

## Imaging the Seismic Crustal Structure of the Western Mexican Margin between 19°N and 21°N

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**Abstract**—Three thousand kilometres of multichannel (MCS) and wide-angle seismic profiles, gravity and magnetic, multibeam bathymetry and backscatter data were recorded in the offshore area of the west coast of Mexico and the Gulf of California during the spring 1996 (CORTES survey). The seismic images obtained off Puerto Vallarta, Mexico, in the Jalisco subduction zone extend from the oceanic domain up to the continental shelf, and significantly improve the knowledge of the internal crustal structure of the subduction zone between the Rivera and North American (NA) Plates. Analyzing the crustal images, we differentiate: (1) An oceanic domain with an important variation in sediment thickness ranging from 2.5 to 1 km southwards; (2) an accretionary prism comprised of highly deformed sediments, extending for a maximum width of 15 km; (3) a deformed forearc basin domain which is 25 km wide in the northern section, and is not seen towards the south where the continental slope connects directly with the accretionary prism and trench, thus suggesting a different deformational process; and (4) a continental domain consisting of a continental slope and a mid slope terrace, with a bottom simulating reflector (BSR) identified in the first second of the MCS profiles. The existence of a developed accretionary prism suggests a subduction–accretion type tectonic regime. Detailed analysis of the seismic reflection data in the oceanic domain reveals high amplitude reflections at around 6 s [two way travel time (twtt)] that clearly define the subduction plane. At 2 s (twtt) depth we identify a strong reflection which we interpret as the Moho discontinuity. We have measured a mean dip angle of  $7^\circ \pm 1^\circ$  at the subduction zone where the Rivera Plate begins to subduct, with the dip angle gently increasing towards the south. The oceanic crust has a mean crustal thickness of 6.0–6.5 km. We also find evidence indicating that the Rivera Plate possibly subducts at very low angles beneath the Tres Marias Islands.

**Key words:** Rivera Plate, Middle America Trench, crustal structure, seismic imaging, subduction plate, BSR.

### 1. Introduction

The tectonics, seismicity and magmatism in the western part of central Mexico is largely controlled by the subduction of the Cocos and Rivera oceanic plates beneath the North American (NA) Plate, the Middle America Trench (MAT) being the morphologic expression of the subduction contact (Fig. 1). The Rivera Plate is a key structural element to understand the complex geodynamic interactions that occur at the western coast of Mexico. ATWATER (1970) was the first to suggest the existence of this microplate. Since then, several authors have shown that the Rivera Plate is kinematically distinct from the NA and Cocos Plates (EISSLER and McNALLY, 1984; BANDY and YAN, 1989; DEMETS and STEIN, 1990), although the precise location of the Rivera–Cocos boundary is still controversial since no clear bathymetric features can be clearly associated with the plate boundary (EISSLER and McNALLY, 1984; BOURGOIS and MICHAUD, 1991). Seafloor accretion occurs along the western boundary Rivera plate, at the Pacific–Rivera Rise (PRR), whereas to the east, the lithosphere of the Rivera plate is consumed at the trench where the plate has been dated as late Miocene ( $\sim 9$  Ma) based on seafloor magnetic anomalies (KLITGORD and MAMMERICKX, 1982). The age of the Cocos Plate varies along the MAT, with jumps in ages occurring across several fracture zones. Thus, the younger and shallower Cocos crust near the Rivera Plate is dated as 10 Ma whereas at 90°W it is dated as 25 Ma old (COUCH and WOODCOCK, 1981).

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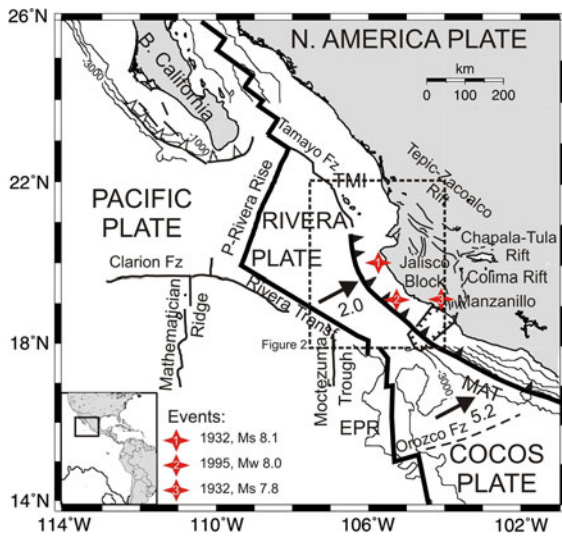


Figure 1

General tectonic setting of western Mexico. Four lithospheric plates act in the area: Pacific, Rivera, Cocos and North American. Arrows indicate relative convergence rates (cm/year) between the oceanic and continental plates. Red stars show rupture zones for the 1932 and 1995 events (PACHECO *et al.*, 1997). Black square highlights the area of Fig. 2. TMI Tres Marias Islands, MAT Middle America Trench, EPR East Pacific Rise

There are still points to be clarified regarding the Rivera Plate subduction patterns. Among them, the convergence direction and rate (KOSTOGLODOV and BANDY, 1995; DEMETS and WILSON, 1997; BANDY *et al.*, 1998; DEMETS and TRAYLEN, 2000), the recent strike-slip deformation (BANDY *et al.*, 2005), the seismic activity (NIXON, 1982), and a plausible evolution model for the junction area of the East Pacific Rise (EPR), the Rivera Transform and the MAT (MAMMERICKX, 1984; BOURGOIS *et al.*, 1988; DEMETS and WILSON, 1997; BANDY *et al.*, 1998; MICHAUD *et al.*, 2001; BANDY *et al.*, 2005). In terms of seismic data, only a few single channel seismic profiles are available in the literature (BOURGOIS *et al.*, 1988; BOURGOIS and MICHAUD, 1991; KHUTORSKOY *et al.*, 1994; MICHAUD *et al.*, 1996) and one threefold profile (BANDY *et al.*, 2005). These data show active shallow strike-slip tectonics and a subsidence in the upper (first second twtt) continental slope area at 18.5°N, although the subducting Rivera Plate crustal structure remains unidentified. Therefore, the studies of the internal structure of the overriding plate have relied primarily on potential field data (BANDY *et al.*, 1993;

BANDY *et al.*, 1999). The subduction of the Rivera Plate remains a matter of debate due to the poorly controlled shape of the subducted plate (EISSLER and McNALLY, 1984; PARDO and SUÁREZ, 1993; BANDY *et al.*, 1999), and the low background seismicity compared to the rest of the MAT to the south. Regarding this low seismicity, there are few historical earthquakes at the Rivera-NA plate boundary, which raises the possibility that the Rivera Plate subducts aseismically (NIXON, 1982). However, some of the largest destructive earthquakes reported in recent history occurred offshore of the Jalisco region (19°N), such as the 1932 (Ms 8.1 and Ms 7.8) Jalisco earthquakes (SINGH *et al.*, 1985) and the 9 October 1995 ( $M_w$  8.0, 17 km depth epicentre and 5 m of tsunami) Colima earthquake in the southeast flank of the region (COURBOULEX *et al.*, 1997). The main event of the 1995 earthquake was a subduction related thrust event that activated normal faults along the northwest margin of Manzanillo (19°N and 105°W, Fig. 1), clearly showing present day plate convergence. However, it is not clear if the  $M_w$  7.4 event of 22 January 2003 occurred along the current thrust interface between the Rivera and NA Plates (SINGH *et al.*, 2003).

The angle of subduction of the Rivera Plate has been computed by accurately relocating hypocenters (e.g., PARDO and SUÁREZ, 1993, 1995). The inferred Wadatti-Benioff zone indicates a steeper dip for the Rivera Plate than the adjacent Cocos Plate. This has led to the proposal of a step in the slab between the Cocos and Rivera Plates at the present time (FERRARI *et al.*, 2001) due to the slab rollback mechanism, acting on the Rivera Plate underlying the NA Plate, during a period of very low convergence rate (19 mm/year on average) between 8.5 and 4.6 Ma (DEMETS and TRAYLEN, 2000). The seismicity causes a significant seismic hazard to the coastal regions of Mexico, as well as areas considerably inland, including Mexico City (CURRIE *et al.*, 2002). A strong understanding of the Mexico subduction region (geometry, seismic zone of subduction, faults and rupture width, etc.) and detailed information about the crustal structure along the Rivera Plate are required to carry out seismic hazard studies. Other constraints are comprehension of the limits of the lateral and vertical extent of the Rivera Plate as well

as plate tectonic models, including the opening of the Gulf of California.

For these reasons, in 1996, the Spanish *R/V Hespérides* and the Mexican *R/Vs Altair and Humboldt* surveyed the northwestern Mexican margin between 16°N and 30°N in a geophysical experiment named the Crustal Offshore Research Transect by Extensive Seismic Profiling, or CORTES-P96 (DANOBEITIA *et al.*, 1997). Swath bathymetry, backscattering and multichannel seismic reflection data profiles (Fig. 2) were acquired within the Rivera subduction zone extending from 21°N to 19°N. In this paper, we present five post-stack time migrated MCS sections (Fig. 3) that show for the first time in this area, seismic images from the Earth's surface down to the Mohorovicic discontinuity (Moho) that enable us to seismically characterize the crustal structure of the overriding and subducting plates offshore Puerto Vallarta, describe the spatial distribution of the incoming plates (sediment, crust and mantle lithosphere) and identify some of the processes occurring in this area.

## 2. Geological Setting

The western margin of Mexico between 26°N and 23°N is structurally composed of a transform margin made up of a set of spreading centers linked by a fault system (Fig. 1). The right lateral fault system is the southward prolongation of the San Andreas Fault across the Gulf of California. The 70 km Tamayo transform fault connects the southernmost spreading segment in Gulf of California (the Alarcon Rise) with the PRR at 23°N. This spreading center, located between 23°N and 19°N, is the western plate boundary between the Rivera and Pacific Plates and its spreading velocities have fluctuated between intermediate and fast rates over the past 10 Ma (average full spreading rate of around 9.7 cm/year, DEMETS and TRAYLEN, 2000). The Rivera Transform is the southern plate boundary between the Rivera and Pacific Plates and the MAT the eastern plate boundary between the Rivera and NA Plates.

The geodynamic history since 25 Ma starts with the collision of the Pacific-Farallon seafloor-spreading center against the convergent western margin of

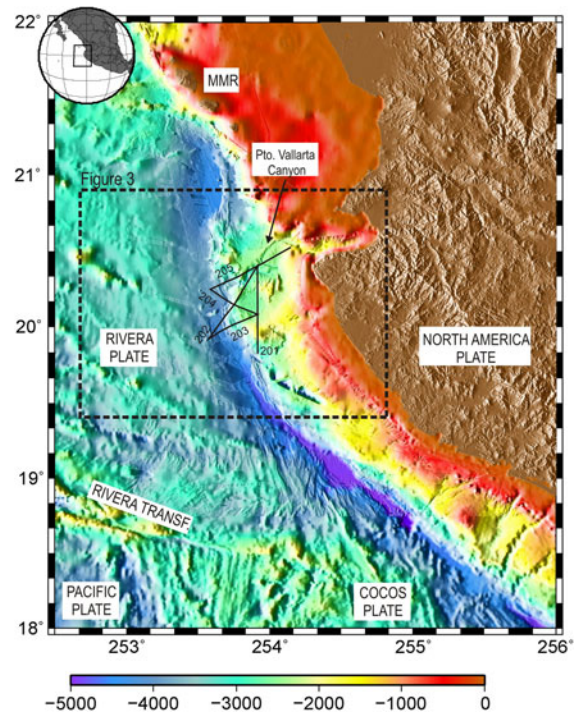


Figure 2

Location of ship tracks of the CORTES geophysical profiles, numbered from 201 to 205, acquired offshore of Puerto Vallarta and analyzed in the present study. Additional bathymetry data is from surveys of the *R/V Jean Charcot* and *R/V Marion Dufresne* (Mona survey), the NGDC database and GEBCO (2008) (30 min arc cell grid resolution). *Shaded Bathymetry* has been displayed illuminated from the west. *MMR* Maria Magdalena Rise. *Black square* shows the study area

NA. This collision marked the beginning of a major change in the tectonic evolution and volcanism of western NA (ATWATER, 1970, 1989). Some authors propose a final reorganization in the Middle Miocene (6.5–3.5 Ma) triggered by the jump of the EPR to its present location, transferred by the development of the Rivera Transform (MAMMERICKX, 1984; MAMMERICKX and KLITGORD, 1982; LONSDALE, 1991). Alternatively, LONSDALE (1995) proposes that the northward propagation of the EPR to its present location took place without any clear early connection with the PRR, suggesting a broad diffuse dextral shear zone connecting the two spreading centers before the full development of the Rivera Transform. Even if the connection between the EPR and the Rivera Transform is imprecise, multibeam and backscatter data collected during the CORTES-P96 experiment pointed out that the EPR reached the

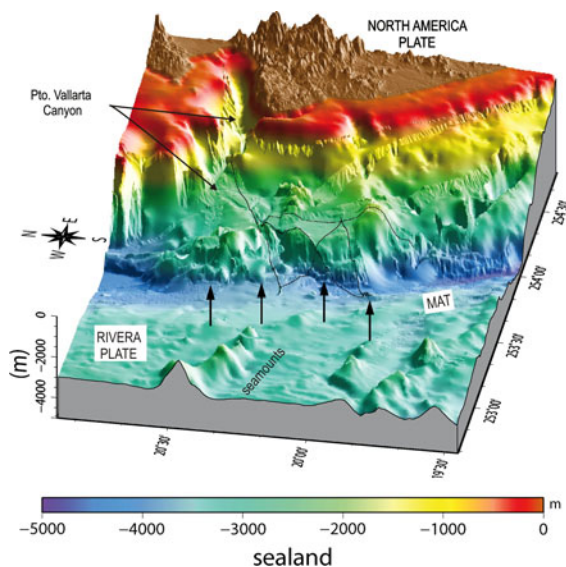


Figure 3

3D shaded relief bathymetry of the study area, looking eastward. MCS lines have been projected on the seafloor to aid in the interpretation of seismic data. Black arrows mark the deformation front, emphasizing the increasing distance towards the trench with latitude. The collision with MAT of seamount chains oriented perpendicular to the MAT, observed along the margin, push the frontal sediment prism towards the coast as is observed between the second and third black arrow. Note the sediment infill of the trench by the Puerto Vallarta Canyon. Bathymetric data is described in

Fig. 2

trench (MICAUD *et al.*, 2001). This suggests that the EPR extended northward of the Rivera Transform, consistent with the findings of BANDY (1992) based on marine magnetic data, and subducted beneath the NA plate before 2 Ma without the need of any connection with the Rivera Transform. The convergence rate reported at the MAT shows significant variations during the last 10 Ma, with convergence stopping between 2.5 and 1 Ma (DEMETS and TRAYLEN, 2000). The current reported value of Rivera-NA relative convergence rate is a matter of debate. It ranges from 2.0 cm/year, based on the accurately located hypocenters of local and teleseismic earthquakes (PARDO and SUÁREZ, 1995), to 5 cm/year based on seismotectonic relationships (KOSTOGLODOV and BANDY, 1995) which relate seismic characteristics of subduction zones (maximum magnitudes, maximum seismic depths, etc.) to plate tectonic parameters (convergence rates, age of the oceanic lithosphere, etc.). The most recent estimations derived from

reconstruction of magnetic anomalies for the last 0.78 Ma, give Rivera Plate convergence rates of 3.3–4.3 cm/year along the NA Plate in the area of the Jalisco Block (BANDY and PARDO, 1994; DEMETS and WILSON, 1997; BANDY *et al.*, 1998; DEMETS and TRAYLEN, 2000).

The mechanism (slab-pull) that powers the subduction and moves the plate is well known and is caused by slightly more dense mantle lithosphere of the Rivera Plate than that underlying North American Plate, with one peculiarity. As density excess increases as the lithosphere ages and thickens, and the lithosphere becomes negatively buoyant (namely, subducting) when it is 10–30 million years old (DAVIES, 1992), the <10 Ma buoyant crust of the Rivera Plate resists subduction. This resistance results in a strong coupling between plates having higher magnitude earthquakes and shallower dips compared to those plates subducting old lithospheres. The strain regime behind the magmatic arc for the subducting of the young Rivera lithosphere is expected to be strongly compressional (folding and thrusting), and the maximum magnitude earthquakes must occur under these conditions (young and fast lithosphere) beneath the continental crust arcs (STERN, 2002).

The direction of convergence between the Rivera and NA Plates at the MAT becomes progressively more oblique (in a counter-clockwise sense relative to the trench-normal direction) northward along the end of the MAT (19°N–21°N), commonly termed the Jalisco subduction zone (JSZ) (e.g. BANDY, 1992; LONSDALE, 1995; KOSTOGLODOV and BANDY, 1995; DeMets and WILSON, 1997; DEMETS and TRAYLEN, 2000). This area comprises the northern part of the MAT between the Tres Marias Islands and the southern tip of the Colima Rift (Fig. 1). The depth of the slab under western Mexico is poorly constrained, but local earthquake data indicate a Benioff zone for the Rivera Plate bending from around 10° at 20 km depth to 50° at 40 km depth, whereas the Cocos Plate is sub-horizontal at the same depth (PARDO and SUÁREZ, 1993). This change of dip angle is unrelated to the thermal structure of the slabs and the present rate of subduction due to the similar age and comparable subduction rates of both plates. A rollback of the slab when the relative convergence between the

Rivera and NA Plates decreased to a very low rate at the end of Miocene was proposed as a plausible explanation (FERRARI *et al.*, 2001).

The Jalisco Block (JB) is bounded landwards by the Tepic-Zacoalco Rift on the NE and by the Colima Rift on the SE (Fig. 1). Rifting and volcanism have been proposed to be associated with the northward detachment of the JB from the NA Plate (LUHR *et al.*, 1985) at the very low rate of  $<5$  mm/year (DEMETTS and STEIN, 1990; BANDY and PARDO, 1994), starting in the Pliocene–Quaternary. Recent strike-slip deformation within the forearc region of the JSZ has also been reported by shallow ( $<1$  s twtt penetration) seismic data collected offshore the Jalisco Block (BANDY *et al.*, 2005). That study also provided additional evidence for recent subsidence within the area offshore of Manzanillo in agreement with previous works (MERCIER DE LEPINAY *et al.*, 1997; RAMÍREZ-HERRERA and URRUTIA-FUCUGAUCHI, 1999).

The uplift-subsidence history proposed for the entire margin along the JSZ from the Tres Marias Islands to the Manzanillo area starts with uplift and emergence before the late Miocene (6.5 Ma) and continuing subsidence during the late Miocene–Lower Pliocene until the Pliocene–Quaternary boundary ( $\sim 2$  Ma). Regional subsidence of an active margin is generally related to tectonic erosion. After the Pliocene–Quaternary boundary, the Tres Marias began to be uplifted (McCLOY *et al.*, 1988), whereas the Manzanillo area started to subside, certainly due to the fragmentation associated with the development of the JB during the Pliocene–Quaternary, at a subsidence rate of 0.35 mm/year (MERCIER DE LEPINAY *et al.*, 1997). For the Holocene period, in the active tectonic margin environment of the Jalisco area, a new model is proposed where the coseismic subsidence (centimetre-scale) produced by large offshore earthquakes is rapidly recovered during the post-seismic and interseismic periods, yielding a general coastal uplift (RAMÍREZ-HERRERA *et al.*, 2004). In other words, the slow long-term uplift is considered the most important factor to the total net vertical motion (uplift) of the Jalisco area. Based on the first reported organisms dated with radiocarbon along the Jalisco coast, an average rate of about 3 mm/year for tectonic uplift since 1,300 years BP has been computed (RAMÍREZ-HERRERA *et al.*, 2004).

### 3. MCS Data

The data set analysed in this study is composed of five MCS profiles (profiles 201–205, Fig. 2), totalling 280 km and acquired during the CORTES-P96 cruise, is located in the subducting domain of the Rivera Plate off Puerto Vallarta, at the contact with the NA Plate. The five seismic profiles used in this work have three different orientations with respect to the direction of the trench axis: profiles 203 and 205 are perpendicular, profiles 202 and 204 are oblique and profile 201 is parallel to the MAT (Fig. 2). The profiles were acquired using a 2.4 km long streamer with 96 channels at 2 ms sampling interval, towed 165 m behind the ship at 9 m depth. The source used by the Spanish R/V *Hesperides* was a tuned airgun array of 50 l (3,000 in<sup>3</sup>). The shooting rate was 30 s. Quality control and preliminary stacking were done onboard, while final processing of MCS data through 9 s (twtt) and a 16-fold coverage stack and migration was done at the Department of Geophysics of the Institute of Earth Sciences *Jaume Almera* and in the Unidad de Tecnología Marina-CSIC (Barcelona, Spain).

The seismic processing flow includes band-pass filtering (5–9–58–62.5 Hz), editing of noisy traces, divergence correction, and internal mute to reduce the water bottom multiple effects. After CMP sorting, a minimum phase predictive deconvolution was performed (50–350 ms). Stacking velocity analysis every 200 CDP maximum interval and NMO correction were performed. The profiles were finally Kirchhoff post-stack time migrated. The final MCS sections were band-pass filtered, normalized and trace mixed.

In the following sections, the components of the subduction zone are described, and their interactions are discussed.

## 4. Analysis of MCS Data and Discussion

### 4.1. Shallow Crustal Structure

The northernmost profile 205 (Fig. 4) provides the first ever reported seismic image of the active margin in the area offshore of Puerto Vallarta. The upper and

western part of profile 205 was already published in a study of the heat flow through the margin (MINSHULL *et al.*, 2005). From offshore to onshore (NE orientation) we have identified the following morphological features: deformation front (CMP 1,500), trench (CMP 2,500), accretionary prism (CMP 2,500–3,600), a well-developed forearc basin (CMP 3,600–5,600), backstop limit at (CDP 4800), and continental slope and mid slope terrace (CMP 5,600–6,400). We also recognized the presence of erosion as mass wasting affecting the slope is also identified (CMP 5,700–6,300).

The joint interpretation of profiles 205 (Fig. 4), 204 (Fig. 5), 202 (Fig. 6) and 203 (Fig. 7) in the oceanic domain indicate that the trench-fill sediments progressively thicken landward. The maximum thickness of the trench-fill decreases towards the south being around 2 s twtt in profile 205 (CMP 2,400, Fig. 4), 1.52 s twtt in profile 204 (CMP 2,200, Fig. 5), 0.85 s twtt in profile 202 (CMP 14,000, Fig. 6), and 0.6 s twtt in profile 203 (CMP 1,200, Fig. 7), respectively. Assuming an average P-wave velocity of 2.5 km/s for the sedimentary cover as suggested by the velocity analysis of the MCS data, we obtain a maximum thickness of 2.5 km for section 205, 1.9 km for 204, 1.1 km for 202 and 0.75 km for 203. The different thickness and deformation of the shallower reflectors between the northern and southern profiles may be explained by increasing infill of terrigenous sediments associated with drainage from the head of the Puerto Vallarta Canyon (Fig. 3), pointed to in profile 205 (CMP 3,700 and 4,100; Fig. 4) and profile 201 (CMP 4,700, Fig. 8). The trench-fill sediments show a significant deformation seaward of the trench in the northern sections 205 (CMP 1,900–2,400, Fig. 4) and 204 (CMP 2,100–2,400, Fig. 5), indicating a recent deformation at the northern end of the MAT. The observed sediment thickness in the trench off Puerto Vallarta, despite the decreasing tendency observed southwards due to the infill of the Puerto Vallarta Canyon, is similar to that observed in the Cascadia and southwest Japan subduction zones, which are of comparable age and covered with 1.5–3.5 km of sediment (WANG *et al.*, 1995). Nevertheless, opposite of what has been observed in the trench off Puerto Vallarta, a lack of a thick cover of sediments (~200 m) has been noticed to the south and

especially in the area of the boundary between the Rivera and Cocos Plates. Of potential importance is the sediment thickness on top of the plate that slows the rate of cooling of the oceanic lithosphere and thus changes its thermal structure. A poor sediment cover for the Rivera Plate has been assumed during the computation of the thermal modeling in the Mexico subduction zone published by CURRIE *et al.* (2002). Therefore, in light of these new crustal images, thermal models may need to be revised, at least in the northern part of the Rivera Plate, to be consistent with the new seismic observations. In addition, the crust of the Rivera Plate may be warm enough to melt (<10 Ma and slowly subducted), possibly aided by greater friction across the subduction interfaces, producing adakites such as the ones investigated by FERRARI *et al.* (2001). This also has to be considered during the modelling. One should bear in mind that sediments in most subducted zones melt but subducted crust only melts when it is young and hot enough (JOHNSON and PLANK, 1999).

The southernmost profiles 202 (CMP 15,000, Fig. 6) and 203 (CMP 400, Fig. 7) clearly illustrate a set of normal faults reaching the surface. The structure of the subducting plate consists of grabens and horsts that are products of the extensional stress due to bending of the plate, which might facilitate sediment subduction and the percolation of fluids. These faults, arriving up to the seafloor, might indicate recent tectonic activity related to the dip augmentation of the Rivera Plate since 8.5 Ma, when bending occurred at the time the Rivera Plate slowed the convergence (7.2–4.8 Ma) as recorded by the trenchward migration of the volcanic front (FERRARI *et al.*, 2001). Fluids are likely to percolate and circulate along these faults deep into the overriding plate, probably favouring the formation of gas hydrates and significantly cooling the oceanic plate as shown by marine heat flow observations (ZIAGOS *et al.*, 1985; PROL-LEDESMA *et al.*, 1989; KHUTORSKOY *et al.*, 1994). The increase of the amount of fluids (including asthenospheric rising) started in the Pliocene and released from the subducting slab of the Rivera Plate due to the increase of the convergence is confirmed by the subsequent volcanic rate increment (FERRARI *et al.*, 2001). The distance from the trench axis to the deformation front differs from one section to another as well. From north to south, the

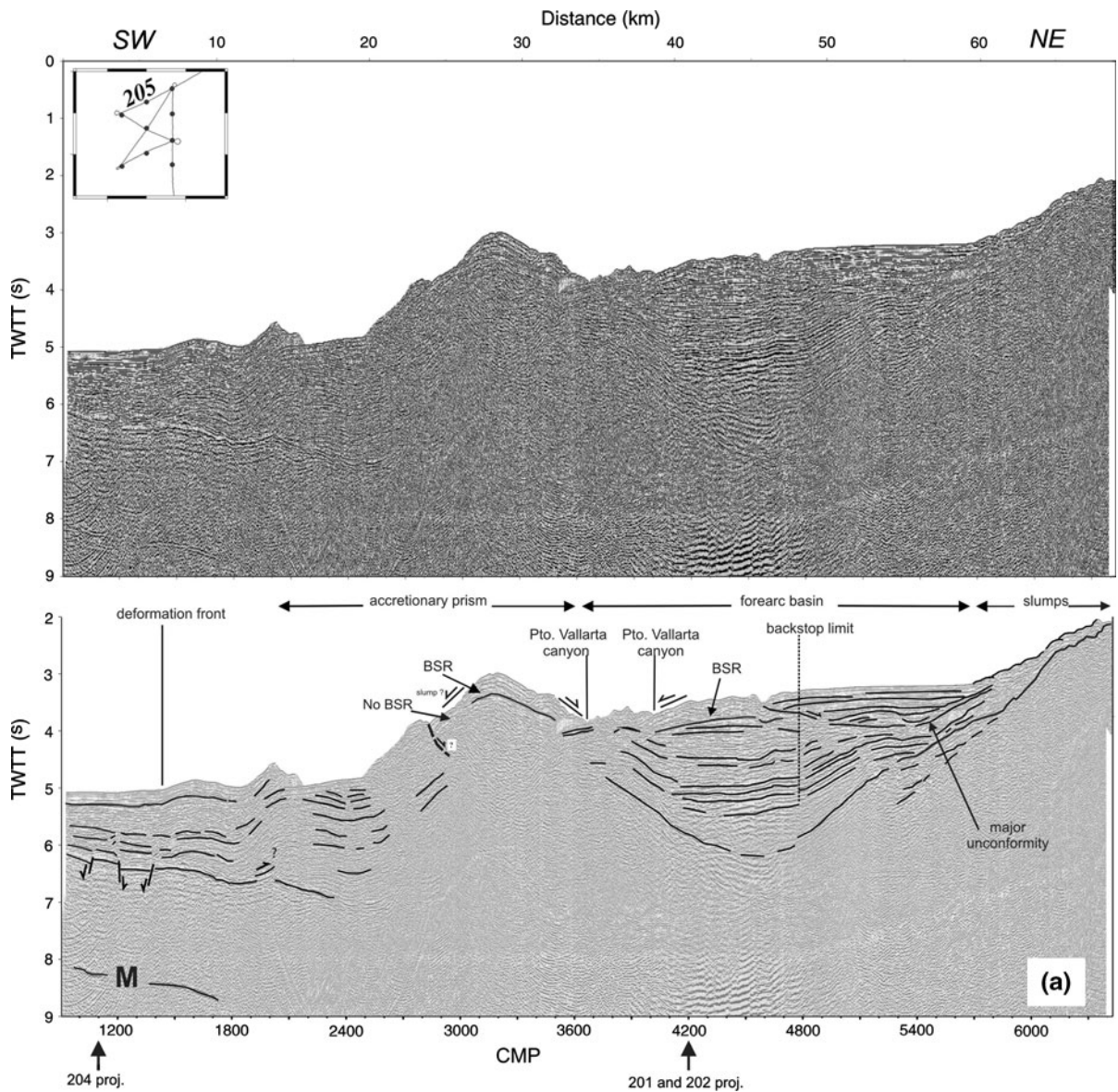


Figure 4

*Top panel* shows the un-interpreted time migration section of profile 205 (see the *text* for processing sequence). *Left-inner box* (as well as Fig. 2) shows the location of the profile; *bottom panel* displays the interpreted profile, with noticeable features such as the Moho discontinuity detected around 8.0–8.5 s twtt (CMP 1,000–1,800), the interruption of the BSR due to the Puerto Vallarta Canyon (CMP 3,500–4,000) or a high slump (CMP 3,000) at the accretionary prism. *M* Moho discontinuity

deformation front is 12 km westward from the trench axis in section 205 (CMP 1,500, Fig. 4), 5 km in profiles 204 (CDP 1,400, Fig. 5) and 202 (14,100, Fig. 6), and the distance is undetectable in the southern profile 203 (Fig. 7), as we can summarize in Fig. 3 by the black arrows. The basement is also faulted beneath the sedimentary layers at 1.1–1.3 s

twtt (1.3–1.6 km depth) in the northern sections (CMP 1,200, Fig. 4; CMP 3,000, Fig. 5).

Nevertheless, the existence of an accretionary prism observed in seismic sections indicates a subduction–accretion tectonic regime along this segment of the Rivera margin, in contrast with what has been observed previously (MERCIER DE LEPINAY *et al.*,

1997) off Manzanillo. Whereas subduction–accretion characterizes the Rivera margin in the study area and off Acapulco (100°W) according to the results from DSDP Leg 66 (MOORE *et al.*, 1982), subduction–erosion controls the subduction of the Rivera–Cocos Plates off Manzanillo (104°W), during at least the last 8 Ma (FERRARI *et al.*, 2001). This difference in tectonic regimes, of areas only 500 km apart, has been related with a variation in the geometry of the slab along the trench: the downgoing slab is steeper beneath the JB than off Acapulco (PARDO and SUÁREZ, 1993). However, we observe chains of seamounts stretching hundreds of km seaward of, and perpendicular to, the MAT, offshore (Fig. 3). When subducted, these seamounts destabilize the overlying seafloor and leave a morphological trace across the continental slope that marks their path beneath the surface, as has been described along the MAT along the Costa Rica margin (VON HUENE *et al.*, 2004). A chain of seamounts is pointed directly at profile 202 and the southern part of profile 201 where a morphological elevation of the seafloor is observed in the bathymetric and seismic data (Figs. 3, 6, 8). We speculate that a seamount collision and subduction is responsible for the lack of an extensive accretionary prism observed in line 204 (Fig. 5, CMP 2,100). Subducted seamounts push back the frontal sediment prism after entering the subduction zone leaving a gap the size of the seamount in the continental slope. Seamount subduction is a key point for the study of local tsunami generation.

Landwards, the continental domain is characterized by a forearc basin exhibiting two primarily sequences, an undeformed upper sequence (CMP 4,700–5,700, Fig. 4) separated from a deformed lower sequence by a major unconformity (CMP 3,600–5,700, Fig. 4). The upper undeformed sequence ranges in thickness from few meters until 0.5 s twtt and is mainly composed of sub-horizontal strata. The lower sequence ranges from 1 to 2 s twtt thick and appears to be part of a large and thick basin. The stratigraphic units off Manzanillo sampled during submersible dives were a granitic and volcanic, well-rounded conglomerate overlying pre-Eocene (Late Cretaceous–Palaeocene) plutonic rocks that correlate with the onshore coastal plutonic belt of the Jalisco Block (MERCIER DE LEPINAY *et al.*, 1997). A similar

unconformity exists in the well studied stratigraphy of the Tres Marias Islands, 250 km northward of the Manzanillo area, where McCLOY *et al.* (1988) described massive fine- to medium-grained sandstone, deposited in a non-marine or shallow-marine environment, on top of pre-Eocene granites. The same planktonic assemblages and lithology (siltstone, mudstone and sandstone layers), indicating upper Miocene to lower Pliocene ages, have been described above the conglomerate in both areas. Correlating sedimentary sequences with those observed in the seismic sections suggests that the lower seismic sequence is part of the upper Miocene to lower Pliocene marine basin possibly associated with the opening of the Gulf of California. This could explain why this basin is not present southward as illustrated along the profiles 204, 202 and 203. The above stratigraphic sequence shows the plutonic rocks extending to the trench axis.

The shallow crustal structure of section 201 (Fig. 8) reveals a continental mid slope terrace underlain by sediments with a maximum thickness of 0.5 s twtt (about 375 m), which shows a change of reflectivity that we interpret to be the top of the continental basement. The location of the southern limit of the forearc basin at CMP 5,200 in the profile 201 could indicate a change in the geodynamic setting such as the southern end of the influence of the opening of the Gulf of California.

In the shallow continental domain, strong bottom simulating reflections (BSR) have been clearly imaged along the five MCS profiles (Figs. 4, 5, 6, 7, 8). The presence of a BSR is frequently related to the presence of gas hydrates in the marine sediments, although gas hydrates have also been encountered in regions without BSR (YUAN and EDWARDS, 2000). There are at least two types of origins for the occurrence of BSR. One is related to the presence of gas hydrates causing a negative acoustic impedance contrast between sediments containing gas hydrate and free gas underneath the gas hydrate stability zone (PECHER *et al.*, 1996). Therefore, these BSRs have reversed polarity. The other origin has been related with the strong positive acoustic impedance contrast between silicate rich sediments of the different diagenetic stages: opal A, opal CT and quartz (KASTNER *et al.*, 1977). Therefore, diagenesis-related BSRs have the same polarity as the seafloor



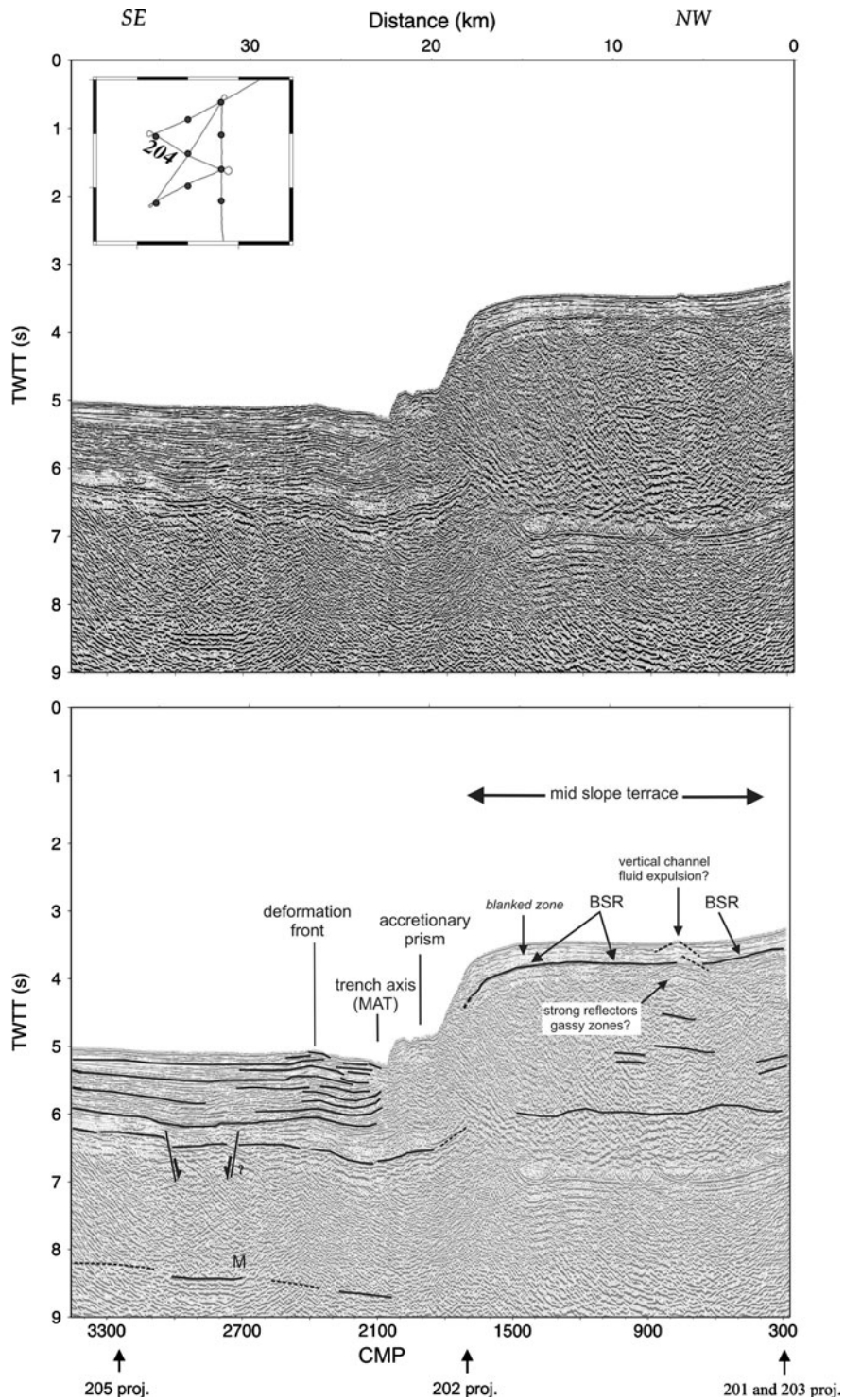


Figure 5

Top panel shows the un-interpreted time migration section of profile 204 (see the text for processing sequence). Left-inner box as well as Fig. 2, shows the location of the profile; bottom panel displays the interpreted profile, with noticeable features such as high-reflective zones beneath 4 s twtt (CMP 700) that could represent gas-charged zones likely expelled at vertical channels (see text for more details) and the Moho discontinuity around 8.0–8.5 s twtt (CMP 2,000–3,400). M Moho discontinuity

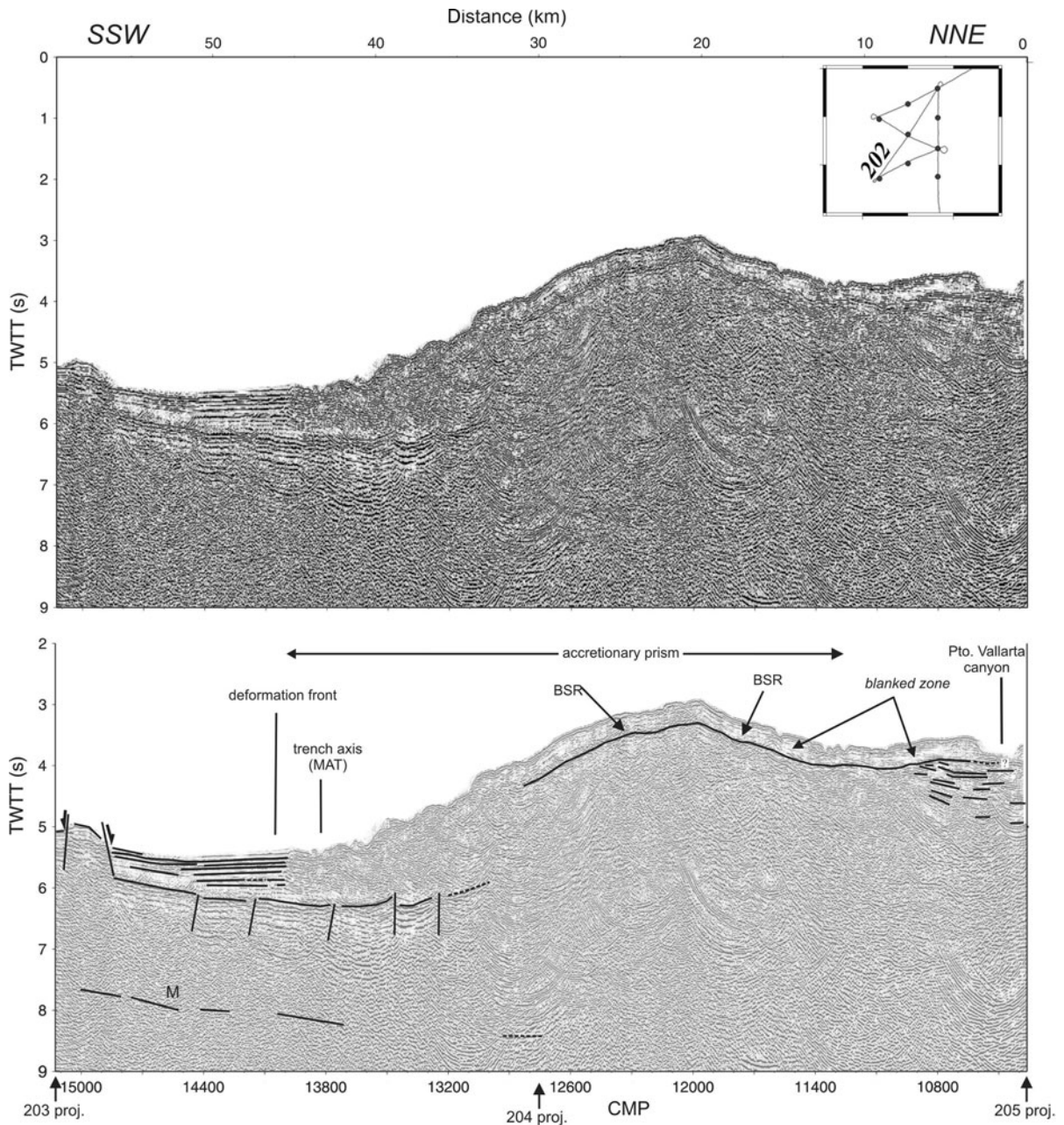


Figure 6

Top panel shows the un-interpreted time migration section of profile 202 (see the text for processing sequence). Left-inner box as well as Fig. 2, shows the location of the profile; bottom panel displays the interpreted profile, with noticeable features such as a highly deformed sequence interpreted as the deformation front, the BSR along the accretionary prism here crossed obliquely, the faulted oceanic crust subducting the prism and the Moho discontinuity around 7.5–8.5 s twtt (CMP 15,000–13,800). *M* Moho discontinuity

reflection. The BSR identified in seismic data off Puerto Vallarta have a reversed polarity with respect to the seafloor (MINSHULL *et al.*, 2005), consequently related with the presence of natural gas hydrates. The

formation of natural gas hydrates is well-known and widely described as a global phenomenon that has been recognized all along the Eastern Pacific margin [e.g. Costa Rica (PECHER *et al.*, 1998); northern

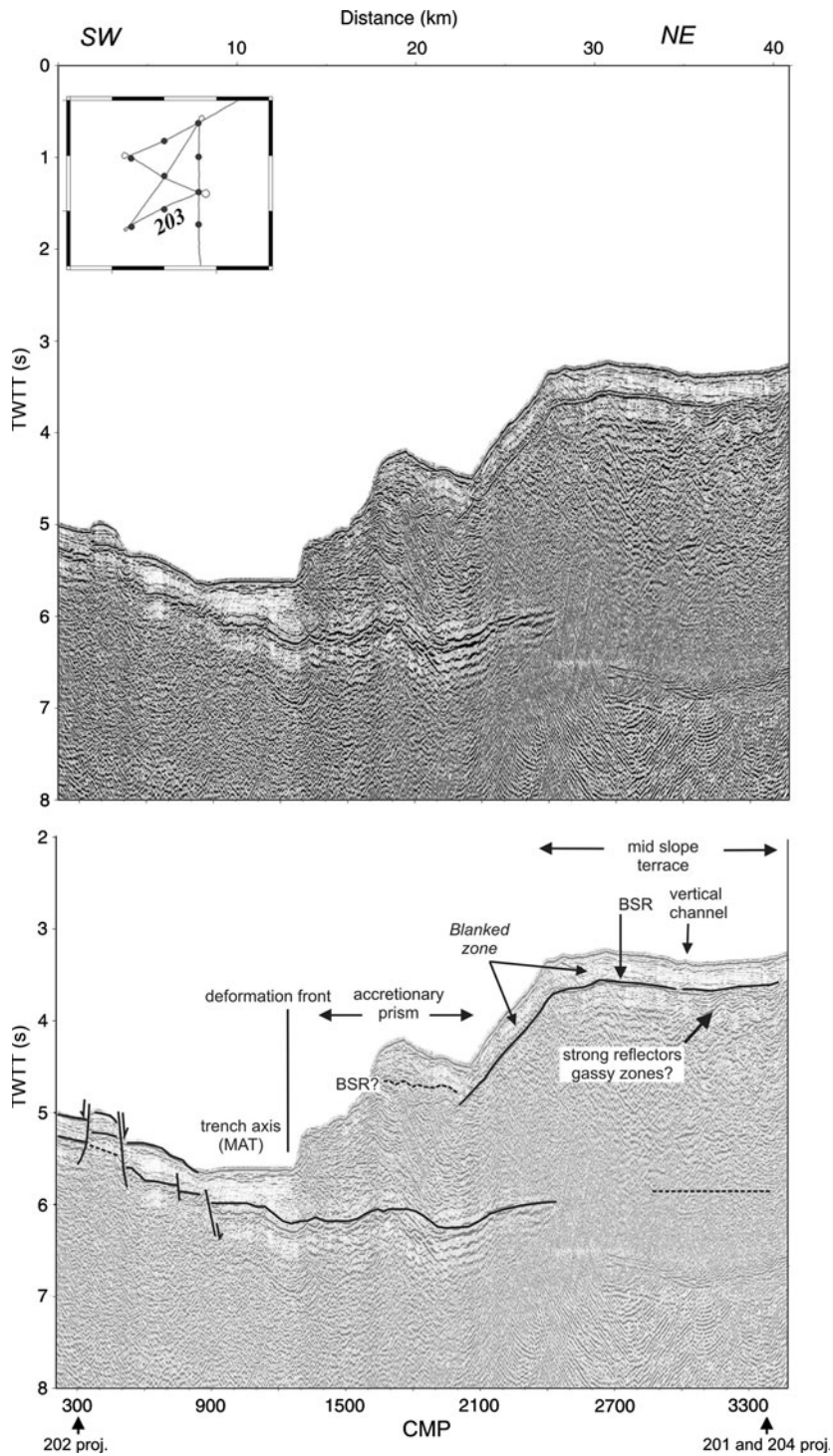


Figure 7

Top panel shows the un-interpreted time migration section of profile 203 (see the text for processing sequence). Left-inner box as well as Fig. 2, shows the location of the profile; bottom panel displays the interpreted profile, with noticeable features such as the high reflective zones beneath 4 s twtt (CMP 3,000) that could represent gas-charged zones and a surface expression of near-vertical channels. In this southernmost profile, the deformation front coincides with the trench axis

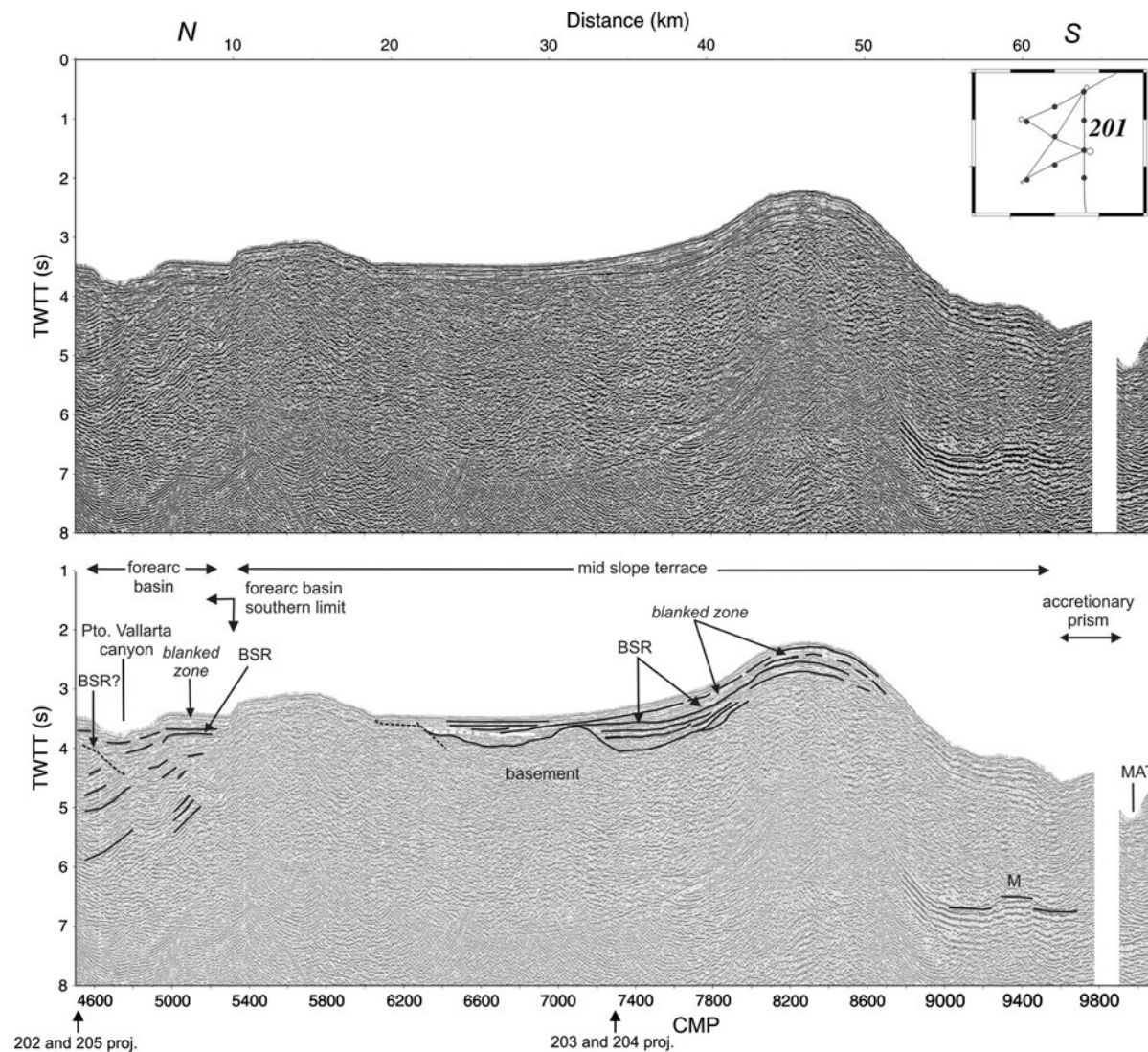


Figure 8

Top panel shows the un-interpreted time migration section of profile 201 (see the text for processing sequence). Left-inner box as well as Fig. 2, shows the location of the profile; bottom panel displays the interpreted profile, with noticeable features such as a low reflectivity of the blanked zone above the BSR (CMP 7,600–8,500) and the Moho discontinuity around 7 s twtt on the southernmost part of the line (CMP 9,000–9,700). *M* Moho discontinuity

California (BROOKS *et al.*, 1991); Peru (PECHER *et al.*, 1996); Pacific ocean off Mexico, Guatemala and Panama (SHIPLEY *et al.*, 1979); Gulf of California (LONSDALE, 1985)]. We have detected the widespread distribution of the BSR not only in the accretionary prism offshore of Puerto Vallarta, but also in the forearc basin, the continental slope and the mid slope terrace. A BSR is, however, absent in areas affected by slumping, as can be observed in profile 205 (CDP

3,500–4,000, Fig. 3). A similar situation has been described in the Peruvian margin (PECHER *et al.*, 1998). We speculate that the gas may escape through the fractures that appear to cross the base of gas hydrate stability zone near CDP 800 in profile 204 (Fig. 5). Vertical fluid expulsion channels and sea-floor venting sites have also been recognized in northern Cascadia (HYNDMAN *et al.*, 2001) and the Sea of Okhotsk (LÜDMANN and WONG, 2003) linked with

BSR. When these structures reach the seafloor, they are associated either with pockmarks or with dome-like structures (profile 204, CMP 700). The pale reflectivity above the BSR, known as a *blanked zone* (e.g., KORENAGA *et al.*, 1997), is clearly recognized in all the profiles at 0.2 s twtt below the BSR and it has been associated with hydrate cementation or porosity filling suppressing the impedance contrasts between the layers (Figs. 5, 6, 7, 8).

#### 4.2. Deep Crustal Structure

Seismic imaging is the best method to investigate the structure of subduction zones and becomes highly

dependent on the material properties (seismic velocities) and the depth of the earthquakes in the specific case of seismic tomographic imaging. Producing images of a young lithosphere with shallow earthquakes becomes challenging, but in the meantime, we have imaged the deep crustal structure using active multichannel seismics. The analysis and interpretation of the MCS profiles allows us to identify, for the first time in the area of the subduction Rivera Plate, the major structures of the margin at deep crustal levels.

Seismic images show crustal thickness of 3 s twtt for the subducting Rivera Plate (roughly  $\sim 6.5$  km thick) and measured dip angles of subduction, from

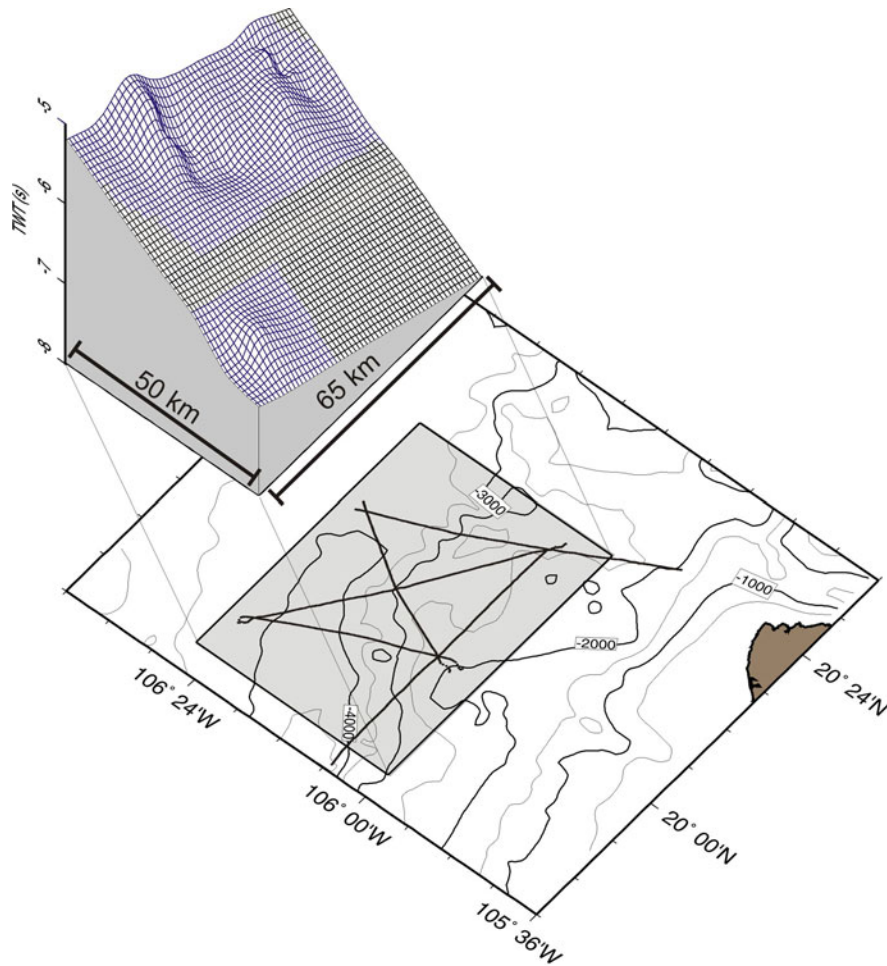


Figure 9

*Block diagram* showing the top of the subducted slab of the Rivera Plate, with a dip angle of  $6^\circ$  in the northern part of the block and  $8^\circ$  in the south under the Jalisco Block. This dip distribution suggests that the Rivera Plate is also being subducted to the north. *Blue-areas* are well controlled by the seismic lines whereas *black-areas* are inferred from the interpolation. Note the presence of subducted ridges

north to south, of  $6^\circ$  in profile 205 (Fig. 4),  $6.5^\circ$  in profile 204 (Fig. 5), and  $8^\circ$  in profile 203 (Fig. 7). This decreasing tendency towards the north is related to the termination of the subduction north of profile 205 in the oceanic domain. These values are consistent with the  $10^\circ$  dipping Wadatti-Benioff zone at 20 km depth estimated from local seismicity data by PARDO and SUÁREZ (1993).

To illustrate the geometry of the top of the subducted slab off Puerto Vallarta, we compute a 3D block diagram (Fig. 9) using the depth (in seconds twtt) obtained from the MCS sections and using a nearest neighbour average algorithm. The area well controlled by existing data is displayed in blue in the block diagram, whereas the interpolated areas are shown in black. The 3D block points out the eastward subduction of the Rivera Plate beneath the continent with an average dip angle of  $7^\circ \pm 1^\circ$  as previously discussed. Surprisingly, it seems also to subduct, or bend, towards the north. This result agrees with an oblique convergence between the Rivera and NA Plates at  $20.95^\circ\text{N}$   $106.25^\circ\text{W}$  (KOSTOGLODOV and BANDY, 1995). New additional seismic data and geologic sampling north of Puerto Vallarta will facilitate answering specific questions such as the age of Maria Magdalena Rise (MMR, Fig. 2), a bathymetric feature of about 500 m relief located at the northern ending of the Jalisco subduction zone in the area of Tres Marias Islands. The uplift of the Tres Marias escarpment may be helped by the gently northward convergence of the Rivera Plate under the North American Plate, where upper Miocene hemipelagic muds crops out (LONSDALE, 1989) as a consequence of a history of successive processes of subduction and opening of the Gulf of California. Also, the nature of the underlying crust (oceanic or continental), which is still under discussion (LONSDALE, 1995) and may be related to a previous location of the EPR before a westward jump during the opening of the Gulf of California, could be resolved acquiring new geophysical and geological data.

### 5. Conclusions

The new seismic data presented herein provide new insight into the crustal structure at the contact

between the Rivera and North American Plates, offshore of Puerto Vallarta. We summarized our conclusions as follows:

1. The Rivera Plate subducts beneath the NA Plate with, from north to south in the trench axis, a dip angle ranging from  $6^\circ$  to  $8^\circ$ . Although data are not conclusive, the subduction seems to continue northward and the Tres Marias Islands could be uplifted as a consequence of this subduction.
2. Tectonic observations based on MCS data indicate that there are significant structural differences from north to south of  $20.2^\circ\text{N}$ . In the trench-fill wedge, the sedimentary infill is 2.5 km thick near the trench axis, and there is evidence of normal faulting at the top of the oceanic crust. The topography of the slope is quite rough due to slumping and a well developed, 25 km-wide, forearc basin is constituted of two primary sequences. These two sequences have been split by a major unconformity; the lower unit is of Miocene age. South of  $20.2^\circ\text{N}$  the forearc basin is not seen; instead, the upper continental crust is composed of one stratigraphic sequence with a faulted thin sedimentary cover (0.75 km) below the seafloor, west of the trench, which is another indication of recent deformation.
3. We identify a BSR at 0.25–0.4 s twtt in the seismic data with reverse polarity with respect to the seafloor, demonstrating the occurrence of gas hydrates offshore northwestern Mexico between  $19^\circ\text{N}$  and  $21^\circ\text{N}$ . Vertical expulsion morphologies have been observed proving fluid circulation through the detected active fault systems despite the relatively thick sedimentary coverage.
4. The set of nearly vertical normal faults, formed by plate flexure, reaching the surface in the oceanic crust west of the Middle America Trench seems to help, when subducted, the circulation of fluids (fluid percolation) and the formation of gas hydrates in the continental domain.
5. The presence of a well developed accretionary prism suggests a subduction–accretion type regime instead of a subduction erosion regime as is present along the convergent margin of the Rivera Plate off Manzanillo. This difference may be related with a variation in the geometry of the downgoing slab along the trench.

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