IMAGING THE SEISMIC CRUSTAL STRUCTURE OF THE WESTERN MEXICAN MARGIN BETWEEN 19°N AND 21 °N

Rafael Bartolomé^{1*}, Juanjo Dañobeitia¹, François Michaud², Diego Córdoba³,
Luis A. Delgado-Argote⁴

¹Unidad de Tecnología Marina-CSIC, Centre Mediterrani d'Investigacions
Marines i Ambientals (CMIMA), Passeig Marítim de la Barceloneta 37-49,
08003 Barcelona, Spain

²Géosciences Azur, UMR 6526, Université Pierre et Marie-Curie, La Darse,
BP 48, 06235 Villefranche-sur-Mer cedex, France

³Universidad Complutense de Madrid, 28040 Ciudad Universitaria, Madrid,
Spain

⁴CICESE, Carr. Tijuana-Ensenada km 107, 22800 Ensenada, Baja California,
Mexico

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*Corresponding author:

Dr. Rafael Bartolomé

Unidad de Tecnología Marina-CSIC

Centre Mediterrani d'Investigacions Marines i Ambientals (CMIMA)

Passeig Marítim de la Barceloneta, 37-49

08003 Barcelona, Spain

Ph: +34-932309500

Fax: +34-932309555

e-mail: rafael@utm.csic.es

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ABSTRACT

3000 km 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 km 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; (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 reveal 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 evidences

1 indicating that the Rivera Plate possibly subducts, at very low angles, beneath
2 the Tres Marias Islands.
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6 **1. Introduction**

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10 The tectonics, seismicity and magmatism in the western part of central Mexico
11 is largely controlled by the subduction of the Cocos and Rivera oceanic plates
12 beneath the North American (NA) plate, the Middle America Trench (MAT)
13 being the morphologic expression of the subduction contact (Figure 1). The
14 Rivera plate is a key structural element to understand the complex geodynamic
15 interactions that occur at the western coast of Mexico. Atwater (1970) was the
16 first to suggest the existence of this microplate. Since then, several authors
17 have shown that the Rivera plate is kinematically distinct from the NA and
18 Cocos plates (Eissler and McNally, 1984; Bandy and Yan, 1989; DeMets and
19 Stein, 1990), although the precise location of the Rivera-Cocos boundary is
20 still controversial since no clear bathymetric features can be clearly associated
21 with the plate boundary (Eissler and McNally, 1984; Bourgois and Michaud,
22 1991). Seafloor accretion occurs along the western boundary Rivera plate, the
23 Pacific-Rivera Rise (PRR), whereas to the east, the lithosphere of the Rivera
24 Plate is consumed at the trench where the plate has been dated as late Miocene
25 (~9 Ma) based on seafloor magnetic anomalies (Klitgord and Mammerickx,
26 1982). The age of the Cocos plate varies along the MAT, with jumps in ages
27 occurring across several fracture zones. Thus, the younger and shallower
28 Cocos crust near the Rivera plate is dated as 10 Ma whereas at 90°W it is dated
29 at 25 Ma old (Couch and Woodcock, 1981).
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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 3-fold 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 Suarez, 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 (M_s 8.1 and M_s 7.8) Jalisco earthquakes (Singh et al., 1985) and the October 9, 1995 (M_w 8.0, 17 km depth epicentre and 5m of tsunami) Colima earthquake in the southeast flank of the region (Courboux et al., 1997). The main event of the 1995 earthquake was a

1 subduction related thrust event that activated normal faults along the northwest
2 margin of Manzanillo (19°N and 105°W, Figure 1), clearly showing present
3 day plate convergence. However, it is not clear if the Mw=7.4 event of January
4 22, 2003 occurred along the current thrust interface between the Rivera and
5 NA plates (Singh et al., 2003).
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10 The angle of subduction of the Rivera Plate has been computed by accurately
11 relocating hypocenters (e.g., Pardo and Suarez, 1993; Pardo and Suarez, 1995).
12 The inferred Wadatti-Benioff zone indicates a steeper dip for the Rivera plate
13 than the adjacent Cocos plate. This has led to the proposal of a step in the slab
14 between the Cocos and Rivera Plates at the present time (Ferrari et al., 2001)
15 due to the slab rollback mechanism, acting on the Rivera Plate underlying the
16 NA plate, during a period of very low convergence rate (19mm/year on
17 average) between 8.5 Ma and 4.6 Ma (DeMets and Traylen, 2000). The
18 seismicity causes a significant seismic hazard to the coastal regions of Mexico,
19 as well as areas considerably inland, including Mexico City (Currie et al.,
20 2002). A strong understanding of the Mexico subduction region (geometry,
21 seismic zone of subduction, faults and rupture width, etc.) and detailed
22 information about the crustal structure along the Rivera Plate is required to
23 carry out seismic hazard studies. Comprehension of the limits of the lateral and
24 vertical extent of the Rivera Plate will also constrain as well plate tectonic
25 models, including the opening of the Gulf of California.
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39 For these reasons, in 1996 the Spanish *R/V Hespérides* and the Mexican *R/V's*
40 *Altair and Humboldt* surveyed the northwestern Mexican margin between 16°N
41 and 30°N in a geophysical experiment named Crustal Offshore Research
42 Transect by Extensive Seismic Profiling, CORTES-P96 (Dañobeitia et al.,
43 1997). Swath bathymetry, backscattering and multichannel seismic reflection
44 data profiles (Figure 2) were acquired within the Rivera subduction zone
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1 extending from 21°N to 19°N. In this paper, we present five post-stack time
2 migrated MCS sections (Figure 3), that show, for the first time in this area,
3 seismic images from the Earth's surface down to the Mojo that enable us to
4 seismically characterize the crustal structure of the overriding and subducting
5 plates offshore Puerto Vallarta, describe the spatial distribution of the
6 incoming plates (sediment, crust and mantle lithosphere) and identify some of
7 the processes occurring in this area.
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10 **2. Geological setting**

11 The western margin of Mexico between 26°N and 23°N is structurally
12 composed of a transform margin made up of a set of spreading centers linked
13 by a fault system (Figure 1). The right lateral fault system is the southward
14 prolongation of the San Andreas Fault across the Gulf of California. The 70 km
15 Tamayo transform fault connects the southernmost spreading segment in Gulf
16 of California (the Alarcon Rise) with the PRR at 23°N. This spreading center,
17 located between 23°N and 19°N, is the western plate boundary between the
18 Rivera and Pacific Plates and its spreading velocities have fluctuated between
19 intermediate and fast rates over the past 10 Ma (average full spreading rate of
20 around 9.7 cm/year, DeMets and Traylen, 2000). The Rivera Transform is the
21 southern plate boundary between the Rivera and Pacific Plates and the MAT
22 the eastern plate boundary between the Rivera and NA plates.
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25 The geodynamic history since 25 Ma starts with the collision of the Pacific-
26 Farallon seafloor-spreading center against the convergent western margin of
27 NA. This collision marked the beginning of a major change in the tectonic
28 evolution and volcanism of western NA (Atwater, 1970; Atwater, 1989). Some
29 authors propose a final reorganization in the Middle Miocene (6.5-3.5 Ma)
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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 trench (Michaud et al., 2001) suggesting 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 Ma 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/yr based on the accurately located hypocenters of local and teleseismic earthquakes (Pardo and Suárez, 1995) to 5 cm/yr 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/yr 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).

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

24 The direction of convergence between the Rivera and NA plates at the
25 MAT becomes progressively more oblique (in a counter-clockwise sense
26 relative to the trench-normal direction) northward along the end of the MAT
27 (19°-21°N), commonly termed the Jalisco subduction zone (JSZ) (e.g. Bandy,
28 1992; Lonsdale, 1995; Kostoglodov and Bandy, 1995; DeMets and Wilson,
29 1997; DeMets and Traylen, 2000). This area comprises the northern part of the
30 MAT between the Tres Marias Islands and the southern tip of Colima rift
31 (Figure 1). The depth of the slab under the western Mexico is poorly
32 constrained, but local earthquake data indicate a Benioff zone for the Rivera
33 Plate bending from around 10° at 20 km depth to 50° at 40 km depth, whereas
34 the Cocos Plate is subhorizontal at the same depth (Pardo and Suarez, 1993).
35 This change of dip angle is unrelated to the thermal structure of the slabs and
36 the present rate of subduction, due to the similar age and comparable
37 subduction rates of both plates. A rollback of the slab when the relative

1 convergence between the Rivera and NA plates decreased to a very low rate at
2 the end of Miocene was proposed as a plausible explanation (Ferrari et al.,
3 2001).
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6 The Jalisco Block (JB) is bounded landwards by the Tepic-Zacoalco Rift on
7 the NE and by the Colima Rift on the SE (Figure 1). Rifting and volcanism
8 have been proposed to be associated with the northwestward detachment of the
9 JB from the NA plate (Luhr et al., 1985) at a very low rate of <5mm/year
10 (DeMets and Stein, 1990; Bandy and Pardo, 1994), starting in the Pliocene-
11 Quaternary. Recent strike-slip deformation within the fore-arc region of the
12 JSZ has also been reported by shallow (< 1s twtt penetration) seismic data
13 collected offshore the Jalisco block (Bandy et al., 2005). That study also
14 provided additional evidences for recent subsidence within the area offshore of
15 Manzanillo in agreement with previous works (Mercier de Lepinay et al., 1997;
16 Ramirez- Herrera and Urrutia-Fucugauchi, 1999).
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19 The uplift-subsidence history proposed for the entire margin along the
20 JSZ from the Tres Marias Islands to the Manzanillo area starts with uplift and
21 emergence before the late Miocene (6.5 Ma) and continuing subsidence during
22 the late Miocene-Lower Pliocene until the Pliocene-Quaternary boundary (~2
23 Ma). Regional subsidence of an active margin is generally related to tectonic
24 erosion. After the Pliocene-Quaternary boundary, the Tres Marias began to be
25 uplifted (McCloy, 1988) whereas the Manzanillo area started to subside,
26 certainly due to the fragmentation associated with the development of the JB
27 during the Pliocene-Quaternary, at a subsidence rate of 0.35mm/year (Mercier
28 de Lepinay et al., 1997). For the Holocene period, in the active tectonic margin
29 environment of the Jalisco area, a new model is proposed where the coseismic
30 subsidence (centimetre-scale) produced by large offshore earthquakes is
31 rapidly recovered during the post-seismic and interseismic periods, yielding a
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1 general coastal uplift (Ramírez-Herrera et al., 2004). In other words, the slow
2 long-term uplift is considered the most important factor to the total net vertical
3 motion (uplift) of the Jalisco area. Based on the first reported organisms dated
4 with radiocarbon along the Jalisco coast, an average rate of about 3 mm/year
5 for tectonic uplift since 1300 years BP has been computed (Ramírez-Herrera et
6 al., 2004).

3. MCS data

17 The data set analysed in this study is composed of five MCS profiles (profiles
18 201-205, Figure 2), totalling 280 km and acquired during the CORTES-P96
19 cruise, is located in the subducting domain of the Rivera plate off Pto. Vallarta,
20 at the contact with the NA plate. The five seismic profiles used in this work
21 have three different orientations respect to the direction of the trench axis:
22 profiles 203 and 205 are perpendicular, profiles 202 and 204 are oblique and
23 profile 201 parallel to the MAT (Figure 2). The profiles were acquired using a
24 2.4 km long streamer with 96 channels at 2 ms sampling interval, towed 165 m
25 behind the ship at 9 m depth. The source used by the Spanish R/V Hesperides
26 was a tuned airgun array of 50 l (3000 in³). The shooting rate was 30 s.
27 Quality control and preliminary stacking were done onboard, while final
28 processing of MCS data through 9 s (twtt) and a 16-fold coverage stack and
29 migration was done at the Department of Geophysics of the Institute of Earth
30 Sciences *Jaume Almera* and in the Unidad de Tecnología Marina-CSIC
31 (Barcelona, Spain).

44 The seismic processing flow includes band-pass filtering (5-9-58-62.5 Hz),
45 edition of noisy traces, divergence correction, and internal mute to reduce the
46 water bottom multiple effects. After CMP sorting, a minimum phase predictive

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deconvolution was performed (50-350 ms). Stacking velocity analysis every 200 CDP maximum interval and NMO correction were performed. The profiles were finally Kirchhoff poststack 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 (Figure 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 1500), trench (CMP 2500), accretionary prism (CMP 2500-3600), a well-developed forearc basin (CMP 3600-5600), backstop limit at (CDP 4800), and continental slope and mid slope terrace (CMP 5600-6400). We also recognized the presence of erosion as mass wasting affecting the slope is also identified (CMP 5700-6300).

The joint interpretation of profiles 205 (Figure 4), 204 (Figure 5), 202 (Figure 6) and 203 (Figure 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 2400, Figure 4), 1.52 s twtt in profile 204 (CMP 2200, Figure 5), 0.85 s twtt in profile 202 (CMP 14000, Figure 6), and 0.6 s twtt in profile 203 (CMP 1200, Figure 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 increase of the infill of terrigenous sediments associated with drainage from the head of the Puerto Vallarta Canyon (Figure 3), pointed to in profile 205 (CMP 3700 and 4100; Figure 4) and profile 201 (CMP 4700, Figure 8). The trench-fill sediments show a significant deformation seaward of the trench in the northern sections 205 (CMP 1900-2400, Figure 4) and 204 (CMP 2100-2400, Figure 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 to 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 plate. 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

1 the subduction interfaces, producing adakites such as the ones investigated by
2 Ferrari et al. (2001). This also has to be considered during the modelling. One
3 should bear in mind that sediments in most subducted zones melt but
4 subducted crust only melts when it is young and hot enough (Johnson and
5 Plank, 1999).

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10 The southernmost profiles 202 (CMP 15000, Figure 6) and 203 (CMP 400,
11 Figure 7) clearly illustrate a set of normal faults reaching the surface. The
12 structure of the subducting plate consists of grabens and horsts that are
13 products of the extensional stress due to bending of the plate, which might
14 facilitate sediment subduction and the percolation of fluids. These faults,
15 arriving up to the seafloor, might indicate recent tectonic activity related to the
16 dip augmentation of the Rivera Plate since 8.5 Ma, when bending occurred at
17 the time of the Rivera plate slowed the convergence (7.2-4.8 Ma) as recorded
18 by the trenchward migration of the volcanic front (Ferrari et al., 2001). Fluids
19 are likely to percolate and circulate along these faults deep into the overriding
20 plate, probably favouring the formation of gas hydrates and significantly
21 cooling the oceanic plate as shown by marine heat flow observations (Ziagos et
22 al., 1985; Prol-Ledesma et al., 1989; Khutorskoy, et al., 1994)). The increase of
23 the amount of fluids (including asthenospheric rising) started in the Pliocene
24 and released from the subducting slab of the Rivera plate due to the increase of
25 the convergence is confirmed by the subsequent volcanic rate increment
26 (Ferrari et al., 2001). The distance from the trench axis to the deformation front
27 differs from one section to another as well. From north to south, the
28 deformation front is 12 km westward from the trench axis in section 205 (CMP
29 1500, Figure 4), 5 km in profiles 204 (CDP 1400, Figure 5) and 202 (14100,
30 Figure 6), and the distance is undetectable in the southern profile 203 (Figure
31 7), as we can summarize in Figure 3 by the black arrows. The basement is also

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1 faulted beneath the sedimentary layers at 1.1-1.3 s twtt (1.3-1.6 km depth) in
2 the northern sections (CMP 1200, Figure 4; CMP 3000, Figure 5).
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4 Nevertheless, the existence of an accretionary prism observed in seismic
5 sections indicates a subduction-accretion tectonic regime along this segment of
6 the Rivera margin, in contrast with what has been observed previously
7 (Mercier de Lepinay et al., 1997) off Manzanillo. Whereas subduction-
8 accretion characterizes the Rivera margin in the study area and off Acapulco
9 (100°W) according to the results from DSDP Leg 66 (Moore et al., 1982),
10 subduction-erosion controls the subduction of the Rivera-Cocos Plates off
11 Manzanillo (104°W), during at least the last 8 Ma (Ferrari et al., 2001). This
12 difference in tectonic regimes, of areas only 500 km apart, has been related
13 with a variation in the geometry of the slab along the trench: the downgoing
14 slab is steeper beneath the JB than off Acapulco (Pardo and Suárez, 1993).
15 However, we observe chains of seamounts stretching hundreds of km seaward
16 of, and perpendicular to, the MAT, offshore (Figure 3). When subducted, these
17 seamounts destabilize the overlying seafloor and leave a morphological trace
18 across the continental slope that marks their path beneath the surface as has
19 been described along the MAT along the Costa Rica margin (von Huene et al.,
20 2004). A chain of seamounts is pointed directly at profile 202 and the southern
21 part of profile 201 where a morphological elevation of the seafloor is observed
22 in the bathymetric and seismic data (Figure 3, 6 and 8). We speculate that a
23 seamount collision and subduction is responsible for the lack of an extensive
24 accretionary prism observed in line 204 (Figure 5, CMP 2100). Subducted
25 seamounts push back the frontal sediment prism after entering the subduction
26 zone leaving a gap the size of the seamount in the continental slope. Seamount
27 subduction is a key point for the study of local tsunami generation.

Landwards, the continental domain is characterized by a forearc basin exhibiting two primary sequences, an undeformed upper sequence (CMP 4700-5700, Figure 4) separated from a deformed lower sequence by a major unconformity (CMP3600-5700, Figure 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 (Figure 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

1 the top of the continental basement. The location of the southern limit of the
2 forearc basin at CMP 5200 in the profile 201 could indicate a change in the
3 geodynamic setting such as the southern end of the influence of the opening of
4 the Gulf of California.
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8 In the shallow continental domain, strong bottom simulating reflections (BSR)
9 have been clearly imaged along the five MCS profiles (Figures 4-8). The
10 presence of a BSR is frequently related to the presence of gas hydrates in the
11 marine sediments, although gas hydrates have been also encountered in regions
12 without BSR (Yuan and Edwards, 2000). There are at least two types of origins
13 for the occurrence of BSR. One is related to the presence of gas hydrates
14 causing a negative acoustic impedance contrast between sediments containing
15 gas hydrate and free gas underneath the gas hydrate stability zone (Pecher et
16 al., 1996). Therefore, these BSRs have reversed polarity. The other origin has
17 been related with the strong positive acoustic impedance contrast between
18 silicate rich sediments of the different diagenetic stages opal A, opal CT and
19 quartz (Kastner et al., 1977). Therefore, diagenesis-related BSRs have the same
20 polarity as the seafloor reflection. The BSR identified in seismic data off
21 Puerto Vallarta have a reversed polarity with respect to the seafloor (Minshull
22 et al., 2005), consequently related with the presence of natural gas hydrates.
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24 The formation of natural gas hydrates is well-known and widely described as a
25 global phenomenon that has been recognized all along the Eastern Pacific
26 margin (e.g. Costa Rica (Pecher et al., 1998); northern California (Brooks et
27 al., 1991); Peru (Pecher et al., 1996); Pacific ocean off Mexico, Guatemala and
28 Panama (Shipley et al., 1979); Gulf of California (Lonsdale, 1985). We have
29 detected the widespread distribution of the BSR not only in the accretionary
30 prism offshore of Puerto Vallarta, but also in the forearc basin, the continental
31 slope and the mid slope terrace. A BSR is however absent in areas affected by
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slumping, as can be observed in profile 205 (CDP 3500-4000, Figure 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 (Figure 5). Vertical fluid expulsion channels and seafloor 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 to hydrate cementation or porosity filling suppressing the impedance contrasts between the layers (Figure 5-8).

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.

1 Seismic images show crustal thickness of 3s twtt for the subducting Rivera
2 Plate (roughly ~ 6.5 km thick) and measured dip angles of subduction, from
3 north to south, of 6° in profile 205 (Figure 4), 6.5° in profile 204 (Figure 5),
4 and 8° in profile 203 (Figure 7). This decreasing tendency towards the north is
5 related to the termination of the subduction north of profile 205 in the oceanic
6 domain. These values are consistent with the 10° dipping Wadatti-Benioff zone
7 at 20 km depth estimated from local seismicity data by Pardo and Suárez
8 (1993).
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10 To illustrate the geometry of the top of the subducted slab off Puerto Vallarta,
11 we compute a 3-D block diagram (Figure 9) using the depth (in seconds twtt)
12 obtained from
13

14 the MCS sections and using a nearest neighbour average algorithm. The area
15 well controlled by existing data is displayed in blue in the block diagram,
16 whereas the interpolated areas are shown in black. The 3D block points out the
17 eastward subduction of the Rivera plate beneath the continent with an average
18 dip angle of $7^{\circ} \pm 1^{\circ}$ as previously discussed. Surprisingly, it seems also to
19 subduct, or bend, towards the north. This result agrees with an oblique
20 convergence between the Rivera and NA plates at 20.95°N 106.25°W
21 (Kostoglodov and Bandy, 1995). New additional seismic data and geologic
22 sampling north of Puerto Vallarta will facilitate answering specific questions
23 such as the age of Maria Magdalena Rise (MMR, Fig. 2), a bathymetric feature
24 of about 500 m relief located at the northern ending of the Jalisco subduction
25 zone in the area of Tres Marias Islands. The uplift of the Tres Marias
26 escarpment may be helped by the gently northward convergence of the Rivera
27 Plate under the North-American Plate, where upper Miocene hemipelagic
28 muds crops out (Lonsdale, 1989) as a consequence of a history of successive
29 processes of subduction and opening of the Gulf of California. Also, the nature
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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 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 ° to 8°. 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 °N. In the trench-fill wedge, the sedimentary infill is 2.5 km thick near the trench axis, and there are evidences 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 primarily sequences. These two sequences have been split by a major unconformity, the lower unit is of Miocene age. South of 20.2°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°N and 21°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 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.

6. Acknowledgements

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Figure captions:

Figure 1: General tectonic setting of western Mexico. Four lithospheric plates act in the area: Pacific, Rivera, Cocos and North America. Arrows indicate relative convergence rates (cm/yr) 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 the figure 2. TMI: Tres Marias Islands, MAT: Middle America Trench, EPR: East Pacific Rise.

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.

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 figure 2.

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 figure 2, shows the location of the profile; a) Bottom panel displays the interpreted profile, with noticeable features such as the Moho discontinuity detected around 8.0-8.5 s twtt (CMP 1000-1800), the interruption of the BSR due to the Puerto Vallarta Canyon (CMP 3500-4000) or a high slump (CMP 3000) at the accretionary prism. M: Moho discontinuity.

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 figure 2, shows the location of the profile; a) Bottom panel displays the interpreted profile, with noticeable features such as high-reflective zones beneath 4s twtt (CMP 700) that could represent gas-charged zones likely expelled at vertical channels (see text for more details) and the Moho discontinuity around 8.0-8.5s twtt (CMP 2000- 3400). 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 figure 2, shows the location of the profile; a) 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 7.5-8.5s twtt (CMP 15000-13800). M: Moho discontinuity.

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 figure 2,

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shows the location of the profile; a) Bottom panel displays the interpreted profile, with noticeable features such as the high reflective zones beneath 4 s twtt (CMP 3000) 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 figure 2, shows the location of the profile; a) Bottom panel displays the interpreted profile, with noticeable features such as a low reflectivity of the blanked zone above the BSR (CMP 7600-8500) and the Moho discontinuity around 7 s twtt on the southernmost part of the line (CMP 9000-9700). M: Moho discontinuity.

Figure 9: Block diagram showing the top of the subducted slab of the Rivera plate, with a dip angle of 6° in the northern part of the block and 8° 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.

Dear Pr. Dr. Bill Bandy,

I send you the new version of the manuscript "IMAGING THE SEISMIC CRUSTAL STRUCTURE OF THE WESTERN MEXICAN MARGIN BETWEEN 19°N AND 21 °N".

I have taken into account all of the changes and remarks suggested to improve the English. The corrections are visible in the text, in yellow.

Nevertheless, I would like to make some comments.

Yours sincerely,

Rafael Bartolome

Comment #1:

I extremely appreciate your effort to improve the English in the manuscript. I have accepted most of your suggestions.

Comment #2:

I used "Rivera Transform" instead of "Rivera Fracture Zone" throughout the manuscript and figures, following your recommendation. However, other authors use the expression "Rivera Fracture Zone" as:

Sánchez, J. J. and Núñez-Cornú, F. J. (2009), Seismicity and Stress in a Tectonically Complex Region: The Rivera Fracture Zone, the Rivera–Cocos Boundary, and the Southwestern Jalisco Block, Mexico, Bulletin of the Seismological Society of America; v. 99, no. 5, 2771-2783.

Comment #3:

Following the comment #18 of Reviewer 2 during the first round of revisions

18) *The black arrows are not very helpful.*

I had modified figure 3 (and figure caption), and no longer had the black arrows.

Now I had the comment:

Figure 3. The revise figure is missing the 4 black arrows marking the deformation front as well as ship tracks. They were present on the original submission.

I can submit again the old version of Figure 3 where the black arrows marking the deformation front are present. But I would welcome an agreement between the two revisions. I have no preference between the two versions, black arrows don't change the substance of the paper, only helps the interpretation of the morphology in the bathymetric data. However, we need to take into account that a sentence should be modified depending on the final decision in Comment r14, page 14.

I checked Figure 3 and the ship tracks have been present in all of the versions I submitted. If you continue having problems with this figure I can re-submit it in another format (gif, pdf,...)

Comment #4:

Following your recommendation b30, I labelled the major unconformity on Figure 4.

Comment #5

The problems with the references have been solved:

References

1. The following references are in the list of references but were not mentioned in the manuscript.

--Davies, 1992

Davies, 1992 is mentioned in the manuscript in page 8, so the reference is preserved in the list.

--Sanchez et al., 2009

This reference has been deleted for the reference list.

--Stern, 2002.

Stern, 2002 is mentioned in the manuscript in page 8, so the reference is preserved in the list.

2. The following reference is referenced in the manuscript but is not in the reference list

--Ramirez-Herrera and Urrutia Fucugauchi, 1999.

The reference is now in the reference list:

Ramírez-Herrera, M.T. and Urrutia-Fucugauchi, J. (1999), Morphotectonic zones along the coast of the Pacific continental margin, southern Mexico, *Geomorphology* 28, 237–250.

Figure 1
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Figure 1: Bartolome et al.

Figure 2
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Figure 2:
Bartolome et al.

Figure 3
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Figure 3:
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Figure 4
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Figure 4:
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Figure 5
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Figure 7

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Figure 8
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Figure 8:
 Bartolome et al.

Figure 9
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Figure 9: Bartolome et al.