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Original paper

Morphology and magnetic survey of the Rivera-Cocos plate boundary of Colima, Mexico

Juan Ramón Peláez Gaviria, Carlos A. Mortera Gutiérrez*, William L. Bandy and François Michaud

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Resumen

La propagación del segmento Pacífico-Cocos de la dorsal East Pacific Rise (EPR-PCS) ha alterado significativamente la configuración de la placa en el extremo norte de la Trinchera Mesoamericana. Esta propagación de la dorsal, la colisión del segmento EPR-PCS con la trinchera Mesoamericana, la separación de las placas Rivera y Cocos, y la formación de la Transformada de Rivera han ocasionado un ensamble complejo de elementos morfo-tectónicos en el área del límite entre placas Rivera-Cocos, contrastante a lo típico de un límite transformante entre placas. Los datos marinos existentes de magnetismo y batimetría han sido inadecuados para resolver esta complejidad, por lo que una malla densa de datos del campo magnético total fue colectada durante las campañas oceanográficas MARTIC-04 y MARTIC-05 del buque oceanográfico B/O El PUMA en 2004 y 2006. Estos datos han clarificado considerablemente el patrón de las lineaciones magnéticas contiguas a la Trinchera Mesoamericana, e interesantemente un alto magnético en forma de *en echelon,* orientado NE-SW observandolo alejado del Graben de Manzanillo, hacia mar. Desafortunadamente, la naturaleza exacta del límite entre Rivera-Cocos permanece imprecisa. Pero estos datos muestran que el segmento de la dorsal EPR-PCS alcanza la latitud (~18.3ºN) de la actual Transformada de Rivera en la isócrona magnética $2A_3$ (~3.5Ma) y se propaga más hacia el norte, interceptando la Trinchera Mesoamericana aproximadamente en 1.7 Ma (Chron 2). En 1.5 Ma, el esparcimiento oceánico cesó a lo largo de la dorsal EPR, al norte de 18.3ºN, y la dorsal EPR-PCS desde entonces ha retrocedido hacia el sur en asociación con la propagación hacia el sur del centro de esparcimiento Moctezuma Spreading Segment (MSS). Al norte de 18.3ºN, el piso oceánico cercano a la trinchera se ha fracturado en menores bloques que presentan levantamientos, posiblemente debido a la subducción de la litosfera recién formada por el EPR-PCS.

Palabras clave: anomalías magnéticas marinas, tectónicas de placas, Dorsal 'East Pacific Rise', trinchera Mesoamericana, reconstrucciones de las placas.

Abstract

The propagation of the Pacific-Cocos Segment of the East Pacific Rise (EPR-PCS) has significantly altered the plate configuration at the north end of the Middle America Trench. This ridge propagation, the collision of the EPR-PCS with the Middle America Trench, the separation of the Rivera and Cocos plates and the formation of the Rivera Transform have produced a complex arrangement of morphotectonic elements in the area of Rivera-Cocos plate boundary, atypical of an oceanic transform boundary. Existing marine magnetic and bathymetric data has proved inadequate to unravel this complexity, thus, a dense grid of total field magnetic data were collected during campaigns MARTIC-04 and MARTIC-05 of the B/O EL PUMA in 2004 and 2006. These data have greatly clarified the magnetic lineation pattern adjacent to the Middle America trench, and have revealed an interesting *en echelon*, NE-SW oriented magnetic high offshore of the Manzanillo Graben. We interpret these new data to indicate that the EPR-PCS ridge segment reached the latitude (~18.3ºN) of the present day Rivera Transform at about Chron $2A_3$ (~3.5Ma) and propagated further northward, intersecting the Middle America Trench at about 1.7 Ma (Chron 2). At 1.5 Ma spreading ceased along the EPR north of 18.3ºN and the EPR-PCS has since retreated southward in association with a southward propagation of the Moctezuma Spreading Segment. North of 18.3ºN the seafloor near the trench has been broken into small, uplifted blocks, perhaps due to the subduction of the young lithosphere generated by the EPR-PCS.

Key words: marine magnetic anomalies, plate tectonics, East Pacific Rise, Middle America Trench, Mexico, plate reconstructions, Rivera-Cocos plate boundary.

J.R. Peláez Gaviria
C.A. Mortera Gutiérrez*
W.L. Bandy
Instituto de Geofísica
Universidad Nacional Autónoma de México
Ciudad Universitaria
Delegación Coyoacán, 04510
México D.F., México
*Corresponding author: cmortera@geofisica.unam.mx

F. Michaud
Géosciences Azur,
La Darse, BP48, 06235
Villefranche-sur-Mer, France

Introduction

The collision of the East Pacific Rise (EPR) with the western margin of the North American Plate has been recorded along the continental margin of North America from Alaska to Mexico (e.g. Atwater, 1989). The most recent collision appears off Manzanillo, Mexico (Figure 1), in the area located between the northern end of the Pacific-Cocos segment of the East Pacific Rise (EPR-PCS) and the Middle America Trench (MAT) where there exists two closely spaced triple junctions formed between the Rivera, Pacific, Cocos and North American plates (e.g. Atwater, 1970; Molnar, 1973). Thus, this site should be ideal for studying the processes associated with the approach and collision of a seafloor spreading center with a subduction zone. Unfortunately, the Rivera-Cocos plate boundary the Rivera Transform and the remnant paleo-Rivera Transform are also located near the collision zone and significantly complicate the morphologic elements associated with this collision (e.g. Bandy, 1992).

The complexity of the seafloor morphology and seafloor magnetic lineations in this area in conjunction with, for the most part, poorly navigated magnetic data and sparse multibeam coverage, has led to several proposals as to the plate configuration and tectonic history of this area (e.g., Mammerickx and Carmichael, 1989; Bourgois and Michaud, 1991; Bandy, 1992; Lonsdale, 1995; DeMets and Wilson, 1997). Thus, to better define the morphology and tectonic history of this area, total field marine magnetic data were collected during two campaigns, MARTIC04 in 2004 and MARTIC05 in 2006, aboard the B/O EL PUMA and combined with multibeam data collected during the 2002 BART/FAMEX campaigns of the NO L'Atalante. Some of the bathymetric data of the BART/FAMEX campaigns conducted in this area have been previously published (Bandy *et al.,* 2005; 2008); however, the majority of the data in the area located between the MAT and the EPR-PCS remained unpublished.

Previous Work

Several proposals exist concerning the evolution of the northernmost segment of the EPR-PCS, particularly regarding its relation to the southern limit of the Rivera plate. Discriminating between these proposals has proved difficult due to the highly complex tectonics of the zone and to the poor spatial coverage of the magnetic and multibeam bathymetric data. Many previous studies have used the seafloor morphology and the seafloor spreading magnetic lineation data to try to resolve the kinematics and deformational history of this area. Some of these studies were of a regional focus (e.g., Mammerickx and Klitgord,

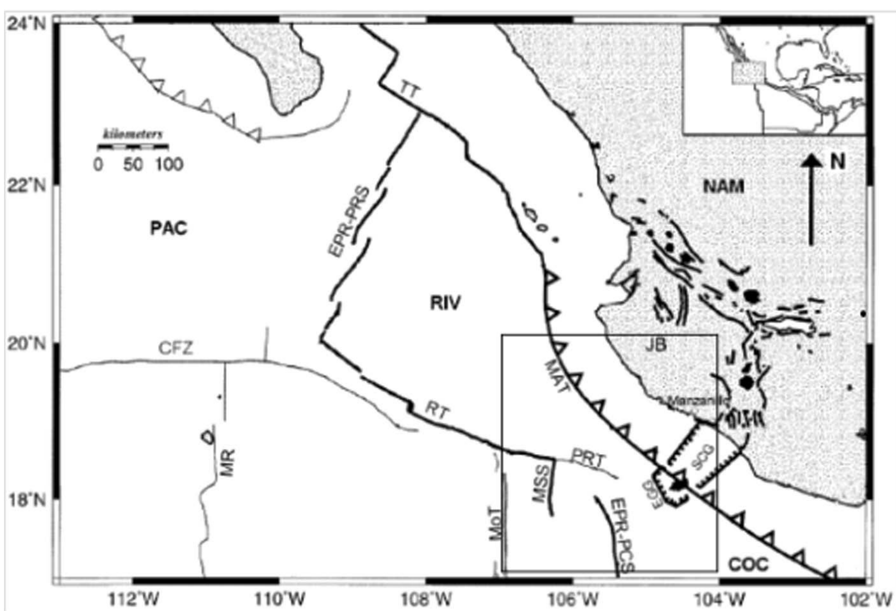

Figure 1. Morphotectonic elements of the study area. The abbreviations are: PAC = Pacific Plate; NAM = North American Plate; COC = Cocos Plate; RIV = Rivera Plate; MR = Mathematician Ridge; MoT = Moctezuma Trough; EGG = El Gordo Graben; SCG = Southern Colima Graben; JB = Jalisco Block; TT = Tamayo Transform; RT = Rivera Transform; PRT = Paleo Rivera Transform; MSS = Moctezuma Spreading Segment; EPR-PRS = East Pacific Rise Pacific-Rivera Segment; EPR-PCS = East Pacific Rise Pacific-Cocos Segment; MAT = Middle American Trench. Modified from *DeMets and Traylen* (2000).

1982; Klitgord and Mammerickx, 1982; Atwater, 1989); whereas others were focused more directly on various aspects of the kinematics of the Rivera Plate (e.g., Eissler and McNally, 1984; DeMets and Stein, 1990; Bandy, 1992; Bandy and Pardo, 1994; DeMets and Wilson, 1997; Bandy *et al.,* 1997, 1998, 2000; DeMets and Traylen, 2000; Jaramillo and Suárez, 2011) or on the complexities of the various boundaries of the Rivera Plate (e.g., Bourgois *et al.,* 1988; Bandy *et al.,* 1995, 2005, 2008; Kostoglodov and Bandy, 1995; Pardo and Suárez, 1995; Lonsdale, 1995; Michaud *et al.,* 1997, 2000, 2001; Bandy *et al.,* 2000; Bandy and Hilde, 2000; Serrato-Díaz *et al.,* 2004). Although all of these studies have made significant contributions to understanding the tectonics of the Rivera plate, they have yet to provide a clear understanding of either the recent evolution of the northernmost segment of the EPR-PCS, or the nature of the Rivera-Cocos plate boundary.

Mammerickx and Klitgord [1982] and Klitgord and Mammerickx [1982] showed that the magnetic lineations of the EPR formed since 5 Ma document a relocation of seafloor spreading from the Mathematician Ridge to the present location of the EPR as the EPR propagated northward from the Orozco Facture Zone to the area of the Rivera Transform. They proposed that the propagation ceased at about 3.5 Ma (Figure 2A) and that the northward extent of the propagation was at the Rivera Transform. In contrast, Bandy (1992) (see also Bandy and Hilde, 2000) proposed that the EPR-PCS propagated north of the Rivera Transform, reaching its northern limit near the MAT at ~1.77Ma (Figure 2B). They also proposed that at 1.5 Ma (Figures 2C and 2D), the part of this spreading center located north of the Rivera Transform was abandoned/decapitated by the formation of the Rivera Transform, a proposal that is consistent with the subsequent findings of Lonsdale (1995). Michaud *et al.* (2001) proposed that the EPR-PCS may have extended even further northward than that proposed by Bandy (1992) and that the ridge segment north of the Rivera Transform has since been subducted beneath the Jalisco Block (Figure 2C).

The nature of the boundary between the Rivera and Cocos plates, as well as the relative motion across the boundary, is also controversial and various proposals have been presented. These proposals can be classified into three main groups. The first group proposes that the boundary is a generally NE-SW oriented sinistral transform boundary, the exact orientation and location being somewhat different in the various proposals (Atwater, 1970; Molnar, 1973; Reid, 1976; Nixon, 1982; Eissler and McNally, 1984; Mammerickx and Carmichael, 1989; DeMets and Stein, 1990; Lonsdale, 1995). A variant on this proposal is that of DeMets and Wilson (1997) who proposed that the boundary is a difuse zone of left lateral, NNE-SSW oriented shearing. The second group (Bandy, 1992; Kostoglodov and Bandy, 1995; Bandy *et al.,* 1995, 1998, 2000; Bandy and Hilde, 2000; Serrato-Díaz *et al.,* 2004) proposes that El Gordo Graben is the tip of a rift between the Rivera and Cocos plates and that this rift is currently propagating SW towards the EPR, resulting in a situation that is analogous

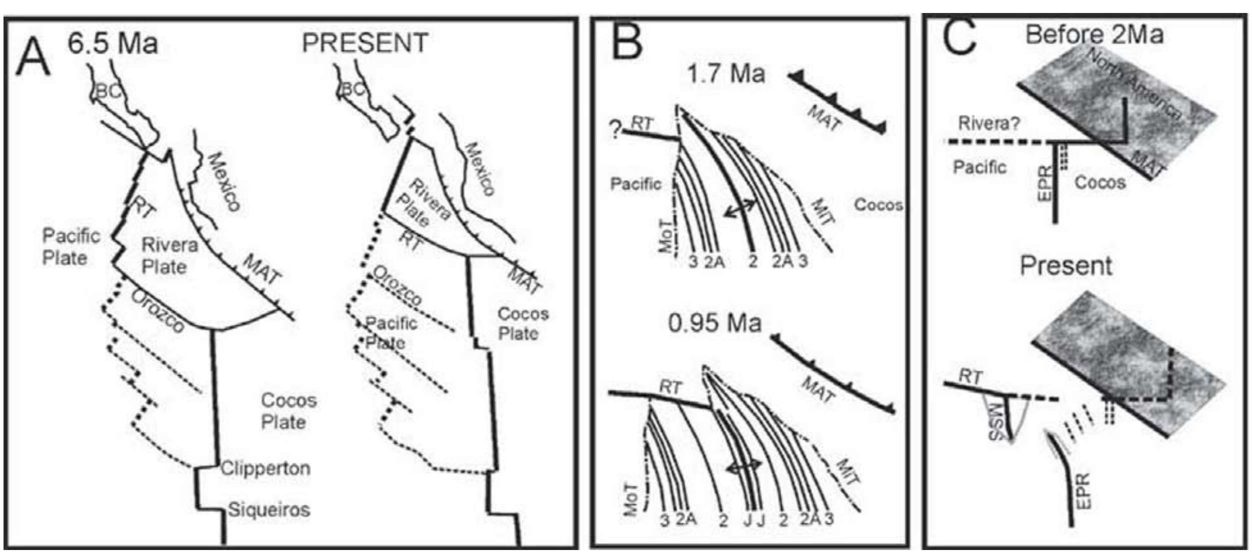

Figure 2. Previous models for the evolution of the area between the EPR, RT and MAT off Manzanillo. A) Mammerickx and Klitgord (1982) for the periods 6.5 Ma and the present day. (B) Bandy and Hilde (2000) for 1.7 Ma and 0.95 Ma. (C) Michaud *et al*. (2001) for the periods 2 Ma and the present day.

to the present day Galapogos triple junction (Lonsdale, 1988). The divergence between the Rivera and Cocos plates is proposed by Bandy (1992) to be the result of the ridge-trench collision off the southern tip of Baja California at about 8 Ma (Lonsdale, 1991) and subsequent pivoting of the Rivera plate away from the rest of the Cocos Plate, a proposal that is consistent with the results of recent seismic studies (Yang, *et al.,* 2009; León Soto *et al.,* 2009). The third group proposes that it is a diffuse boundary between the Cocos and North American plates (Michaud and Bourgois, 1995; Michaud *et al.,* 1997).

Data and Methods

Two primary data sets were used in this study. The first consists of the previously unpublished total field magnetic data obtained during the MARTIC04 (October 28-November 9, 2004) and MARTIC05 (January 10-31, 2006) campaigns of the B/O EL PUMA. The ship tracks along which the magnetic data was collected are shown in Figure 3. The second data set consists of the multibeam data collected in the study area during the BART/FAMEX campaigns of the NO L'Atalante conducted in 2002: these data are previously unpublished except near the Moctezuma Spreading Center (MSS) where they have been published in Bandy *et al*. (2008). These data were supplemented with data from the following sources: Ridge Project database, United States National Geophysical Data Center (NGDC), USGS and Harvard earthquake databases. The ages of the lithosphere in the study area were determined from the seafloor marine magnetic lineations, constrained by one recent radiometric age determination of one seafloor sample dredged during MARTIC04 (Canet *et al.,* 2008). The details of this age determination are given in Schaaf *et al.* (manuscript in preparation).

Total field marine magnetic data were collected using a GEOMETRICS G877 marine proton precession magnetometer which has a resolution of 0.1 nT (Geometrics, Inc., 2001). To avoid ship effects, the sensor was towed 250 meters behind the B/O EL PUMA, which has a length of 50 meters. A measurement was taken every 2 seconds. The locations of the measurements have been corrected for layback as the data were being recorded using the GEOMETRICS MAGLOG light program.

To correct for the diurnal variation during MARTIC-04, a permanent base station was installed (19º 7' 20.68'' N y 104º 23' 59.36'' W) within the 'El Naranjo' campus of the Universidad del Mar de Colima, Manzanillo, Colima. Readings were taken with the Sintrex Envimag proton precession magnetometer at 5 min intervals. A magnetic storm began on November 7 and

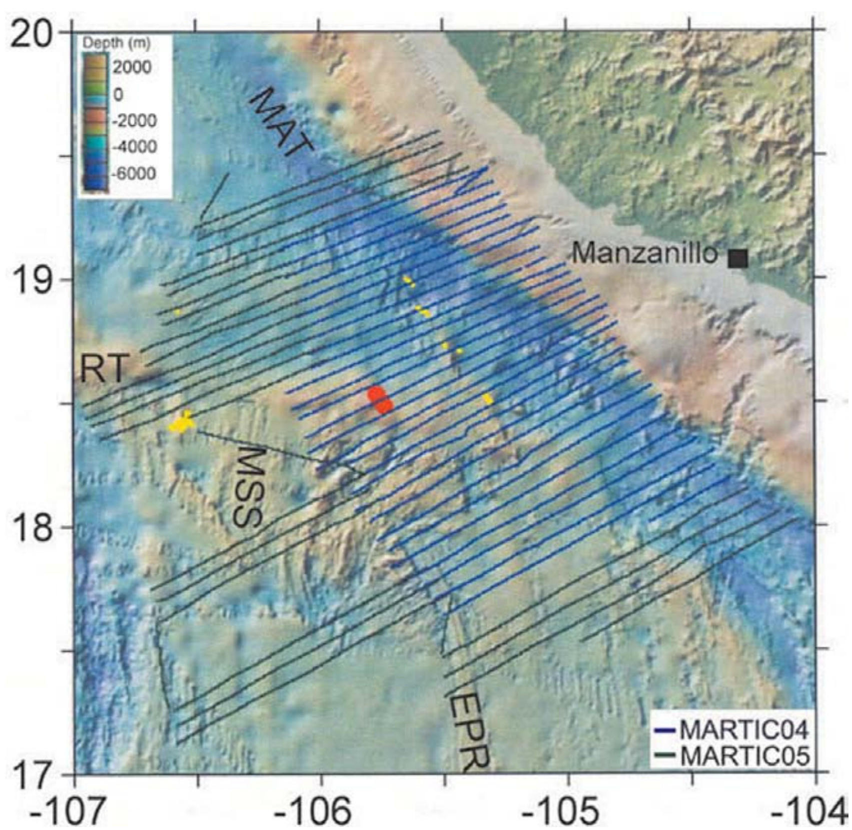

Figure 3. Map of the ship tracks along which the magnetic data was collected. The tracks of MARTIC04 are shown in blue and those of MARTIC05 are shown in green. Dredge sites are shown in red (samples obtained and age dated) and yellow (no sample obtained). Background bathymetry map from GeoMapApp (www.geomapapp.org).

data collected during the storm were not used. The base station magnetometer was down on November 1 and November 2. For these two days, the magnetic record from the permanent observatory at Teoloyucan, México was used to make the diurnal corrections, after having been shifted to fit the Colima data. More information on the treatment of the base station data can be found in Peláez Gaviria (2008).

To correct for the diurnal variation during MARTIC-05, a permanent base station was set up in the UNAM Biological Reserve, Chamela, Jalisco (19º 29’ 56.1’’ N y 105º 02’ 32.1’’ W). Readings were taken at 1 minute intervals using a GEOMETRICS G856AX proton precession magnetometer.

The selection criteria for both base stations were that the stations were located (1) in an area having a low magnetic gradient (<4.5 nT/m), (2) less than 150 km from the study area, (3) more than 60 meters from buildings, roads, power lines, or any other objects that might generate magnetic noise (Breiner, 1973).

After removing the diurnal variation the data were next corrected for ship’s heading following the methods presented by Bullard and Mason (1961), Whitmarsh and Jones (1969) and Buchanan *et al*. (1996). Next, these values were reduced to magnetic anomaly values by subtracting out the value of the main field using the IAGA IGRF-10 Model which was obtained from the United States National Geophysical Data Center.

The multi-beam bathymetric data of the 2002 BART/FAMEX campaigns were collected with a dual SIMRAD EM-12 multi-beam system and the raw data was processed using the CARAIBES software while onboard by IFREMER technicians to produce a 200 x 200 meter grid of bathymetric values. These values were combined with existing multibeam data to produce a new bathymetry map (Figure 4).

Results

The new map of the seafloor magnetic anomaly lineations (Figure 5) indicates that in the southern part of the study area, the recent magnetic anomalies are for the most part continuous and undisrupted south of 17.6°N, consistent with the seafloor morphology (Figure 4). North of 17.6°N, in the area immediately west of the EPR-PCS, the older lineations are unidentifiable as they have been disrupted both by the recent southward propagation of the MSS and the recent northward propagation of the northern tip of the EPR-PCS. The lineations are also unidentifiable in the area located between the active tip of the EPR-PCS and the Paleo-Rivera Transform.

East of the EPR-PCS two abandoned ridge segments are identified (segments P1 and P2, Figure 5). The magnetic lineations indicate that seafloor spreading along ridge segment P1 ceased just after the time of anomaly 1R as Anomaly J is observed to both sides of P1. This is slightly older than that proposed by Bandy *et al.* (2008) who proposed that P1 was abandoned at 0.7 Ma based on the anomaly pattern along the MSS. The time of abandonment of P2 is not determinable from the magnetic data. However, P2 is most likely associated with a southward cessation of spreading along the EPR-PCS and therefore, seafloor spreading along P2 most likely ceased within the past 0.78 m.y.

Between P1 and the MAT, anomalies 3_1 to 1R are observed within the study area. Anomalies 3_1 to $2A_2$ terminate at the southern boundary of the El Gordo Graben, whereas anomalies1R and J extend undisrupted northward to the latitude of the paleo-Rivera Transform. Anomaly $2A_1$ and Anomaly 2 also appear to extend northward to 18.5°N. However, in contrast to anomalies 1R and J, anomalies 2 and $2A_1$ are disrupted, particularly in the area just west of the El Gordo Graben at 18.0°N where both anomalies exhibit a significant decrease in their magnitudes. On the north flank of this area of decreased magnitude, Anomaly $2A_1$ may be deflected westward (i.e. the crust appears to be rotated clockwise). On the south flank of this area of decreased magnitude, Anomaly 2 also appears to bend slightly westward. This pattern of disruption is consistent with the proposal of Bandy (1992) that the El Gordo Graben is the tip of a SW propagating rift situated between the Rivera and Cocos plates.

Also to the east of the EPR, Anomaly $2A_1$ exhibits a prominent westward deflection at 18.4°N where it approaches a prominent, ENE-WSW elongated, magnetic high (henceforth is termed the “Manzanillo Magnetic Lineament”). This westward bend suggests that the area of the Manzanillo Magnetic Lineament may be located within a generally east-west trending sinistral shear couple.

Consistent with previous studies (e.g. Lonsdale, 1995), the older magnetic lineations located north of the Rivera Transform, lineations $4A_1$ to $5N_2$, are deflected westward as they approach the Rivera Transform, in good agreement with the bathymetric data (Figure 4). In contrast, the new data shows that none of the lineations located east of $5N_2$ are deflected westward; instead they exhibit a slight eastward deflection as they approach the Manzanillo Magnetic Lineament. This is also observed in the bathymetric data where a difference in the seafloor morphology is observed to either side of 105.8ºW north of the Rivera Fracture Zone/

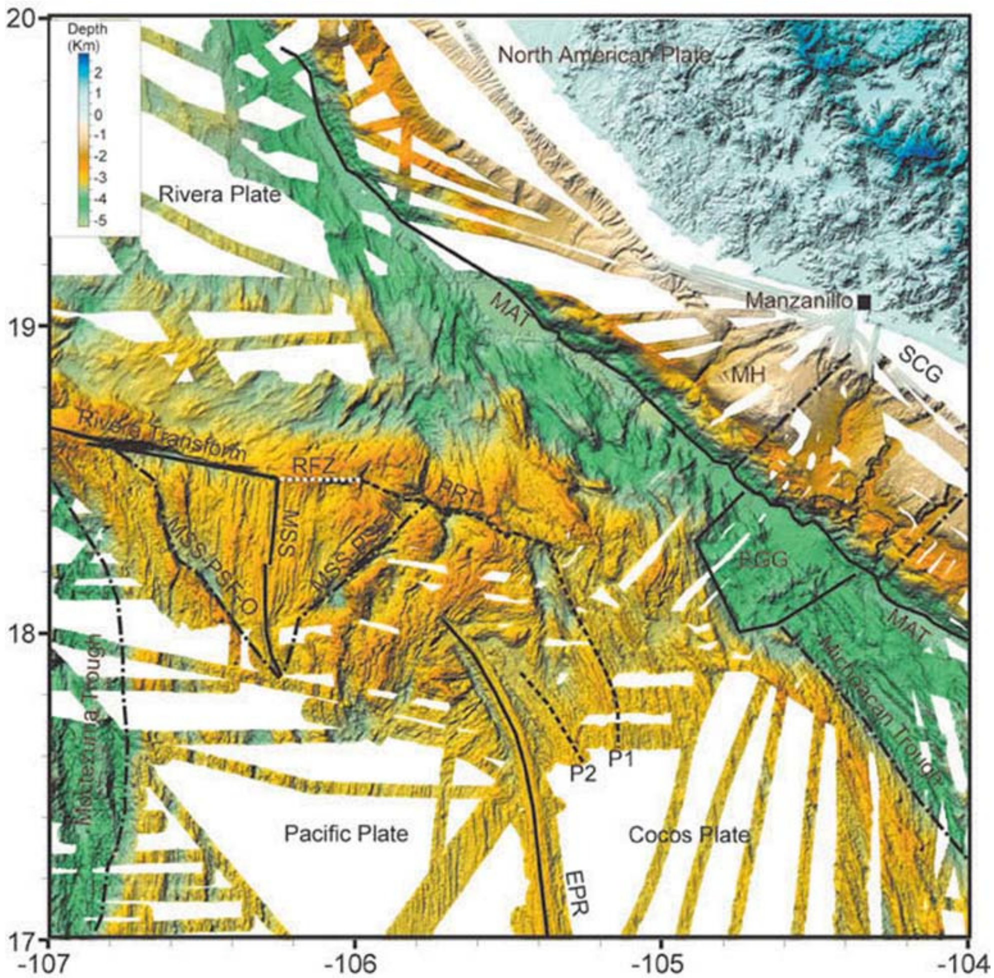

Figure 4. Principle morphotectonic elements superimposed on bathymetry. The bathymetry map was constructed using the available multibeam, including previously unpublished data from the 2002 FAMEX/BART campaigns. Abreviations are: RFZ = Rivera Fracture Zone; MH = Manzanillo horst; MSS-PSF-O = Outer Pseudo-Fault associated with the propagation of the Moctezuma Spreading Segment; MSS-PSF-I = Inner Pseudo-Fault associated with the propagation of the Moctezuma Spreading Segment; P1 y P2: relict spreading segments of the EPR. Other abbreviations are those used in Figure 1.

paleo-Rivera Transform (terminology from Bandy *et al.* (2008)). The broad positive anomaly located just east of Anomaly $5N_2$ has been tentatively identified as Anomaly 2 by Bandy (1992). This anomaly terminates against the west end of the Manzanillo Magnetic Lineament) and it intersects the MAT off Chamela, Jalisco (at 19.3°N).

The Manzanillo Magnetic Lineament consists of two ENE-WSW segments which are offset in a right-stepping manner in the trench. This lineament is aligned with the Manzanillo graben (e.g., Bandy *et al.,* 1993) and its projection is towards the port of Manzanillo. It is tempting to associate this lineament with a transform boundary between the Rivera and Cocos plates, however the lineament does not coincide with any bathymetric feature typically associated with a major transform plate boundary (Figures 4 and 6). Further, the right-stepping offset of the two segments of the lineament indicates that if it were a transform, the sense of motion would be dextral. This is in contrast to the sinistral sense of motion indicated by the deflection of Anomaly 2 across the lineament as noted above. Hence, the origin of this lineament is uncertain.

The bathymetry in this area can be divided into several morphotectonic zones (Figure 6). Several of these zones have been described in previous studies. These include: (1) zones A which are clearly formed in relation to the propagation of the EPR-PCS and MSS (Mammerickx,1984; Bandy, 1992; and Bandy *et al.,* 2008); (2) zones F (west of the Moctezuma Trough and east of the Michoacan trough) are the old crust created at the Mathematician Ridge through which the EPR propagated (Mammerickx and Klitgord, 1982;

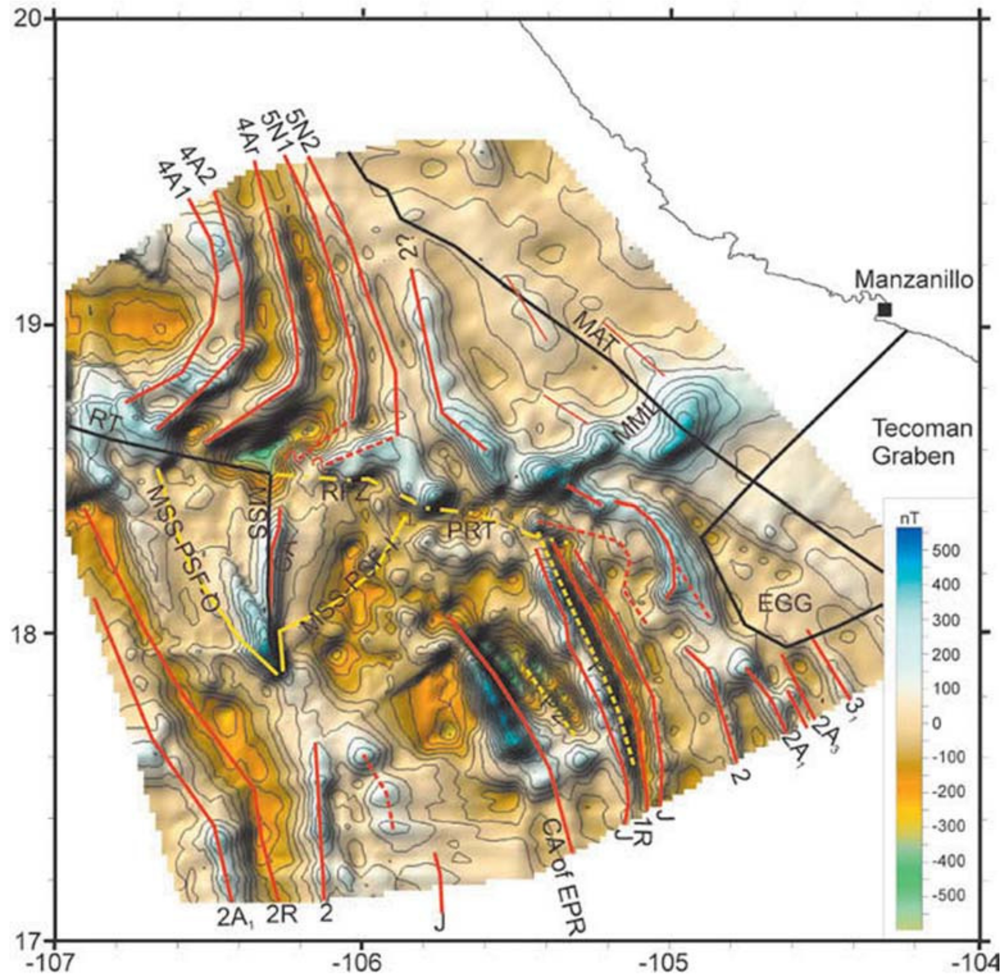

Figure 5. Magnetic anomaly map. The principle morphotectonic elements are superimposed to aid in the interpretation. Number on the lineations are the lineation identifications. MML = Manzanillo Magnetic Lineament. See figures 1 and 4 for definitions of the other abbreviations.

Klitgord and Mammerickx, 1982); and (3) Zone B is the old crust formed at the Rivera Rise which is bent westward as it approaches the Rivera Transform. This bending has been proposed to be due to shearing during the initial formation of the Rivera Transform (Lonsdale, 1995).

Several previously undiscribed morphotectonic zones can be seen in the new bathymetric map. The first of these, Zone C, confirms that the EPR-PCS has indeed propagated north of the paleo-Rivera transform as proposed by Bandy (1992). The western limit of this zone is clearly marked by a change in seafloor fabric as well as by a prominent escarpment (the tectonic pseudofault of the propagator) that is down-dropped to the east (Figure 4). The seafloor spreading fabric within zone C trends NNW-SSE and unlike the seafloor fabric in zone B to the west, the seafloor fabric does not bend westward as it approaches the paleo-Rivera Transform. This spreading fabric is cut by two short, parallel, NNE-SSW striking faults near the MAT at 19°N (Figure 4). The eastern tectonic pseudofault of Zone C is not entirely clear, but may correspond to the NNW-SSE bathymetric ridge located between -105.2° and -105.4°. The age of the seafloor within zone C on its western side (see Figure 3 for location) has been dated as 1.4 ± 0.7 Ma and 1.3 ± 0.3 Ma (Schaaf *et al*., 2009), consistent with the proposal that the broad, anomaly located east of anomaly $5N_2$ may indeed be Anomaly 2.

The new bathymetric data also indicates that the MAT in this area can be subdivided into three morphologic zones (D1, D2 and E on Figure 6). A prominent east-west oriented, down-to-the-north escarpment (for reasons ex-plained in the next section, this escarpment is called the Paleo-Transformada de Colima or the PCoT) separates zone D1 to the north from zone D2. North of the PCoT the flat trench floor widens

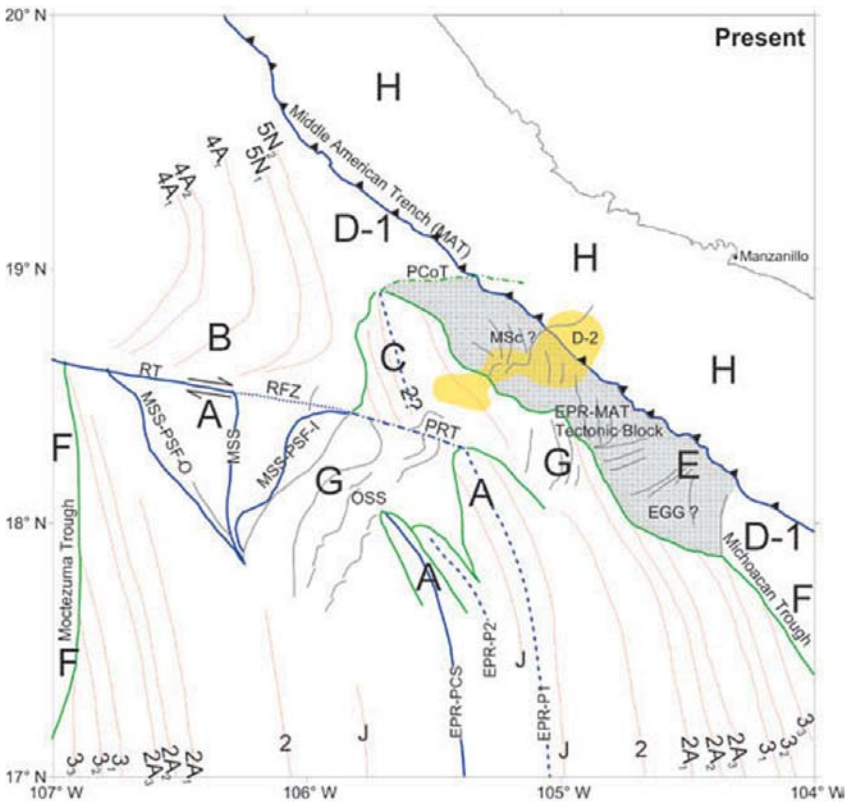

Figure 6. Magnetic anomaly lineations superimposed on a schematic representation of the different morphotectonic zones in the study area. See text for details. PCoT = Paleo-Colima Transform, OSS = Overlapping Spreading System, MSc = Manzanillo Escarpment, Morphologic zone H is the Continental Shelf. See figures 1 and 4 for definitions of the other abbreviations.

abruptly. Zone E is the El Gordo Graben area (Bourgois *et al.,* 1988) which is a zone of high heat flow (Khutorskoy *et al*., 1994) and thinned oceanic crust (Serrato–Diaz *et al.,* 2004). Zone D-2 is a previously unrecognized zone containing seamounts, fault scarps (the most prominent of which is herein referred to as the Manzanillo Escarpment) oriented perpendicular to the strike of the trench and small bathymetric ridges that rise above the sediment cover. Zones D-1 are the typical trench morphotectonic domains. The morphologic complexities of zones D-2 and E are most likely associated with deformation within the Rivera-Cocos Plate Boundary. It is also important to note that zone D-2 contains the Manzanillo Magnetic Lineation.

The part of Zone G located just west and NW of the El Gordo Graben, was first identified near the trench by Michaud *et al.* (2000). The seafloor in this zone is oriented clockwise of that exhibited by the crust formed at the EPR-PCS. Michaud *et al*. (2000) propose that this difference in reorientation may reflect older crust formed along the EPR-PCS prior to 1.5 Ma. Alternatively, it may in reflect the disruption of young crust formed at the EPR-PCS due to the SW propagation of the El Gordo Graben towards the EPR (Bandy, 1992), or more generally, to disruption related to the development of the Rivera-Cocos plate boundary.

Tectonic history of the Rivera-Cocos plate boundary

The results of this study in conjunction with the results of prior studies indicate that the complex morphology in the boundary between the Rivera and Cocos plates is the result of the effects of (1) the northward propagation of the EPR-PCS through the older, pre-existing seafloor formed at the Rivera Rise and its eventual collision with the MAT off Chamela, (2) the subsequent decapitation of the EPR-PCS during the initial formation of the Rivera Transform, (3) deformation associated with the formation of the Rivera-Cocos plate boundary, and (4) reorganizations of both the location and directions of propagation (i.e. several episodes of self-decapitation (Macdonald *et al.,* 1988) or cyclic rift failure (Wilson, 1990) and the formation of the MSS).

The new revision of the magnetic anomalies, the new age date and the new multibeam bathymetric data confirm the presence of a relict spreading center that propagated past the latitude of the El Gordo Graben terminating at the MAT (~19.2ºN) at ~1.7Ma (Figure 7). At this time the

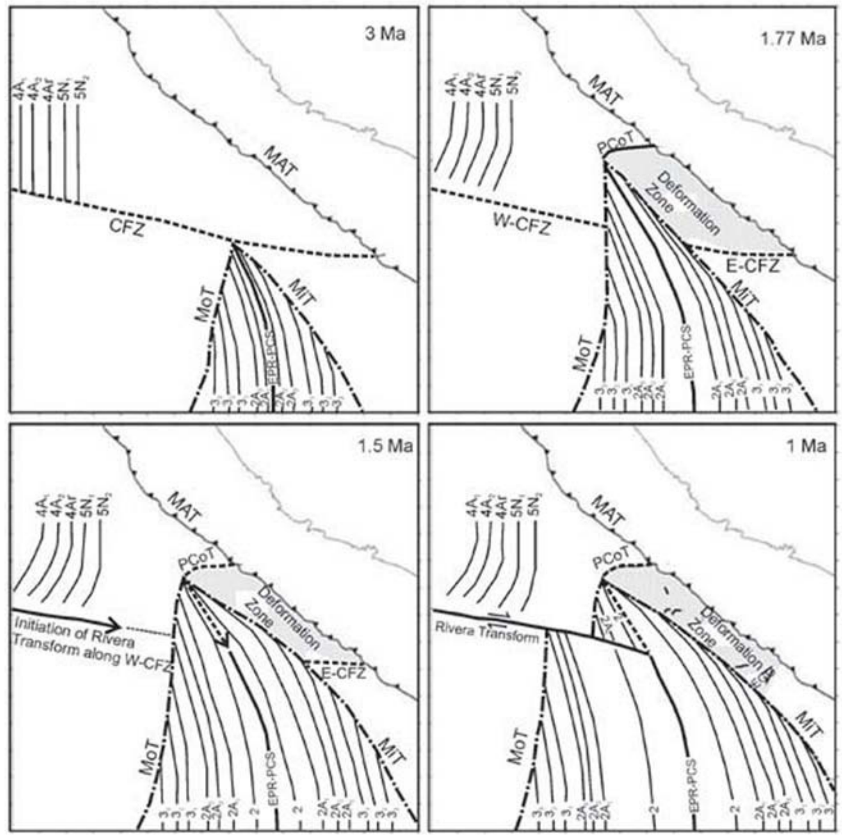

Figure 7. Schematic representations of the tectonic evolution from 3 Ma to 1.0 Ma.

PCoT may have formed in a manner proposed by Michaud *et al.* (2000). Specifically, prior to the southward cessation of spreading, the PCoT may have formed as a transform linking the tip of the EPR-PCS with the MAT. If so, the presence of the PCoT implies that a segment of the EPR has been subducted below the Jalisco margin north of Chamela (see Figure 2b). Shortly after 1.7Ma, the spreading center was abandoned perhaps as a gradual southward progressing cessation of spreading, or as an abrupt decapitation due to the formation of the Rivera Transform at 1.5 Ma.

Between 1.5 and 0.7 Ma the EPR-PCS stabilized at the present-day relict spreading center P1 and the Rivera Transform-EPR eastern junction was located at the northern tip of P1. It is very tempting to propose that the Manzanillo Magnetic Lineament was a transform boundary between the Rivera and Cocos plates during this time. However this is unclear as the western extent of this lineament lies to the north of the junction of the paleo-Rivera Transform with P1 and the morphology associated with this lineament is not convincingly that of a major plate boundary transform. Alternatively, since 1.5 Ma the area east of the decapitated EPR tip, west of the MAT, south of the PCoT and north of the inferred East Clarion Fracture Zone (E-CFZ), appears to have been broken into small crustal blocks that have been rotated and uplifted: the Manzanillo Magnetic Lineation, and its associated Manzanillo Escarpment, may be a result of this deformation.

At about 0.7 Ma the plate boundary again became unstable and the EPR-PCS once again began to retreat southward undergoing at least two episodes of self-decapitation which resulted in relict rift P1 and the present day rift tip which has recently been propagating northward and may be decapitated in the future. In conjunction with this new period of southward cessation of spreading along the EPR-PCS, the MSS has propagated southward since its inception at 0.7 Ma (Bandy, 1992; Bandy *et al.,* 2008) which has led to the present-day morphology illustrated in Figure 6.

Clearly, the present-day morphotectonic elements are not those typically observed for major transform plate boundaries, and as a result the nature of the boundary remains unclear. The deformation of the bathymetry and magnetic lineations west of the El Gordo Graben are clearly consistent with a SW propagating zone of extension between the Rivera and Cocos plates as proposed by Bandy (1992). However, this alone would not explain the strike slip focal mechanism solutions

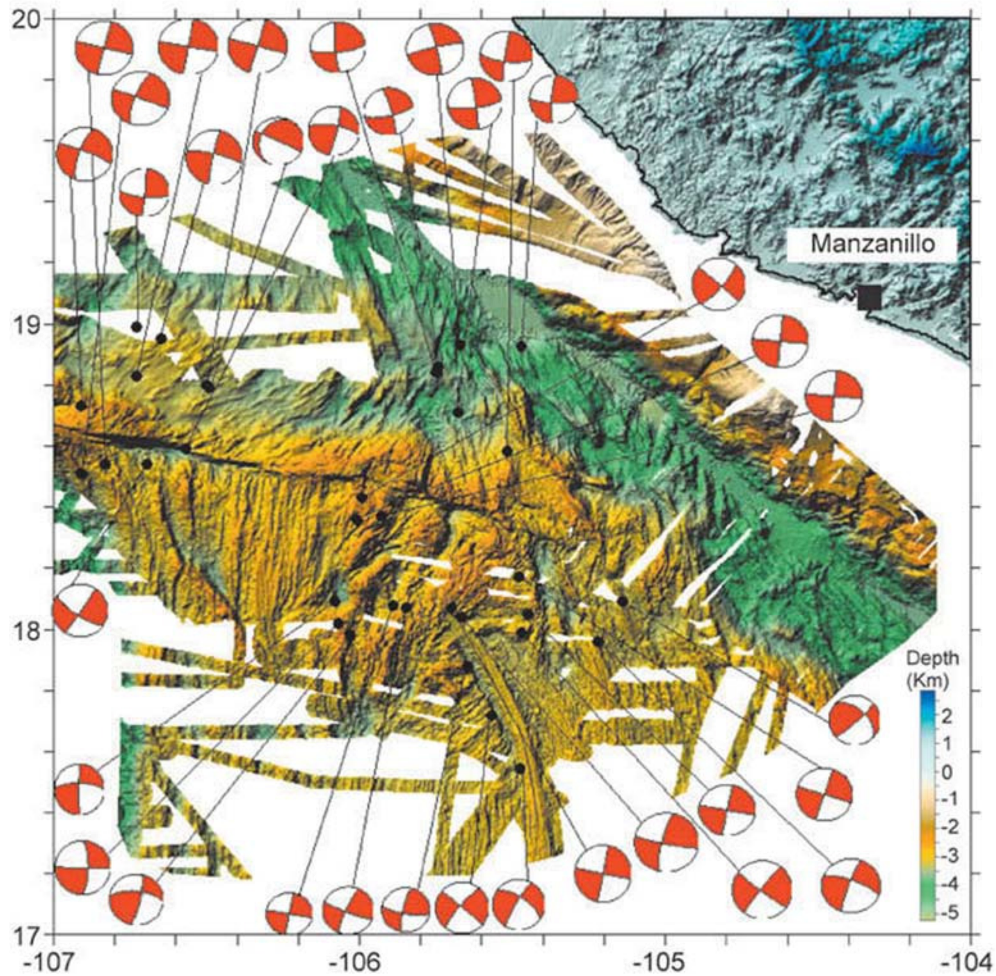

Figure 8. Earthquake Centroid Moment Tensor solutions (as of July 2007) superimposed on the new bathymetry map. Note the strike slip mechanisms within the area just seaward of the MAT. Focal mechanism solutions obtained from the USGS (http://neic.usgs.gov/neis/sopar/) and the Centroid Moment Tensor Catalogue (2007) (http://www.globalcmt.org/CMTsearch.html).

for events occurring in this region (Figure 8). Alternatively, the most prominent deviation in the magnetic lineations occurs north of the El Gordo graben, at the Manzanillo Magnetic lineament. However, the orientation of this lineament is not consistent with the orientation of the nodal planes of the focal mechanisms of earthquakes occurring in this area; this magnetic lineation does not poses a transform morphology; and it does not cut across morphotectonic zone C (i.e. it does not connect with either the MSS or with the EPR-PCS). Thus, it does not appear to be the present day boundary. Given the magnetic and morphologic signature of this area, the present day Rivera-Cocos boundary, if it exists, appears to be a broad zone of deformation, extending from the El Gordo Graben, at which it appears to be extensional, to 19°N where is appears to be subjected to either N-S or E-W oriented shear stresses.

Conclusions

The principle conclusions of this study are:

(1) The development of the Rivera-Cocos plate boundary is influenced by the evolution of the EPR-PCS and its close proximity to the MAT as well as by the formation of the Rivera Transform.

(2) A prominent high amplitude, en echelon, magnetic anomaly oriented roughly perpendicular to the MAT is observed between 18.4°N and 18.8°N. This anomaly (the Manzanillo Magnetic Lineament) consists of two, right-stepping, en-echelon segments and is aligned with the Manzanillo Trough formed within the continental slope and shelf area of the overriding North American plate. Anomaly $2A_1$ bends sharply westward as it approaches this lineament from the south indicated that it marks a crustal discontinuity.

(3) The origin of the Manzanillo Magnetic Lineament is uncertain. It connects with neither the MSS nor the active EPR-PCS, thus, it does not appear to be an active plate boundary. The lineament coincides with the Manzanillo Escarpment: however, this morphologic feature is not typical of a transform plate boundary. Thus, it does not appear to be an older, presently inactive plate boundary.

(4) The anomalies on the Rivera plate north of the Manzanillo Magnetic Lineation exhibit a slight eastward bend as they approach this lineation, in sharp contrast to lineations of the Rivera plate to the west (e.g., Anomalies $5N_2$, $5N_1$, 4Ar, etc.) which bend sharply westward as they approach the Rivera Transform/Paleo-Rivera Transform.

(5) The EPR-PCS propagated northward, past the present day location of the Rivera Transform, intersecting the MAT at about 1.7 Ma. The present day location of the ridge trench intersection is off Chamela, Jalisco at 19.2ºN.

(6) At 1.5 Ma, spreading ceased north of the present day location of the Rivera Transform, perhaps being decapitated by the formation of the Rivera Transform.

(7) Since 1.5 Ma the EPR-PCS has undergone an overall southward cessation of spreading, during which short pulses of northward ridge propagation and subsequent abandonment occurred, leaving behind several relict rift tips.

(8) The morphotectonic elements of the boundary zone do not clearly define the nature of the plate boundary, however these elements in conjunction with earthquake focal mechanisms of events occurring in the boundary zone suggest that the boundary is a broad zone where N-S extension is occurring in the southern part of this zone, whereas the northern part of the zone is dominated by shear stresses.

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