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New insights into the subducting oceanic crust in the Middle American Trench off western Mexico (17–19°N)

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Abstract

We present new multibeam bathymetric and multichannel seismic data on the Middle American Trench, between 17 and 19°N. These data show, north of the present tip of the East Pacific Rise, unsedimented seafloor with an abyssal hill fabric bare of sediments at the outer wall of the trench (18°30'N). Two multichannel seismic profiles orthogonal to the Middle American Trench display clear oceanic crust extending more than 20 km beneath the overriding plate. These seismic images suggest that the subducting oceanic crust along the Middle American Trench is younger than previously proposed. This result, therefore, implies a new location for the East Pacific Rise termination in relation to the trench. The subduction of this young oceanic crust off western Mexico provides new constraints on the deformation and magmatism of the western Mexican mainland. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: East Pacific Rise; gravity; magnetics; Mexico; Middle America Trench; seismic reflection; subduction

1. Introduction

Current subduction zone models presented over the last 25 years have established that the thermal structure of a subduction zone depends on a wide range of parameters (Jarrard, 1986; Peacock, 1996). Some of the most significant ones are the thermal structure (age) of the incoming litho-

sphere, the convergence rate, the geometry of subduction, and the rate of shear heating along the subduction shear zone. The age of the subducting oceanic crust at the trench strongly influences the deformation (Cloos, 1993) and magmatic processes (Maury et al., 1996) taking place on the overriding plate.

The tectonics, seismicity and magmatism in the western part of central Mexico are largely controlled by the subduction of the Cocos and Rivera oceanic plates beneath the North American plate. The Cocos and Rivera plates are bounded westward by the East Pacific Rise (EPR) and by the Rivera Rise respectively. Based on seafloor spread-

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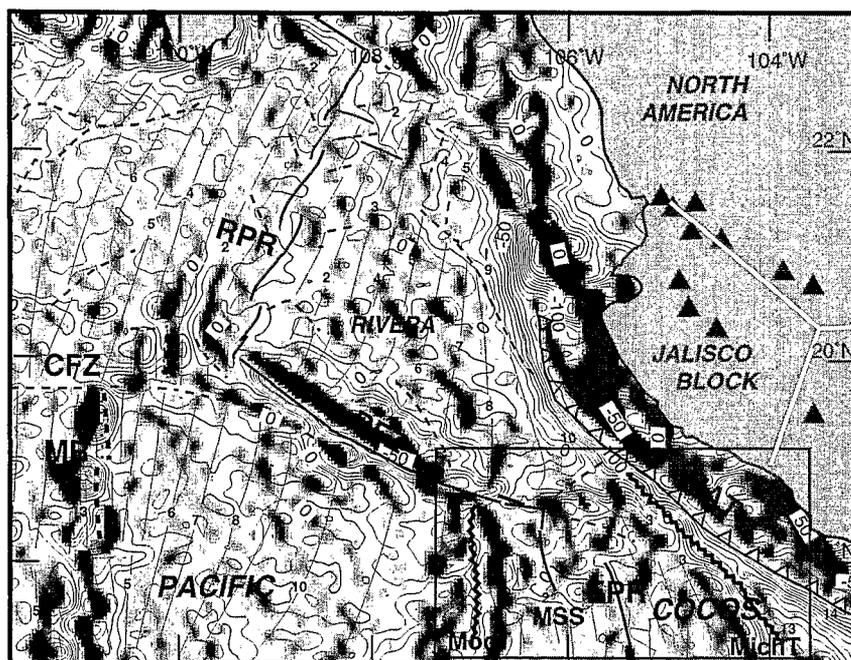


Fig. 1. Location map of the study area [modified from Lonsdale (1995)]. The sea-surface gravity anomalies in milligal are from the global grid of Smith and Sandwell (1997). Thick black lines designate the principal active tectonic features; white lines indicate the Jalisco block boundaries; thin black lines show crustal isochrons in Ma (Lonsdale, 1995). Dashed lines indicate inactive tectonic features and thick dashed lines correspond to the failed spreading centres. Solid black triangles show the locations of the principal volcanoes of the western Trans-Mexican Volcanic Belt. The rectangular box shows the area of Fig. 2. Abbreviations are: MAT, Middle America Trench; MSS, Moctezuma spreading segment; MG, Manzanillo graben; EGG, El Gordo graben; EPR, East Pacific Rise; RPR, Riviera–Pacific Rise; MR, Mathematician Ridge; CFZ, Clarion Fracture Zone; RFZ, Riviera Fracture Zone; MocT, Moctezuma Trough; MichT, Michoacan Trough (marked by thick zigzag black lines).

ing magnetic anomalies, the subducting oceanic crust is older than 14 Ma at 17°N, and older than 10 Ma at 20°N (Fig. 1) (Mammerickx and Klitgord, 1982; Atwater, 1989; Kostoglodov and Bandy, 1993). It also exhibits significant lateral variations in the dip of the slab (Pardo and Suarez, 1995). In spite of the EPR location close to the trench, no younger oceanic crust is presumed to be subducting beneath the Middle American Trench (MAT) (Stock and Lee, 1994; Lonsdale, 1995).

Swath bathymetry, backscatter and MCS data provide structural and crustal information of the outer wall of the trench around 18°30'N that suggest the oceanic crust consumed at the trench is younger than previously thought (Mammerickx and Klitgord, 1982). This argues against the

former models of the EPR evolution and its possible interaction with the MAT.

2. Geological setting

The oceanic crust off western Mexico was formed, prior to the development of the EPR spreading centre, along the Mathematician Ridge, located several hundred kilometres to the west (Fig. 1). The present EPR spreading centre propagated northward into 12 Ma old oceanic crust built along the failed Mathematician Ridge. The two crustal provinces (i.e. crust formed at the EPR and Mathematician Ridge) are separated by the Moctezuma trough to the west and the Michoacan trough to the east (Fig. 1). These troughs are

interpreted as the initial site of spreading along the EPR, which is contemporary with the cessation of spreading along the Mathematician Ridge (Mammerickx et al., 1988). The crust accreted at the northern EPR, with a maximum age of 4 Ma, is located offshore of western Mexico (Mammerickx and Klitgord, 1982; Atwater, 1989), and the EPR terminates near the trench (Lonsdale, 1995). It is generally considered that the oceanic crust formed along the EPR has not yet reached the MAT (Fig. 1) (Lonsdale 1995). Nevertheless, a new analysis of magnetic anomalies suggests that a section of the outer wall of the MAT is 4–2 Ma old (Massell and Lonsdale, 1997).

A variety of models have been published for the northern end of the EPR, where it intersects the Rivera Fracture Zone and the MAT (Mammerickx, 1984; Bourgois and Michaud, 1991; Bandy, 1992; Bandy et al., 1995, 1999; DeMets and Wilson, 1997). Some authors propose that the EPR propagated north of the present-day location of the EPR–Rivera transform system (Bandy et al., 1988; Lonsdale, 1995; Bandy and Hilde, 1999). End-member models speculate that the EPR reached the trench (Mammerickx and Carmichael, 1989; Sisson et al., 1994). According to Bourgois et al. (1988), the EPR would actually include the short Moctezuma spreading segment (Fig. 1), which trends N05°E and is offset 100 km westward. However, DeMets and Wilson (1997) and Michaud et al. (1997) present evidence that the Moctezuma spreading segment is part of the Pacific–Rivera plate boundary rather than the Pacific–Cocos plate boundary. This is compatible with the plate configuration of Bandy (1992) that proposed for the first time that the Moctezuma spreading centre and the EPR tip formed an overlapping system.

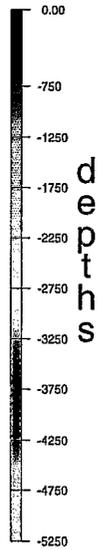
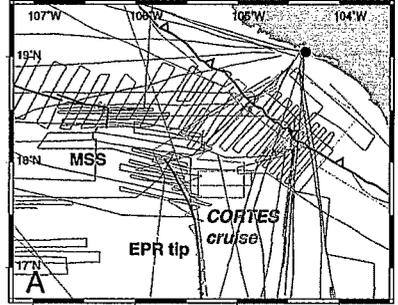
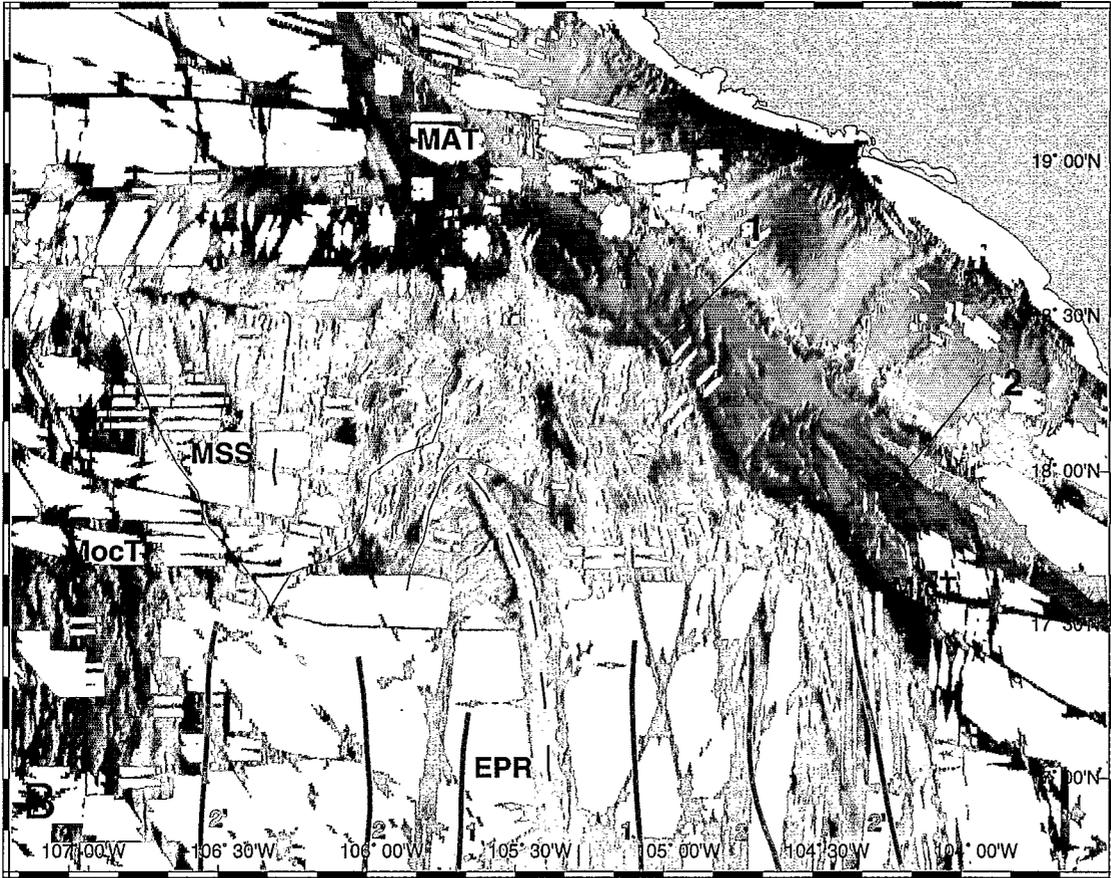
Adjacent to the EPR termination area, subduction–erosion is reported on the inner wall of the trench (Michaud et al., 1995; Mercier de Lepinay et al., 1997; Calmus et al., 1999). An anomalously shallow down-dip limit of the seismicity beneath the western Mexican mainland suggests that the oceanic slab could be relatively thin (Melbourne et al., 1997). Further, the depth of the slab under the western Mexican Volcanic Belt is not known (Pardo and Suarez, 1993). Moreover, the western

Mexican Volcanic Belt is spatially and compositionally a complex volcanic arc (Lange and Carmichael, 1991; Righter and Carmichael, 1992; Wallace et al., 1992; Ferrari et al., 1997; Luhr, 1997). The volcanic rocks have variously been correlated with the relocation of the Pacific–Rivera Rise into the Jalisco Block active rifting (Luhr et al., 1985; Luhr, 1997), with the presence of a hotspot beneath the continent (Moore et al., 1994), or to a slab break associated with the subduction of the Cocos–Rivera plate boundary (Bandy et al., 1995, 1999).

3. Data

The geophysical data used in this study come from different data sets. The gravity and MCS profiles are from the CORTES-P96 cruise (Dañobeitia et al., 1996). The swath bathymetry is from several surveys: *N/O Jean Charcot* (Bourgois et al., 1988), *R/V Thomas Washington* cruises (Mammerickx, 1984) and CORTES-P96 cruise (Fig. 2A). The conventional bathymetry, gravity and magnetics data are from the NGDC data set. We have applied a gaussian filter low-pass filter (>10 km; skip gap <5 km) to each NGDC magnetic profile, and then a robust bilinear trend (Wessel and Smith, 1995). The gridded file was obtained by a nearest neighbour gridding algorithm (bathymetry, $0.25 \text{ km} \times 0.25 \text{ km}$ grid) or by a continuous surface gridding algorithm (other data, $2 \times 2 \text{ km}$ grid).

Multichannel seismic reflection data were acquired also with the *R/V Hespérides* during the CORTES-P96 cruise across the trench (Dañobeitia et al., 1997), using a 2.4 km long streamer with 96 channels. The energy source was a tuned airgun array of 50–1 (3000 in³) with a shot interval of 30 s. Seismic data quality control and preliminary stack processing were done aboard the *R/V Hespérides*. The final processing was done at the Department of Geophysics of the Institute of Earth Sciences, Jaime Almera, with a conventional marine seismic processing flow. To increase and homogenize the signal-to-noise ratio, we edited the noisy traces and muted electronically the generated spikes. However, the receiver and source coupling



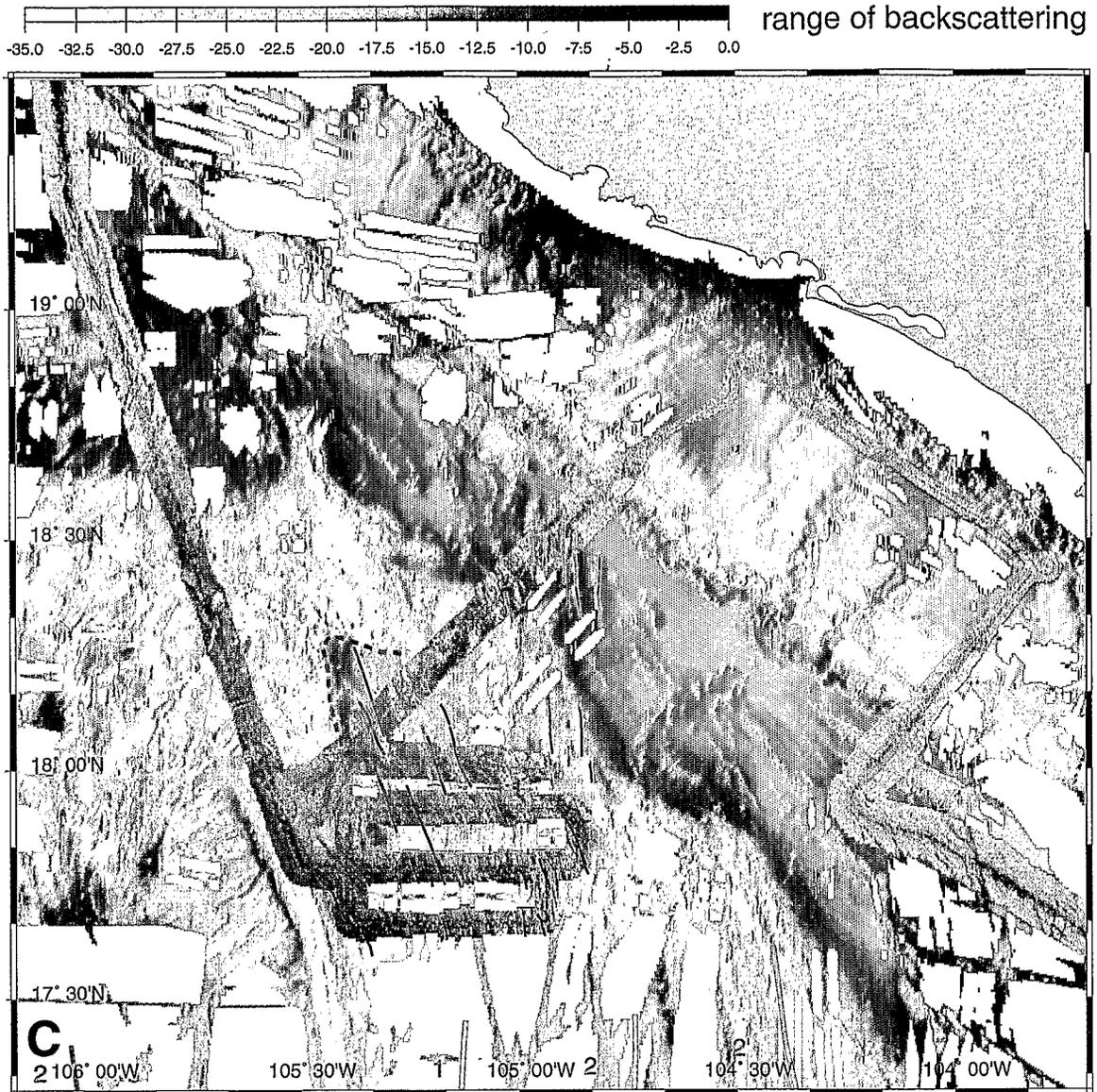
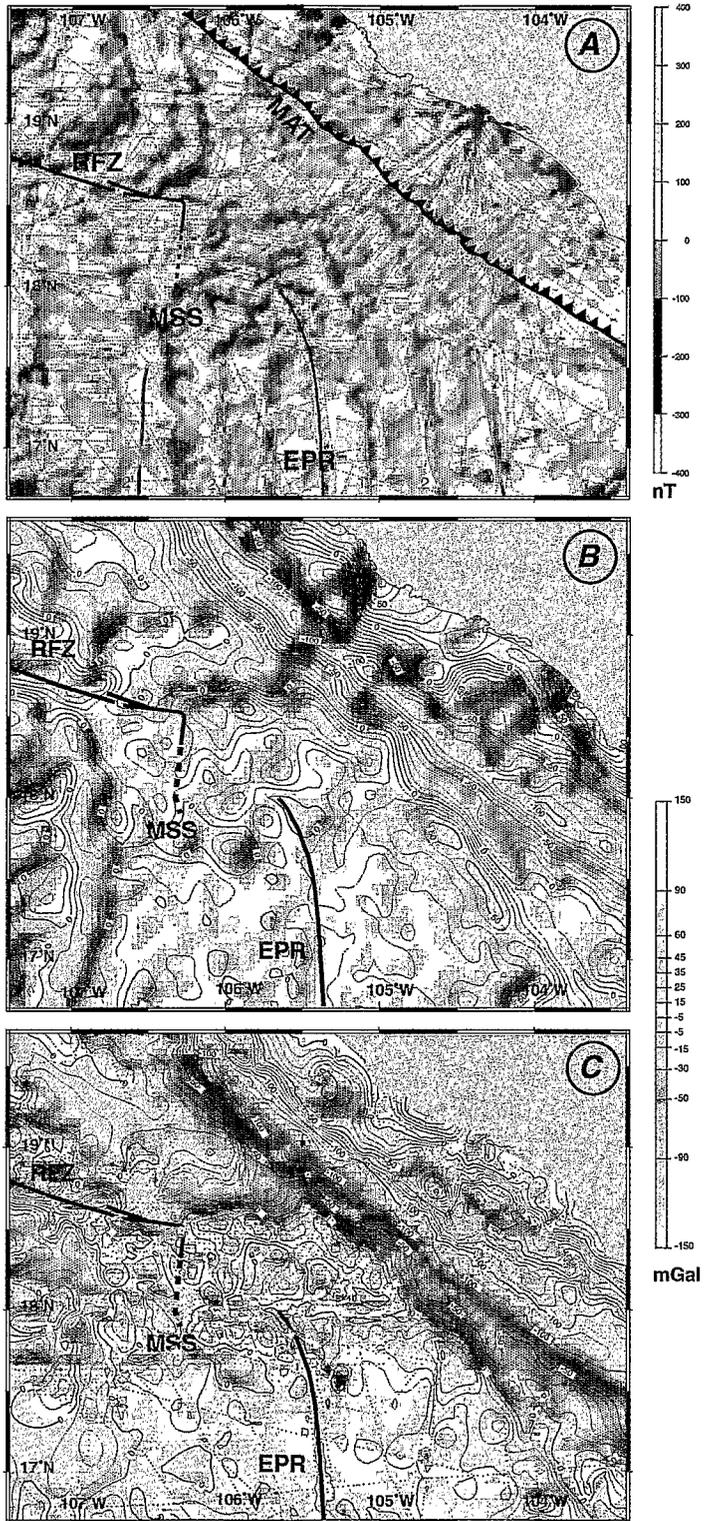


Fig. 2. (A) Tracks of swath bathymetry cruises. Conventional wide-beam echo-sounding tracks are not shown. Abbreviations are the same as in Fig. 1. (B) Colour shaded bathymetric relief map (250 m \times 250 m grid) illuminated from the west from conventional and swath bathymetry (data from NGDC and IFREMER). The red thick lines correspond to the magnetic lineations from Cande et al. (1989); $2' = 3.5$ Ma. Thick black lines are location of the MCS profiles. Dashed lines are EPR and the MSS axes. Thin black lines indicate wakes of the EPR–MSS overlapping system from Bandy (1992) and DeMets and Wilson (1997). (C) Enlarged view of the backscattered imagery. Strong acoustic backscatter returns are shown in dark; areas with weak backscatter returns are shown in white. The EPR tip exhibits homogeneously high reflectivity that continues until the outer wall of the trench at $18^{\circ}30'N$. In contrast, at $17^{\circ}55'N$ and at $19^{\circ}30'N$ the outer wall of the trench exhibits weak backscatter returns. Red lines emphasize the N–S spreading abyssal hill fabric and blue lines the westward curving abyssal hill fabric. Blue dashed lines correspond to possible pseudofaults associated with failed rifts.



is constant in marine data acquisition. An ensemble balancing step was needed to balance the shot gathers when there was an air gun failure. Post-stack time migrations were used for final display with a trace mixing (seven traces). A constant velocity time migration (Stolt, 1978) was applied to Profile 106, and a constant velocity phase shift migration for profile 104 (Gazdag, 1978).

4. Results

4.1. Morphologic observations

South of 17°30'N, the EPR axis strikes N–S and it bends to the NNW between 17°30'N and 18°N (Fig. 2). The seafloor topography, west of the EPR axis exhibits an NE–SW lineation, and has a blocky character, with a typical relief of 800 m. To the east, the abyssal hill fabric extends to the north tip of the EPR tip at 18°20'N, where a V-shaped structure is observed. This feature is interpreted as a pseudofault associated with a northward-propagating rift. The main orientation of the abyssal hills is 150° to 170°, showing off a westward bending similar to the curvature of the present EPR tip. Toward the trench, at 18°30' the seafloor also shows a similar abyssal hill fabric with a typical relief of 500 m. However, towards the outer wall the trench is N–S, significantly different from the trench-parallel fabric (NW–SE) found at the outer wall at 18°N. At the intersection of these N–S and NW–SE seafloor fabrics with the trench, it is 500–700 m shallower than in the adjacent trench segments.

Based on the acoustic reflectivity of the seafloor from backscatter records, the EPR tip contains the most recently accreted seafloor in the area (Fig. 2C). Northeast of the EPR tip, toward the trench and across the area with abyssal hill fabric, the backscatter imagery also shows high reflectivity, indicating that this area is devoid of sediments. In contrast, near the trench, the abyssal hill fabric

south of 18°N and north of 19°20'N, displays a low reflectivity due to the sediment cover.

4.2. Magnetic anomalies

The compilation of magnetic anomalies shows N–S-trending spreading anomalies south of 17°30'N. To the east of the EPR tip and north of 17°30'N (Fig. 3A), isochrons 1 (0.78 Ma) and 2 (1.8 Ma) bend to the west. There is a good correlation between the curvature of the magnetic lineations and the seafloor fabric. The Moctezuma spreading segment, located west of the EPR tip, is placed at the centre of a large triangular positive magnetic anomaly, compatible with the location of the ridge axis proposed by Bandy (1992) and Bandy and Hilde (1999).

On the outer wall of the trench, no lineations have been identified as being related to the N–S structural trend observed on the bathymetric data, although a high-amplitude magnetic anomaly is visible at this latitude in the trench.

4.3. Gravity

The gravity data (Fig. 3B), derived from the global gravity map of Sandwell and Smith (1997), show clearly a strong negative anomaly narrowing between 18 and 19°N that corresponds to the trench. This narrowing is bounded by a positive anomaly to the west that fits roughly with the oceanic crust formed along the EPR, and indicates the extent to which young oceanic crust is entering the MAT. This young oceanic crust is bounded to the west (107°W) by an N–S linear negative anomaly corresponding to the Moctezuma trough. A similar E–W gravity anomaly trend, between 106°30'N and 105°N, delimits the EPR oceanic crust, which is marked by a high positive anomaly. The gravity signature of the Michoacan trough is not the mirror image of the Moctezuma trough and its western flank is highlighted by a large positive anomaly instead. Gridded ship-track grav-

Fig. 3. (A) Magnetic anomalies in nanotesla (compiled from the NGDC data bank). The dotted lines correspond to the cruises where magnetics data were collected. (B) Sea-surface gravity anomalies in milligal (Sandwell and Smith, 1997). (C) Ship-track gravity anomalies including NGDC and CORTES-P96 data. The dotted lines correspond to the cruises where gravity data were collected.

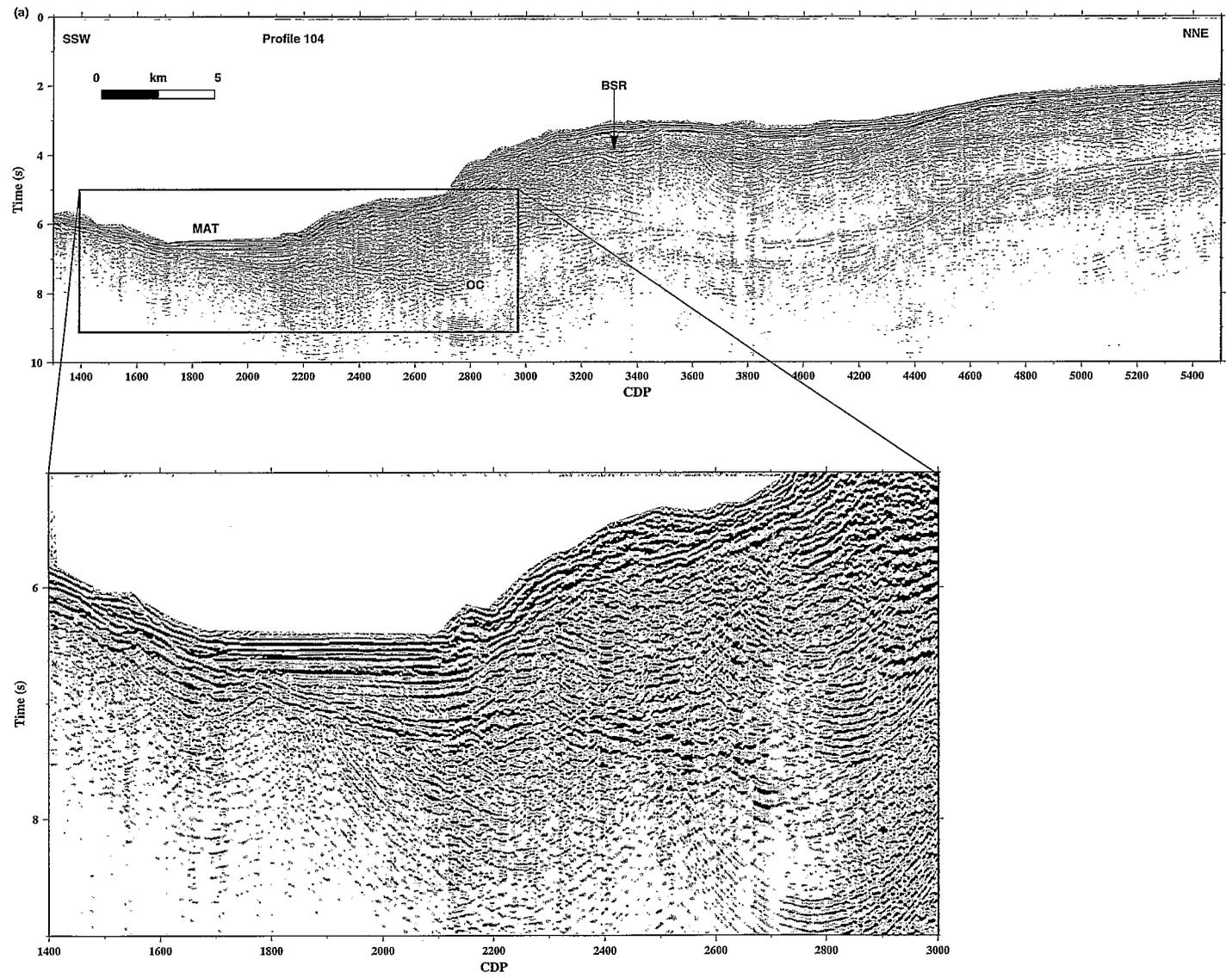


Fig. 4.

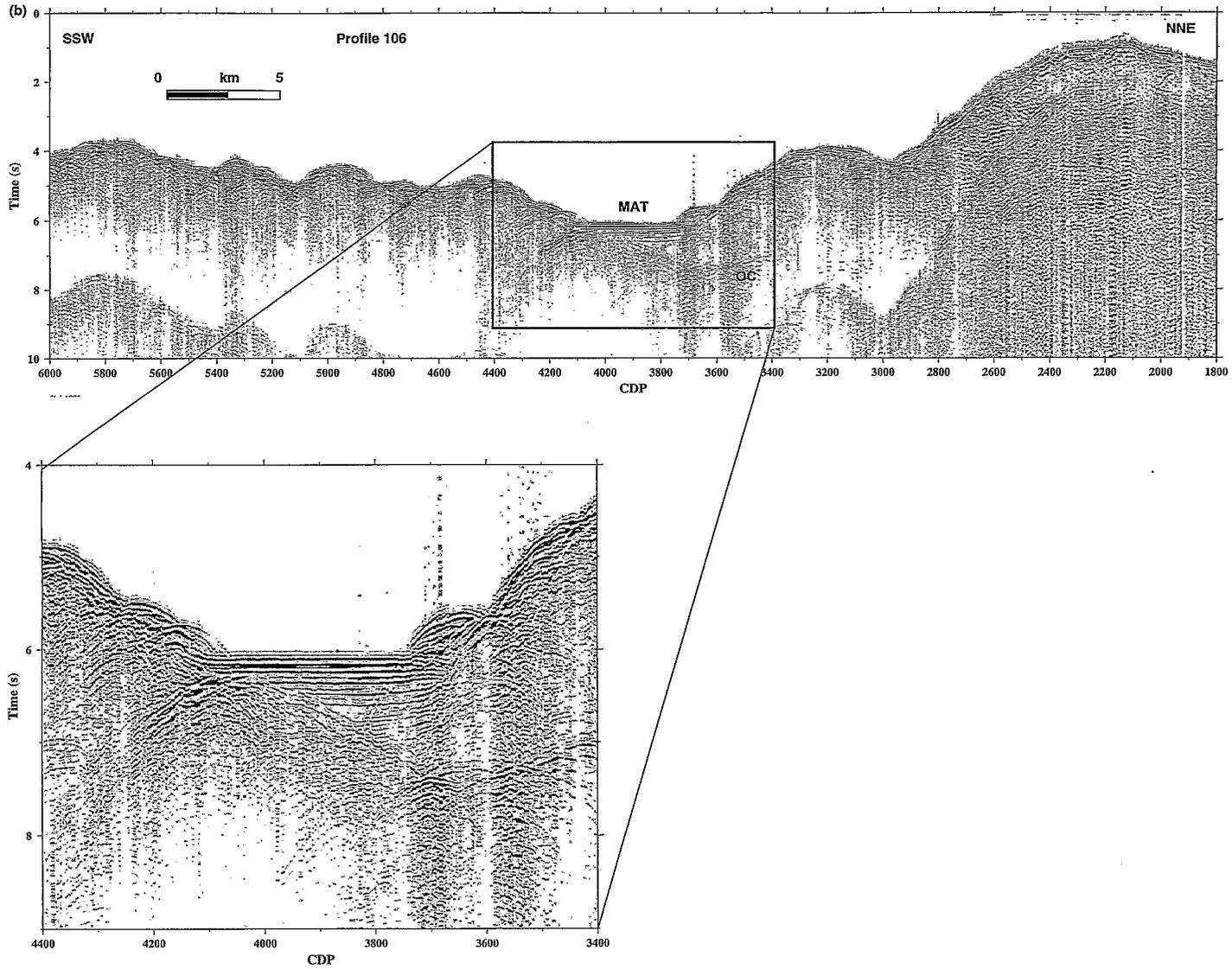


Fig. 4. (continued)

ity data compilations, including the data collected during the CORTES-P96 cruise (Fig. 3C), show similar patterns, and also corroborate the strong negative anomaly narrowing between 18 and 19°N.

4.4. Description of seismic reflection data

The seismic data used to constrain the top of the oceanic slab entering the trench at approximately 18°30'N, 104°30'W consist of two profiles perpendicular to the MAT (Dañobeitia et al., 1997). Fig. 4A and B displays the MCS profiles 106° and 104° acquired along track 1 and track 2, respectively (Fig. 2B). The southernmost transect (profile 104, Fig. 4A) features an eastward gently deepening oceanic crust that subducts beneath the Mexican crust with an apparent dip of 8–10°. The top of the oceanic crust is observed beneath the inner wall of the trench for about 20 km (see inset of Fig. 4A). The subduction complex is characterized by a sedimentary wedge horizontally layered (between CMPs 1600 and 3000) with a maximum thickness of about 1500–1700 m (Fig. 4A). To the east of this structure the sea-floor is undulated, suggesting a slightly deformed wedge (CDPs 2100–2800). This structure also displays arcuate events that, after migration, turn into undulated reflectors, which is further evidence of deformation. Conspicuous reflectivity above the seafloor multiple characterizes the Mexican margin in this transect. Profile 104 displays a sediment cover overlying the oceanic crust at the outer wall of the trench, and more than 200 m of sediments are observed seaward of the trench. East of the trench, profile 104 (Fig. 4A) shows a prominent reflector at 0.8 s below the seafloor that presumably corresponds to a bottom-simulating reflector (BSR).

The northernmost transect (profile 106, Fig. 4B) features a very irregular seafloor, and the subduction zone is characterized by a prominent arcuate event at the western end of the sedimentary wedge (CDP 4100). The thickness of the wedge reaches approximately 1600 m (between CDPs 3600 and 4100). Further east the wedge is strongly deformed

(between CDPs 2800 and 3600), and the seafloor consists of a 10 km long bulge with a maximum topographic relief of 4 km. Arcuate events within this bulge structure are indicative of deformation fabrics. Profile 106 crosses the trench where the oceanic crust is lacking a sedimentary cover.

The high-amplitude arcuate event located at CDP 4100 (inset Fig. 4B) is indicative of a sharp geological feature within the subducting oceanic plate. This strong diffraction pattern is probably the result of faulting (near-vertical fault) perpendicular to the seismic profile. The subducted oceanic plate is characterized by an apparent dip of 8–10° up to CDP 3500, where the reflectivity becomes horizontal. The reflectivity at this location (CDPs 3300–3500) is also characterized by arcuate events, suggesting a diffraction pattern due to a series of blocks limited by almost vertical faults.

The contrasting seismic signatures between these two profiles are probably the result of different subduction regimes. The deformation to the north is evidenced by the broken subducting oceanic plate and topographic relief; in contrast, at the southern transect there is a gently dipping subduction zone.

The results from profile 106 (Fig. 4B) agree with the backscatter observations that show a lack of sediment at the oceanic crust from the tip of the EPR to the outer wall of the trench. From the outer wall of the trench toward the continent, the top of the oceanic crust beneath the inner wall of the trench is observed along more than 10 km (see inset of Fig. 4B), and does not show significant sedimentary cover. The broken subducting oceanic plate continues landward beneath the lower slope of the inner wall. There is no evidence of any abrupt step related to the contact between the old crust formed at the Mathematician Ridge and the younger crust formed along the EPR, which is the northward prolongation of the Michoacan trough. Nevertheless, we cannot exclude the possibility that the high amplitude arcuated event located at CDP 4100 (profile 106, inset Fig. 4B) corresponds to the boundary between these two crustal provinces.

Fig. 4. Stacked seismic section for (A) profile 104, (B) profile 106; see Fig. 2B for location. CDP distance is 12.5 m. Total profile length is 52.5 km. See text for processing sequence. MAT: Middle American Trench; OC: Top of the oceanic crust.

5. Discussion

Previous results concerning the subducted slab entering the northern MAT propose that the crust is slightly older than 12 Ma. A crust of this age should have several hundred metres of sediments on top of oceanic crust, according to results from DSDP 473 (Yeats and Haq, 1981) and to the study of Moore and Shipley (1988). However, our results show a striking difference of the sedimentary cover between the two MCS profiles.

Many authors state that the EPR is connected with the San Andreas transform system through the Rivera transform, the Rivera–Pacific Rise and the Gulf of California (Mammerickx and Klitgord, 1982; Mammerickx, 1984; Lonsdale, 1991). Early development of the Rivera transform as the result of an eastward jump of the Mathematician spreading centre (prior to 3.5 Ma) precludes any northward propagation of the EPR termination (Fig. 5A). A recent model by Lonsdale (1995) proposes that the EPR propagated northward without any clear connection with the Pacific–Rivera Rise (Fig. 5B). The EPR propagated northward of its present-day location and the Rivera

transform fault developed later (<2 Ma), when the Pacific–Rivera Rise axis evolved into a series of short ‘en echelon’ spreading axes. The existence of a broad shear zone is assumed, before the initiation of the Rivera transform, in order to accommodate dextral shear between the EPR and the Pacific–Rivera Rise. This diffuse dextral shear zone includes the trace of the Clarion Fracture Zone that is located southward of the northernmost segment of the Mathematician Ridge.

The narrow zone of V-shaped propagating fabric, west of the EPR tip, cuts through an orthogonal linear fabric and thus indicates that the present-day axis formed more recently. Consequently, the oceanic seafloor east of the EPR tip was not formed along the present EPR tip axis. The Moctezuma spreading segment and the EPR tip is considered as a significant overlapping system that developed during the last 1 Ma (Bourgeois et al., 1988; Lonsdale, 1995; DeMets and Wilson, 1997; Bandy and Hilde, 1999). We propose that, when the Moctezuma spreading segment matured, the EPR tip began to curve and to retreat southward to its present position.

Before the development of the Moctezuma

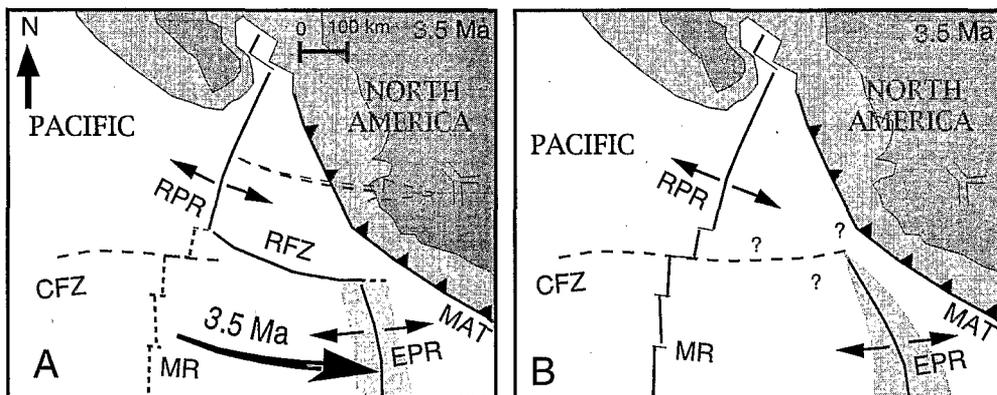


Fig. 5. Models of the EPR termination. (A) The EPR connects with the Rivera–Pacific Rise through the Rivera Fracture Zone following an eastward jump of spreading activity from the Mathematician Ridge (MR) to the EPR, prior to 3.5 Ma. Short dashed lines indicate the failed Mathematician Ridge (Mammerickx and Klitgord, 1982). The dashed arrow corresponds to an incipient eastward spreading jump into the continent, suggested by Luhr et al. (1985). This model precludes any northward prolongation of the EPR termination. (B) The EPR propagates northward while the Mathematician Ridge is still an active spreading centre. A broad diffuse dextral shear zone, including the trace of the sinistral Clarion Fracture Zone (CFZ, dashed line) is assumed to connect the two spreading rises before the birth of the Rivera Fracture Zone [after Lonsdale (1995)]. This model questions the location along the trench of the EPR termination.

spreading segment, the EPR was already mature at this latitude, as illustrated by NS features revealed by magnetic lineations (south of 17°30'N, Fig. 2). The N–S bathymetric lineations observed on the outer wall of the trench at 18°30'N correspond to the northward prolongation of the seafloor spreading fabric observed south of 17°30'N. There is no evidence of a broad distributed shear zone prior to the genesis of the Rivera transform, either from the spreading fabric on the outer wall of the trench (18°30'N), or from the equivalent seafloor south of 17°30'N.

We cannot exclude that the Michoacan trough is crossed by profile 106 beneath the lower slope of the inner wall of the trench. In this case, the oceanic crust formed along EPR is just nearing the trench. Consequently, a counterpart of the N–S seafloor-spreading fabrics observed on the outer wall of the trench is expected between the seafloor accreted at the Moctezuma spreading centre and the Moctezuma trough. The seafloor between the Michoacan and Moctezuma troughs is not symmetric, and neither the bathymetric data (Fig. 2B), nor the structural trends (N20°W) of this area (DeMets and Wilson, 1997), allow us to define unambiguously a possible symmetry. Moreover, the northern termination of the Michoacan trough is unclear, and along the outer wall of the trench no trough has been crossed on profile 104.

At the location where the young oceanic crust is subducted, the trench is narrower and approximately 500 m shallower than the neighbouring sides. The area lies adjacent to large submarine canyons on the continental margin. The shoaling of the trench is probably due to the sediments supplied by the submarine canyons. The difference in trench depth cannot be attributed to differences in sediment infill, as the sediment thickness from the two seismic profiles is not significantly different (Fig. 4). We suggest that this shallowing is caused instead by the subduction of younger, and therefore shallower, oceanic crust. Based on the observations, we believe that the oceanic crust formed along the EPR is not only arriving at the trench, but is also subducting beneath it. The connection between the EPR and the Rivera fracture zone before the development of the overlapping system is still unresolved.

6. Conclusion

The main conclusion derived from our study is that the subducting oceanic crust at 18°30'N was formed along the EPR and not along the Mathematician Ridge or Rivera Rise. Between the northernmost EPR segment and the MAT, this seafloor spreading fabric overtakes the EPR tip. The analyses of seafloor morphology, gravity, magnetics, and seismic data suggest that the age of the subducting oceanic crust is younger than previously thought. A large overlapping system developed, after 1 Ma, in association with a southward retreat of the EPR tip. The presence of young oceanic crust along the outer wall of the trench puts in question the evolution of the EPR termination before the development of this overlapping system.

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