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Reply

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1. Introduction

We thank *Bandy et al.* [this issue] for their thoughtful comments regarding results presented by *DeMets and Wilson* [1997] and we welcome the opportunity to further discuss the merits of both our and their model for the recent relative motions of the Pacific, Rivera, and Cocos plates. Bandy et al. criticize three principal aspects of *DeMets and Wilson* [1997]: whether we properly computed the 0.78 Ma Pacific-Rivera finite rotation and its uncertainties, whether the 0.78 Ma Pacific-Rivera finite rotation is appropriate for describing instantaneous Pacific-Rivera plate motion, and whether Rivera-Cocos motion at present includes any component of divergence along the diffuse Cocos-Rivera plate boundary. As we describe below, Bandy et al.'s criticisms of our finite rotations and their uncertainties are based on their misunderstanding of our technique and use of the data; we believe that the finite rotations and uncertainties we derived are both accurate and precise. We further believe that Bandy et al.'s concern about the appropriateness of the 0.78 Ma Pacific-Rivera finite rotation for modeling instantaneous Pacific-Rivera and Rivera-Cocos motion stems largely from their interpretation of the eastern Rivera transform fault trend, which we question. We thus consider their evidence for changes in the relative velocities of these plates since 0.78 Ma to be unconvincing and we remain confident in our conclusions regarding present-day Cocos-Rivera relative motion and the nature of the boundary between these two plates.

2. The Pacific-Rivera Finite Rotation for 0.78 Ma

Bandy et al. [this issue] question the validity of our Rivera-Pacific finite rotation for two reasons: our use of conjugate points in estimating plate slip directions and an alleged misfit of the direction predicted by our model to the observed trend of the eastern Rivera transform fault. The former point represents a misunderstanding by Bandy et al. of how we used conjugate points in our analysis. We used conjugate points for numerical experiments with incomplete data, not in our final solutions for finite rotations. We thought we had described that adequately on p. 2791.

As for the eastern Rivera transform fault trend, *Bandy et al.* [this issue] state that Figure 5 of *DeMets and Wilson* [1997] shows a "readily apparent" misfit of 7° between the slip direction predicted by our 0.78 Ma average Pacific-Rivera rotation and the trend of the transform fault. We presume that Bandy et al. are comparing the small circle about our Pacific-Rivera rotation pole to the line that shows an interpretation of the fracture zone location from Bandy's previous work (the citation in Figure 2 was not repeated in Figure 5). In retrospect, we erred in displaying an interpretation of the eastern Rivera transform fault preferred by Bandy and others [*Bandy*, 1992; *Bandy et al.*, this issue; *Michaud et al.*, 1996, 1997] because it gave the mistaken impression that our goal was to derive a model that fit their interpretation of the eastern Rivera transform fault. Our interpretation of the location of the active and relict transform fault differs significantly from that of Bandy and others for reasons described below.

The regional bathymetry reveals a prominent south facing escarpment over most of the Rivera fracture zone from 107°W to 106°W [*Bourgois et al.*, 1988a; *Michaud et al.*, 1996, 1997]. Where an active transform fault would be expected, west of the ridge axis at 106.27°W, there is typically a trough separating the escarpment from the well-developed abyssal hills south of the fracture zone. At the ridge axis and to the east, ridges defining the escarpment turn sharply and plunge to merge with ridge-parallel abyssal hills, without an intervening trough. Such patterns are common at ridge-transform intersections along the East Pacific Rise [e.g., *Fox and Gallo*, 1989; *Barth et al.*, 1994], and we present a summary sketch in Figure 1. By analogy with better studied ridge-transform intersections, especially the eastern Clipperton transform [*Gallo et al.*, 1986; *Kastens et al.*, 1986], we consider the base of the escarpment to be the best indication of the location of the relict transform fault east of the axis. In contrast, the interpretation of *Bandy* [1992] follows the trough west of the axis to define the active transform but switches to the top of the escarpment to track the relict transform to the east. The region of greatest disagreement between our and Bandy's interpretation of the eastern Rivera fracture zone is where his interpretation changes from the base to the top of the escarpment. As we describe in more detail below, our 0.78 Ma Pacific-Rivera rotation gives an excellent fit to our alternative interpretation of the location of the active and relict parts of the transform fault as well as other reliable indicators of the slip direction along this part of the Rivera transform.

Bandy et al. also question whether the uncertainties we derived for our rotations are too small, particularly in comparison to uncertainties stated for the widely used NUVEL-1 model [*DeMets et al.*, 1990]. The uncertainty in our Pacific-Rivera finite rotation in the direction parallel to the 20°N-22°N isochrons is dominated by the uncertainties we assign to the nine crossings of the eastern Rivera fracture zone that constrain our model. We used a 1-sigma value of 1 km for these nine data, which leads to a ±2.5 km uncertainty when projecting the 95% confidence interval for the finite rotation into the confidence region for the reconstructed position of a fracture zone point. The rms misfit of a great circle segment to the rotated fracture points is 0.55 km, so the scatter in the data does

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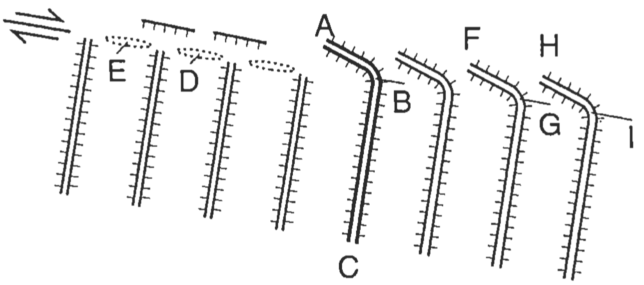

Figure 1. Schematic ridge-transform intersection, reflecting our interpretation of the eastern Rivera transform and sharing features in common with many intermediate to fast-rate transforms. Bold lines A-B-C show the neovolcanic zone, and dashed ovals show bathymetric depressions. We interpret the trend of lines connecting E-D or D-B as reflecting the present-day motion direction, and we match the positions of E-D to G-I to constrain our finite rotation solutions. In contrast, as we understand *Bandy et al.* [this issue], they interpret the trend of D-A as the active motion direction and the trend of F-G or H-I as the past motion direction.

not require a larger uncertainty. Certainly, there could be systematic bias that would not be reflected in the scatter, and readers should consider the possibility that such a bias might be larger than the formal uncertainties. We point out, however, that we used similar techniques in our Cocos-Pacific reconstruction, where the opposite sense of offset for the Clipperton and Siqueiros fracture zones would cause most sources of bias to cancel. We obtained similar precision for these fracture zones, with negligible disagreement between the right-stepping Clipperton and left-stepping Siqueiros, and good agreement between our 0.78 Ma average and indicators of present day Cocos-Pacific motion [e.g., *DeMets et al.*, 1990].

We are not concerned about our uncertainties being smaller than any reported for NUVEL-1 by *DeMets et al.* [1990]. That study made several compromises in order to solve for present-day global plate velocities. One is that the data consist of a mixture of 3.16 Ma average seafloor spreading rates and directional data such as earthquake slip vectors that average over much shorter intervals. Any motion changes since 3 Ma will cause inconsistencies that will increase the uncertainties. Another is that the technique of fitting spreading rates on individual profiles at a range of orientations is less reliable than fitting great circles to digitized isochron points, especially where the isochron segmentation is not well mapped. Because most of the data consisted of earthquake slip vectors, considered the least reliable category, especially in subduction zones, *DeMets et al.* [1990] used uncertainties larger than indicated by scatter for that category to preserve the importance of rates and transform azimuths. The large uncertainties for the earthquake slip directions propagate into large uncertainties in the angular velocities that describe plate motions. Our uncertainties are comparable to those reported by *Wilson* [1993] and *Weiland et al.* [1995], who used dense, well navigated data to determine 0.78-Ma finite rotations.

3. Present-Day Pacific-Rivera and Cocos-Rivera Motions

DeMets and Wilson [1997] averaged plate velocities since 0.78 Ma because the uncertainties of finite rotations are much more easily quantified than for "instantaneous" motions, in which plate rates are extrapolated from the longer-term seafloor spreading record. Uncertainties in deriving recent motions from long-term averages derive not only from possible changes in motion, as pointed out by Bandy et al., but also derive from an unavoidable ambiguity in defining the reference frame in which motion may have been constant. Below, we expand on our previous discussion regarding possible evidence for changes in Rivera plate motion. We also discuss reference frame issues, which we did not adequately describe previously.

Our derivation of present Cocos-Rivera motion from the vector sum of the Rivera-Pacific and Cocos-Pacific average rotation vectors contains the hidden assumption that motion of both plates has been constant in the frame of the Pacific plate. Under the equally plausible assumption that Cocos-Rivera relative motion has been fixed relative to the Cocos or Rivera plate, the Rivera-Cocos angular velocity changes only slightly from its Pacific-fixed vector sum, moving from a longitude of 102.1°W to 101.8°W. At 104°W-105°W, the approximate longitude of the diffuse Rivera-Cocos plate boundary, the Pacific-fixed vector sum predicts motion about 2 mm/yr faster than does the vector sum assuming fixed Rivera or Cocos plates. Thus changing the reference frame in which we compute the Rivera-Cocos angular velocity leads to only small changes in our model for present Rivera-Cocos motion.

More serious is the possibility that motion has changed significantly since 0.78 Ma. The data that best record present-day motions are earthquake focal mechanisms and bathymetric expressions of active transform faults. In the context of evaluating the motion across the Cocos-Rivera boundary, azimuths from the nearby eastern Rivera transform provide the most important constraints on Pacific-Rivera motion in the vicinity of the diffuse Cocos-Rivera plate boundary. We disagree with the conclusion of *Bandy et al.* [this issue] that slip directions for the eastern Rivera transform fault show evidence for a post-0.78 Ma change in the Pacific-Rivera direction.

In our opinion there are two areas of the eastern Rivera transform where the trace of the active fault is clearly expressed in the bathymetry (Figure 2). A fairly continuous trough extends from slightly west of the spreading center, about 106.3°W, and continues westward to 106.8°W. The average strike of this trough is 102°, and following the arctan(width/length) technique of *DeMets et al.* [1994], a width of 2 km implies an uncertainty of ±2°. Farther west, the eastern end of a major trough has a narrow and clearly defined floor at 107.15°W-107.45°W. The average strike is 108° ± 4°, with the larger uncertainty resulting from the shorter length where the trough is well defined.

The 102° (S78°E) azimuth we interpret for the eastern Rivera transform fault is 8° clockwise from the azimuth of S86°E quoted by *Bandy et al.* [this issue]. They do not describe the basis for their measurement, but if their interpretation agrees with that of *Michaud et al.* [1996], they appear to be connecting the deepest point (~3360 m) in a trough at 106.38°W with the highest point (~2650 m) on a ridge at 106.28°W. That ridge can reasonably be interpreted to be an extension of the neovolcanic zone ridge, which is at a depth of about 2900 m south of 18.50°N. Such intersection highs are common on the East Pacific Rise and are clearly constructed on older seafloor across the transform fault from the active spreading ridge [*Fox and Gallo*, 1989; *Barth et al.*, 1994]. As such, they should not be interpreted to be coincident with the location of the transform fault.

We agree that the axis of the Manzanillo spreading segment

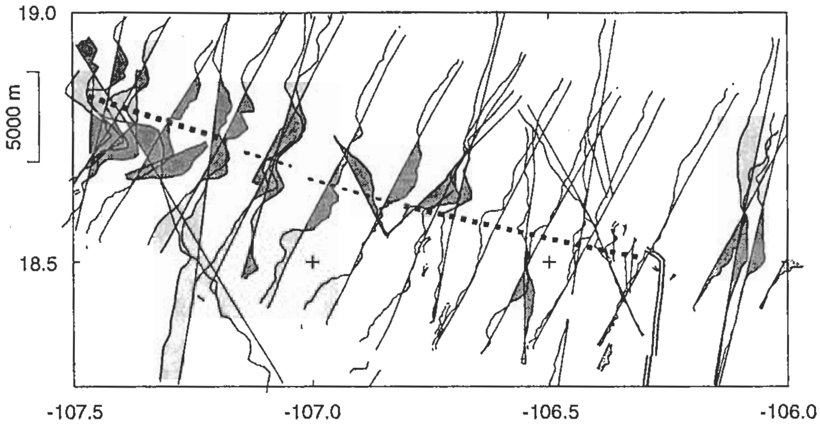

Figure 2. Bathymetric profiles crossing the eastern Rivera fracture zone. Depths are plotted perpendicular to ship tracks, with darker shading shallower than 2800 m. The dashed lines show our interpretation of the locations of active transform fault strands following troughs, with bolder lines where the fault strikes can be measured more reliably.

trends about 005° where it intersects the 102° trending eastern Rivera transform fault. We are not concerned, however, about the implication that the ridge strike is slightly counterclockwise (7°) from perpendicular to the relative motion direction. At the well-mapped Orozco transform [*Madsen et al.*, 1986], the mid-Orozco spreading center has a trend of 164°, not perpendicular to the transform fault at 080°. As is the case for the Manzanillo segment and eastern Rivera transform fault, the discrepancy is counterclockwise, typical of left-stepping ridge offsets.

Our Pacific-Rivera pole [*DeMets and Wilson*, 1997], constrained by 0.78 Ma average rates from 18.4°N to 22.0°N, gives a superb fit to both the bathymetrically constrained Rivera transform azimuths interpreted by ourselves and other workers [*DeMets and Stein*, 1990; *Lonsdale*, 1995; *Michaud et al.*, 1997] and our up-to-date compilation of Rivera transform fault earthquake slip directions (Figure 3). In particular, the predictions of an instantaneous pole we derived to best fit only Rivera transform fault earthquake slip vectors falls everywhere within the uncertainties of the predictions of our 0.78-Ma average pole. The predicted fault curvature is greater than that predicted by the more distant poles of *DeMets and Stein* [1990] and *Bandy* [1992], which included data north of 22°N that are now thought to record Pacific-North America motion [*Lonsdale*, 1995; *DeMets and Wilson*, 1997]. The predicted curvature is less than that predicted by *Bandy et al.* [this issue], which is heavily influenced by their 094° interpretation of the trend of eastern Rivera transform fault. We consider the section of the transform fault near 107.0°W-107.4°W to be especially important. Our interpretation of the bathymetric trend of the active transform here is within 1° of that of *Lonsdale* [1995] and *Michaud et al.* [1997] and is within the scatter of numerous slip vector determinations. In contrast, Bandy et al.'s pole fits all of these well-constrained observations poorly.

Extrapolation of the Pacific-Rivera direction along the Rivera

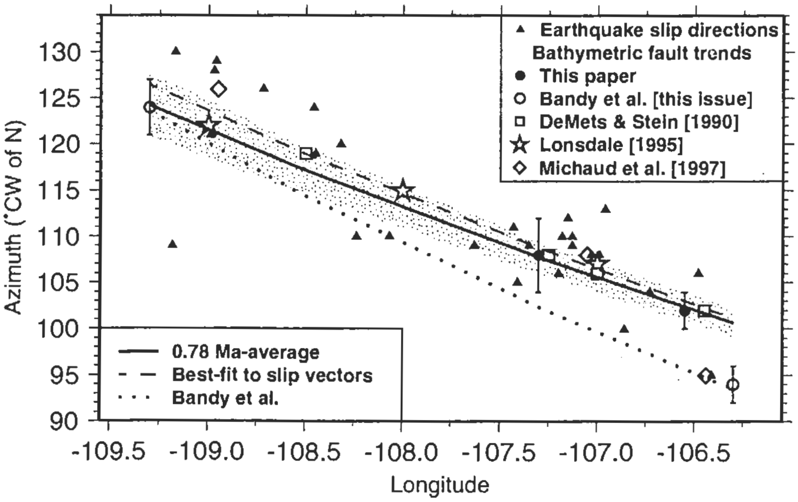

Figure 3. Data and model predictions for the current direction of motion on the Rivera transform fault. Solid triangles show earthquake slip directions compiled from published sources and centroid moment tensor solutions current through November 1997. All other symbols show transform fault azimuths interpreted by various workers (see legend). The 0.78 Ma average model represents the predictions of the Pacific-Rivera 0.78 Ma angular velocity from *DeMets and Wilson* [1997] and the best fit model optimizes the least squares fit to only the earthquake slip directions. Shaded region shows 95% prediction uncertainties and error bars show standard errors.

transform fault to its eastern end (106.3°W-106.5°W) using either the observed azimuths from 109°W to 107°W or the 0.78 Ma average Pacific-Rivera rotation of *DeMets and Wilson* [1997] gives predicted directions of 099°-103° (Figure 2). These agree well with our and other interpretations [*Lonsdale*, 1995] of the transform azimuth at this location, which suggests that within the uncertainties of the observations, the simplest model for motion along the Rivera transform fault is one in which two plates have rotated about a relatively fixed pole since 0.78 Ma. *Michaud et al.* [1997] recognized the inconsistency between their interpretation of the trend of the eastern segment of the Rivera transform and the trends of the other segments and suggested that an additional plate boundary might be needed. We prefer the simpler explanation that trends of 094°-095° near the eastern Rivera transform fault do not represent Pacific-Rivera relative motion direction.

4. A Minimum Convergence Model for Rivera-Cocos Motion at the El Gordo Graben

One question posed by *Bandy et al.* [this issue] and other papers [*Bandy and Pardo*, 1994; *Kostoglodov and Bandy*, 1995] is whether models for present Rivera-Cocos motion predict extension in the seafloor offshore from the Colima graben, in the feature named the El Gordo graben by *Bourgois et al.* [1988b]. To paraphrase to the point of oversimplifying, our 0.78 Ma average Rivera-Cocos angular velocity predicts 16±4 mm/yr (>99% confidence limit) of northward convergent motion of the Cocos plate relative to Rivera at the edge of the El Gordo graben, whereas Bandy et al. suggest that allowing for recent changes in motion, divergence between the Rivera and Cocos plates could occur in the vicinity of the El Gordo graben within the model uncertainties. We are skeptical of such claims, primarily because such arguments depend critically on accurately estimating data uncertainties and propagating these uncertainties into model uncertainties, both difficult tasks. For example, there is no basis for assigning a numerical uncertainty to any estimate of an instantaneous Pacific-Rivera rate because such a rate can only be guessed in the absence of geodetic measurements. Because both the rotation rates and their uncertainties are arbitrary, any confidence interval derived from the vector sum has significant arbitrary components.

Rather than propagating errors around an estimate of a best fit pole, the technique adopted by *Bandy et al.* [this issue], we instead estimate an end-member Rivera-Cocos rotation using Rivera-Pacific and Cocos-Pacific poles that we selected so as to minimize the predicted convergence between Rivera and Cocos without grossly misfitting well-constrained Pacific-Rivera and Pacific-Cocos data. We then use the predictions of the summed Cocos-Rivera pole as a lower bound for convergent motion. With the location of rotation poles assumed to be fixed, the degrees of freedom introduced by the unknown rotation rates are limited, and in a special case useful to this discussion, the unknown rates do not affect the direction of Rivera-Cocos motion.

Consider the possibility that the present-day rotation poles for Cocos-Pacific and Rivera-Pacific are in the same location as the 0.78 Ma average poles, but the present rates differ from the average rates. The present Cocos-Rivera pole will lie somewhere on the great circle passing through the Cocos-Pacific and Rivera-Pacific poles, and this great circle will intersect all small circles about those poles at a 90° angle (Figure 4). If the

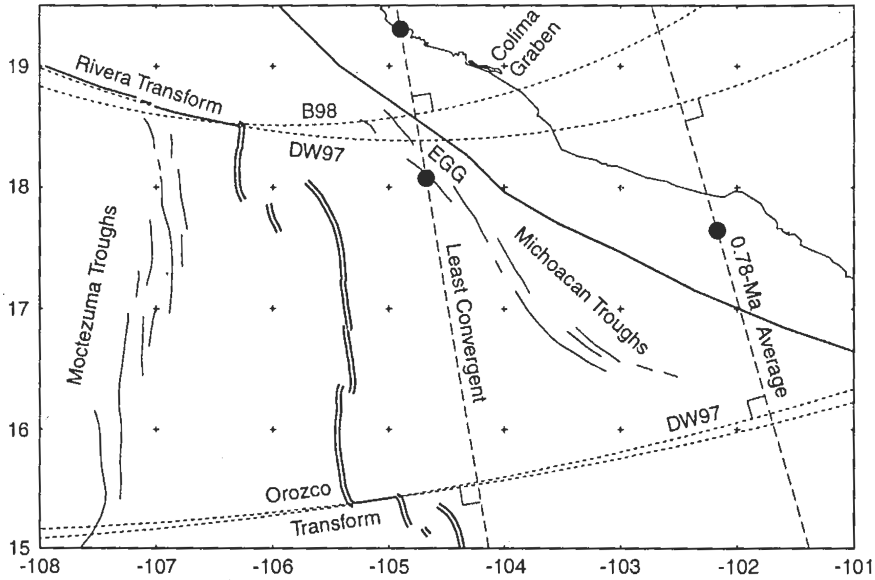

Figure 4. Estimates of present Cocos-Rivera rotation pole locations. Dotted lines are small circles about poles relative to the Pacific plate, with DW97 signifying *DeMets and Wilson* [1997] and B98 signifying *Bandy et al.* [this issue]. Dashed lines are great circles showing the possible locations of vector sum poles with the location but not rate of poles relative to Pacific specified. For example, if the rates but not the locations of the DW97 0.78 Ma average pole have changed, the current pole would shift along the great circle away from the average pole (solid circle). Motion of Cocos relative to Rivera would still have a northward component everywhere offshore west of 102.1°W. Allowing for possible change in pole location within what we consider generous uncertainties could shift the pole position as far west as the least convergent great circle, with the two solid circles spanning the range of pole positions if the Pacific-Rivera spreading rate is unchanged somewhere on their boundary. Even with these changes in motion direction, significant offshore extension between Cocos and Rivera is not possible with a credible plate boundary location. EGG is El Gordo graben.

changes in rate are small, the present pole will lie on the great circle near the average pole. Even if the rate changes are large, the component of Rivera-Cocos motion parallel to the great circle will be zero at any point on the great circle, and at any point west of the great circle, Cocos motion will have a northward component relative to Rivera.

If we instead assume that both the Pacific-Rivera and Pacific-Cocos present slip directions differ significantly from their 0.78 Ma average directions, then a model that minimizes Rivera-Cocos convergence requires both a counterclockwise change of the Pacific-Cocos slip direction and a clockwise change of the Pacific-Rivera direction (see Figures 2 and 3 of *Bandy et al.* [this issue]). To represent the counterclockwise limit of the current slip direction along the eastern Rivera transform fault, we use the Pacific-Rivera pole position estimated by *Bandy et al.* [this issue]. We consider this a very generous estimate of the uncertainty in motion direction given the poor fit of this pole to active Rivera transform data east of 108°W (Figure 3). For the clockwise limit of northern Pacific-Cocos plate motion, we perturb our 0.78 Ma average pole to have a motion direction of 082° at the Orozco transform, instead of the well-mapped 080° strike of this feature [*Madsen et al.*, 1986]. The great circle defined by these poles, labeled "least convergent" in Figure 4, passes through the El Gordo graben. If the northern Cocos-Pacific rate has been constant and the present Rivera-Pacific rate matches the 0.78 Ma average rate at some point along the Pacific-Rivera boundary, the Cocos-Rivera pole position will fall between 18.1°N and 19.3°N. Pole positions in this range cannot produce significant extension in the El Gordo graben with any reasonable geometry for the Cocos-Rivera boundary, and the situation improves only slightly if slower Rivera-Pacific motion yields a more southerly Cocos-Rivera pole. Pole positions more consistent with present-day motion data will yield a Cocos-Rivera pole east of the "least convergent" great circle. A lower bound for the trend of the eastern Rivera transform that we consider more reasonable, say 098°, would predict a minimum convergence rate of about 6 mm/yr in the vicinity of the El Gordo graben.

We look forward to further discussion of the reasons that *Bourgois et al.* [1988b], *Bandy* [1992], and *Bandy et al.* [this issue] consider the El Gordo graben to be an active feature. We find it simpler to interpret this feature as part of the Michoacan troughs, the eastern pseudofault formed by propagation of the East Pacific Rise along the eastern boundary of the Mathematician plate [*Mammerickx et al.*, 1988]. Both the Michoacan troughs and the conjugate Moctezuma troughs are complex features, commonly consisting of two or three parallel depressions apparently formed as grabens (Figure 4). We do not see any important differences between the El Gordo graben and any of about a dozen other short grabens that compose these major troughs. We acknowledge the possibility that minor recent activity on the northern Michoacan troughs might result from bending stresses associated with subduction, but we suspect that El Gordo graben has been interpreted as active solely because it aligns with the onshore Colima graben.

5. Summary

We believe that evidence bearing on changes since 0.78 Ma in Pacific-Rivera plate motions do not support the conclusions advanced by *Bandy et al.* [this issue] that the Pacific-Rivera direction in the vicinity of the eastern Rivera transform fault has changed by 19°-27° since 1.0 Ma. Detailed inspection of earthquake slip vectors and fault azimuths along the Rivera transform fault (Figure 3) instead suggests that the Pacific-Rivera slip direction has remained nearly constant since 0.78 Ma. This implies that the 0.78 Ma average angular velocities described by *DeMets and Wilson* [1997] adequately describe present-day Pacific-Rivera-Cocos-North America relative motions. The predicted velocity of Cocos relative to Rivera across the diffuse boundary between these two plates is thus northward to NNE at rates exceeding 10 mm/yr. The details of the deformation across the diffuse boundary remain unclear, but the interpretation of *Eissler and McNally* [1984], who concluded from seismic data that the boundary trends about N10°E near 105°W, remains consistent with the plate kinematic data.

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