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Structure of the southern Jalisco subduction zone, Mexico, as inferred from gravity and seismicity

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RESUMEN

Un modelo característico de la estructura geológica de la zona de subducción de Jalisco (JSZ) es determinado por la comparación de las anomalías gravimétricas a lo largo de un perfil perpendicular a la costa de Jalisco cerca de Barra de Navidad con la anomalía calculada de una sección geológica transversal restringida por datos de sismicidad. El espesor de la corteza continental del bloque de Jalisco es en promedio ~38 km, y aumenta gradualmente hacia el este hasta un espesor máximo de 44 km. La densidad de la parte superior de la litosfera en subducción aumenta a una profundidad de ~30 km, reflejando quizá una transición de fase de basalto a eclogita como se ha propuesto para la zona de subducción de Chile. El manto superior al oeste de la trinchera muestra densidades menores relativamente al resto del manto superior. Esta zona de baja densidad es más gruesa cerca de la Cordillera del Pacífico Este (EPR) y disminuye hacia el este en dirección de la Trinchera Mesoamericana, y esto puede reflejar una zona extensa de magma emplazada a lo largo del EPR, similar a la observada en el EPR a los 16°S.

PALABRAS CLAVE: Gravimetría, tectónica, estructura cortical, bloque de Jalisco, México.

ABSTRACT

A type-model of the geological structure of the Jalisco subduction zone was determined by matching gravity anomalies observed along a profile perpendicular to the Jalisco coast near Barra de Navidad with the gravitational attraction of a geologic cross section constrained by seismicity data. The thickness of the continental crust of the Jalisco block averages ~38 km, and gradually thickens eastward reaching a maximum thickness of 44 km. The density of the upper part of the subducting lithosphere increases at a depth of ~30 km, perhaps reflecting a phase transition of basalt to eclogite as has been proposed for the Chile subduction zone. The upper mantle west of the trench exhibits lower densities relative to the rest of the upper mantle. This low density zone is thickest near the East Pacific Rise and thins eastward towards the Middle America Trench, and may reflect a broad zone of magma emplacement along the East Pacific Rise, similar to that observed at the East Pacific Rise at 16°S.

KEY WORDS: Gravity, tectonics, crustal structure, Jalisco block, western Mexico.

INTRODUCTION

The subduction of the Rivera plate beneath western Mexico along the Jalisco subduction zone (JSZ) is the dominant geologic process controlling the recent seismic activity and tectonic deformation within the crust of western Mexico. In this century alone, this process has generated three large, destructive, earthquakes; the two June 1932 events (e.g., Singh *et al.*, 1985) and the October 9, 1995 event (e.g. Courboulès *et al.*, 1997; Melbourne *et al.*, 1997; Pacheco *et al.*, 1997a; Ortiz *et al.*, 1998; Escobedo *et al.*, 1998). In relation to its importance, few studies have been conducted to determine the detailed structure of the JSZ.

The seismicity occurring within the JSZ (Figure 1) (e.g., Eissler and McNally, 1984; Kostoglodov and Ponce, 1994; Pardo and Suárez, 1993, 1995) adequately defines the ge-

ometry of the subducting Rivera plate only in the southern part of the JSZ. As a result, studies of the internal structure of the overriding plate, the Jalisco block, have relied primarily on potential field data. Further, these studies have been undertaken mainly within the boundaries of the Jalisco block; namely, the Colima (Allan, 1985; Urrutia-Fucugauchi and Molina-Garza, 1992; Serpa *et al.*, 1992; Bandy *et al.*, 1993, 1995, 1996; Molina-Garza and Urrutia-Fucugauchi, 1993; Medina *et al.*, 1996) and the Tepic-Zacoalco (Alatorre-Zamora and Campos-Enríquez, 1991; Couch *et al.*, 1991; Campos-Enríquez and Alatorre-Zamora, 1998) rift systems. One regional study (Urrutia-Fucugauchi and Flores-Ruiz, 1996; Flores-Ruiz, 1997) of the Bouguer gravity field of the entire Trans-Mexican volcanic belt addressed the crustal structure of the interior of the Jalisco block. Further, these studies have not incorporated into their models the constraints imposed by seismicity data.

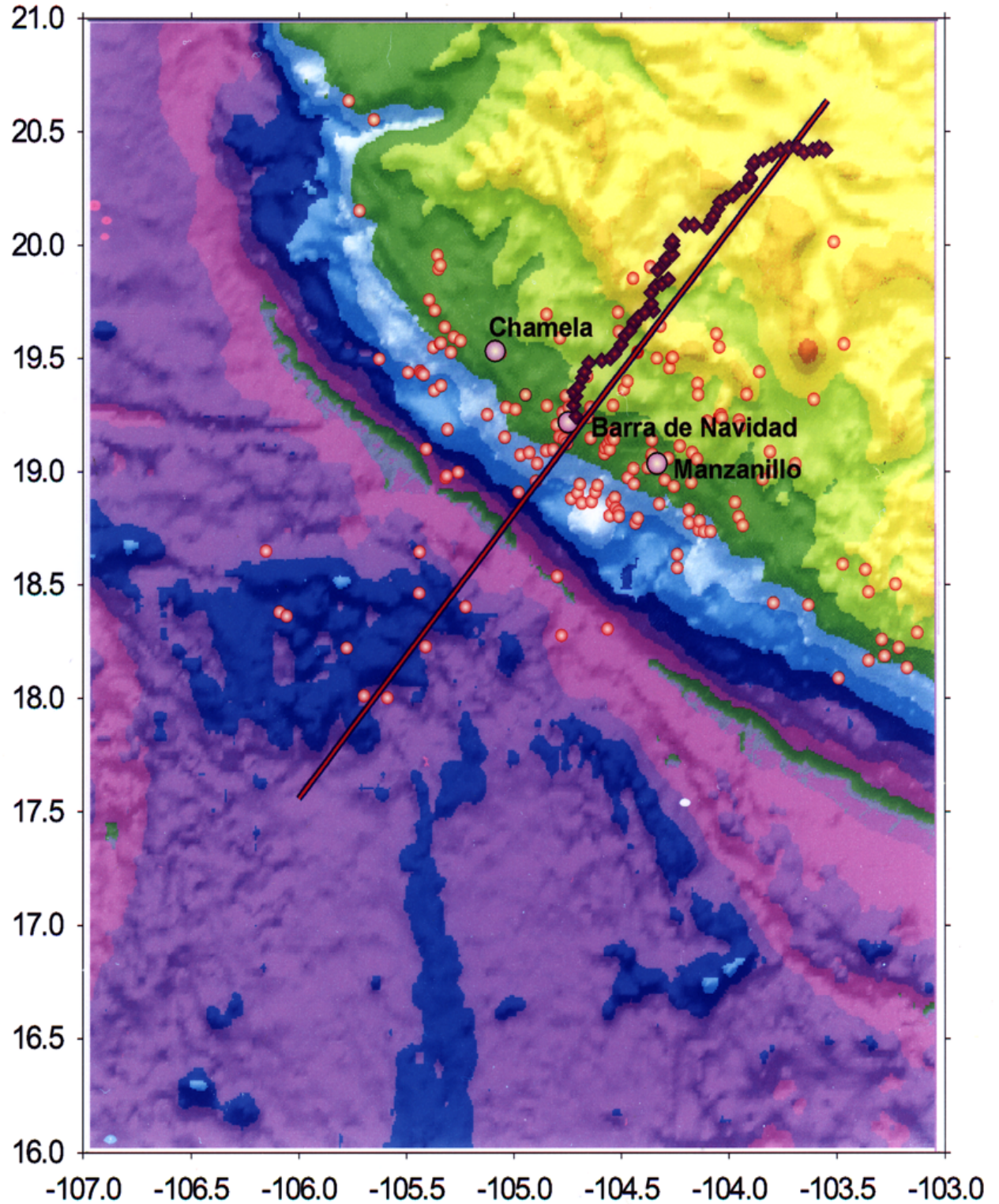


Fig. 1. Bathymetric-topographic map of the study area (Smith and Sandwell, 1997) and the location of the Barra de Navidad gravimetric profile analyzed in this study. Red diamonds are the gravimetric stations. Small yellow circles are the epicenters of the seismic events from Hurtado *et al.* (1998) whose loci were used to constrain the geometry of the subducting slab. Thin black line is the coastline.

The purpose of the present study is to determine a type-model, characteristic of the gross crustal structure of the Jalisco block, from an integrated study of the seismicity and the gravity data. We choose the southern part of the JSZ as the area in which to develop this type-model for two reasons. First, the seismicity of this area can be used to constrain the geometry of the subducting slab, independent of the gravity data. Such a constraint allows for a more accurate determination of the crustal structure from the gravity data. Second, the continental crust in this region is uncomplicated by volcanic processes. The resulting model may prove useful as a starting point for future investigations into the nature of the JSZ, particularly in the northern part of the JSZ where seismic activity is low.

GEOLOGIC SETTING

The JSZ, at which the Rivera plate converges with the Jalisco block, comprises the northern part of the Middle America trench (MAT) between the Tres Mariás Islands and the southern Colima rift. The subduction process occurring within this zone produces large earthquakes (e.g., Singh *et al.*, 1985; Pacheco *et al.*, 1997a); however, the background seismicity is low compared to the rest of the MAT to the south. In addition, this background seismicity decreases considerably northward from the southern Colima rift (Eissler and McNally, 1984; Kostoglodov and Ponce, 1994).

The Jalisco block is bounded to the NE and SE by the Tepic-Zacoalco and Colima rift systems, and to the SW by the MAT. The Jalisco block exhibits two distinct surface lithologic zones; namely, the Late Cretaceous-Paleocene coastal plutonic belt (e.g. Schaaf *et al.*, 1993, 1995), and, to the NE, a zone of Cretaceous to early Cenozoic silicic ash flows which are intruded by numerous Plio-Quaternary basalts (e.g., Luhr *et al.*, 1989; Lange and Carmichael, 1990; Richter and Carmichael, 1992; Wallace *et al.*, 1992). The thickness of the central part of the Jalisco block has been determined from spectral methods applied to gravity data to be ~40 km (Urrutia-Fucugauchi and Flores-Ruiz, 1996). The thickness of the crust along the NE and SE boundaries of the Jalisco block has been determined to be either ~25 km (Urrutia-Fucugauchi and Flores-Ruiz, 1996) or ~43 km (Urrutia-Fucugauchi and Molina-Garza, 1992). In the southern part of the JSZ, the subducting slab initially dips at an angle of 9° to 16° (Pardo and Suárez, 1993; Ortiz *et al.*, 1998; Melbourne *et al.*, 1997; Escobedo *et al.*, 1998) down to mantle depths of about 20 km, and then increases gradually to a constant dip of ~50° below a depth of 40 km. A more recent, better constrained model of the top of the Wadati-Benioff zone in this area (Hurtado *et al.*, 1998), indicates an initial dip of 13° down to mantle depths of 20 km, gradually increasing to 46° at depths below 50 km. In the northern part of the JSZ, the geometry of the Wadati-Benioff zone is poorly defined due

to the low level of seismic activity.

The inner trench wall of the southern JSZ is comprised of four geologic units (Mercier de Lepinay *et al.*, 1997). The first, located at the base of the inner trench wall, consists of siltstone, mudstone and sandstone layers. The second unit consists of Late Cretaceous-Paleocene granodiorites and gabbros which are correlated with the onshore coastal plutonic belt of the Jalisco block. This unit is in thrust contact with the underlying sedimentary unit. The third unit, which unconformably overlies the plutonic unit, is a massive conglomerate containing granitic and volcanic well-rounded pebbles. The uppermost unit consists of upper Miocene to lower Pliocene siltstone. The above sequence indicates the lack of an extensive accretionary prism in this area, and that the plutonic rocks extend to the trench axis. Further, the sequence suggests that subduction erosion has been occurring since the upper Miocene-lower Pliocene. This is suggested by recent studies (Melbourne *et al.*, 1997; Pacheco *et al.*, 1997a) which conclude that there is a lack of unconsolidated, porous sediments within the plate interface zone.

The composition of the inner trench wall in the central part of the JSZ is not known. However, the stratigraphic sequence on the Tres Mariás Islands (McCloy *et al.*, 1988) is similar to that observed in the southern part of the JSZ (Mercier de Lepinay *et al.*, 1997), suggesting that the observations made in the inner trench wall of the southern JSZ can be applied to the central part of the JSZ.

The geologic cross section type-model presented in this study was determined by matching the observed gravity data with the gravitational attraction of the 2-D geologic model calculated using an algorithm based on Talwani *et al.* (1959). The top of the Wadati-Benioff zone is constrained by seismicity data.

GRAVITY AND BATHYMETRY DATA

The onland gravity data used in this study were collected at 54 stations (Figure 1) during January 1993 and November 1994 using the LaCoste & Romberg model G geodetic gravimeter #247. These stations were located along Highway 80 between Barra de Navidad, on the Pacific coast, to the intersection of Highways 80 and 54, about 30 km south of Guadalajara. Station spacing was about 5 km which yields a wavelength resolution of 10 km. The measured values were corrected for the effects of theoretical earth-tides and reduced to Bouguer anomaly values employing the WGS-84 ellipsoid formulas (United States Defense Mapping Agency, 1987), assuming a reference density of 2.67 g/cm³. We estimate the accuracy of the observations, corrected for the tidal effect, to be "0.05 mGal. Terrain corrections were applied employing the digital data base of Aiken *et al.* (1997). Station elevations were determined employing a Paulin survey

micro-altimeter, in conjunction with elevations from INEGI, 1:50 000 scale, topography sheets. We estimate the error in elevation to be half the contour spacing on these topographic maps, or “10 m, which translates to an accuracy of “2 mGal for the Bouguer anomaly values. Station locations were determined from INEGI 1:50 000 scale topography maps in the southern part; whereas to the north, locations were determined by GPS (non-differential) measurements. We estimate the accuracy of the station locations to be ± 200 m. The base station for this survey is located in the Instituto Oceanográfico in Manzanillo, at $19^{\circ}03'45.545''\text{N} \pm 0.017''$, $104^{\circ}18'08.800''\text{W} \pm 0.023''$, and the elevation with respect to the WGS-77 ellipsoid is -11.15 meters, 2.5 meters above mean sea level. The observed gravity at the base station is 978581.46 ± 0.07 mGal. The Manzanillo base is tied to LAGSN77 gravity station #9712-62 in Puerto Vallarta (Ness, 1984).

Offshore, the gravity data used in this study are the free-air anomaly values derived from satellite altimetry data by Sandwell and Smith (1997). These data have a reported accuracy of 3-7 mGal and a horizontal wavelength resolution of 20 to 30 km (Sandwell and Smith, 1997; Yale *et al.*, 1998; Green *et al.*, 1998).

The bathymetric data used in the model are taken from the digital gridded (2' x 2' grid) bathymetric database of Smith and Sandwell (1997). These data are derived from quality controlled ship depth soundings and the interpolation between these soundings was guided by satellite altimetry data from the Geosat and ERS-1 spacecrafts. The estimated horizontal resolution of this data is between 1 and 25 km, depending on the density of ship depth soundings.

EARTHQUAKE DATA

Earthquake data used in this study (Figure 2) to constrain the geometry of the subducting slab under the southern part of the JSZ are those of Hurtado *et al.* (1988) and Pacheco *et al.*, (1997a). These two data sets include data from local seismic networks, and provide the best constrained hypocenter information.

The earthquake data of Hurtado *et al.* (1998) consist of seismic events recorded by 13 portable broadband digital seismographs deployed from March to July 1996, plus records from permanent seismic stations operated by the University of Colima (RESCO), and the broadband station CJIG (Chamela) operated by the National Seismological Service, UNAM. The hypocenters were located using the program SEISAN (Haskov, 1997) with the velocity model of Domínguez *et al.* (1996), using $V_p/V_s = 1.64$ as for the Colima area. Hypocentral locations were considered reliable, and were included in the data set, when they met the following criteria: (1) The locations were done using at least three

P-wave and three S-wave readings on three stations; (2) The root mean square error (rms) was less than 0.4 s in the final locations; and (3) The estimated hypocentral errors were less than 20 km.

The earthquake data set of Pacheco *et al.* (1997a) consists of the locations of the aftershocks of the October 9, 1995, $M_w=8.0$ thrust earthquake (Figure 2). Only aftershocks with an epicentral distance to the profile in Figure 1 of less than 20 km were used.

In addition to the hypocenter information, we include in our data set eight focal mechanisms (Figure 2) determined by Hurtado *et al.* (1998) using the method of P-wave first motion polarities. The other focal mechanisms from body wave inversion shown on Figure 2 are from Pardo and Suárez (1993), and Pacheco *et al.* (1997b).

RESULTS

The geologic type-model (Figure 2) of the JSZ derived from gravity and seismicity data consists of (1) the water layer, (2) the continental crust of the overriding North American plate or, specifically, the Jalisco block, (3) the oceanic lithosphere of the Rivera plate and (4) the upper mantle. The difference between the observed gravity and that calculated from the model can be seen in Figure 2. The standard deviation of the difference between the observed and modeled anomalies is ~ 7 mGal, and the mean difference is ~ 1 mGal.

In this model, the continental unit is in direct contact with the subducting oceanic plate for a distance of 100 km eastward of the trench axis, where the crust thickens from 0 km at the trench to 32 km. Eastward of the area where the crust is in direct contact with the subducting plate, the crust gradually thickens from 32 km to 44 km at a distance of 300 km from the trench axis.

The continental crust consists of an upper crustal layer (density 2.80 g/cm^3), a lower crustal layer (density 2.90 g/cm^3), and a thin sedimentary layer (density 2.30 g/cm^3) which overlies the upper crustal layer in the continental slope region. The upper crust has an average thickness of approximately 10 km and extends westward to the trench axis. From the coast, about 70 km east of the trench, the boundary between the upper and lower crust deepens slightly, reaching its greatest depth 115 km from the trench axis. Several normal-faulting events are located near the boundary between the lower and upper crust where it attains its greatest depth. East of this point, until a point located 235 km from the trench axis, the boundary gradually shoals. A deepening of the boundary is indicated by the model east of this point; however, this deepening should be viewed with caution as it is

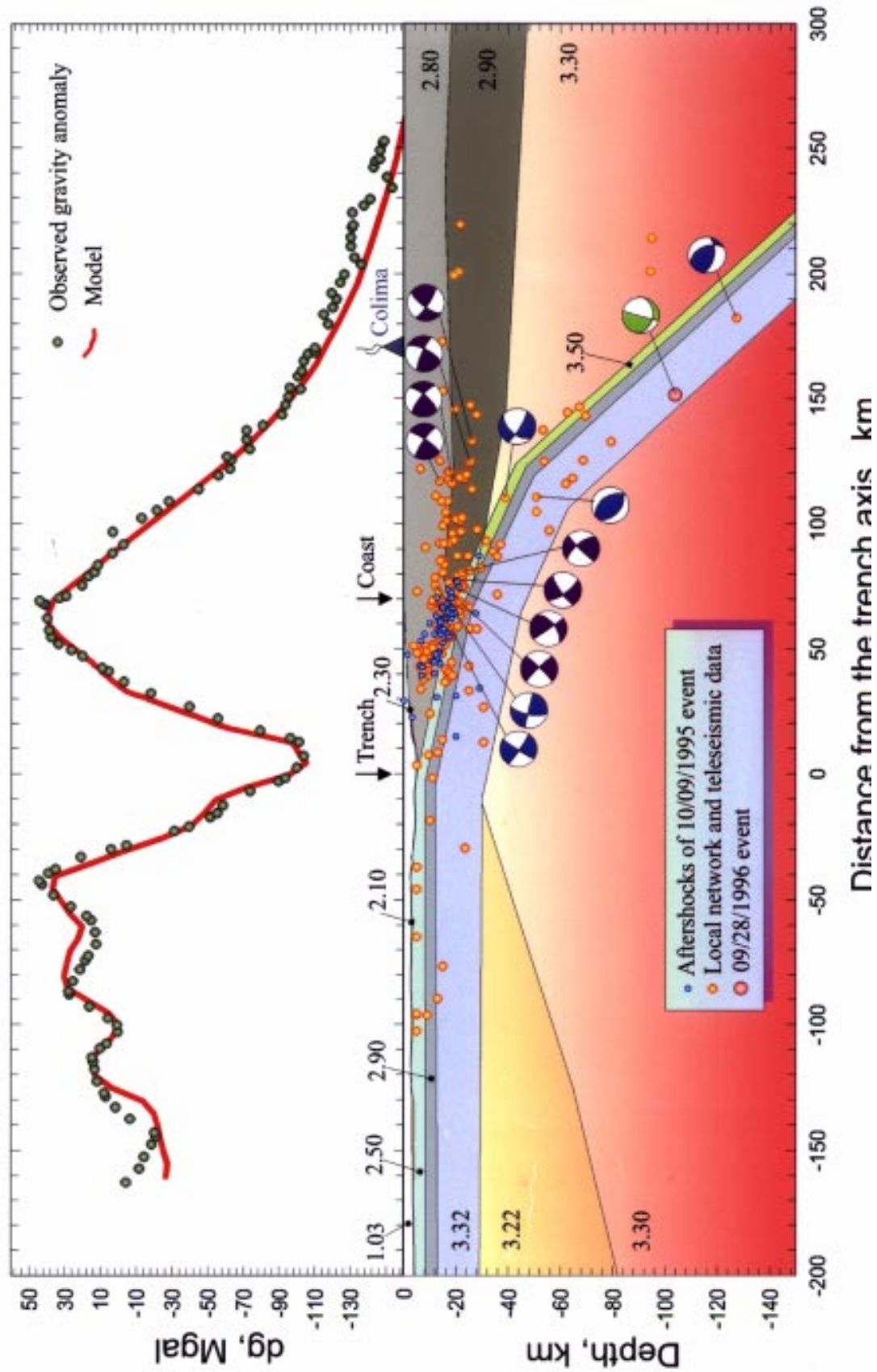


Fig. 2. Top: Free-Air (ocean side) and complete Bouguer (continental side) gravity anomalies on the Barra de Navidad profile (see Figure 1 for profile location). Green dots indicate observed values and red line indicates values computed from the model. Bottom: structural density model and seismic data (colored circles, see legend) along the profile. Focal mechanisms are: blue quadrants from Hurtado *et al.* (1998), violet quadrants from Pardo and Suárez (1993), and green quadrants is the event of 09/28/1996 from Pacheco *et al.* (1997b). Numbers inside colored fields are the densities in g/cm³ accepted for the model. Note that the maximum recorded depth of seismicity directly under the Barra de Navidad profile is around 80 km, while there are several deeper earthquakes in the southeastern part of the Jalisco subduction zone which are also shown on the figure.

near the edge of the data spread.

The lower crustal layer extends westward, terminating just under the coast. This layer thins eastward, and abuts the subducting oceanic crust of the Rivera plate. The boundary between this layer and the underlying upper mantle gradually deepens eastward. The upper mantle under the Jalisco block is modeled to have a density of 3.30 g/cm^3 , a value often assumed for the upper mantle in this region (e.g., Couch *et al.*, 1991).

The oceanic lithosphere of the Rivera plate is modeled as consisting of three layers with densities of 2.5, 2.9, and 3.32 g/cm^3 , respectively. A best-fit line through the hypocentral depths of the aftershocks of the 1995 Jalisco/Colima earthquake indicates that the subducting slab has an initial dip of $10.2^\circ \pm 2.9^\circ$, which is consistent with earlier studies. The density of the upper layer increases to 3.5 g/cm^3 within the subducting plate at a mantle depth of about 30 km.

As under the Jalisco block, the upper mantle beneath the oceanic crust is assumed to have, in general, a density of 3.30 g/cm^3 . However, to fit the observed gravity anomaly it was necessary to include a wedge shaped body with lower than normal upper mantle densities. This low-density zone thins eastward away from the East Pacific Rise.

DISCUSSION

The regional model for the JSZ derived from the gravity and seismicity data displays two anomalous density zones; namely, a high density zone in the upper layer of the subducting oceanic lithosphere at depths below 30 km, and a broad wedge-shaped upper mantle zone underlying the oceanic plate to the southeast.

These two anomalous density zones are needed to fit the observed and calculated values. The green curve on Figure 3 illustrates the fit between the observed gravity and a model which excludes these two zones. The calculated gravity attraction of this model fits the observed data within the trench; however, it is too low northeast of the trench, and it is too high southwest of the trench. The orange curve illustrates the effect of adding a higher density zone within the upper layer of the subducting slab below depths of 30 km. Inclusion of this layer produces a good fit to the observed values within the trench and to the area northeast of the trench, but still provides a poor fit southwest of the trench. The red curve on Figure 3 illustrates the modeled gravitational attraction when both zones are included. Inclusion of the two zones of anomalous densities provides a good fit to the observed values along the entire profile.

Geologic processes which could explain these anomalous

density zones have previously been reported. Grow and Bowin (1975) include in gravity models of the Chile subduction zone a high density layer at the top of the subducting Nazca plate beneath the South American plate. They propose that this layer is the result of a phase transition from basalt to eclogite assumed in previous studies to occur at a depth of about 30 km.

Recent studies of mantle upwelling beneath mid-ocean ridges (The Melt Seismic Team, 1998) indicate that the magma emplacement may not be confined to a narrow, shallow zone centered beneath the ridge axis as previously thought. Instead, it may be emplaced over a wide, deep zone which may be several hundred kilometers wide. Further, this zone of emplacement may extend to depths of over 100 km, and may be asymmetric with respect to the ridge axis. The southwest end of the gravity profile crosses a broad, bathymetrically high region in the area of the East Pacific Rise (EPR). Thus, the low density upper mantle zone present in the regional geologic model may reflect a broad zone of magma emplacement associated with spreading along the EPR in our area.

In our model, the thickness of the continental crust of the Jalisco block averages ~38 km, which is consistent with the value of ~40 km determined by Urrutia-Fucugauchi and Flores-Ruiz (1996) for the central part of the Jalisco block. Our results indicate that the crust gradually thickens eastward towards the boundary where it reaches a maximum thickness of 44 km, thus supporting the study of Urrutia-Fucugauchi and Molina-Garza (1992) which indicates a crustal thickness of ~43 km.

CONCLUSIONS

An integrated study of gravity and seismicity data along a profile perpendicular to the Jalisco coast near Barra de Navidad provides new data and insights on the structure of the southern Jalisco subduction zone. The thickness of the continental crust of the Jalisco block averages ~38 km and gradually thickens eastward to ~44 km. The density of the upper part of the subducting lithosphere increases at a depth of ~30 km. The upper mantle west of the trench exhibits lower densities than the rest of the upper mantle. This low density zone is thickest near the EPR and thins eastward towards the MAT. It may reflect a broad zone of magma emplacement along the EPR, similar to that observed along the EPR at

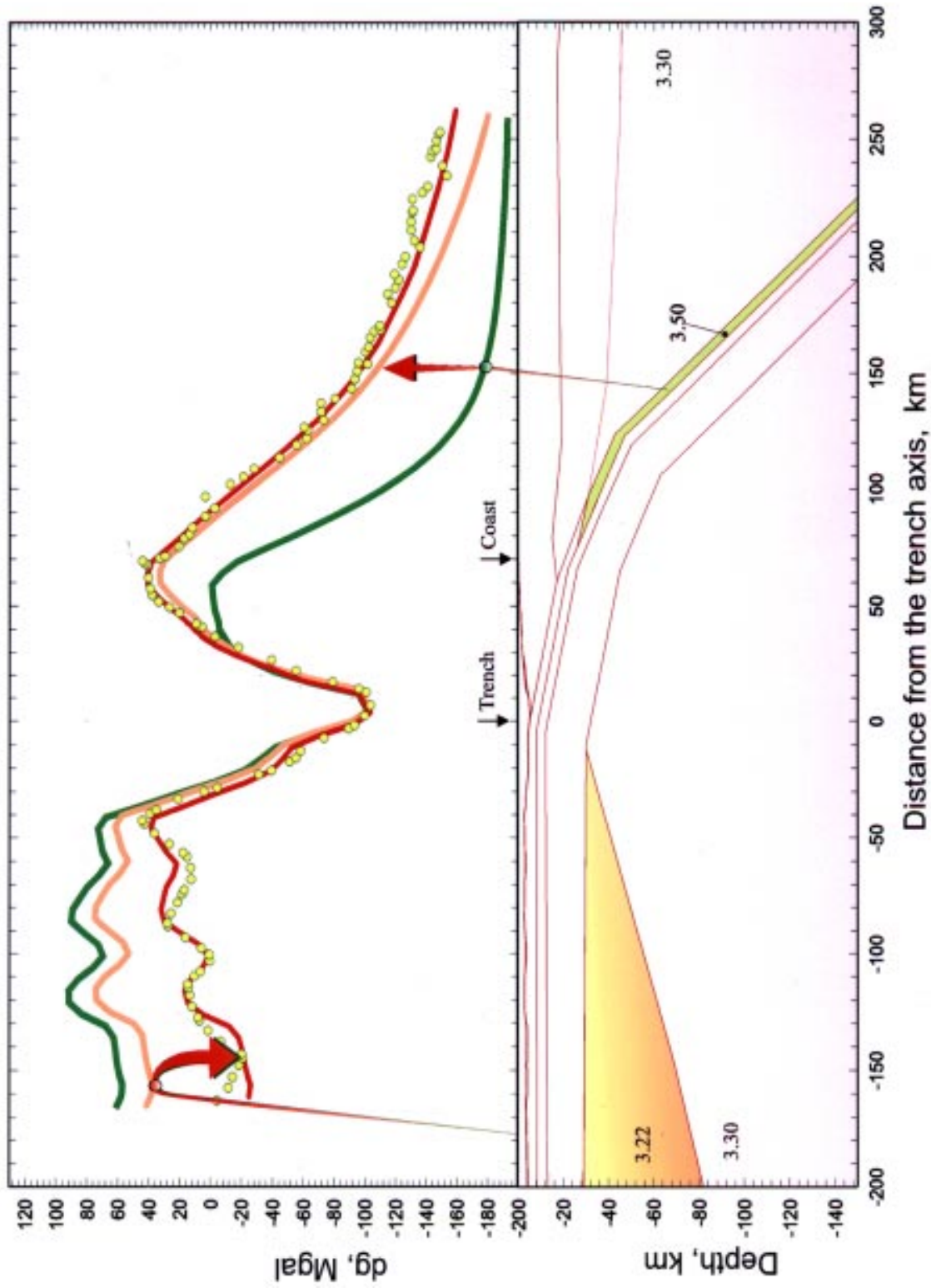


Fig. 3. Gravity model adjustment. Top: yellow dots are observed gravity anomalies, green line indicates a modeled fit without the gravity effect of the low density (3.22 g/cm^3) mantle body located under the EPR and the effect of the high density layer (3.50 g/cm^3 , presumably of eclogite composition) in the subducted oceanic crust. The upward directed arrow and the difference between the pink and green lines indicate the gravity effect of the high density layer. The downward directed arrow and the difference between the pink and red (best fit) lines indicate the effect of the low density body. Bottom: structural density model (same as that shown in Figure 2). Light green is the high density layer. Yellow is the low density mantle body.

16ES (The MELT Seismic Team, 1998).

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