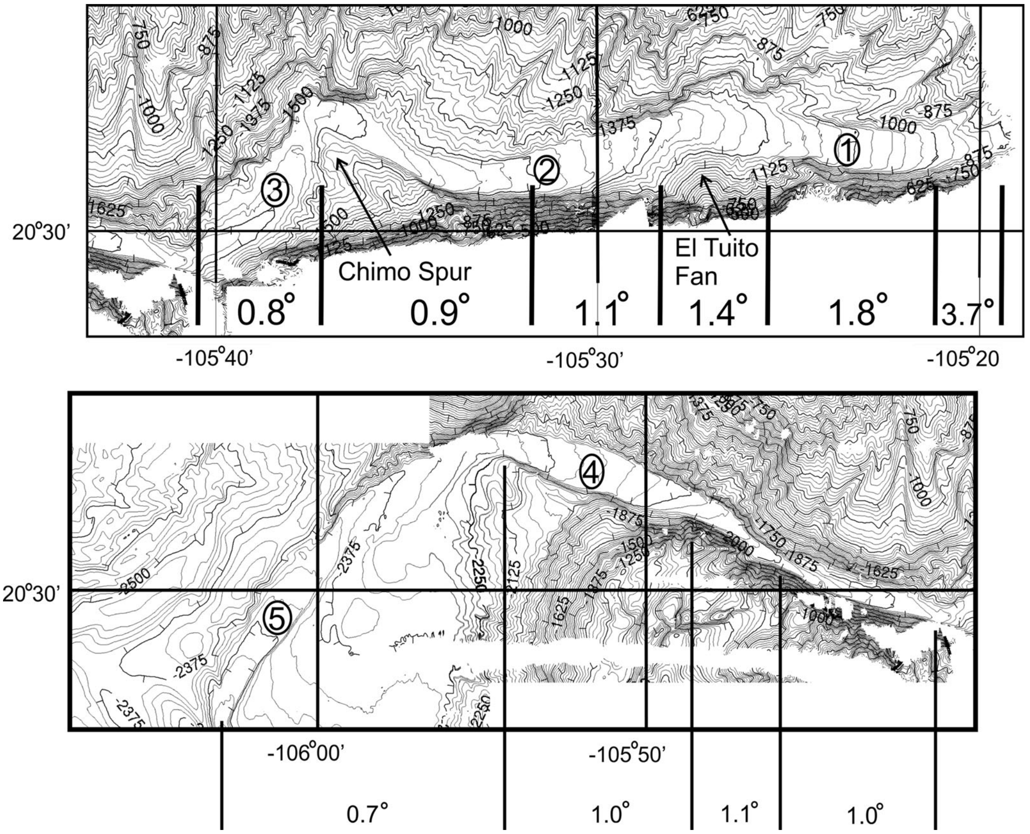

Figure 9

Contour map of the Banderas canyon (contour interval is 25 m). Numbers along the canyon are the slope (in degrees) of the canyon floor. Note that the canyon steepens east of 105°20′W where it begins bends northward towards its terminus (not imaged) near Puerto Vallarta. *Circled numbers* designate the canyon segment

that this abrupt deflection of the canyon is controlled by this fracture system. Indeed, segment 5 appears to run on the east flank of a NE–SW oriented bathymetric ridge. The slope of the canyon floor is 0.7° along segment 5, and the canyon runs out of the survey area at 106°04′W. Again, there are no slope reversals or knickpoints along segment 5 to indicate recent tectonic activity in this area.

4.2.1.3 Mass Wasting Features in the Canyon The northern wall of the canyon exhibits signs of abundant slope instabilities and mass wasting whereas, the southern wall appears to be quite stable (Fig. 7). Perhaps this is due to differences in the type of rock forming the two walls. Although no dredge sample have been collected in this area, it is likely that the southern canyon wall is made up of granites. Given the dendritic drainage pattern, the steep upper part of the northern canyon wall may also be made up of granites or highly consolidated sediments. The geometry of the more gently sloping lower part of the northern wall suggests that this area is made up of several large turbidite fans formed by sediments flowing into the canyon from the north. Figure 10 illustrates that the lower canyon wall adjacent to the canyon floor on the north side is quite steep and appears to truncate the main channels of the turbidite fans, similar to that observed in the Capbreton Canyon off the coast of Spain and France (Mulder et al. 2004). The knickpoints within these channels formed by the truncation do not show any signs of northward retreat, as they should if these channels were active. This is good evidence that, recently, the main channel (i.e. the canyon thalweg) has had the most activity; activity sufficient to erode the frontal part of the fans (Neil Mitchell, personal communication). However,

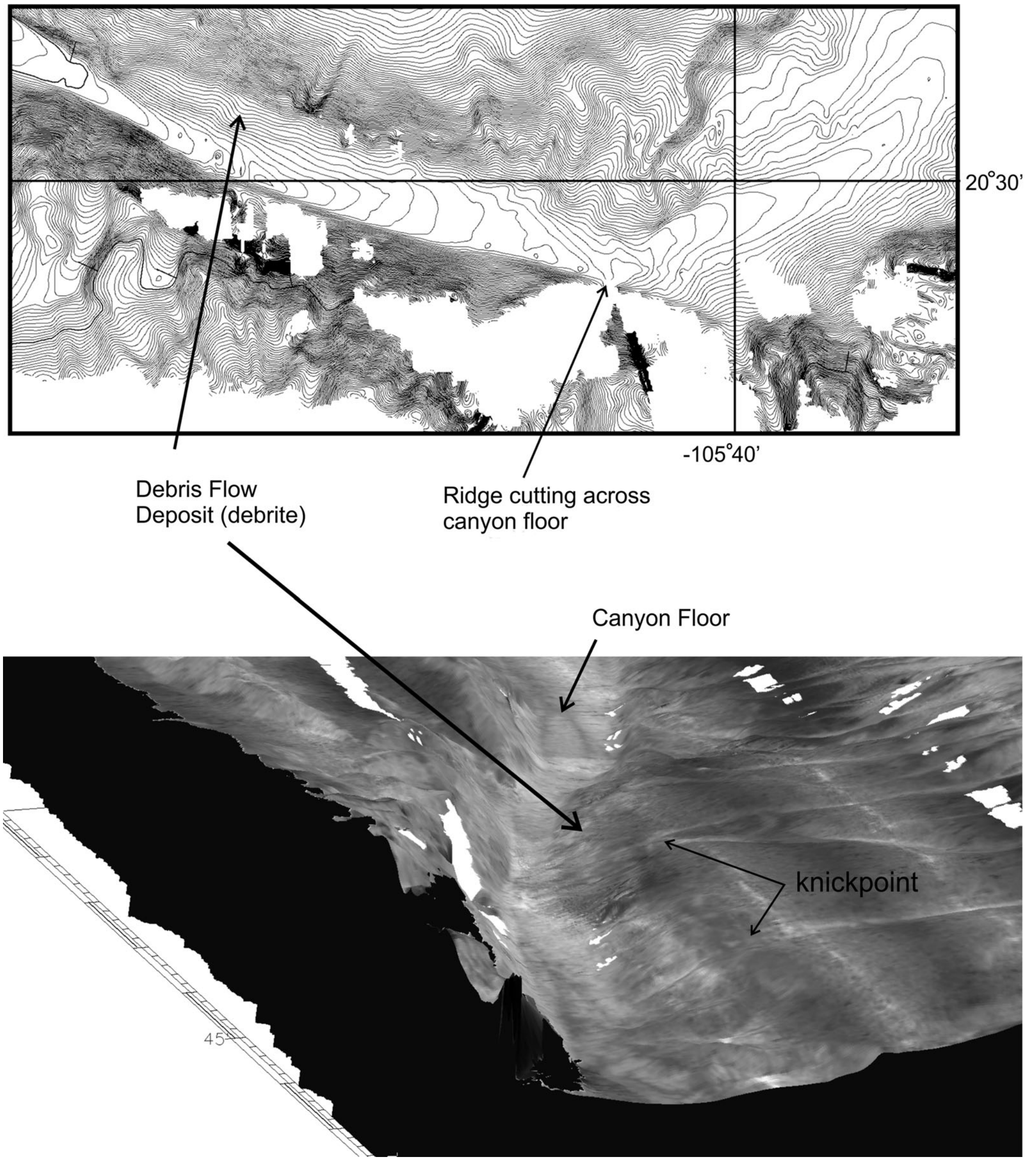

Figure 10
Top Bathymetric contour map (contour interval = 10 m), illustrating the low relief ridge cutting across the canyon floor between canyon segments 3 and 4. This is the only noticeable disruption of the canyon floor sediments in the survey area. *Bottom* 3-D image of seafloor reflectivity image draped on bathymetry illustrating (1) the sediments being deposited on top of the canyon floor, thus reducing the width of the canyon floor, and (2) the lack of a nothward regression of the knickpoints of the main drainage channels of the northern wall

sediments of the westernmost of the turbidite fans on the lower northern wall appear to have flowed over the canyon floor reducing its width at 105°45′W (Fig. 10). Thus, at least some of these channels have been recently active, perhaps activated by storm conditions as proposed for the Capbreton Canyon by Mulder et al. (2004) or by earthquakes. Numerous slump scarps are noted on the NW side of canyon segment 3 (Fig. 7) as well as adjacent to the El Tuito fan, further suggesting that the lower part of the northern wall is made up of unconsolidated, or loosely consolidated, sediments that are unstable.

4.2.2 *Shallow Subsurface Geology of the Northern Bay Provence*

The northernmost of the east–west oriented seismic reflection profiles (profile 2 located in water depths of about 55 m, Fig. 11) shows that the shallow subsurface (<50 m below the seafloor) geology within the western half of the Northern Bay Province consists of two distinct seismic (depositional) sequences separated by an erosional, angular unconformity.

In profile 2, the lower sequence exhibits high amplitude, continuous, parallel to subparallel, wavy, internal reflectors that form a series of anticlines and synclines. These structures are also observed on profile 1 (Fig. 11), and from these two profiles we determined that the strike of syncline SA is N70°E. The internal reflectors of the lower sequence are truncated at an angular unconformity at its upper boundary along the entire length of profile 2 (a distance of 10 km), suggesting that this sequence most likely underlays much of the Northern Bay Province. The lithology of the rocks comprising this sequence is unknown, however, the characteristics of the internal reflectors of this sequence suggests that these are deposits of neritic marine sediments (e.g., Sangree and Widmier 1977). The angular unconformity is not eroded uniformly, but instead, contains several pinnacles, some of which outcrop on the seafloor. This either indicates that the lower sequence consists of material which exhibit variable resistance to erosion or that these pinnacles may be small reefs. Dredging is planned for the future to determine the lithology of the outcrops of the lower sequence.

The thickness of the upper sequence is varied. In the middle part of profile 2, this sequence is less than 2 m thick, and in several places the rocks of the lower sequence appear to outcrop on the seafloor. In this central area the angular unconformity is for the most part horizontal. To the west, the angular unconformity dips ~0.5° to the west until it flattens at a point located just east of syncline SA where the maximum thickness of sediments (15 m) in the overlying sequence is observed. In this area, the upper sequence consists of two units: an overall higher reflectivity upper unit that is free of horizontal reflectors (indicating no significant variation in the type of sediment being deposited), and a lower unit with low amplitude continuous internal reflectors. These internal reflections show an eastward onlapping on the angular unconformity suggesting either tectonic uplift of the central area or subsidence and subsequent infilling of the western area. Since the eastern part of profile 2 crosses the north flank of the Mid-Bay Magnetic High, we favor a tectonic uplift due to magma emplacement in the central area of profile 2. Alternatively, instead of tectonic movements, the geometry of the unconformity (i.e. a step-like profile) could be explained by coastal erosion produced by an abrupt ~20 m rise in sea level during the last eustatic rise in sea level (Neil Mitchell, personal communication; Trenhaile 2002). More data is needed to distinguish between the two possibilities.

On the eastern end of profile 2, the thickness of the upper sequence increases compared to that over the high central area. However, only the upper unit of the upper sequence is present. The angular unconformity dips eastward and is offset about 4 m by a buried fault. No faults are observed to abruptly displace the seafloor along the entire extent of profile 2. The presence of the angular unconformity at water depths of 55 m indicates that either this unconformity formed during the last major drop in sea level or that the area has recently subsided by at least this amount.

Profile 4 (Fig. 12), also oriented east–west but located south of profile 2, nearer to the Banderas Canyon in water depths of around 140–200 m, shows thicker sediments relative to those observed on profile 2. The exact thickness of sediments is not determinable from the data since the angular unconformity noted on profile 2 is not observed on profile 4 (we assume that it is buried by these sediments). However, from profile 4 the minimum sediment thickness is 70 m. Like profile 2, no faults are observed to cut the seafloor on profile 4. Profile 3 (Fig. 13) illustrates that this increase in sediment thickness towards the canyon is not gradual, but instead occurs across a large fault (F4), downthrown to the south. This fault is the only fault noted to clearly offset the seafloor reflector in this area, the offset being 15 m. The multibeam bathymetric data (see inset of Fig. 13) that was collected concurrent with these seismic reflection profiles indicates that this fault strikes N71°E.

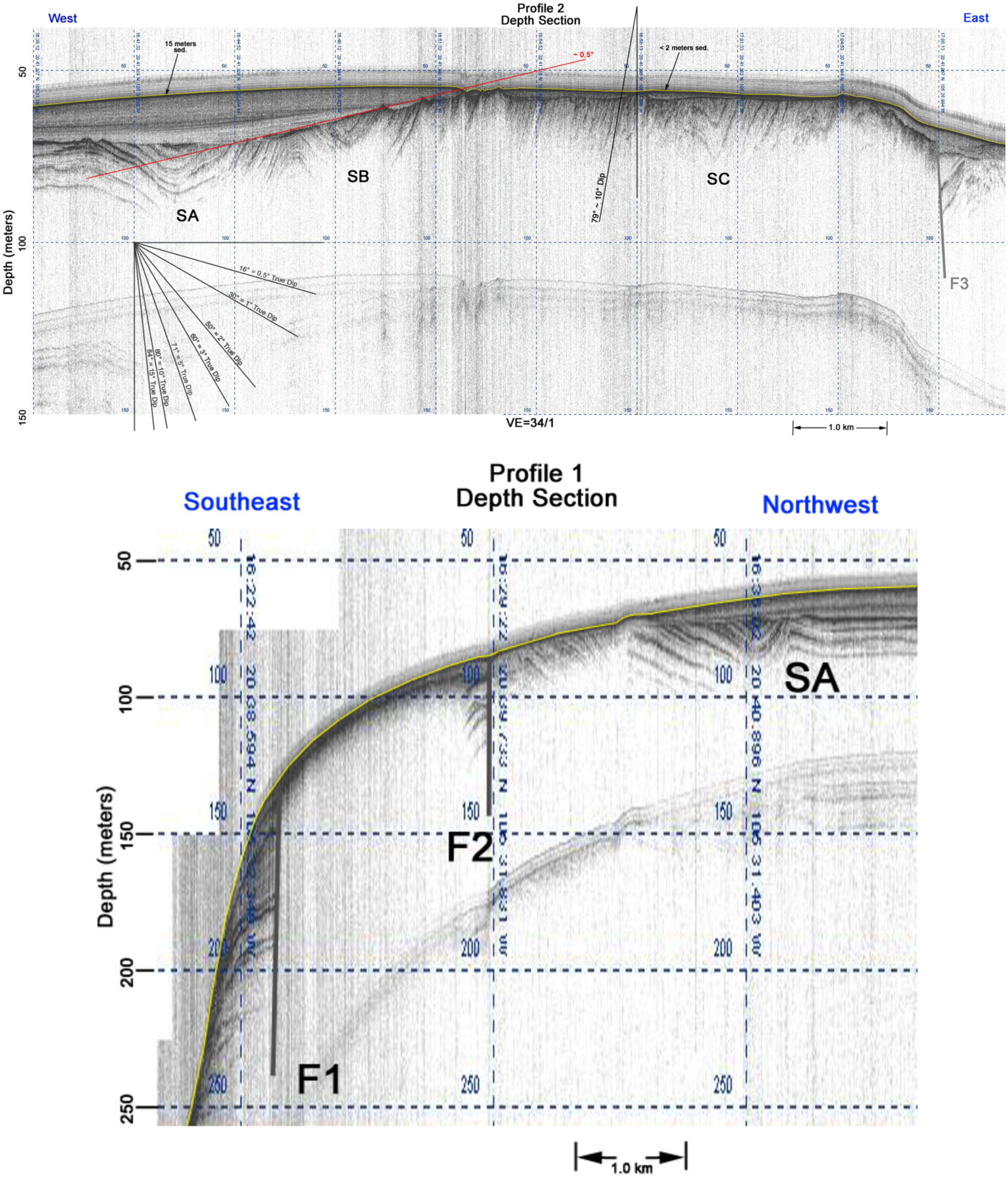

Figure 11

Top Seismic reflection profile 2 illustrating the shallow subsurface structure in the western part of the Northern Bay Province. *S* syncline, *F* fault. The vertical exaggeration of all profiles shown in this study is ∼34:1. A *graph* is presented showing the relationship between observed and actual dips. *Bottom* Seismic reflection profile 1. See Fig. 4 for profile locations. *Vertical scale* is in meters calculated from the two-way travel time using a velocity of 1450 m/s. Note that the apparent sedimentary layer above the seafloor is the effect of the time varying gain and *bottom* detection *algorithm* and is not a real sedimentary layer (i.e. the time varying gain started too soon)

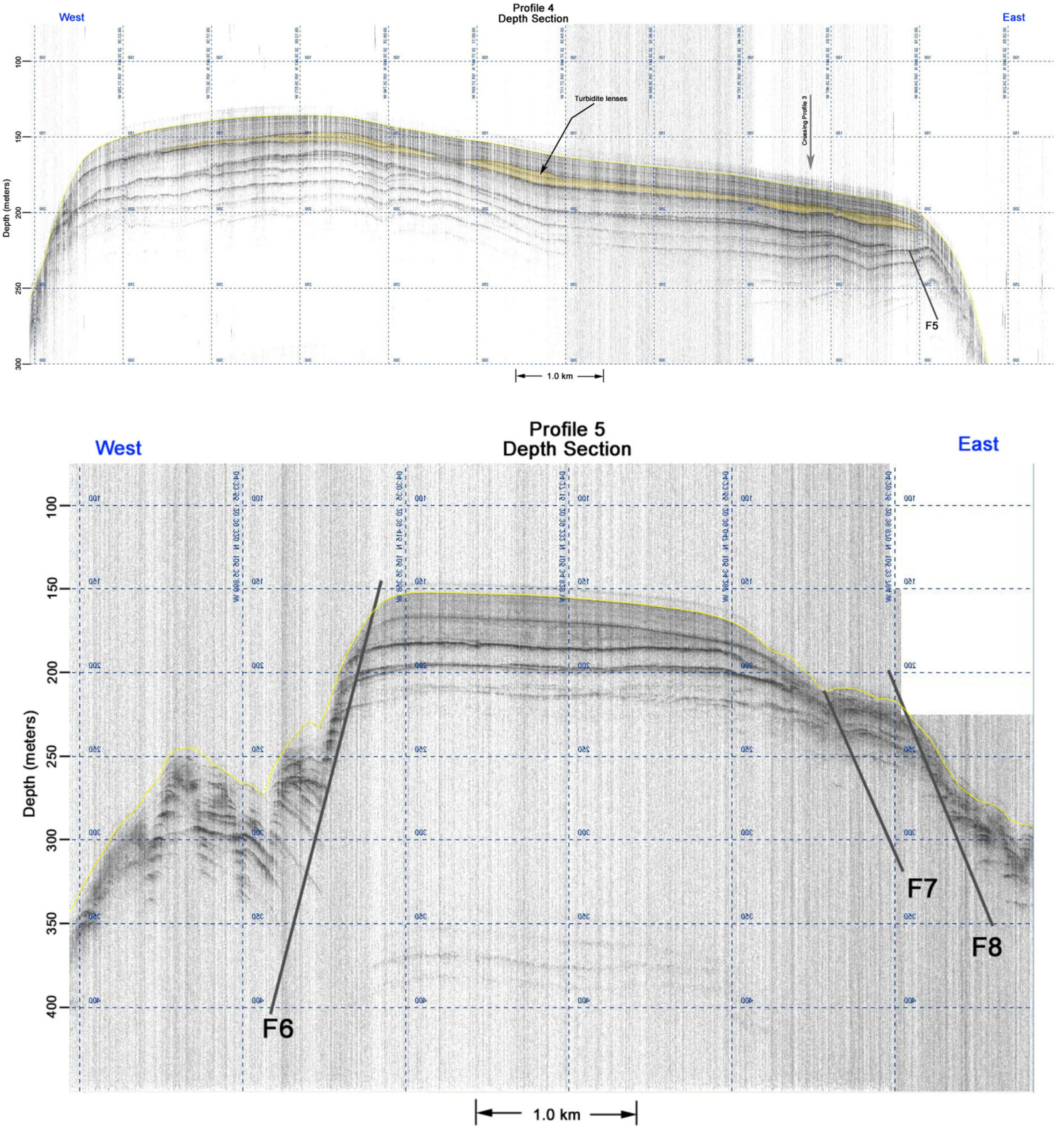

Figure 12
Seismic reflection profiles 4 (*top*) and 5 (*bottom*) further illustrating the shallow subsurface structure in the Northern Bay Province. See Fig. 4 for profile locations

Overall, the internal reflectors of the sediment sequence observed on profile 3 are continuous, parallel to subparallel, and wavy. Amplitudes are variable. These characteristics again indicate deposition with the neritic zone within which the energy alternates between high and low energy (Sangree and Widmier 1977). There is evidence for a higher energy depositional environment at about 10–15 m below the seafloor (see also profile 4) where one can observe several lenses of what appear to be massive turbidite deposits.

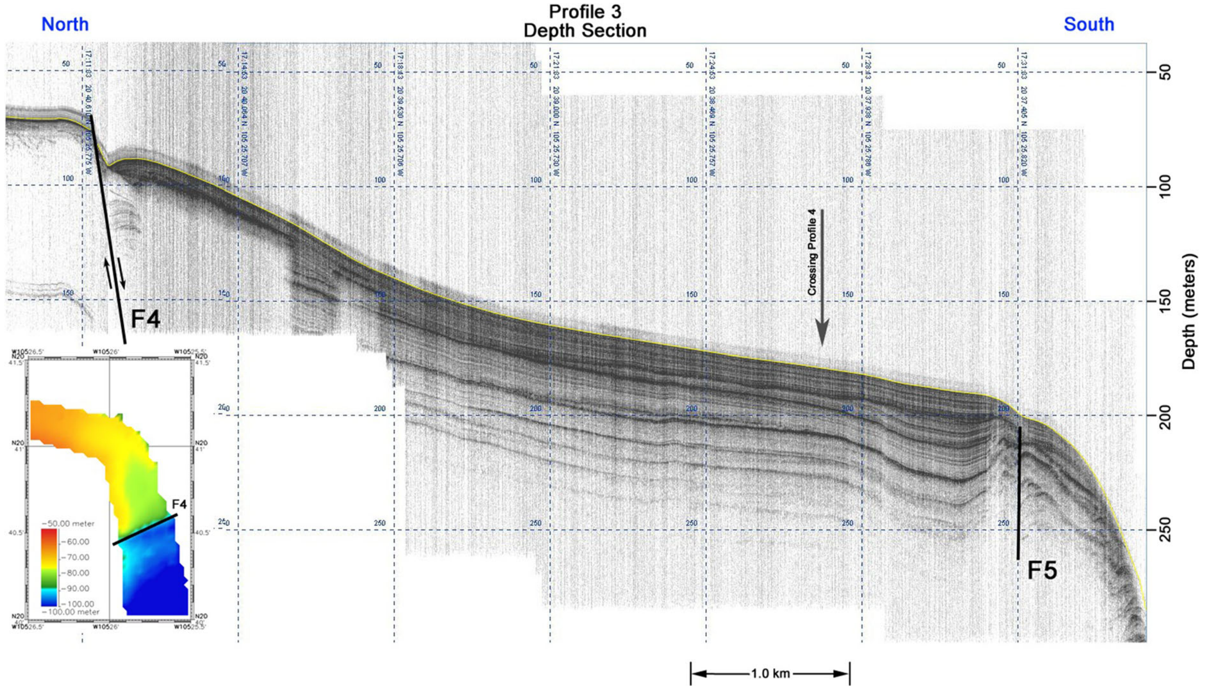

Figure 13

Seismic reflection profile 3 illustrating the shallow subsurface structure in the Northern Bay Province. See Fig. 4 for profile location. *Inset* shows the orientation of fault F4 as determined from multibeam bathymetric data. F4 offsets the seafloor reflector by 15 m and the sediment thickness on the *downthrown side* is about 60 m compared to about 2 m on the *upthrown side* indicating that the throw on the basement (not imaged) is at least 75 m

4.2.3 Shallow Structure of the Marietas Ridge (Punta Mita Province)

Although a continuation of the Punta Mita Province, the Marietas Ridge changes trend at the islands of Isla Larga and Isla Redonda located about 8 km SW of Punta Mita (Fig. 6). Specifically, between Punta Mita and these two islands, the Marietas Ridge strikes at an azimuth of ~212°. However, these two islands along with the EL Morro rock (located at 20°41′, −105°37′) and three more small rocks (herein called "Las Tres Tortugas", located at 20°40.1′, −105°39.3′) are aligned at an azimuth of ~247°. It is also of interest that the Isla Larga and Isla Redonda are aligned east–west, as are the Las Tres Tortugas. These alignments suggest that the Marietas Ridge has had a complex development history, which most likely includes the shallow intrusion of dykes along deep-seated faults. Magnetic modeling, planned for the future, could clarify the development history of the ridge.

The seismic reflection data of this study provide the first published images of the shallow crustal structure of the Marietas Ridge, in particular the SW part of the ridge located south of Las Tres Tortugas. There, the Marietas Ridge strikes at an azimuth of ~230° and is asymmetric, the ridge crest being located on the east side of the ridge (Figs. 14, 15). The recent sediments noted on the seismic profiles in the Northern Bay Province are absent over this ridge, with the exception some sediments infilling a few small seafloor depressions. Therefore, the internal reflectors essentially belong to one seismic sequence. This sequence is disrupted like the lower seismic sequence noted to the east, however, with the presently available data we cannot confirm that they are indeed the same sequence. The age and lithology of the rocks comprising this sequence are unknown, but since several of these rocks outcrop on the seafloor, the age and lithology could be determined in the future by dredging.

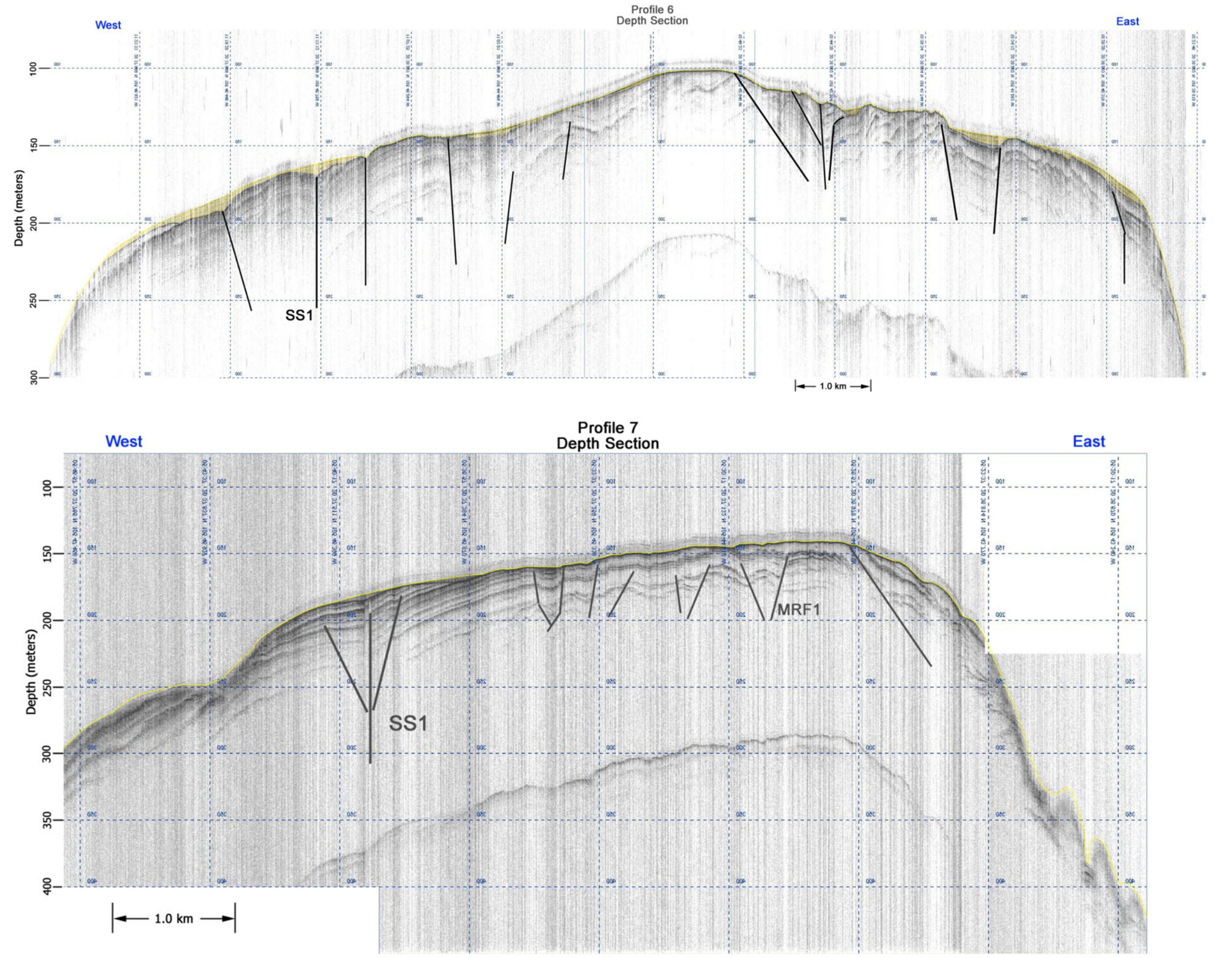

Figure 14

Seismic reflection profiles 6 (*top*) and 7 (*bottom*) illustrating the shallow subsurface structure of the SW end of the Marietas Ridge. *SS* for strike-slip fault, *MRF* Marietas Ridge Fault. Note the well-developed negative flower structure associated with fault SS1 west of the ridge crest. See Fig. 4 for profile location

The internal reflections of this sequence differ east and west of the ridge crest (see profile 6, Fig. 14). Specifically, under and to the east of the ridge crest the internal reflectors are parallel, wavy, and discontinuous with mixed high and low amplitudes. This character is typical of faulted neritic sediments, the faulting occurring after sediment deposition. In contrast, in the western part of the ridge, away from the ridge crest, although the internal reflectors are also parallel with mixed high and low amplitudes, they are more even and continuous than those found to the east. This indicates substantially less disruption of the sedimentary layers, however, the internal reflectors of the western area are disrupted by a well-developed, negative flower structure (SS-1 on profiles 6, 7 and 8; Figs. 14, 15), which indicates that SS-1 is a transtensional fault (e.g., Harding et al. 1985). SS-1 strikes parallel to the ridge crest suggesting that its development is related to the development of the ridge. Another major fault, (normal fault MRF#1, profiles 7 and 8), which offsets the internal reflectors by about 20 m, strikes parallel to the ridge crest, leading us to conclude that, in general, the observed disruption of this sequence is concurrent with the formation of the ridge. Also in the western area, the upper reflectors of this sequence exhibit erosional truncation at the seafloor reflector indicating that the eastern area has been uplifted and

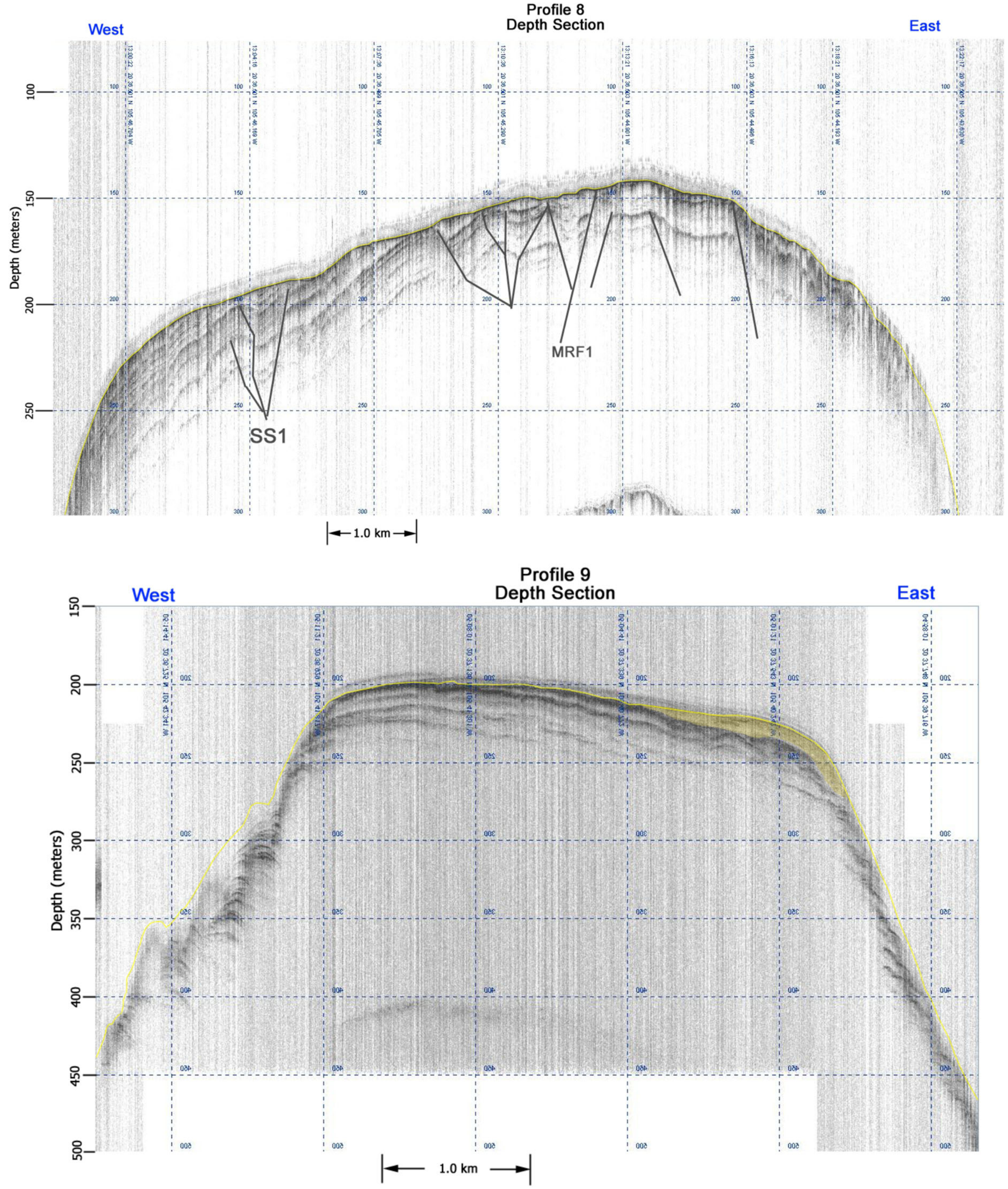

Figure 15
Seismic reflection profiles 8 (*top*) and 9 (*bottom*) illustrating the shallow subsurface structure of the SW end of the Marietas Ridge. *SS* strike-slip fault, *MRF* Marietas Ridge Fault. Again, note the well-developed negative flower structure associated with fault SS1 west of the ridge crest. See Fig. 4 for profile location

eroded. This is consistent with the lack of recent sediments over the ridge.

5. *Discussion*

5.1. *Present Day Stress*

As illustrated in Fig. 6 the area of the Bahía de Banderas contains at least five families of lineaments attesting to the complex tectonic history of this region. The lineaments have preferred orientations of north–south, N35°E–N45°E, N70°E, east–west, and N110°E.

Although the N110°E lineaments are observed throughout the region, they are the dominate lineament south of the bay. These lineaments control the course of the Banderas Canyon along the canyon segments 4 and 7 and the west half of canyon segment 5. Further, structural highs in the western part of Slope Terrace Province exhibit a similar strike (Fig. 6). Recent seismicity has been associated to these lineaments (e.g., Rutz López et al. 2013). The knickpoint at the east end of canyon segment 4 may also be the result of recent tectonic activity along at least one of these lineaments.

On the north side of the bay and within the Valle de Banderas, two families of lineaments dominate; one with a preferred orientation of N35°E to N45°E and another with a preferred orientation of N70°E. The N35°E–N45°E lineaments clearly form the NW and SE boundaries of the Valle de Banderas (e.g., Ferrari et al. 1994). Further, Arzate et al. (2006) also found a series of buried faults with the same orientation within the valley. The overall orientation of the Punta Mita Province (including the Marietas Ridge) also exhibits this orientation. The N70°E lineaments are observed on both sides of the Valle de Banderas (e.g., Ferrari et al. 1994) and within the Northern Bay Province (Núñez-Cornú et al. 2000) where they are associated with hydrothermal activity.

The remaining two families of lineaments are less dominant. A few short east–west lineaments are observed in the Punta Mita Province and along the southern margin of the bay. The north–south lineaments are sparse, being mainly observed south of the bay. No seismicity has been associated with these lineaments suggesting that they are older features.

Concerning the question of the present day stress field of the area, within the confines of the bay east of the Marietas Ridge, we observe only one major fault which we can unequivocally say is presently active; namely the large normal fault (F4) which trends N71°E and which is observed to displace the seafloor reflector by 15 m on seismic profile 3. If this fault has purely normal dip-slip, then its orientation indicates that the current stress field in the bay is extensional and that the tensional axis is oriented N19°W. Further, a similar trend was found for the main fracture of the active hydrothermal system “Fisura de la Coronas” located on the north side of the Bay (Núñez-Cornú et al. 2000). From these observations, along with the lack of unequivocal evidence for recent activity along the N35°W–N45°W family of lineations, we conclude that the N71°E family of lineations is indicative of the present day stress field at least within the bay, and probably also within the Valle de Banderas.

If our conclusion is correct and the entire Puerto Vallarta graben is presently being subjected to NNW–SSE directed tension, then the NE striking faults bounding, and located within, the Valle de Banderas represent a previous stress regime, and thus, the tensional axis has since rotated clockwise to a more northerly direction, one that is more parallel to the strike of the Middle America Trench west of the bay. This is consistent with the proposal of Kostoglodov and Bandy (1995) that the recent tectonic activity within this area is due to the highly oblique subduction of the Rivera plate with respect to the North American plate. The N19°W direction for the tensional axis is more parallel to the strike (roughly north–south) of the MAT in this area. Reorientation of the stress field in this area has been previously proposed by several investigators (e.g., Ferrari et al. 1994; Arzate et al. 2006).

The seismic reflection data also provide evidence for such a clockwise shift in the tensional axis. Specifically, these data image transtensional faulting within the SW part of the Punta Mita province (the Marietas Ridge), which is made up of structures belonging to the family of N45°E lineaments. If, as we propose, the N45°E trend is older, then a clockwise rotation of the tensional axis would produce transtension along pre-existing structures having this trend.

The gently sloping, undisrupted canyon floor also supports the proposal that the N110°E and N45°E lineations are representative of older stress fields and that the area of the canyon is not presently being subjected to intense tectonism. The only possible exception that we see in our data is the N110°E trending lineament that outcrops on the canyon floor, forming the 10 m high ridge. These observations lead us to conclude that the N110°E and N45°E lineaments are indicative of older stress regimes. However, it appears that some of these lineaments may have reactivated at present (Rutz López et al. 2013; Núñez-Cornú et al. 2016).

5.2. *The Existence of the Banderas Fault*

The idea of the existence of a major structural lineament passing through the Bahía de Banderas to the Middle America Trench dates back to the work of von Humboldt (as reported on by Mooser 1972) who proposed that the Trans-Mexican Volcanic belt marked a regional mega-shear, later proposed to be the continuation of the Clarion fracture zone (Menard 1955). More recently, Lyle and Ness (1991) presented such a lineament in their bathymetric map of the area and several subsequent investigators have presented, ad hoc, the lineament in their work (Alvarez 2007; Alvarez et al. 2010) calling it the Banderas Fault; although some have questioned its existence (e.g., Núñez-Cornú et al. 2000).

The data presented herein clearly indicate that there is no major morphotectonic or magnetic structure that can be traced extending from the bay completely across the study area. The Canyon Magnetic High (Fig. 4) is confined to the bay and the east–west magnetic low running through the center of the bay terminates within the survey area. The canyon itself bends southward prior to reaching the Middle America Trench, being deflected by NE–SW striking structures, so it is clearly not marking the presence of a major tectonic structure extending westward from the bay to the MAT. Further to the west, though still east of the trench, the structural highs and lows trend NW–SE (Fig. 5), not east–west.

The lack of evidence for a major block boundary between the bay and the MAT calls into question the proposals that the Rio Ameca Graben marks the northern boundary of the Jalisco Block. However, the difference in the magnetic signature of the Slope Terrace Province north and south of the latitude of the bay does indicate that a structural and/or compositional change of the crust occurs in the area of the bay.

5.3. *Sediment Transport Characteristics*

Although no direct observations of sediment transport were made during the study, several characteristics can be gleaned from the geophysical data. The lack of knickpoint retreat on the drainage channels at the base of the northern canyon wall (Fig. 10) indicates that these channels have experienced little activity since the time that the main channel was last entrenched, and that the majority of the recent activity has been within the canyon thalweg (Mitchell, person. comm.), similar to that described by Mulder et al. (2004) for the Capbreton Canyon. This, along with the broad, flat nature of the canyon floor, leads us to propose that most of the recent sediment transport within the canyon most likely occurred during major storms when the sediment content of the two main rivers (Rio Ameca and Rio Cuale) was high. Hyperpycnal flows from these rivers, produced during storms, transported the sediments into the canyon; most likely down the two large, flat floored, channels (channels 1 and 2, Fig. 5) that feed the canyon from the east. These flows most likely extended down the entire length of the canyon thalweg, producing the broad, flat, gently seaward dipping canyon floor morphology.

During dry periods, the discharge of the rivers is low, <1 m^3s^{-1} for the Rio Ameca (CNA-SEMARNAT 1999, as reported in Plata and Filonov 2007), thus during these times, fine grained sediments are probably distributed throughout the bay by hypopycnal flows emanating from these rivers.

The debris flow deposits within the canyon floor (Fig. 10) and the slump scarps on the canyońs northern wall (Fig. 7) indicate that part of the sediment feeding the canyon originates from mass wasting of the canyon's northern wall. These mass-wasting events may be triggered by wave action or due to erosion at the base of the canyon wall by the hyperpycnal flows during storms. Alternatively, the mass-wasting events may be triggered by earthquakes.

The presence of the El Tuito Fan within the canyon floor indicates that, here, a significant amount of sediments are flowing down the steep southern wall, a source being the granitic highlands to the south. It is not known if the fan is a long-term feature (i.e. comprised of coarse grained sediments) or if it is a transient structure (comprised of finer grained sediments) that will be washed away during a future storm. However, given the steepness of the canyon's southern wall, coarse-grained sediments could be easily transported to the canyon floor, similar to the transport of coarse-grained sediments to the deep waters of fjord deltas via submarine chutes (Prior et al. 1981).

The distribution of recent sediments observed on the seismic reflection profiles appears to indicate that sediments are being reworked within the bay during storms, the depth of the wave base being greater at the mouth of the bay (i.e. over the Marietas Ridge). Specifically, on profiles 6 thru 9, crossing the Marietas Ridge, the wave base appears to be between 220 and 160 m. In contrast, the wave base within the bay appears to be only 60–70 m (profiles 2 and 3). This can be explained by a damping of the wave energy within the bay or by a divergence of the wave field due to the submarine canyon.

5.4. *Origin of the Submarine Canyon*

Several researchers (Arzate et al. 2006, 2010; Alvarez 2007) have recently proposed that the Banderas Canyon lies within a half graben, with the steep southern wall being the main fault and the more gentle western wall representing reverse drag of the basement layer into the main fault. Further, it was proposed that this main fault was of regional extent, extending completely across the continental slope to the MAT.

Several observations lead us to reconsider these claims about the possible origins of the Banderas Canyon, these are: (1) the results of this study contradict the previous claim that a major fault extends to the MAT along the westward prolongation of the Banderas Canyon (how can such a large fault, the main fault of the half-graben, be confined to only the bay?) (2) the previous studies did not consider the alternative that the gentle northern canyon wall may be due to sediments being deposited at the base of a steep normal fault rather than reverse drag, (3) the quality of the previous magnetic data was poor (most likely the result of the non-conventional marine magnetic acquisition method employed), and the locations of the previous models were poorly selected (we feel that it would have been better had the modeled profiles been located within the confines of the bay, east of the Marietas Ridge), and (4) the disagreement between the proposed model and the results of Rutz López et al. (2013). Given our results, we propose two (Fig. 16) other possible origins of the Bandera Canyon in addition to the previously proposed half-graben model.

Figure 2 illustrates the presence of an east–west oriented silicic tuff unit, sandwiched between the cretaceous granites of the Puerto Vallarta batholith, located onshore where the canyon is projected to intersect the coast. The tuffs, being softer than the adjacent granites and volcanic in origin, would be more easily eroded than the granites. Thus, the tuff deposits may continue into the bay and the canyon may simply originate from preferential erosion of the tuffs, i.e. the overall course of the canyon is being controlled by the location of the tuffs (upper panel Fig. 16). In this scenario the steep southern wall of the canyon was formed by the uplift of the Puerto Vallarta Batholith to the south noted in previous studies and may also mark the contact between the granites and the tuff unit. The more gently sloping lower northern wall is the result of turbidite deposition in the northern part of the erosional canyon, the turbidites forming large coalescing fans.

Alternatively (lower panel in Fig. 16), the characteristics of the canyon may be the result of both uplift of the Puerto Vallarta Batholith south of the canyon in conjunction with a generally NW movement of the Punta Mita Province away from the rest of the Puerto Vallarta batholith. Like the previous scenario, in this scenario the steep southern canyon wall was formed by the uplift of the Puerto Vallarta batholith to the south. Tension within and north of the bay, perhaps related to the opening of the Gulf of California, was accommodated by at least one normal fault, the fault plane of which is the steeper, highly eroded upper part of the northern wall. Sediments

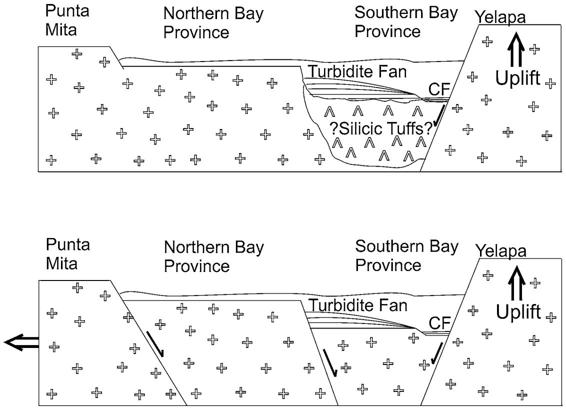

Figure 16
Cartoon illustrating two additional possible scenarios for the development of the Banderas Canyon, namely erosion of the tuffs (*top*), and uplift of the Puerto Vallarta batholith to the south in conjuction with a NW movement of the batholith to the north (*bottom*). *CF* channel floor

originating from the main rivers emptying into the bay to the north were transported over the fault and deposited on the downthrown block at the base of the fault as extensive sediment fans. In this scenario, the gentle lower part of the northern slope is due to the formation of these sediment fans and is not due to a southward bending of the basement as it approaches the southern canyon wall.

We propose that, given the available data, all three scenarios are possible. Plans are currently being made to acquire surface dredge samples and multichannel seismic reflection data capable of penetrating the turbidite fan deposits within the northern part of the canyon to determine the thickness of these sediments as well as the attitude of the top of the basement block underlying the turbidite fans. From these data one should be able to distinguish which of the three scenarios is correct.

6. *Conclusions*

1. A N71°E striking fault offsets the seafloor reflector within the central part of the bay by about 15 m. The thickness of the upper sedimentary section increases from less than 2 m on the up thrown block to more than 65 m on the down thrown block indicating that it is a major, presently active, normal fault. The strike of this fault is similar to the strike of the fractures associated with the Fisura de las Coronas located on the north side of the bay. This suggests that the bay is currently being subjected to NNW-SSE extension. This is almost parallel to the strike of the MAT in this area, consistent with the proposal that this area is being subjected to trench parallel stresses produced by highly oblique convergence between the Rivera and North American plates at the north end of the MAT.
2. The seismic reflection data reveals the presence of negative flower structures that disrupt the seafloor reflector on the west side of the Marietas Ridge indicating that the ridge is presently undergoing transtensional deformation. The numerous, small, high-frequency magnetic anomalies that lie along the southern prolongation of this ridge are consistent with the presence of volcanics, similar to those observed on the Islas Marietas and within Punta Mita. Thus, we propose that the Punta Mita province encompasses the Marietas Ridge and the area of these magnetic anomalies. As such it forms the western limit of the Northern Bay Province.
3. No evidence has been found in the magnetic or bathymetric data to confirm the existence of the previously proposed Banderas fault, a regional east–west striking fault proposed to extend from the bay to the Middle America Trench.
4. The course of the Banderas Canyon is controlled by extensive turbidite fan sedimentation in its eastern extremity and by N110°E and N45°E oriented structural lineaments to the west.
5. The canyon floor is filled by sediments and exhibits almost no evidence for recent tectonic movements.
6. The southern canyon wall is quite steep and very few sediment fan deposits are observed at the base of the southern wall. In contrast, extensive turbidite fans form the lower part of the northern canyon wall, producing a gently southward sloping northern wall.
7. The lack of evidence for the Banderas Fault along with the observation that turbidite fans are responsible for the gentle dip of the northern canyon wall indicates that the previous assertion that the Banderas Canyon is unequivocally related

to the presence of a regional half-graben needs to be re-evaluated. We propose two other alternatives for the development of the Banderas Canyon that are consistent with the available data. The first is that the Banderas Canyon is purely an erosional feature, cutting through a more easily eroded silicic tuff. The second is that it is a combination of uplift of the Puerto Vallarta Batholith south of the bay and a roughly northwestward movement of the area north of the bay.

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