Geofísica Internacional
ISSN: 0016-7169
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Universidad Nacional Autónoma de México
México

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Geofísica Internacional, vol. 37, núm. 3, july-september, 1998, pp. 153-169
Universidad Nacional Autónoma de México
Distrito Federal, México

Geofísica Internacional (1998), Vol. 37, Num.3, pp. 153-169

Southwest migration of the instantaneous Rivera-Pacific Euler pole since 0.78 Ma

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Received: September 19, 1997; accepted: June 8, 1988.

RESUMEN

El establecer un polo/vector de Euler que describa con precisión el movimiento actual entre las placas Rivera y Pacífico ha probado ser difícil. Esto es probablemente debido al error sistemático en los datos obtenidos del movimiento y a los errores causados por una migración SW del polo de Euler Rivera-Pacífico durante varios millones de años. Una nueva estimación del polo actual Euler Rivera-Pacífico, es derivada usando sólo las más recientes estructuras batimétricas formadas a lo largo de los límites Rivera-Pacífico. Este polo de Euler (24.62° N, 105.89° W) se localiza significativamente al SW de todos los polos determinados previamente indicando una continua migración (2°) al SW del polo de Euler Rivera-Pacífico durante los últimos 0.78 Ma. Aunque muchas incertidumbres quedan por resolver, esta migración provee una explicación simple a la discrepancia entre el movimiento precalculado de las placas y (1) las direcciones de la parte oriental final de la falla transcurrente Rivera, (2) la morfología extensional de los límites Rivera-Cocos, y (3) la velocidad de movimiento RIV-NA y Cocos-Norte América a través de los límites Rivera-Cocos indicada por las relaciones sismotectónicas.

PALABRAS CLAVE: Placa Rivera, movimiento reciente de las placas, México, Graben del Colima.

ABSTRACT

Establishing an Euler pole/vector which accurately describes the present-day motion between the Rivera and Pacific plates has proved difficult. This is likely due to systematic errors in the plate motion data; errors arising from a SW migration of the Rivera-Pacific Euler pole during the past several million years. A new estimate of the present-day instantaneous Rivera-Pacific Euler pole is derived herein using only the most recently formed bathymetric features along the Rivera-Pacific boundaries. This Euler pole (24.62°N, 105.89°W) lies significantly SW of all the previous pole determinations, indicating a continued (2° or more) SW migration of the Rivera-Pacific Euler pole during the last 0.78 Ma. Although many uncertainties remain to be resolved, this migration provides a simple explanation for the discrepancies between predicted plate motions and (1) the observed azimuths of the eastern end of the Rivera transform, (2) the extensional morphology of the Rivera-Cocos boundary, and (3) the rates of RIV-NA and Cocos-North America motion across the Rivera-Cocos boundary as indicated from seismotectonic relationships.

KEY WORDS: Rivera plate, recent plate motions, Mexico, Colima Graben.

INTRODUCTION

The relative motion between the Rivera (RIV) and Pacific (PAC) plates has undergone a substantial reorientation during the past several million years [e.g., Macdonald *et al*., 1980; Lonsdale, 1989, 1995], which can be described by a southwest migration of the RIV-PAC Euler pole. This reorientation has introduced systematic errors [Bandy, 1992; Bandy and Pardo, 1994] into the data used in previous determinations of the present-day RIV-PAC Euler pole/vector, resulting in a wide variety (Figure 1) of plate motion models [Minster and Jordan, 1979; Klitgord and Mammerickx, 1982; Ness *et al*., 1985; Bandy and Yan, 1989; DeMets and Stein, 1990; Bandy, 1992; Lonsdale, 1995; DeMets and Wilson, 1997]. However, these models all fail to predict RIV-PAC relative motion parallel to the present-day azimuths of the eastern end of the Rivera transform near the Moctezuma Spreading segment (MSS) [Michaud *et al*., 1997]. Consequently, these models fail to accurately describe present-day RIV-PAC relative motion. The most likely reason for this failure is that the models do not fully account for the effects of the continuance of SW migration of the RIV-PAC Euler pole since 0.78 Ma.

The purposes of the present study are: (1) to estimate the present-day RIV-PAC Euler pole using only the most recently formed structures along the RIV-PAC boundaries for which sufficient data exists for an accurate determination of their orientations, (2) to assess, using this pole, the extent to which the Rivera-Pacific Euler pole has continued its SW migration during the past 0.78 Ma, (3) to determine an acceptable model for the SW migration during the past 0.78 Ma, and (4) to examine whether this model can be used to resolve several discrepancies between predicted plate motions and the morphologic features and seismotectonic relationships existing along the Rivera plate boundaries.

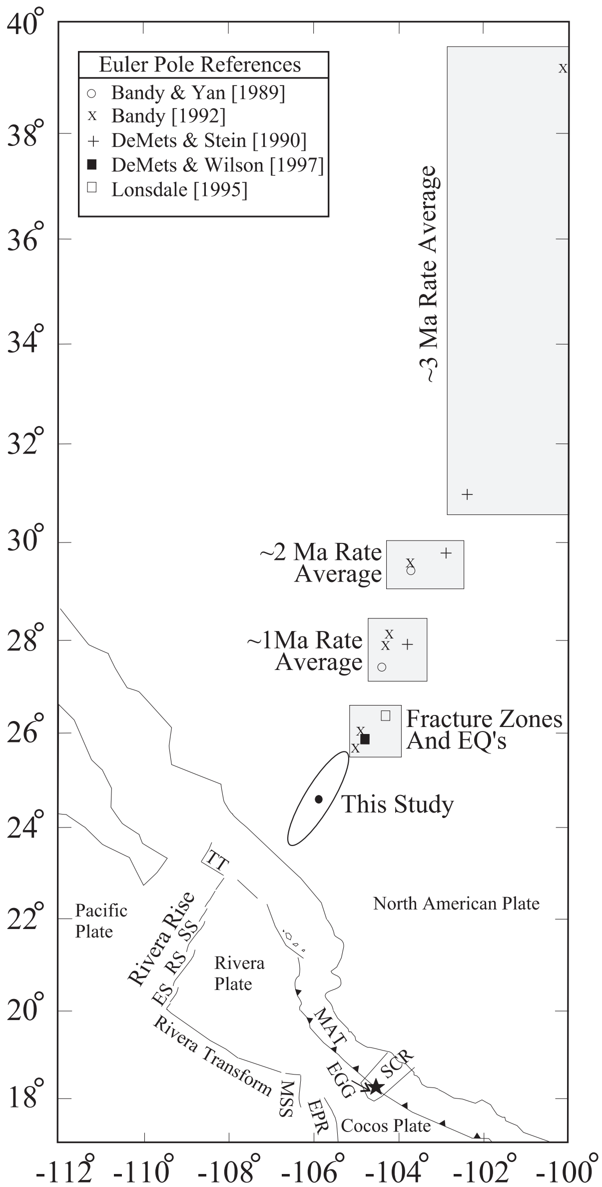

Fig. 1. Estimates of the present-day Rivera-Pacific Euler pole. The Rivera-Pacific Euler pole determined in the present study is marked by a solid circle. The ellipse about this point is the formal 95% confidence region determined from the inversion. See legend for references and symbols of the previous Euler poles. The solid star at the intersection of the El Gordo graben (EGG) and the Middle America trench (MAT) marks the location of the velocity vector diagrams shown in Figure 10. Other abbreviations are TT, Tamayo transform; EPR, East Pacific rise; ES, Elenerth segment; RS, Rise segment; SS, Shield segment; SCR, southern Colima rift; MSS, Moctezuma Spreading Segment.

The results indicate that the most recently formed structural elements comprising the RIV-PAC plate boundaries are best fit by the motions predicted from a RIV-PAC Euler pole located at 24.62°N, 105.89°W, significantly SW of all previous pole determinations. Thus, the RIV-PAC Euler pole appears to have undergone a significant (2° or more) SW migration during the past 0.78 Ma. The migration model developed herein provides a simple explanation for several discrepancies noted between the predictions of previous plate motion models and morphologic and seismotectonic observations along the RIV plate boundaries.

EVIDENCE FOR THE SW MIGRATION OF THE RIV-PAC EULER POLE

A SW migration of the RIV-PAC Euler pole prior to 0.78 Ma is clearly documented in the magnetic lineations and morphology along the boundaries between the RIV and PAC plates [Macdonald *et al*., 1980; Bourgois *et al*., 1988; Lonsdale, 1989; Bandy and Yan, 1989; Mammerickx and Carmichael, 1989; Michaud *et al*., 1990; DeMets and Stein, 1990; Bourgois and Michaud, 1991; Bandy, 1992; Lonsdale, 1995]. Specifically, an increase in spreading rates, an increase in the along-strike gradient of spreading rates, and a clockwise reorientation of the ridge axes (~22° at the Rise segment of the Rivera Rise, Figure 2) are observed along the Rivera Rise (that part of the RIV-PAC spreading center located between the Rivera and Tamayo transforms). Further, a westward relocation of the EPR and a 19° to 27° counterclockwise reorientation of the Rivera transform (Figure 3) are observed at the eastern end of the Rivera transform (near 106°W).

The continued SW migration of the RIV-PAC Euler pole during the last 0.78 Ma is less well defined. However, the clockwise rotation of the axes of the Rivera Rise relative to the strike of the edge of the Central Anomaly to either side of the Rivera Rise (Figure 2), as well as the counterclockwise reorientation of the azimuth of the eastern end of the Rivera transform as it approaches the MSS (Figure 3), indicate that the southwest migration of the RIV-PAC Euler pole has continued into the time period 0 to 0.78 Ma.

PRESENT-DAY, RIV-PAC RELATIVE MOTION MODELS

Several different models exist for the motion of the Rivera plate relative to the Pacific plate. The differences between these models can be attributed to systematic errors introduced into much of the data commonly used to determine present-day plate motions by the SW migration of the RIV-PAC Euler pole (i.e., these models are biased estimates of the present-day RIV-PAC Euler pole).

This is clearly indicated in early studies [Bandy and Yan, 1989; DeMets and Stein, 1990; Bandy, 1992]. These

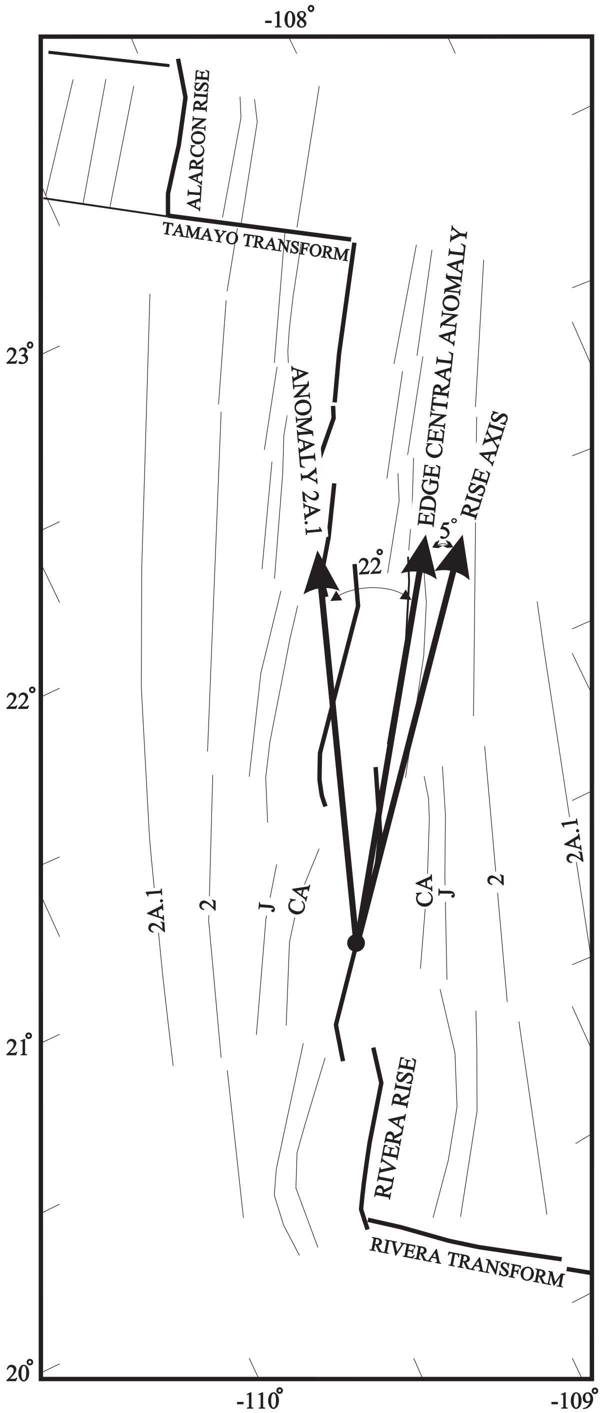

Fig. 2. Magnetic anomaly lineations across the Rivera Rise. Bold arrows illustrate the amounts of clockwise rotation of the Rise segment of the Rivera Rise as determined from magnetic anomaly lineations. Lineations after Lonsdale [1995].

studies employed least squares inversion methods [e.g. Minster *et al*., 1974] wherein plate motion directions were determined both from the morphology of the Rivera transform and earthquake slip vectors located along the Rivera transform; average spreading rates were determined from the separation of magnetic anomaly lineations across the Rivera Rise. The results of these studies indicated that the calculated present-day RIV-PAC Euler poles are shifted northeastward of its probable correct position (Figure 1), the amount of the shift depending on the length of time over which the rates were averaged. Specifically, spreading rates determined using the separation of Anomaly 2A (~3 Ma averaged rates) across the Rivera Rise yielded poles located NE of those calculated using the separation of Anomaly 2 (~2 Ma averaged rates). Similarly, the poles calculated using the separation of Anomaly 2 were located NE of those determined using the separation of anomalies J, 1R and the edge of the Central Anomaly (~1 Ma averaged rates). In each study, all pole determinations incorporated identical earthquake slip vectors and transform azimuths; thus, the differences between the Euler poles are due to increases in the along-strike gradient of the separation between magnetic anomaly lineations across the Rivera Rise [Bandy, 1992]. In other words, there has been a continuous increase of the along-strike gradient of spreading rates along the Rivera Rise, indicating a SW migration of the RIV-PAC Euler pole. This increase has introduced systematic errors into the data used to establish the present-day RIV-PAC Euler pole, resulting in biased estimates of the pole.

In several present-day RIV-PAC relative plate motion models, present-day spreading rates were calculated from the separation of the edge of the central anomaly across the Rivera-Rise [Bandy and Yan, 1989; DeMets and Stein, 1990; Bandy, 1992; Lonsdale, 1995; DeMets and Wilson, 1997]. Although the increase in the gradient of spreading rates along the Rivera Rise prior to 0.78 Ma is clear, determining whether this increase has continued during the past 0.78 Ma is not possible solely from magnetic anomaly lineations. However, as mentioned above, morphologic observations suggest that the SW migration of the Euler pole has continued during the past 0.78 Ma. If so, these models of present-day RIV-PAC motion are similarly biased. Evidence that these models are indeed biased is provided by the fact that the RIV-PAC relative motions predicted by these models misfit by ~7° the orientation of the eastern end of the Rivera Transform (Figure 4).

Two other studies [Bandy, 1992; Lonsdale, 1995] determined present-day RIV-PAC Euler poles by methods which excluded the rate data determined from the separation of the magnetic anomaly lineations across the Rivera Rise, thus avoiding the systematic errors introduced into the rate data by the southwest migration of the RIV-PAC Euler pole. These methods determined the Euler pole (1) solely from the curvature of the gross morphology of all the segments comprising the Rivera transform [Lonsdale, 1995], (2) solely from earthquake slip vectors along the entire Rivera transform [Bandy, 1992], and (3) from a combination of earthquake slip vectors along the entire Rivera transform and the azimuth of

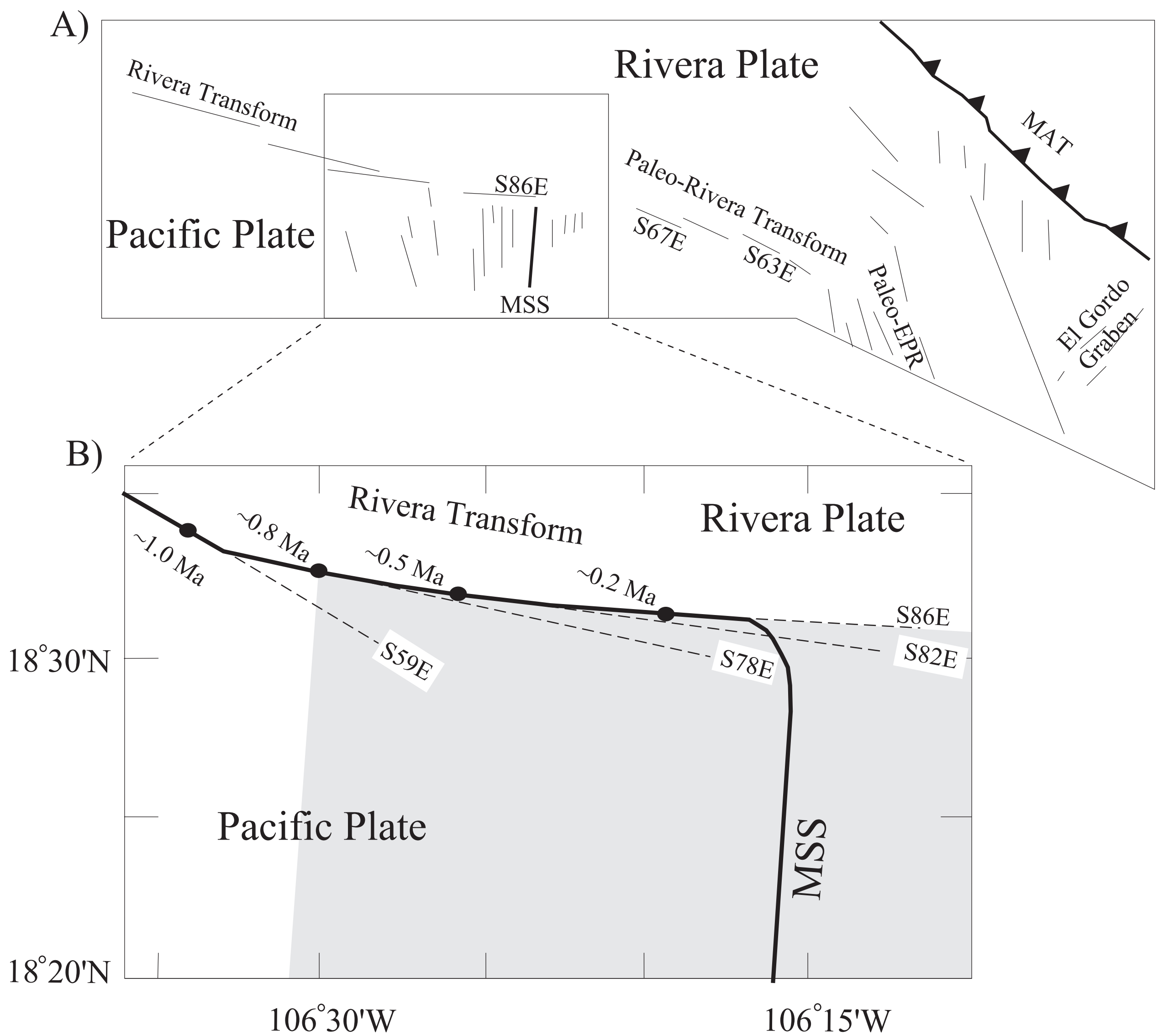

Fig. 3. Line drawing representation of the orientations of the morphologic features at the eastern end of the Rivera transform. Illustrated are the westward relocation of the EPR and the recent counterclockwise reorientation of the Rivera transform as it approaches the Moctezuma spreading segment (MSS). Labels on dashed lines are the direction of the tangents to the Rivera transform at the positions marked by the solid circles. Ages adjacent to solid circles represent the ages of the Pacific Plate immediately south of the transform. These ages were determined from magnetic anomaly lineations and by assuming a constant spreading rate at the MSS since 0.78 Ma. Original bathymetric maps from which the line drawing interpretation was determined are from Bourgois *et al*. [1988] and Michaud *et al*. [1996].

the Rivera transform at selected locations [Bandy, 1992]. As expected, these methods yielded RIV-PAC Euler poles located further to the SW than the earlier methods (Figure 1). Consequently, these poles appeared to reflect more accurately the location of the present-day RIV-PAC Euler pole. However, as recently pointed out [Michaud *et al*., 1997], the motions predicted by these poles do not provide an acceptable fit (Figure 4) to the orientation of the Rivera transform near its intersection with the MSS (located at 106.25°W). Thus, it appears that even the transform and earthquake data yield biased estimates of present-day RIV-PAC relative motions.

In summary, the RIV-PAC Euler pole has been migrating SW during the past several million years. This migration has introduced systematic errors into much of the data commonly used to determine present-day plate motions, resulting in biased estimates of the present-day RIV-PAC Euler pole.

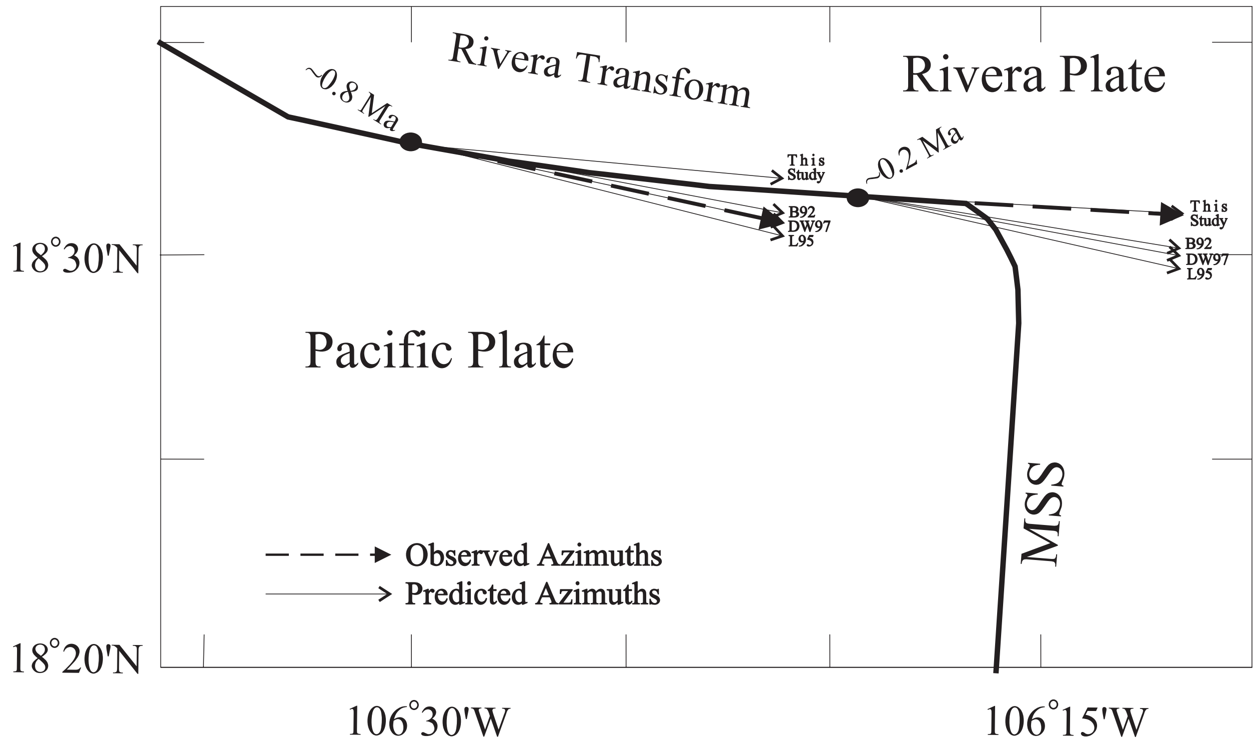

Fig. 4. Comparison of the azimuths of the Rivera transform versus predicted azimuths of RIV-PAC relative motion at the eastern end of the Rivera transform. Bold dashed arrows represent the tangents to the Rivera transform at the locations marked by solid circles. Labeled, thin, solid arrows indicate the azimuths of RIV-PAC relative motion predicted by the RIV-PAC Euler vectors of this study, Bandy [1992] (B92), DeMets and Wilson [1997] (DW97), and Lonsdale [1995] (L95). See text for discussion.

NW MIGRATION OF THE PAC-COCOS EULER POLE

Of importance to the discussion of RIV-Cocos relative motion presented later is the change in the relative motion between the Pacific and Cocos plates indicated by the morphologic features comprising the Pacific-Cocos spreading center [Fox *et al*., 1988; Perram and Macdonald, 1990; Carbotte and Macdonald, 1992, 1994; Macdonald *et al*., 1992; Alexander and Macdonald, 1996; Pockalny *et al*., 1997]. These features indicate that Pacific-Cocos relative motion has reoriented up to 9° counterclockwise since about 2.5 Ma; with 5° of counterclockwise rotation occurring since 0.5 Ma. Further, PAC-Cocos stage poles [Macdonald *et al*., 1992; Pockalny *et al*., 1997] indicate that the PAC-Cocos Euler pole has been migrating NW during at least the past 1.5 Ma (Figure 5).

Pockalny *et al*. [1997] found that a single present-day PAC-Cocos Euler pole could not describe the recent morphology of both the Clipperton and Siqueiros transforms. Consequently, two present-day PAC-Cocos Euler pole models were developed; one from the morphology of the Clipperton transform (herein, the 'Clipperton' model) and one from the morphology of the Siqueiros Transform (herein, the 'Siqueiros' model). However, both models still indicate a NW migration of the PAC-Cocos Euler pole during the past 0.78 Ma (Figure 5).

A question of importance in developing present-day relative plate motion models for the RIV-Cocos and RIV-PAC plate pairs is whether ridge segments reorient rapidly to changing plate motions. In other words, does spreading remain orthogonal to the strike of ridge axes during times of plate motion changes? Macdonald *et al*. [1992] proposed that the two longer first-order segments (the Clipperton to Orozco and the 2°N to Siqueiros segments) of the PAC-Cocos spreading center have adjusted rapidly to the recent change in PAC-Cocos plate motion, and are thus aligned normal to the direction of present-day PAC-Cocos relative motion. However, of the two models proposed by Pockalny *et al*. [1997], only the Clipperton model predicts present-day PAC-Cocos motions which are normal to the strike of these two rise segments; the Siqueiros model misfits the ridge-normal direction at these two rise segments by 3° to 4° in a counterclockwise sense (Table 1). Thus, either the Siqueiros

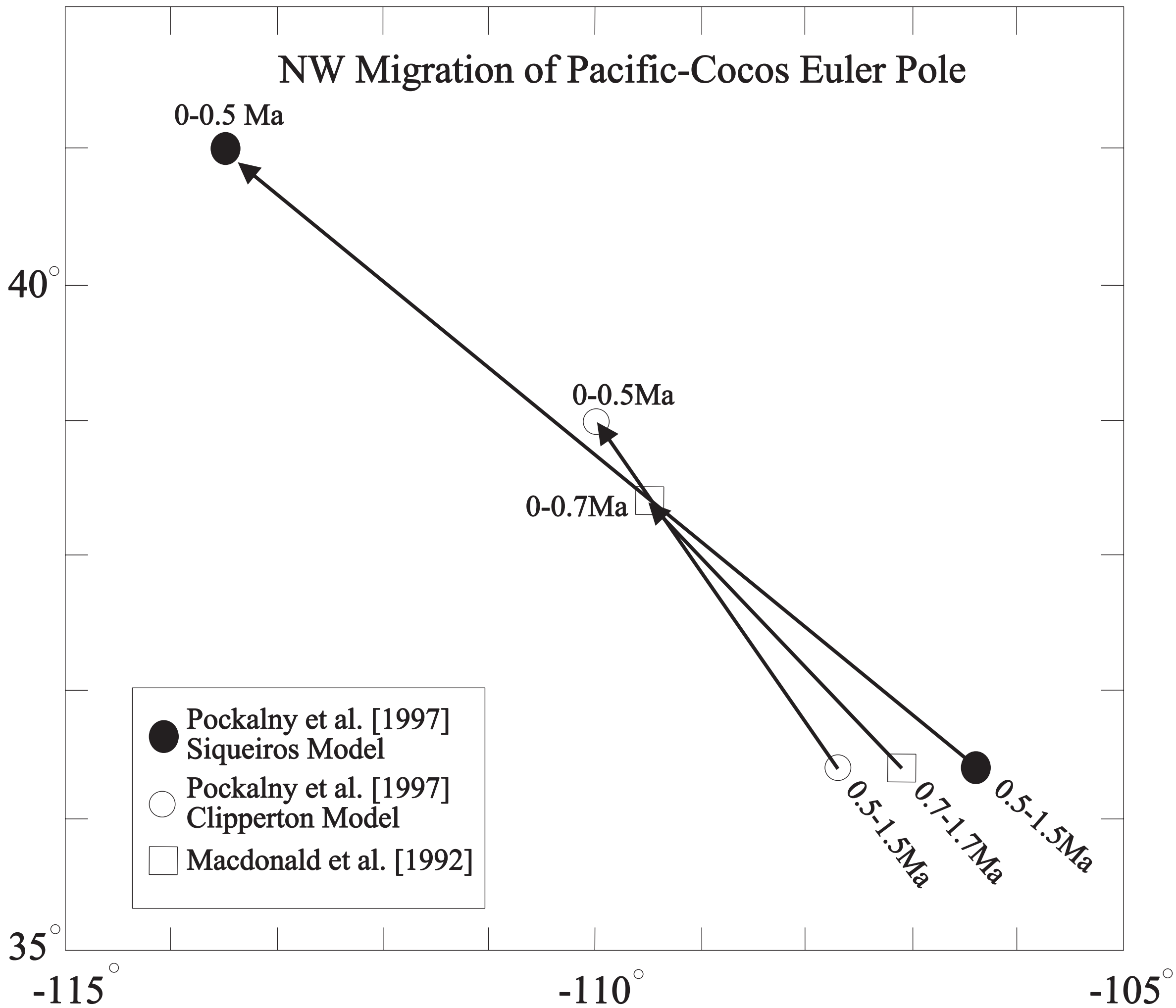

Fig. 5. NW migration of the PAC-Cocos Euler pole since 1.5 Ma. See inset for model references.

Table 1

Relative Plate Motion Directions Predicted by the Present-day Pacific-Cocos Euler Poles of Pockalny *et al.* [1997]

EPR Segment	Latitude (°N)	Longitude (°W)	Clipperton Model	Siqueiros Model	Observed Ridge-Normal Direction
Orozco-Rivera	17.0	105.35	N81°E	N75°E	N82°E ±1°
Clipperton-Orozco	14.0	104.20	N80°E	N75°E	N79°E ±1°
2°N – Siqueiros	7.0	102.75	N80°E	N76°E	N79°E ±1°

model is flawed or spreading is currently non-orthogonal at the two rise segments. If the second possibility is correct, then the Siqueiros model indicates that there may be a significant lag time between a change in the Euler pole and the consequent adjustment of the rise axes to this change. Thus, the question of the response time of ridge reorientation to plate motion changes remains uncertain, and it affects the degree of confidence which can be ascribed to present-day RIV-PAC, RIV-Cocos and PAC-Cocos plate motion determinations.

DATA AND METHODS

RIV-PAC Euler pole

Presently, the following data types exist from which to select: (1) the separation of magnetic lineations across the Rivera Rise, (2) the azimuth of the Rivera transform as determined from its gross scale morphology (i.e. as determined from conventional wide-beam echo-soundings), (3) the earthquake slip vectors along the entire Rivera transform, (4) the azimuth of the Rivera transform as determined from high-resolution bathymetric data, (5) the strikes of the ridge segments comprising the Rivera Rise, and (6) slip vectors of earthquakes occurring along the Rivera transform near the MSS and the Rivera Rise.

From the results of previous studies the first three data types are suspect and should not be used to determine the present-day RIV-PAC Euler pole without first removing the systematic errors. Since a method for determining and removing systematic errors from the first three data types is not readily apparent, these data are not included in our study.

The fourth data type is appropriate. Presently, dense, high-resolution bathymetric coverage from which present-day RIV-PAC motion directions can be reliably determined are available in the literature only at the eastern and western ends of the Rivera Transform. Isolated Seabeam tracks crossing the central part of the Rivera transform have been presented [Michaud *et al*., 1997]. However, these data are of insufficient density and lack the horizontal resolution needed to reliably determine the fine scale topographic features within the central part of the Rivera transform, features from which the present-day directions of RIV-Pacific relative motion might reliably be determined.

The fifth data type may be appropriate if spreading is currently orthogonal to the rise axes. Orthogonal spreading is indicated at the Rivera Rise by the observation that the strike of the Elenerth segment of the Rivera Rise (Figure 1) is nearly perpendicular to the direction of the Rivera transform near its intersection with the Rivera Rise [Lonsdale, 1995; Michaud *et al*., 1997]. However, it is possible that spreading is non-orthogonal; the implications of which are addressed in the discussion section.

The sixth data type may be appropriate, however, none are included in our pole determination for the following reasons. First, no focal mechanisms have been reported for events along the segment of the Rivera transform adjacent to the MSS. Second, although several events exist along the Rivera transform near the Rivera Rise, the slip vectors of these events are highly scattered [Michaud *et al*., 1997] and their epicentral locations are not well constrained. Like previous investigators (e.g., Minster *et al*. [1974]), we attribute this scatter and consequent unreliability to complications in Earth structure near the spreading center. Third, it has been proposed that, in general, the use of earthquake slip vectors along transform faults may be inappropriate, perhaps due to a systematic bias related to an anomalous thermal structure of the lithosphere and sublithosphere near transforms [Argus *et al*., 1989; Gordon, 1995].

Therefore, we include in our data base (Table 2) (1) the azimuth of the Rivera transform segment just west of the MSS (between 106.3°W and 106.4°W), (2) the azimuth of the Rivera transform segment near its intersection with the Rivera Rise (between 109.35°W and 109.45°W), and (3) the directions normal to the strike of the Shield, Rise and Elenerth segments of the Rivera Rise. The azimuth of the Rivera transform just west of the MSS is determined from the Seabeam bathymetric data of Michaud *et al*., [1996]. The remaining data is determined from the various detailed bathymetric maps presented in Lonsdale [1995]. No data was chosen along the Rivera Rise north of 22°N as this region may not represent a boundary between the PAC plate and a rigid RIV plate [Lonsdale, 1995; DeMets and Wilson, 1997]. Our picks of the azimuths of the Rivera transform at its eastern and western end are slightly different than those presented by Michaud *et al*. [1996, 1997], who determined a S85°E and S54°E orientation for the eastern and western ends, respectively. However, as presented in the next section, using either our picks or those of Michaud *et al*. [1996, 1997] produce almost identical results.

This data base is used in the plate motion inversion method of Minster *et al*. [1974] to determine the best-fit estimate of the present-day RIV-PAC Euler pole and the formal uncertainties in its location. Uncertainties, used as weights in the inversion, of 3° were assigned both to the ridge-normal directions of the spreading segments comprising the Rivera Rise and to the azimuth of the Rivera transform near its intersection with the Rivera Rise. A 2° uncertainty was assigned to the azimuth of the Rivera transform near its intersection with the MSS which has almost full seabeam coverage (GPS navigated). These uncertainties are subjective, based on the perceived data quality.

0.78 Ma to 0.0 Ma RIV-PAC SW Migration Model

The data used to derive the model of the SW migration of the RIV-PAC Euler pole since 0.78 Ma consists of morphologic data along the Rivera Rise [Lonsdale, 1995]

Table 2

Pacific-Rivera Data Base and Inversion Statistics

Lat. (°N)	Long. (°W)	Datum (°)	S.D. (°)	Model (°)	Residual (°)	Importance	Reference
18.53	106.37	S86E	2.0	S86E	0.1	0.979	RT near MSS
21.73	108.72	S49E	3.0	S49E	0.4	0.444	Shield Segment
20.23	109.33	S52E	3.0	S55E	-2.7	0.171	Elenerth Segment
20.97	109.00	S54E	3.0	S52E	1.5	0.255	Rise Segment
19.98	109.38	S56E	3.0	S56E	0.2	0.151	RT near Rivera Rise

S.D. is the subjectively assigned data uncertainties.
RT is the Rivera transform.
Residual = Datum - Model.

and the eastern end of the Rivera transform [Michaud *et al*., 1996]. The model is constructed by subdividing what was most likely a continuous SW migration into three discrete periods of constant plate motion centered on 0.78 Ma, 0.5 Ma and the present. An Euler pole is determined for each time period.

The present day RIV-PAC Euler pole of this model is taken to be the one which best fits the most recently formed features comprising the boundaries of the Rivera plate. The method and data used is outlined in the previous section.

The other two poles are chosen so as to account for the observed amount of counterclockwise reorientation of the azimuth of the Rivera transform as it approaches the MSS (Figure 3), as well as the ~5° of clockwise reorientation of RIV-PAC relative motion at the Rivera Rise during the past 0.78 Ma (Figure 2). Specifically, the present location of the pole which was active at 0.78 Ma is determined as the one (1) which fits the present-day orientation of the Rivera transform at its eastern end where the age of the crust immediately south of the transform is 0.78 Ma, and (2) which predicts, relative to the present-day pole, a 5° clockwise reorientation of RIV-PAC relative motion at the Rise segment of the Rivera Rise. The present location of the pole which was active at 0.5 Ma is determined as the one (1) which fits the present-day orientation of the Rivera transform at its eastern end where the age of the crust immediately south of the transform is 0.5 Ma, and (2) which lies between the 0.78 Ma pole and the present-day pole.

RESULTS

Present-day RIV-PAC Euler Pole

The best-fit estimate of the present-day RIV-PAC Euler pole lies at 24.62°N, 105.89°W (Figure 1). The length of the semimajor axis of the 95% confidence ellipse is 1.16°; the length of the semiminor axis is 0.31°; and the azimuth of the semimajor axis is N31.2°E. [Note: employing the previously mentioned values of the azimuths of the Rivera transform determined by Michaud *et al*., [1996, 1997] results in a pole located at 24.73°N, 105.75°W; semimajor axis, 1.21°; semiminor axis, 0.32°; azimuth of semimajor axis, 31.5°]. The directions of predicted RIV-PAC motion (Table 2) misfit (1) the Rivera transform near its intersection of the MSS by only 0.1°, (2) the Rivera transform near its intersection with the Rivera Rise by 0.2°, (3) the Shield segment by 0.4°, (4) the Rise segment by 1.5° and (5) the Elenerth segment by -2.7°. A negative misfit indicates that the predicted value is counterclockwise of the observed value. These differences lie within the subjective uncertainties which were assigned to the data.

The data importances (see Minster *et al*. [1974] for explanation) indicate that our model depends heavily on the well-surveyed azimuth of the Rivera transform segment adjacent to the MSS and, to a lesser degree, the orientation of the Shield and Rise segments of the Rivera Rise (Table 2). The model is relatively insensitive (or robust) both to the orientation of the Elenerth segment and the azimuth of the Rivera transform segment near the Rivera Rise.

0.78 Ma to 0.0 Ma RIV-PAC SW Migration Model

The model of the SW migration of the RIV-PAC Euler pole since 0.78 Ma which satisfies the previously mentioned constraints consists of the following poles: the pole active at present is represented by the newly determined present-day RIV-PAC Euler pole; the present location of the pole which was active at 0.5 Ma is 25.25°N, 105.32°W; and the present location of the pole which was active at 0.78 Ma is 27.11°N, 104.48°W (Figure 6).

Each pole predicts a direction of Rivera-Pacific relative motion which fits to within 0.5° the present-day orientation

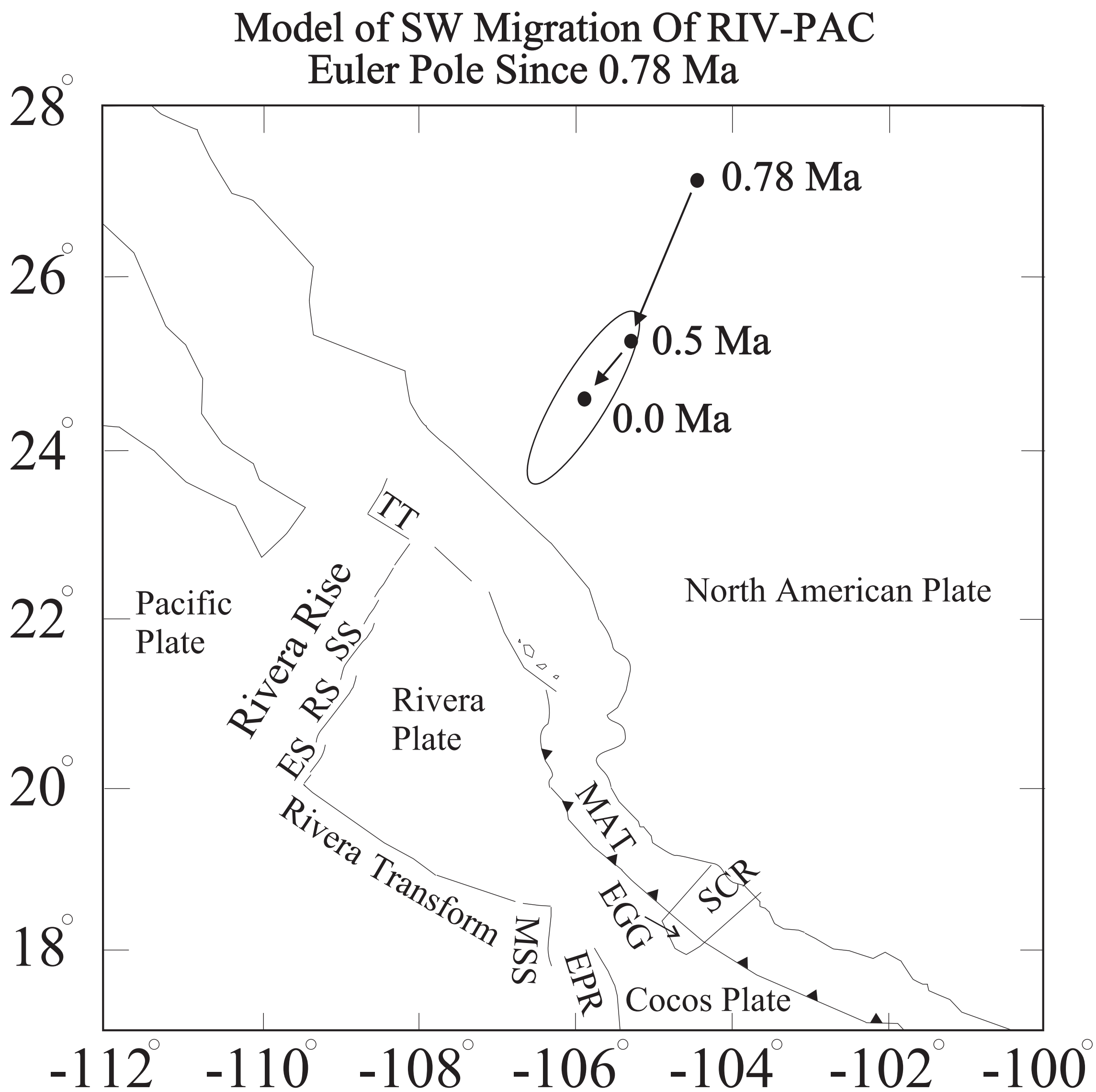

Fig. 6. SW migration model of the RIV-PAC Euler pole since 0.78 Ma. See caption Figure 1 for definition of abbreviations.

of the Rivera transform at its eastern end where the age of the crust immediately south of the transform corresponds to the age of the pole. Further, the 0.78 Ma and the present-day poles predict a direction of motion of the Rivera plate with respect to the Pacific plate of S57°E and S52°E, respectively. Thus, the SW migration model predicts the observed 5° clockwise reorientation of the Rivera Rise since 0.78 Ma.

DISCUSSION

Present-day RIV-PAC Euler Pole

The results indicate that the most recently formed bathymetric features located along the RIV-PAC boundaries, particularly the critical azimuth of the eastern end of the Rivera transform adjacent to the MSS, are best fit by an Euler pole located several degrees SW of previous determinations. However, it is possible that the pole may be located further SW. Specifically, we have assumed that the morphologic features along the RIV-PAC boundaries rapidly adjust to changes in plate motion (i.e., it is assumed that the direction of seafloor spreading remains orthogonal during plate motion changes). Rapid adjustment to plate motion changes has been proposed for the longer, first-order rise segments [e.g., Macdonald *et al*., 1972] and transtensional transforms [Pockalny *et al*., 1997] along the Pacific-Cocos spreading center. However, the misfits (Table 2) of the observed and predicted orientation of the southernmost two segments of the Rivera Rise, although within the assigned uncertainties, suggest that a rapid adjustment may not be the case for the shorter spreading axes comprising the Rivera Rise. Also, the Siqueiros PAC-Cocos model of Pockalny *et al*. [1997] suggests that such a rapid readjustment may not be the case even for the PAC-Cocos spreading center. Thus, if spreading is indeed non-orthogonal at the Rivera Rise, the present-day RIV-PAC Euler pole may lie further SW than the newly estimated, present-day, RIV-PAC Euler pole.

Regardless, the results, along with the observed clockwise rotation of the axes of the Rivera Rise during the past 0.78 Ma [e.g. Lonsdale, 1995] and the counter-clockwise reorientation of the eastern end of the Rivera transform during the past 0.78 Ma [Michaud *et al*., 1996], suggest that a substantial (2° or more) southwest migration of the RIV-PAC Euler pole has occurred during the past 0.78 Ma.

A comparison between the direction of RIV-PAC motion along the Rivera transform predicted from the newly estimated RIV-PAC pole and the orientation of the gross morphology of the Rivera transform indicates that there is a direct relationship between the deep bathymetric trough and areas where a divergent component of motion is predicted, except between 106.7°W and 107.4°W (Figure 7). This relationship is consistent with the proposal of Reid [1976] that the deep transform valley results from a component of divergent RIV-PAC motion. Further, the direction of RIV-PAC relative motion predicted from the new estimate of the RIV-PAC Euler pole coincides well with the alignment of

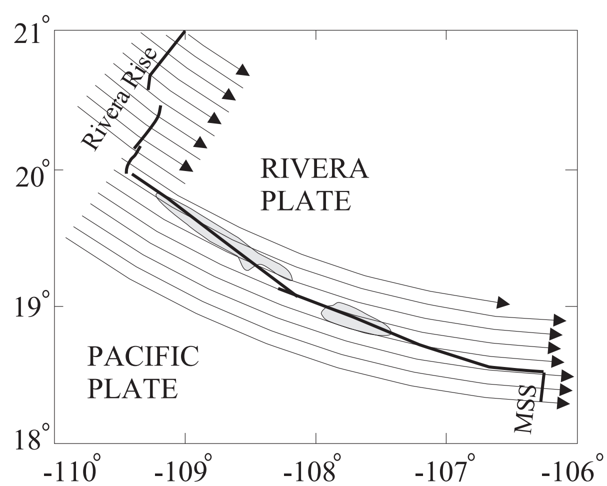

Fig. 7. Direction of motion of the Rivera plate relative to a fixed Pacific plate along the Rivera transform. The Rivera transform, MSS and Rivera Rise are marked by bold lines. The direction of motion of the Rivera plate relative to a fixed Pacific plate as predicted from the newly determined Rivera-Pacific Euler pole is marked by curved arrows. Shaded areas delineate the location of the deep bathymetric trough (depths > 4250 meters) associated with the Rivera transform (after Michaud *et al*. [1997]).

microearthquakes occurring within the Rivera Transform at 108.15°W [Reid, 1976; Prothero and Reid, 1982], a region of the Rivera Transform for which high resolution bathymetric data is lacking.

Discrepancy 1: Misfit of the orientation of the Rivera transform and predicted RIV-PAC motion

Recently published bathymetric data [Michaud *et al*., 1996] indicates that the Rivera transform undergoes a counterclockwise re-orientation as it approaches the MSS (Figure 3). Relative motions predicted by the previous Euler poles of Bandy [1992], Lonsdale [1995], and DeMets and Wilson [1997] all fit the orientation of the transform where the crustal age south of the transform is roughly 0.8 Ma (Figure 4), as well as the orientation of the Rivera transform at it western end. However, they fail to fit the transform orientation near the MSS where the crustal age south of the transform is roughly 0.2 Ma; the difference between the observed and predicted values are about 7°. Conversely, the relative motions predicted by the new Euler pole fit the more recent trend, as well as the western end of the Rivera transform, but misfit the older trend (Figure 4). In fact, a single pole cannot be found whose predicted motions both fit the curvature of the Rivera transform east of 106°33’W and which also fit the orientation of the western end of the Rivera transform.

To resolve this discrepancy, Michaud *et al*. [1997] propose that the Rivera transform does not record Rivera-Pacific relative motion. Instead, they propose that the lithosphere north of the eastern part of the Rivera transform is part of a wide, diffuse plate boundary; whereas the lithosphere north of the western part of the Rivera transform belongs to the North American plate. They base the latter, as did Larson [1972], on the similarity between the orientation of the western Rivera transform and that predicted by the PAC-NA Euler pole.

Although one cannot conclusively rule out their proposal, our results indicate that the discrepancy can be resolved by invoking a SW migration of the RIV-PAC Euler pole during the last 0.78 Ma. Specifically, our SW migration model reproduces the observed counterclockwise re-orientation of the azimuth of the Rivera transform as it approaches the MSS as well as the 5° clockwise reorientation of RIV-PAC relative motion at the Rivera Rise. The 0.78 Ma, 0.5 Ma and the present-day poles all fit the corresponding azimuths of the Rivera transform to within 0.5°. It is interesting to note that the 0.78 Ma averaged RIV-PAC finite rotation pole determined by DeMets and Wilson [1997] lies between the newly estimated present-day pole and the 0.78 Ma pole of our model, as expected if their pole represents the average RIV-PAC motion for the last 0.78 Ma.

Our proposal has one clear advantage over the proposal of Michaud *et al*. [1997]; namely, it accounts for the observed

5° clockwise rotation of the axes comprising the Rivera Rise during the past 0.78 Ma. If the Rivera Rise has been a PAC-NA boundary for the past 0.78 Ma, then one would expect that the axis of the Alarcon Rise, also a PAC-NA boundary located just north of the Tamayo Transform (Figure 2), would likewise exhibit a clockwise reorientation; however such a reorientation is not observed [Lonsdale, 1995; DeMets, 1995].

The migration model indicates that the rate of SW migration of the RIV-PAC Euler pole was about 4°/Ma from 0.78 to 0.5 Ma, and 2°/Ma since 0.5 Ma. Thus, the rate of SW migration appears to be slowing, possibly indicating that the plate reorganization which has been occurring during the past several Ma may be ending. However, we cannot rule out that the present-day RIV-PAC Euler pole may lie further to the SW than our newly determined pole. Consequently, the rate of migration might have been constant since 0.78 Ma.

Discrepancy 2: Extensional features within the area of the RIV-Cocos plate boundary where the predicted motion is compressional.

Several previously published RIV-PAC Euler vectors in conjunction with previously published PAC-Cocos Euler vectors predict as much as 2 cm/yr of N-S to NNE-SSW directed motion between the RIV and Cocos plates along the RIV-Cocos plate boundary near its intersection with the Middle America trench [Nixon, 1982; Eissler and McNally, 1984; DeMets and Stein, 1990; Lonsdale, 1995; DeMets and Wilson, 1997]. Such motion predicts compression along the NE-SW oriented El Gordo graben [Bourgois *et al*., 1988], a prominent extensional structure located along the RIV-Cocos boundary (Figure 8).

To account for this discrepancy, Bandy [1992] and

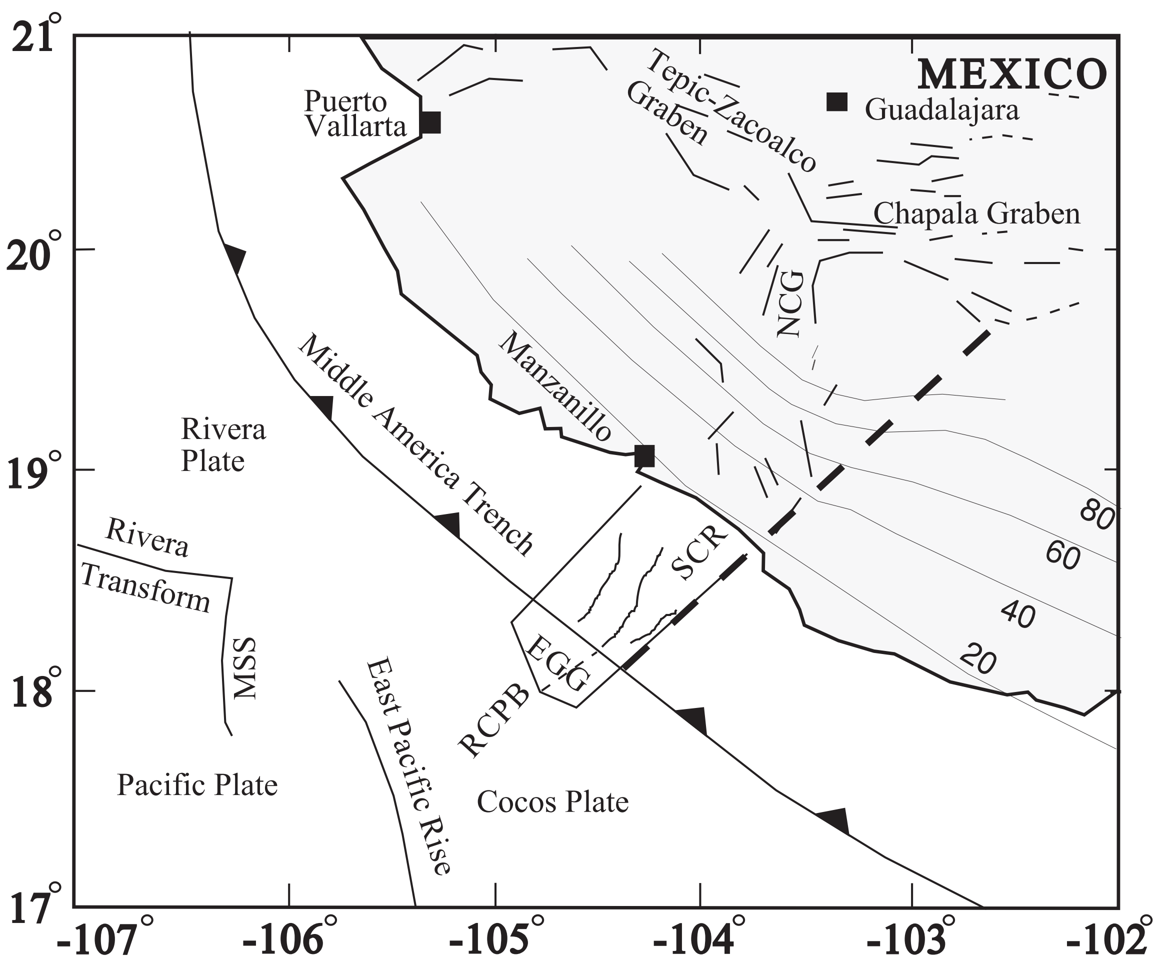

Fig. 8. Map illustrating the NE alignment of the El Gordo graben, southern Colima rift and the marked change in the depth to the top of the Wadati-Benioff zone beneath western Mexico. Contours of the depth (in Km) to the top of the Wadati-Benioff zone from Pardo and Suárez, [1993, 1995]. Bold dashed line, oriented NE-SW, marks the southern limit of the Rivera-Cocos plate boundary beneath southwest Mexico as proposed by Bandy *et al*. [1995]. Abbreviations are: NCG, northern Colima graben; SCR, southern Colima rift; EGG, El Gordo graben; RCPB, Rivera-Cocos plate boundary.

Bandy and Pardo [1994] proposed that the RIV-PAC Euler poles were biased by recent changes in the relative motion between the Rivera and Pacific plates. Thus, the motions predicted from the Euler poles were deemed unreliable, and, consequently, they proposed that the El Gordo graben was formed by recent divergence between the Rivera and Cocos plates. Further, Bandy *et al*. [1995] proposed, based on the alignment of the El Gordo Graben (located within the subducting oceanic plate), the southern Colima rift (located within the overriding continental plate) and the bend of the Wadati-Benioff zone [Pardo and Suárez, 1993, 1995], that the Rivera-Cocos plate boundary extends northeastward, beneath the North American plate, along the marked bend of the Wadati-Benioff zone (Figure 8). Also, they proposed, as did Bandy [1992], that rifting along the boundary has been progressing to the SW and that the El Gordo graben marks the SW tip of this rifting.

Conversely, DeMets and Wilson [1997], giving more weight to the plate motion data than to the morphologic data, the shape of the Wadati-Benioff zone, and the alignment of the major structural features both offshore and onshore, proposed that the predicted motion was reliable and that the motion was being accommodated across a N-S oriented, diffuse shear zone. Thus, they proposed that either the El Gordo graben is not an extensional feature, or that it is an ancient feature, or that it is only one of several features comprising the broad N-S oriented, diffuse, shear zone.

Presently, several uncertainties exist in attempting to assess whether the SW migration model can resolve this discrepancy. The first uncertainty is that, although our study yielded a possible present-day RIV-PAC Euler pole, one cannot reliably determine the present-day angular rotation rate about this pole from existing data (i.e. from marine magnetic anomaly lineations). Thus, in the following discussion we are forced to use, as was Lonsdale [1995], an average rotation rate for the past 0.78 Ma determined from the width of the central anomaly at the Rivera Rise. Specifically, the angular rotation rate about the present-day RIV-PAC Euler pole is taken to be the one which best fits the separation of the edge of the central anomaly along the Rivera Rise, keeping the location of the Euler pole fixed at that of the newly estimated present-day RIV-PAC pole. The angular rotation rate is 6.45°/Ma. The angular rotation rate about the 0.5 and 0.78 Ma poles of our SW migration model are likewise calculated to be 5.56°/Ma and 4.18°/Ma, respectively. Unfortunately, it is impossible to assign any meaningful uncertainties to these rates.

The second uncertainty is that there exists several models for the relative motion between the PAC and Cocos plates since 0.78 Ma. DeMets and Wilson [1997] assume that the relative motion between the PAC-Cocos plates during the past 0.78 Ma is adequately represented by a single pole. In contrast, Pockalny *et al*. [1997] proposed two different models which describe the PAC-Cocos relative motion occurring since 0.78 Ma (the previously mentioned Siqueiros and Clipperton models). Consequently, in the following analysis all three models will be used to investigate the effect of the SW migration of the RIV-PAC Euler pole on the location of the RIV-Cocos Euler poles. We herein term the model of DeMets and Wilson [1997], the ‘fixed pole’ model. One should keep in mind that, like the RIV-PAC angular rotation rate, the angular rotation rate about the present-day PAC-Cocos Euler poles of these models are also 0.78 Ma averages (i.e. they were determined from the width of the central anomaly along the PAC-Cocos spreading center). Given the recent changes in PAC-Cocos relative motion, it is uncertain whether these rates accurately reflect the present-day rates.

The RIV-Cocos Euler poles, calculated by invoking closure about the Pacific-Cocos-Rivera plate circuit using the 0.78 Ma, 0.5 Ma and the present-day RIV-PAC poles of our SW migration model in conjunction with each of the three PAC-Cocos models, are illustrated in Figures 9a, 9b, and 9c. The RIV-Cocos poles calculated using the fixed pole model and the Clipperton model both exhibit a progressive WNW migration towards the El Gordo graben/southern Colima Rift, with the present day pole located within the southern Colima Rift. The RIV-Cocos poles calculated using the Siqueiros model exhibit a SW migration during the past 0.78 Ma.

All three PAC-Cocos models, in conjunction with our RIV-PAC migration model, predict a southwest migration of extension produced by divergence between the RIV and Cocos plates along the proposed NE oriented RIV-Cocos boundary, consistent with the proposed [Bandy, 1992] SW migration of rifting along the boundary. For example, the fixed pole model (Figure 9a) predicts that at 0.78 Ma the region of the boundary NE of 19.2°N, 103.1°W (point A, Figure 9a) was undergoing sinistral transtension, whereas, the region to the SW, sinistral transpression. At 0.5 Ma, the transition point between the transtension and transpression indicated by this model shifted SW to 18.5°N, 103.8°W (point B, Figure 9a). Presently, this point of transition from transtension to transpression now lies within the southern Colima Rift (point C, Figure 9a).

It is interesting to note that the present-day RIV-Cocos pole of this model predicts dextral transtension and transpression along the Rivera-Cocos plate boundary instead of the sinistral transtension and transpression indicated for older times. If the pole has migrated somewhat further to the WNW than indicated in Figure 9a, then the migration model may also account for the right-lateral strike-slip faulting (along roughly east-west oriented nodal planes) of earthquakes occurring in the area of the boundary [Escobedo, 1997; Escobedo *et al*., 1997].

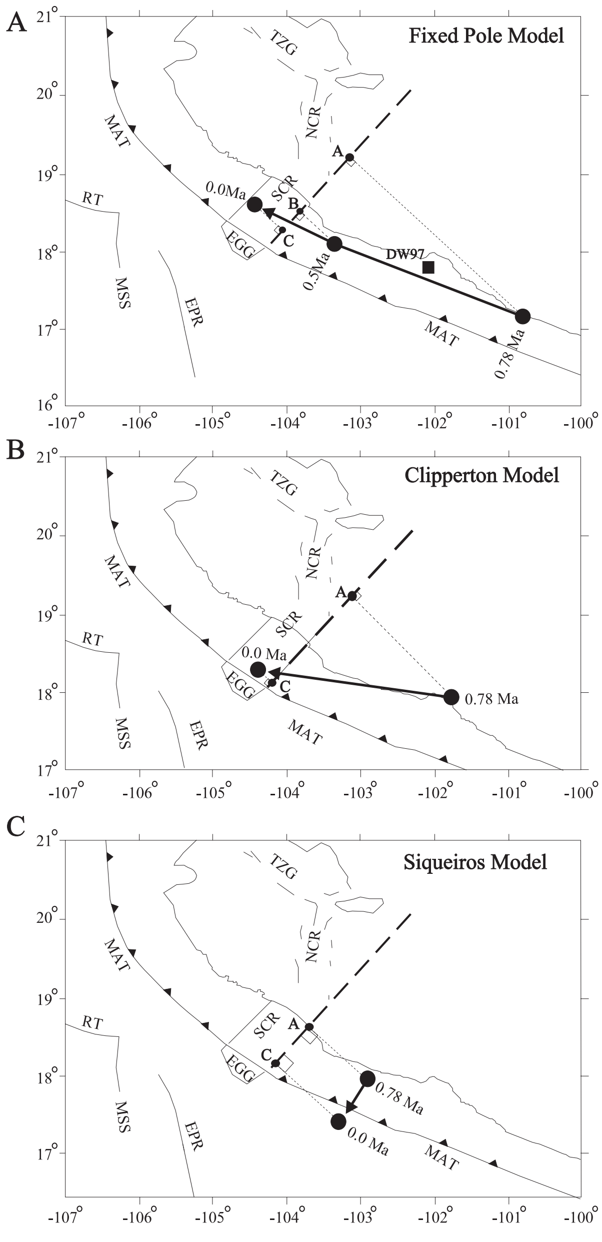

Fig. 9. Migration models for the Rivera-Cocos Euler pole since 0.78 Ma. Models are derived from the RIV-PAC SW migration model of the present study in conjunction with the PAC-Cocos poles of the (A) fixed pole model, (B) Clipperton model, and (C) Siqueiros model. Bold dashed line is the southern margin of the Rivera-Cocos plate boundary beneath Mexico as defined by Bandy *et al*. [1995]. Points A, B, and C located along this boundary represent the transition point between transtension (to the NE) and transpression (to the SW) predicted by the 0.78 Ma, 0.5 Ma, and present-day RIV-Cocos Euler poles, respectively. Solid square labeled DW97 is the 0.78 Ma averaged PAC-Cocos finite rotation pole of DeMets and Wilson [1997]. Abbreviations are: RT, Rivera transform; TZG, Tepic Zacoalco graben. See caption Figure 1 for definition of other abbreviations.

In the study of Bandy [1992], the present day point of transition between extension and compression was proposed, based on morphologic relationships, to lie at the SW margin of the El Gordo Graben, i.e. ahead of the SW propagating rift. Although this proposed location does not exactly coincide with that predicted by the three models, it is conceivable, given the large (regrettably unquantifiable) uncertainties in the analysis as well as the presence of the extensional El Gordo graben and southern Colima rift, that the present day point of transition between transtension and transpression indeed lies at the SW tip of the El Gordo Graben as proposed.

Thus, although there remain many uncertainties which need to be resolved by further study, the model of the SW migration of the RIV-PAC Euler pole since 0.78 Ma provides a plausible explanation for the discrepancy that extensional features are observed in an area where previous, averaged, plate motion models predict compression. The model also provides a simple explanation for the roughly east-west oriented, right-lateral, strike-slip faulting within the Rivera-Cocos plate boundary indicated by focal mechanism solutions of earthquakes occurring within the boundary.

Discrepancy 3: Contrary to predicted motions, seismotectonic relationships indicate that the rate of RIV-NA and Cocos-NA motion are roughly equal across the RIV-Cocos boundary.

Many of the previously published plate motion studies predict up to 3 cm/yr difference between RIV-NA relative motion and Cocos-NA relative motion to either side of the Rivera-Cocos plate boundary [Nixon, 1982; Eissler and McNally, 1984; DeMets and Stein, 1990; Lonsdale, 1995; DeMets and Wilson, 1997]. However, 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.), indicate that the rate of RIV-NA and Cocos-NA motion across the Rivera-Cocos boundary are roughly equal.

To assess whether the SW migration model can resolve this discrepancy, velocity vector diagrams (Figure 10) are constructed to illustrate the relative motions between the PAC, Cocos, RIV and NA plates at the intersection of the El Gordo graben and the Middle America trench (18.3°N, 104.67°W). For all three diagrams, the PAC-NA relative motion vectors are calculated from the PAC-NA Euler vector of DeMets *et al*. [1994]. The RIV-PAC relative motion vector and its 95% uncertainty ellipse are calculated from the newly determined present-day RIV-PAC Euler pole (angular rotation rate of 6.45°/Ma). The PAC-Cocos relative motion vectors are calculated from the present-day PAC-Cocos Euler poles of

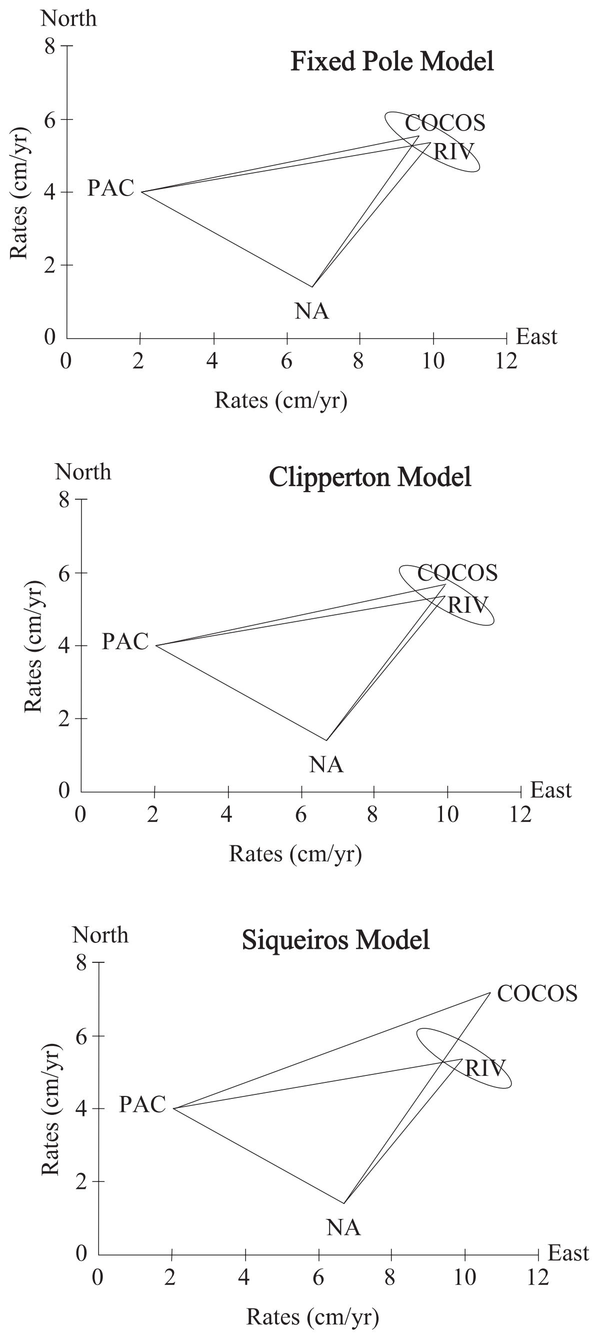

Fig. 10. Velocity vector diagrams illustrating the relative motion between the Rivera (RIV), Pacific (PAC), Cocos and North American (NA) plates at the intersection of the El Gordo graben and the Middle America trench. The error ellipse shown is the 95% confidence region associate with the newly determined Rivera-Pacific Euler pole. The location of the point where the velocities are calculated is marked by the solid star on Figure 1. See text for discussion.

the fixed pole model, the Clipperton model and the Siqueiros model.

The diagrams illustrate that, using the SW migration model, there is no significant (95% confidence level) difference between the present-day rate of RIV-NA and Cocos-NA motion in the area of the RIV-Cocos plate boundary for the fixed pole model and the Clipperton model; consistent with the results of the seismotectonic relationships. Thus, the SW migration model may also provide a simple explanation for this discrepancy if either the fixed pole or Clipperton model of present-day PAC-Cocos motion proves to be correct.

In contrast, there is a significant difference using the Siqueiros model. However, this model does not predict spreading directions normal to the orientation of the rise axes comprising the PAC-Cocos spreading center, and misfits the Orozco to Clipperton segment by 4°, the 2°N to Siqueiros segment by 3°, and the Orozco to Rivera segment by 7°; all in a counterclockwise sense (Table 1). Thus, if the Siqueiros model is correct, then spreading along the PAC-Cocos spreading center must presently be non-orthogonal. A proposal of non-orthogonal spreading during periods of plate motion changes raises the possibility that the RIV-PAC pole may lie further SW than our newly determined present-day pole (calculated assuming orthogonal spreading). If so, the RIV-PAC relative motion at the El Gordo graben would be oriented counterclockwise of that shown in Figure 10. It is also possible that the angular rotation rate about the newly determined present-day RIV-PAC Euler pole is greater than what we have calculated using the separation of the edge of the Central anomaly across the Rivera Rise. Specifically, RIV-PAC spreading rates along the Rivera Rise are noted to have increased from 1.5 to 0.78 Ma [Bandy, 1992]. If this trend of increasing spreading rates has also continued into the time period 0.78 Ma to the present, then the present-day angular rotation rate would be greater than the 0.78 Ma average.

The possibility of a greater angular rotation rate about a RIV-PAC Euler pole located further to the SW than the newly determined Euler vector may well result in an insignificant difference between the present-day RIV-PAC relative motion and PAC-Cocos motion predicted at the El Gordo graben by the Siqueiros model. Thus, it may prove possible that the proposal of a continued SW migration of the RIV-PAC Euler pole during the past 0.78 Ma may also resolve the discrepancy even if the Siqueiros model proves to be correct. Unfortunately, if non-orthogonal spreading is indeed occurring, it may prove impossible to determine the present-day Rivera-Pacific and PAC-Cocos Euler vectors from plate motion data consisting of transform azimuths, earthquake slip vectors and spreading rates determined from the separation of magnetic lineations across spreading centers. Such a determination may, instead, require precise, accurate underwater geodetic measurements.

CONCLUSIONS

The Rivera-Pacific Euler pole which predicts relative motions consistent with the orientations of the most recently formed structural elements of the Rivera-Pacific plate boundaries lies at 24.62°N, 105.89°W. However, due to uncertainties in whether structural elements along plate boundaries readjust rapidly or slowly to changes in Euler pole position, the actual present-day Rivera-Pacific Euler pole may be located further to the southwest than the newly determined pole.

These results together with the results of prior studies indicate that the Rivera-Pacific Euler pole has been migrating SW during the past several million years and that this migration has continued (2° or more) during the past 0.78 Ma. Thus, such a migration must be considered when analyzing the present-day motions of the Rivera plate relative to the adjacent plates.

Although uncertainties exist, a model in which the Rivera-Pacific Euler pole has migrated from 27.11°N, 104.48°W to the newly determined present-day Rivera-Pacific Euler pole (or perhaps further to the SW) during the last 0.78 Ma provides a simple explanation for three discrepancies between the previously predicted motions of the Rivera plate relative to the adjacent North American, Cocos and Pacific plates and the morphology of its boundaries and seismotectonic relationships. Specifically, it provides a simple explanation for the discrepancies between previous plate motion predictions and (1) the observed azimuths of the eastern end of the Rivera transform, (2) the extensional morphology of the Rivera-Cocos boundary adjacent to the Middle America Trench, and (3) the rates of Rivera-North America and Cocos-North America relative motion across the Rivera-Cocos boundary as indicated from seismotectonic relationships. It further provides an explanation for the observed ~5° of clockwise rotation of the Rivera Rise observed during the past 0.78 Ma, and for the right-lateral focal mechanisms of earthquakes located within the Rivera-Cocos boundary region.

ACKNOWLEDGMENTS

This work was partially funded by the Mexican National Council of Science and Technology (CONACyT) grant #1823T9211 and by the Instituto de Geofísica, UNAM, project B502. Special thanks to William Sager and Jaime Urrutia-Fucugauchi for their reviews and suggestions which helped to improve the manuscript.

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