

## A Test of Alternative Caribbean Plate Relative Motion Models

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Two contrasting models have been proposed to describe the present-day motions between the Caribbean Plate and neighboring plates. One model, based on both North America-Caribbean and Cocos-Caribbean data, assumes that North America-Caribbean motion is reflected by the spreading rate (approximately 2 cm/yr) inferred from magnetic anomalies at the Cayman Spreading Center and the azimuths of nearby transforms (Jordan, 1975). This geometry was used by Minster and Jordan (1978) in deriving global plate motion model RM2. The other model, based only on North America-Caribbean data, uses rates and azimuths inferred from the geometry of the Lesser Antilles Wadati-Benioff zone (Sykes et al., 1982). The Cayman Spreading Center data were discounted assuming that they underestimate the full North America-Caribbean motion owing to the complex tectonics of the Greater Antilles. The latter model assumes plate convergence at the Lesser Antilles at a rate about twice as fast as, and an azimuth differing by 25° from, the Jordan model. The two models also differ in their predictions of South America-Caribbean motion; the Jordan model predicts oblique convergence whereas Sykes et al. predict oblique divergence. We use the NUVEL-1 global relative motion data set, which incorporates recent data not used in earlier studies, to discriminate between the alternative models. We find that the Jordan geometry provides a better fit to the direction of North America-Caribbean motion. Moreover, we find that models based on this geometry better fit the direction of Cocos-Caribbean motion observed in earthquake slip vectors along the Middle America Trench. Since the prediction of this direction depends strongly on the rate of North America-Caribbean motion, we conclude that the Jordan model better describes Caribbean Plate motions. The discrepancy between the two models results from the different methods of estimating plate motions. Sykes et al. (1982) report that they determined a Caribbean-North America convergence rate of approximately 4 cm/yr from the length of the Lesser Antilles Wadati-Benioff zone; we employ a similar procedure and obtain a rate closer to 2 cm/yr. We also find that the method they report using to determine the convergence direction is unable to distinguish between the alternative azimuths. We thus conclude that estimates of the rate and direction of plate motion from Wadati-Benioff zone configurations are insufficiently robust and that such estimates are better derived using rates from magnetic anomalies and azimuths from transform faults and slip vectors. We further conclude that successful estimates of relative motion require internal consistency between the Euler vectors of all relevant plates, as demonstrated by the powerful Cocos-Caribbean constraint not incorporated in the Sykes et al. model.

### INTRODUCTION

The motion of the Caribbean Plate relative to neighboring plates is among the poorest known of any major plate. Unresolved tectonic questions remain about almost all portions of the present boundaries (Figure 1) between the Caribbean (CA) and the North American (NA), South American (SA), Cocos (CO), and Nazca (NZ) plates [Burke et al., 1984; Mann and Burke, 1984; Case et al., 1984]. To the east, Atlantic seafloor is subducting beneath the Antilles arc [Molnar and Sykes, 1969; Dorel, 1981; Stein et al., 1982, 1983, 1986; Sykes et al., 1982; Girardin and Gaulon, 1983]. Whether the downgoing plate is part of the North American, South American, or both plates is unclear [Vierbuchen, 1979; Stein et al., 1982]. The subduction is oriented approximately east-west, but the precise

direction is poorly constrained. To the northeast, the Greater Antilles show a complex combination of strike-slip and extensional features [Hess and Maxwell, 1953; Burke et al., 1980] whose relation to the remainder of the Caribbean Plate is not fully resolved. To the northwest, the Motagua fault forms a major left-lateral strike-slip boundary, as shown by the 1976  $M_s$  7.6 Guatemala earthquake [Kanamori and Stewart, 1978]. This boundary is a complicated one involving multiple faults; it is unclear where and how this boundary intersects the Cocos plate to the west [Bowin, 1976; Plafker, 1976; Burkart and Self, 1985] and whether the region to the north has some motion relative to the remainder of the North American plate. Although the SA-CA boundary zone is an extremely complex deformation zone characterized by a diversity of faulting types and directions and microplate tectonics, oblique convergence is generally inferred from geologic and seismic data [Silver et al., 1975; Perez and Aggarwal, 1981; Schubert, 1981; Kellogg and Bonini, 1982, 1985; Speed et al., 1984; Speed, 1985; Vierbuchen, 1984]. The complexities of present-day motions are also reflected in questions about the evolution of the Caribbean plate's boundaries [Pindell and Dewey, 1982; Wadge and Burke, 1983; Speed, 1985; Dewey and Pindell, 1985].

Given these complexities, two distinct models for present relative motion between the Caribbean and adja-

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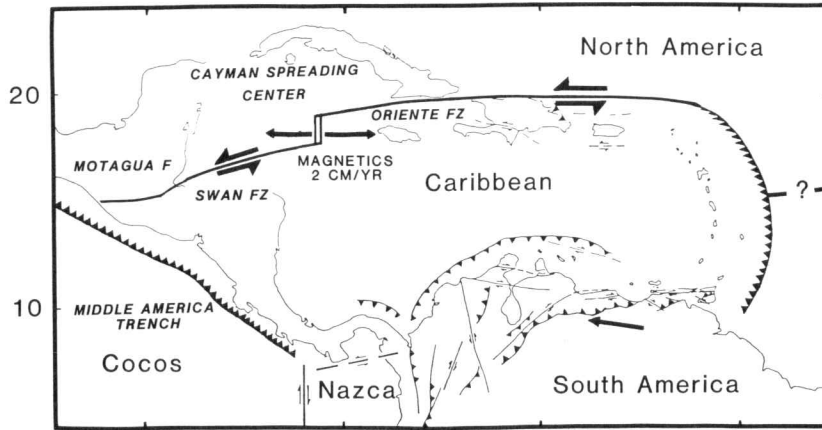
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JORDAN (1975) CARIBBEAN MODEL



SYKES ET AL. (1982) MODEL

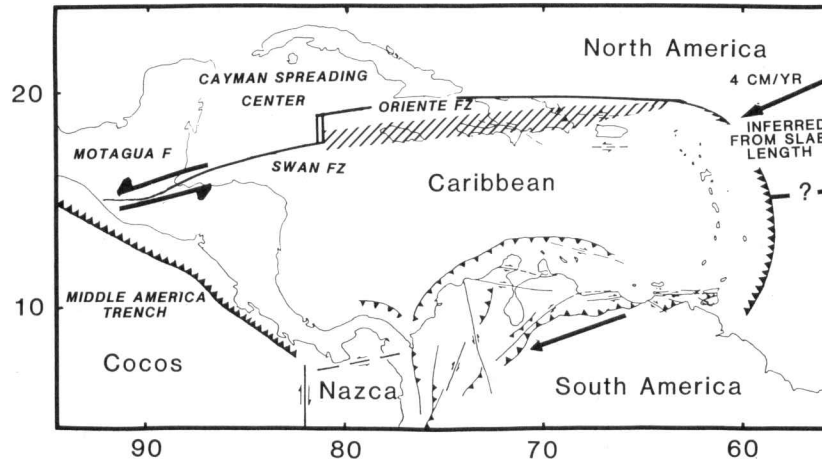


Fig. 1. Alternative models for Caribbean Plate relative motions. The Jordan model, based on the spreading rate and azimuth at the Cayman Spreading Center, predicts approximately 2 cm/yr of NA-CA motion. The Sykes et al. model, based on the configuration of the Lesser Antilles Wadati-Benioff zone, predicts a NA-CA rate approximately twice as high and a more northerly azimuth. The predicted SA-CA motions also differ. The Jordan model predicts oblique convergence at about 2 cm/yr; the Sykes model predicts oblique extension at about 4 cm/yr.

cent plates have been proposed (Figure 1). Jordan [1975] obtained the rate of NA-CA motion from the approximately 2 cm/yr of spreading indicated by magnetic anomalies at the Cayman Spreading Center [Holcombe et al., 1973; Macdonald and Holcombe, 1978]. As the Cayman is the only spreading center along the Caribbean's boundaries, this datum provided the only direct rate measurement possible. He similarly assumed that the Swan and Oriente fracture zones were NA-CA transforms, so their strikes and the mechanisms of earthquakes on them show the direction of plate motion. Additional azimuthal data were taken from focal mechanisms suggesting approximately E-W motion in the Lesser and Greater Antilles. Jordan also used slip vectors from earthquakes along the Middle America trench to determine CO-CA motion. As the SA-CA boundary is too complex to allow unambiguous selection of relative motion data and no direct data exist for NA-SA motion, the remaining Euler vectors were determined by closure. Incorporation of this geometry

into global relative plate motion model RM2 [Minster and Jordan, 1978] yielded the relative motions shown in Figure 1 (top).

An alternative model, proposed by Sykes et al. [1982], assumes that the internal deformation within the Greater Antilles is sufficiently large and extends far enough west that the approximately 2 cm/yr measured at the Cayman Spreading Center underestimates the NA-CA motion. Instead, they used a relation between the downdip length of Wadati-Benioff zone seismicity and the age of the subducting lithosphere to estimate convergence of  $3.7 \pm 0.5$  cm/yr at the Lesser Antilles subduction zone. They also report using the orientation of the Wadati-Benioff zone seismicity to infer a more northerly direction, approximately N65°E, for NA-CA motion at the arc. These interpretations were combined with focal mechanism data to obtain a NA-CA Euler vector. An SA-CA Euler vector was then derived by closure with the NA-SA vector of Minster and Jordan [1978]. The CO-CA relative motion

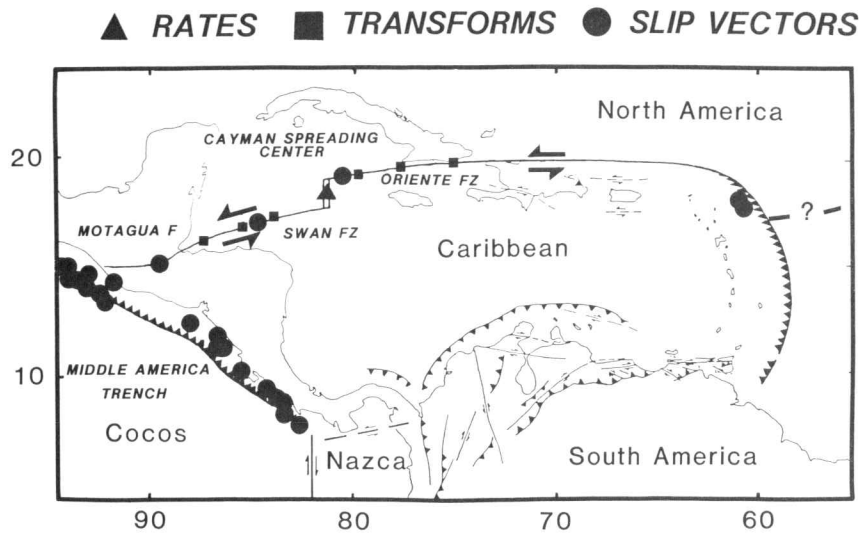


Fig. 2. Data used to test predictions of Caribbean Plate relative motion models.

data were not explicitly considered. This model, summarized in Figure 1 (bottom), has been incorporated in seismic hazard analysis for the Caribbean [McCann and Sykes, 1984]. The factor of 2 difference between the convergence rates predicted by the alternative models is significant for these purposes [Stein et al., 1986].

Our goal in this paper is to use the NUVEL-1 data set, a new data set for global relative plate motions [DeMets et al., 1985, and manuscript in preparation, 1987], to discriminate between the two Caribbean motion models. We compare the predictions of the alternative models for the two boundaries, NA-CA and CO-CA, where direct data exist. As the predicted motions are distinct, discrimination between them is not difficult. Moreover, determination of which model fits best has significance beyond the specific question of NA-CA motion. The alternative models differ in fundamental ways, as do the contrasting methods of determining plate motions. First, the types of data used differ; Sykes et al. [1982] used subduction zone geometry, whereas Jordan used the combination of spreading rates, transform azimuths, and slip vectors normally used in relative motion studies [Chase, 1972; Minster et al., 1974]. Second, the Sykes et al. [1982] model encompasses only three plates (North America, South America, and Caribbean), whereas the Jordan geometry is incorporated into global models in which all plate boundary data are fit simultaneously [Chase, 1972; Minster et al., 1974]. The NUVEL-1 data set, like its predecessors, incorporates spreading rates, transform azimuths, and earthquakes slip vectors from many plate boundaries. The data are individually weighted and then are simultaneously inverted to find a model that both satisfies closure and that best fits the data in a weighted, least-squares sense. The fits of various models can be compared using the reduced chi-square,  $\chi^2_\nu$ , a measure of the root-mean-square, weighted misfit to the data. Overall, we find that the Jordan geometry allows the better fit to our data, that the data used in global plate motion models are more suitable than rates and azimuths inferred from the geometry of the Wadati-Benioff zone for determining relative motions, and that incorporation of all relevant plate boundaries is essential.

#### TESTS OF PLATE MOTION MODELS

To discriminate between the two models, we conduct separate tests for the rate and direction of NA-CA relative motion using the data set shown in Figure 2. Because this data set differs somewhat from that used in the earlier studies, it is worth brief discussion. The data are tabulated by C. DeMets et al. (manuscript in preparation, 1987).

We use data from several regions for NA-CA motion. If the Caribbean Plate behaves rigidly, the plate motion data should satisfy two criteria. First, the data on an individual boundary must be internally consistent. Second, data on each boundary must be consistent with those from the other plate boundaries. As discussed earlier, the choice of the data near the Cayman Spreading Center is pivotal. We adopt the most recent spreading rate estimate, 1.5 cm/yr, given by Rosencrantz and Sclater [1986] from interpretation of magnetic anomalies and the subsidence history. As shown later, despite the possible bias suggested by Sykes et al. [1982], we find this rate to be more consistent with the motion observed on the CO-CA boundary than the higher rate suggested by Sykes et al. The observed, lower, rate is also more consistent with closure of the NUVEL-1 global plate motion model (C. DeMets et al., manuscript in preparation, 1987). Many more azimuthal data are available. Near the Cayman Spreading Center, we use the azimuths of the Oriente and Swan fracture zones and the slip vectors of earthquakes on these features. Farther west, we use the slip vector of the 1976 earthquake on the Motagua fault [Kanamori and Stewart, 1978]. All of these azimuthal data were used in RM2. As discussed shortly, we find them internally consistent and observe no evidence of the bias suggested by Sykes et al. [1982].

For the Antilles arc, our choices differ from RM2. We use no data from the Greater Antilles, given the tectonic complexities there and the possibility that portions of the area may be moving differently from the Caribbean Plate as a whole. In the Lesser Antilles, we use only two slip vectors, from Stein et al. [1982] and Dziewonski et al. [1983a]. Many of the earthquakes with known mechanisms, including several used in RM2, now appear to be intraplate and thus unrepresentative of plate motions [Stein et al., 1982]. We treat these two slip vectors as NA-

CARIBBEAN-NORTH AMERICA

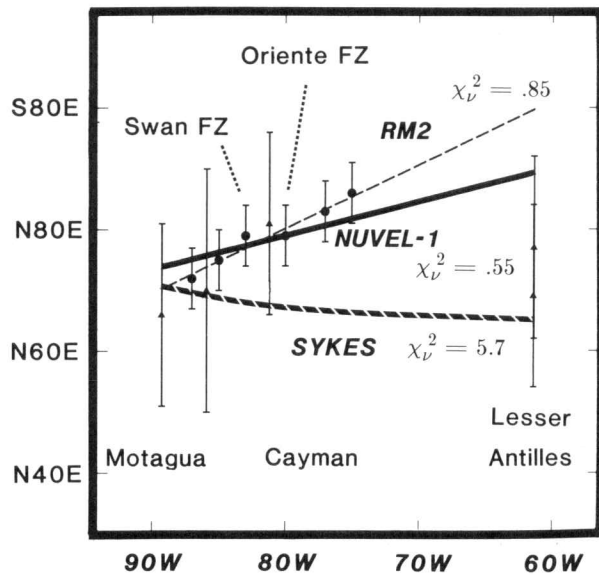


Fig. 3. Azimuth data for NA-CA relative motion from transform faults (dots) and slip vectors (triangles), compared with predictions of different models. Global models RM2 or NUVEL-1, which incorporate the Jordan [1975] geometry, provide a better fit to the aggregate of the data, as shown by the values of  $\chi^2_\nu$ , than the Sykes et al. [1982] model. Note the consistent trend of the data across the Cayman Spreading Center.

CA, rather than SA-CA, since inversion of the global data set yields a smaller error for this choice.

To constrain CO-CA motion, we use slip vectors for earthquakes along the Middle America Trench. Some of these were used in RM2; others were taken from sources including Dean and Drake [1978], Chael and Stewart [1982], Burbach et al. [1984], and the Harvard centroid moment tensor solutions [Dziewonski et al., 1983a, b, 1984a, b]. Owing to the complexities of the SA-CA and NZ-CA boundaries, no data there were used.

North America-Caribbean Direction

The first test examines the fit of the alternative models to the data along the NA-CA boundary. Figure 3 shows the data for the direction of relative motion and the predictions of RM2 [Minster and Jordan, 1978], Sykes et al. [1982], and the NUVEL-1 global data set. The Euler vectors are listed in Table 1. Two vectors are listed for NUVEL-1 because in such global models, Euler vectors for all plate pairs are required to be internally consistent. The resulting global Euler vectors thus differ from the best fitting vectors (BFV) obtained by separately fitting each plate pair with adequate data [Minster et al., 1974]. As the Sykes model was obtained without these constraints, only one Euler vector is given for each plate pair.

The data from the Motagua fault and the Swan and Oriente fracture zones show a systematic trend, with earthquake slip vectors consistent with the transform azimuths. The data are well fit by RM2 or NUVEL-1, as expected since these models were derived using these data. In contrast, the Sykes et al. [1982] model misfits the data. The misfit to the Oriente azimuths may not be a problem because this model assumes a complicated geometry immediately east of the Cayman Spreading Center. The misfit to the Swan data, which both models assume represent NA-CA motion, is significant. Similarly, the consistency of the trends between the Swan and Oriente fracture zones provides no evidence for any change in plate motion direction across the Cayman Spreading Center.

The situation in the Lesser Antilles differs. The NUVEL-1 data set contains NA-CA slip vectors giving a relative motion direction about N70°E. This azimuth is closer to that assumed by Sykes et al. [1982] than to the E-W one proposed by Minster and Jordan [1978]. The different Euler vectors reflect these choices as well as the data farther west. RM2 fits the Motagua to Oriente data best, at the price of misfitting the Lesser Antilles data. The Sykes et al. model fits the Antilles and Motagua slip vectors, at the cost of the Swan and Oriente directions.

TABLE 1. Euler Vectors

Model	Latitude, °N	Longitude, °E	Rate, deg/my
<i>North America - Caribbean</i>			
RM2	-33.8	-70.5	0.22
Sykes et al.	-66.0	48.0	0.36
NUVEL-1 global	-55.2	-60.8	0.11
NUVEL-1 BFV	-57.0	-59.8	0.14
<i>Caribbean - South America</i>			
RM2	73.5	60.8	0.20
NUVEL-1	57.7	-53.6	0.16
Sykes et al.	60.0	-88.0	0.47
<i>Cocos - Caribbean</i>			
RM2	23.6	-115.6	1.54
NUVEL-1 global	24.7	-118.6	1.44
NUVEL-1 without Caribbean and Sykes et al. NA-CA	17.4	-119.8	1.19
NUVEL-1 without Caribbean and NA-CA BFV	23.4	-118.2	1.44

Rotation convention: right-hand rule, first plate rotates counterclockwise with respect to second plate.

**EULER POLES**

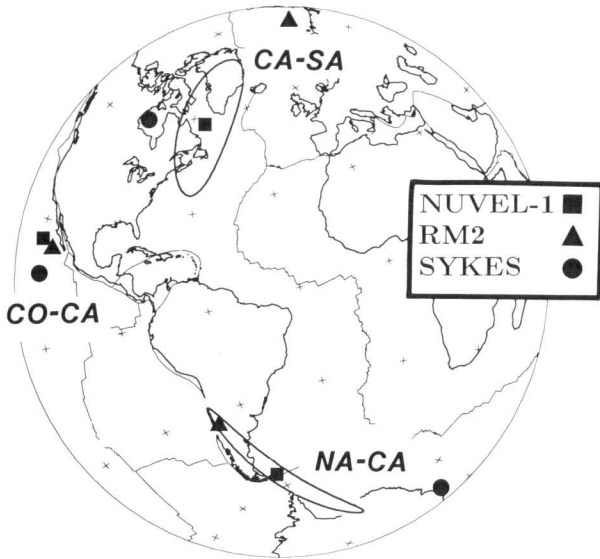


Fig. 4. Euler poles for NA-CA, Caribbean-South America, and CO-CA relative motions. Rotation convention is right-hand rule, first plate rotates counterclockwise with respect to second plate. All NUVEL-1 poles are derived from the global dataset.

NUVEL-1 compromises between the two. The different pole positions (Figure 4) demonstrate this effect.

The overall azimuthal data set is best fit by models like RM2 or NUVEL-1, which fit about equally well. We thus conclude that the direction of NA-CA motion is better described by models based on the *Jordan* [1975] geometry. Such a test cannot, however, discriminate between the

disparate rate predictions, since the *Sykes et al.* [1982] model does not attempt to predict the rate at the Cayman Spreading Center.

*North America-Caribbean Rate*

We next consider the azimuth of CO-CA motion shown by the slip vectors of earthquakes at the Middle America Trench. Predictions of this direction depend critically on the assumed NA-CA rate and can thus be used to discriminate between the *Jordan* [1975] geometry with a rate about 2 cm/yr, and the *Sykes et al.* [1982] model with a rate about 4 cm/yr.

The direction of CO-CA motion is determined explicitly in global models like RM2 or NUVEL-1, and can be compared with the slip vectors. Although the Sykes et al. model gives Euler vectors only for the NA-SA-CA three-plate system, the corresponding CO-CA vector is easily found by addition of a CO-NA vector to the given NA-CA vector. To do this, we determine a CO-NA vector by inverting the NUVEL-1 global data set after deleting all Caribbean data. The resulting Euler vector is thus free of any bias due to the choice of a Caribbean boundary geometry or selection of Caribbean data points. Figure 5 illustrates the strong constraints on CO-NA motion that remain after all data related to the Caribbean Plate boundaries are deleted. Addition of this CO-NA vector and the Sykes et al. NA-CA vector yields a CO-CA vector for the Sykes et al. model (Table 1). The corresponding CO-CA vector for the *Jordan* geometry is found by adding the CO-NA vector to the best fitting NA-CA vector.

Figure 6 compares the Middle America Trench slip vectors to the predictions of four Euler vectors. The Sykes et al. model predicts a direction of  $\sim N10^\circ E$ , significantly

**GLOBAL PLATE CIRCUIT**

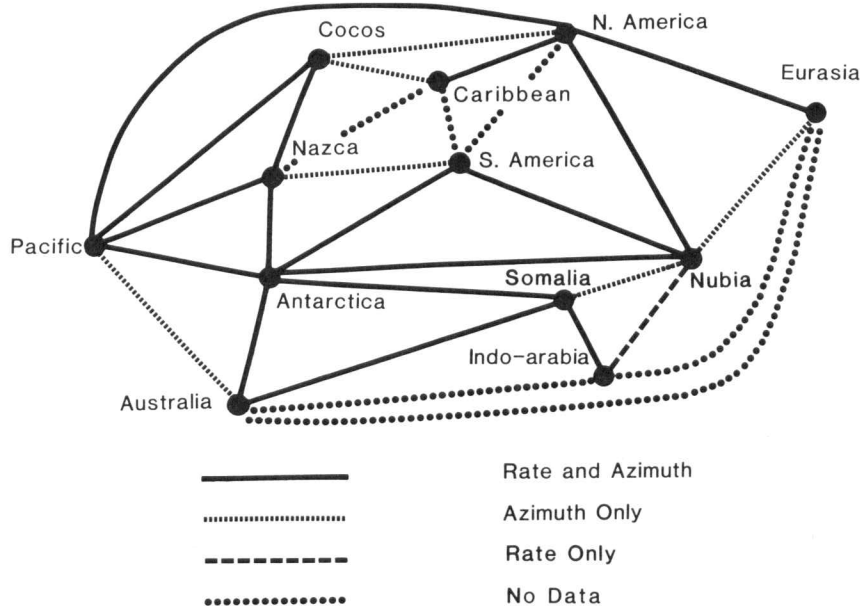


Fig. 5. Global plate circuit used for the NUVEL-1 relative motion model. The Caribbean is only weakly tied into the global circuit, as the only rate datum comes from its boundary with the North American plate at the Cayman Spreading Center, and no data from its boundaries with the South American or Nazca plates are used. Nonetheless, the CO-CA closure provided by the azimuthal data at the Middle America Trench constrains the NA-CA rate adequately so that alternative models can be discriminated.



COCOS-CARIBBEAN

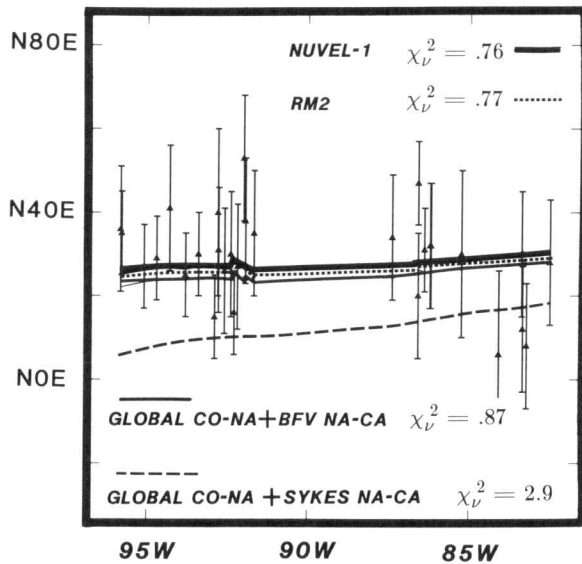


Fig. 6. Middle America Trench slip vector data for CO-CA relative motion, and predictions of different models. Global models RM2 or NUVEL-1, which incorporate the Jordan [1975] geometry, provide a better fit than the CO-CA motion derived from the Sykes et al. [1982] model.

more northerly than the slip vectors. In contrast, global models RM2 and NUVEL-1, which incorporate the Jordan Caribbean geometry, predict an average N30°E convergence, in good accord with the data. The predictions derived from the NA-CA best fit vector also fit the data. We thus conclude that models based on the Jordan geometry better fit the observed CO-CA motion.

Examination of the pole positions (Figure 4) and velocity space analysis demonstrates that the better fit results from the use of the Cayman Spreading Center rate for NA-CA motion. Figure 7 shows the linear velocities of the Caribbean, North American, Cocos, and Pacific (PA) plates at 15°N, 95°W, a point near the NA-CO-CA triple junction. (This construction is valid, although the Pacific plate is not present at this point.) The direction and rate of CO-NA motion are given by global closure, including the PA-CO and PA-NA vectors. Both are reasonably well known, since both rate and azimuth data are available on these boundaries. The resulting CO-NA direction agrees with the slip vectors from the CO-NA boundary along the northwestern Middle America Trench. We thus consider CO-NA motion known, and examine the CO-CA motion predicted at this point by the alternative models for CA-NA motion. The vector diagram illustrates that the predicted direction of CO-CA motion depends on the assumed rate of NA-CA motion. As shown in Figure 6, the direction derived from the Cayman Spreading Center rate fits the observed slip vectors better than the more northerly direction resulting from the higher rate assumed by Sykes et al.

South America-Caribbean Direction

An additional discriminant between the models is the direction of SA-CA motion inferred from geologic data. Structural data and focal mechanisms along the northern

margin of South America suggest approximately NW-SE convergence between the Caribbean and South America since at least 10 Ma [Kellogg and Bonini, 1982, 1985; Speed, 1985]. Seismicity patterns and focal mechanisms suggest that present-day oblique convergence is manifested as slow obduction of the southern Caribbean onto South America east of the El Pilar fault [Perez and Aggarwal, 1981; Speed, 1985]. The predicted SA-CA directions of motion, shown in Figure 1, at 9°N, 68°W, from the NUVEL-1, RM2, and Sykes et al. models are 13 mm/yr at N80°W, 22 mm/yr at N77°W, and 42 mm/yr at S78°W, respectively. All three models have a right-lateral component of strike-slip motion. The Sykes et al. prediction of oblique extension is inconsistent with the observed convergence. In contrast, NUVEL-1 and RM2, which rely on closure from other plate circuits to constrain the pole position (since no SA-CA relative motion data are incorporated into these models), predict highly oblique convergence in accord with the geologic and seismic data.

CONVERGENCE RATE AND AZIMUTH FROM SUBDUCTION ZONE GEOMETRY

Because the NA-CA motion is better described by the approximately 2 cm/yr rate and azimuth corresponding to the magnetic anomalies and transforms at the Cayman Spreading Center than the approximately 4 cm/yr rate and azimuth inferred from the Lesser Antilles subduction zone geometry, we examined the procedure used by Sykes et al. [1982] for this estimation.

They report finding the direction along which the Wadati-Benioff zone lengths are most uniform and assuming that this direction was the convergence azimuth. A number of procedures can be used to define slab length from the seismicity; Sykes et al. [1982] did not show or list

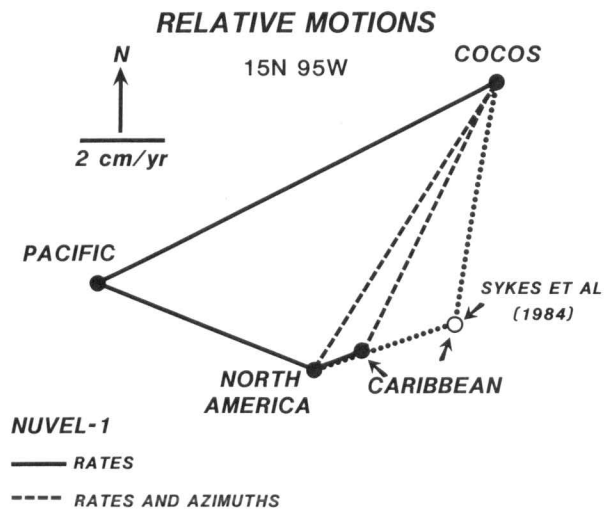


Fig. 7. The velocity vectors of the Caribbean, North America, Cocos, and Pacific plates at 15°N, 95°W, in linear velocity space. Solid and dashed lines are predictions of the NUVEL-1 global plate motion model; dotted lines are predictions of the Sykes et al. model. The vectors show the effect of different NA-CA rates on the azimuth of CO-CA motion. The NA-CA rate (solid line) predicted by NUVEL-1, using the 1.5 cm/yr Cayman spreading rate, fits the direction of CO-CA motion indicated by slip vectors at the Middle America Trench. In contrast, the higher NA-CA rate assumed in the Sykes et al. [1982] model (dotted line) predicts too northerly an azimuth.

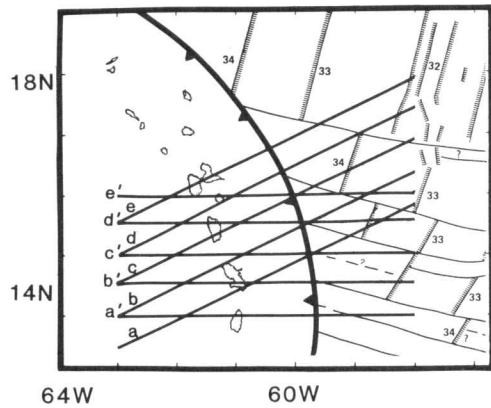


Fig. 8. Location map for Lesser Antilles seismicity cross sections. Primed sections are oriented east-west, approximately the convergence direction predicted by RM2 [Minster and Jordan, 1978]. Unprimed sections are oriented N65°E, the convergence direction predicted by Sykes *et al.* [1982]. Magnetic anomaly identifications are shown for the Atlantic seafloor. Map taken from Westbrook *et al.* [1984].

the cross sections and measurements they used. We measured lengths for five seismicity cross sections (Figure 8) along the RM2 azimuth (EW) and five along the Sykes *et al.* azimuth (N65°E). For these two sets of sections (Figure 9) we found both the mean length and the standard deviation to be statistically indistinguishable. We thus conclude that, for this case, this procedure is inadequate to determine the azimuth of convergence.

The rate estimation method they used relies on a relationship between the length of the Benioff zone, convergence rate, and age of the subducting lithosphere that results from the thermal structure of the downgoing slab. An analytic model of the potential temperature field (tem-

perature neglecting the effects of adiabatic heating and phase changes) in the slab suggests that the distance along the slab to a given isotherm depends on the product of the two key parameters of the subduction process: lithospheric age and convergence rate [McKenzie, 1969, 1970]. Comparison of thermal models to the distribution of Benioff zone seismicity [Sleep, 1973] suggests that earthquakes occur only in portions of the slab below a given temperature. If so, the length of the subduction zone indicated by seismicity should be proportional to the product of lithospheric age and convergence rate. A compilation of data by Molnar *et al.* [1979] shows this effect, although the seismicity seems limited by constant potential temperature rather than the actual temperature. This was resolved by Wortel [1982], using a model in which seismicity was bounded by a material strength rather than a temperature. Calculations of strength with a depth dependent rheology incorporating both temperature and pressure effects yield a curve of limiting strength for seismicity that appears similar to a potential temperature limit.

Figure 10 shows the data used by Molnar *et al.* [1979] plotted with convergence rate as a function of slab length divided by age. Following Sykes *et al.* [1982], we deleted all data from the Caribbean subduction zones. A least squares line constrained to pass through the origin is also shown. We then used the length of the Wadati-Benioff zone on the profiles in Figure 9 and ages from magnetic anomalies for each profile (Figure 8) to find the mean length/age value,  $2.7 \pm 0.3$  cm/yr. The least squares relationship yields a convergence velocity of  $2.3 \pm 0.3$  cm/yr, close to that estimated by models using the Jordan [1975] geometry and the Cayman Spreading Center rate. This is not surprising since, in their original paper, Molnar *et al.* included the Lesser Antilles arc as a data point with a 2 cm/yr convergence rate.

## ANTILLES BENIOFF ZONE LENGTHS

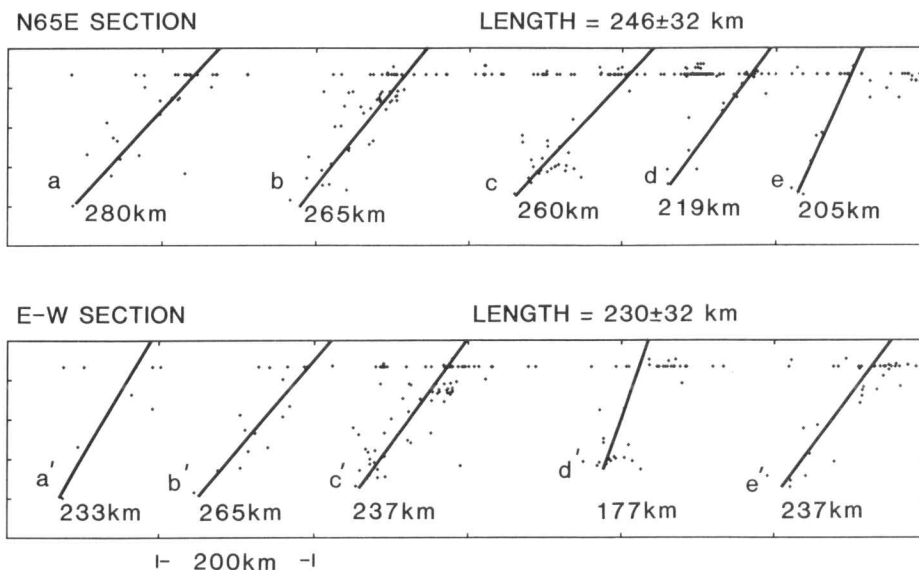


Fig. 9. Lesser Antilles seismicity cross sections and lengths. All sections are 50 km wide. Sykes *et al.* [1982] reported that they determined the azimuth of convergence to be that yielding the most uniform Wadati-Benioff zone lengths. The mean and standard deviation of lengths in the directions predicted by Sykes *et al.* [1982] and by RM2 [Minster and Jordan, 1978] show no significant difference.

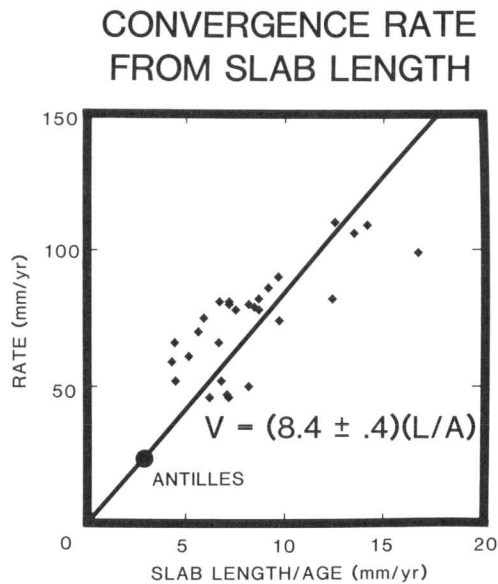


Fig. 10. Subduction zone length, convergence rate and subducting plate age data from *Molnar et al.* [1979]. Using a relation derived from these data, *Sykes et al.* [1982] reported that they determined the convergence rate at the Antilles to be about 4 cm/yr. The subduction zone lengths shown in Figure 9 yield a rate closer to 2 cm/yr.

The higher rate,  $3.7 \pm 0.5$  cm/yr, determined by Sykes et al. using the *Molnar et al.* [1979] data and this method results from adjustments to the slab age made for oblique subduction, and selection of subsets of the data. Without these adjustments, the values they use (265-km length, 80 m.y. age) and the relationship of Figure 10 yield 2.8 cm/yr. We suggest that, since such adjustments produce significant changes in the estimated rate, the method is insufficiently robust for reliable estimation of convergence rates.

#### DISCUSSION

Based on the previous tests, we conclude that models using the *Jordan* [1975] geometry provide the better description of the instantaneous motion between the North American and Caribbean Plates. It is important, however, to recognize the limitations of this statement.

First, global models such as RM2 and NUVEL-1 describe plate motions averaged over the several million years used in measuring spreading rates. For example, NUVEL, which uses magnetics out to anomaly 2', averages over 3 m.y. The models do not attempt to describe motion prior to their averaging interval, which could have been different.

Second, the Caribbean Plate is only weakly "tied" into the global plate circuit (Figure 5). The only rate data available for NA-CA motion are at the Cayman Spreading Center. No data from the SA-CA or NZ-CA boundaries are used. Nonetheless, the closure provided by the CO-CA direction shown by slip vectors at the Middle America Trench constrains the NA-CA rate well enough to exclude the *Sykes et al.* [1982] model.

Third, the conclusion applies to the Caribbean Plate as a rigid entity. Relative plate motion models use data on plate boundaries to describe the motion of entire plates,

assuming the plates are rigid. Since the rate and azimuth of motion at the Cayman Spreading Center were used to characterize NA-CA motion, these results place no constraint on the complex deformation in the Greater Antilles unless the deformation extends far enough to the west that the Cayman Spreading Center motion is less than the total NA-CA motion. If this is not the case, portions of the Greater Antilles can have motion different from the Caribbean Plate. Although much of the motion appears to represent E-W strike slip [*Burke et al.*, 1984] consistent with a diffuse NA-CA boundary, other motions, including north-south shortening near Puerto Rico [*Ladd et al.*, 1977], would not violate our results. Instead, other motions would suggest complexities beyond the model of a simple boundary between distinct North American and Caribbean Plates. The misfit to the Lesser Antilles slip vectors may be due to similar complexities.

The relative motions do, however, offer some insight into the extent to which Cayman Spreading Center motion is representative of NA-CA motion. We have seen that the Jordan geometry, in which the Cayman Spreading Center motion corresponds to all NA-CA motion, fits the data better than the Sykes et al. model in which an equal fraction of the plate motion occurs in the Greater Antilles. The data thus suggest that deformation within the Greater Antilles is either small or not reflected in the Cayman Spreading Center motion since greater NA-CA rates provide poorer fits to the Middle America Trench data (Figures 6, 7). Specifically, the approximately 2 cm/yr of strike slip implied by the Sykes et al. model seems unlikely; we cannot exclude the possibility that the 0.4 cm/yr of strike slip observed in Jamaica over the last 10 m.y. [*Burke et al.*, 1980] extends to the Cayman Spreading Center and should be added into the NA-CA motion. We consider 0.5 cm/yr motion to be below the resolution of our analysis, which is limited by several factors. The Cayman rate, derived from the few available magnetic profiles over a short ridge segment, may be somewhat inaccurate or unrepresentative. It may be inappropriate to compare it with geological data averaged over different time intervals. Finally, deviations from rigidity within the Caribbean Plate and elsewhere in the plate circuit may contribute to the misfit of the model to the data.

These observations thus summarize the sense in which we find it useful to consider the Caribbean as a rigid plate. It is rigid to the extent that NA-CA motion inferred from the Cayman Spreading Center is consistent with CO-CA motion at the Middle America Trench. These data alone cannot, on the other hand, distinguish a model in which the Caribbean is a rigid plate with complex boundaries in the Antilles and northern South America from a situation in which much of the eastern Caribbean does not act rigidly. The former possibility, which seems more plausible, is the case observed for other plates and suggested by the distribution of seismicity along the boundaries of the Caribbean Plate.

#### CONCLUSIONS

The *Jordan* [1975] model better describes Caribbean Plate motions than the model of *Sykes et al.* [1982]. Comparison of the alternative models demonstrates two general principles applicable to other plate boundaries: (1) all



relevant plates should be incorporated in an internally consistent model, as demonstrated in this study by the usefulness of the direction of CO-CA motion and (2) data from magnetic anomalies, transform azimuths, and slip vectors better determine relative plate motions than Wadati-Benioff zone geometry.

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## REFERENCES

- Bowin, C., Caribbean gravity field and plate tectonics, *Geol. Soc. Am. Spec. Pap.*, 169, 1976.
- Burbach, G. V., C. Frohlich, W. D. Pennington, and T. Matumoto, Seismicity and tectonics of the subducted Cocos plate, *J. Geophys. Res.*, 89, 7719-7735, 1984.
- Burkart, B., and S. Self, Extension and rotation of crustal blocks in northern Central America and effect on the volcanic arc, *Geology*, 13, 22-26, 1985.
- Burke, K., J. Grippi, and A. M. C. Sengor, Neogene structures in Jamaica and the tectonic style of the northern Caribbean Plate boundary zone, *J. Geol.*, 88, 375-386, 1980.
- Burke, K., C. Cooper, J. F. Dewey, P. Mann, and J. L. Pindell, Caribbean tectonics and relative plate motions, in *The Caribbean-South American Plate Boundary and Regional Tectonics*, edited by W. E. Bonini, R. B. Hargraves, and R. Shagam, pp. 31-63, Geological Society of America, Boulder, Colo., 1984.
- Case, J. E., T. L. Holcombe, and R. G. Martin, Map of geologic provinces in the Caribbean region, in *The Caribbean-South American Plate Boundary and Regional Tectonics*, edited by W. E. Bonini, R. B. Hargraves, and R. Shagam, pp. 1-30, Geological Society of America, Boulder, Colo., 1984.
- Chael, E. P., and G. S. Stewart, Recent large earthquakes along the Middle America Trench and their implications for the subduction process, *J. Geophys. Res.*, 87, 329-338, 1982.
- Chase, C. G., The N plate problem of plate tectonics, *Geophys. J. R. Astron. Soc.*, 29, 117-122, 1972.
- Dean, B. W., and C. L. Drake, Focal mechanism solutions and tectonics of the Middle America arc, *J. Geol.*, 86, 111-128, 1978.
- DeMets, C., R. G. Gordon, S. Stein, D. F. Argus, J. Engeln, P. Lundgren, D. G. Quible, C. Stein, S. A. Weinstein, D. A. Wiens, and D. F. Woods, NUVEL-1: A new global plate motion data set and model, *Eos Trans. AGU*, 66, 368-369, 1985.
- Dewey, J. F., and J. L. Pindell, Neogene block tectonics of eastern Turkey and northern South America: Continental applications of the finite difference method, *Tectonics*, 4, 71-83, 1985.
- Dorel, J., Seismicity and seismic gaps in the Lesser Antilles Arc and earthquake hazards in Guadeloupe, *Geophys. J. R. Astron. Soc.*, 67, 679-696, 1981.
- Dziewonski, A. M., A. Friedman, D. Giardini, and J. H. Woodhouse, Global seismicity of 1982: Centroid moment tensor solutions for 308 earthquakes, *Phys. Earth Planet. Int.*, 33, 76-90, 1983a.
- Dziewonski, A. M., A. Friedman, and J. H. Woodhouse, Centroid moment tensor solutions for January-March, 1983, *Phys. Earth Planet. Int.*, 33, 71-75, 1983b.
- Dziewonski, A. M., J. E. Franzen, and J. H. Woodhouse, Centroid moment tensor solutions for April-June, 1983, *Phys. Earth Planet. Int.*, 33, 243-249, 1983c.
- Dziewonski, A. M., J. E. Franzen, and J. H. Woodhouse, Centroid moment tensor solutions for July-September, 1983, *Phys. Earth Planet. Int.*, 34, 1-8, 1984a.
- Dziewonski, A. M., J. E. Franzen, and J. H. Woodhouse, Centroid moment tensor solutions for October-December 1983, *Phys. Earth Planet. Int.*, 34, 129-136, 1984b.
- Girardin, N., and R. Gaulon, Microseismicity and stresses in the Lesser Antilles dipping seismic zone, *Earth Planet. Sci. Lett.*, 62, 340-348, 1983.
- Hess, H. H., and J. C. Maxwell, Caribbean research project, *Geol. Soc. Am. Bull.*, 64, 1-6, 1953.
- Holcombe, T. L., P. R. Vogt, J. E. Matthews, and R. R. Murchison, Evidence for seafloor spreading in the Cayman Trough, *Earth Planet. Sci. Lett.*, 20, 357-371, 1973.
- Jordan, T. H., The present-day motions of the Caribbean Plate, *J. Geophys. Res.*, 80, 4433-4439, 1975.
- Kanamori, H., and G. S. Stewart, Seismological aspects of the Guatemala earthquake of February 4, 1976, *J. Geophys. Res.*, 83, 3427-3434, 1978.
- Kellogg, J. N., and W. E. Bonini, Subduction of the Caribbean Plate and basement uplifts in the overriding South American plate, *Tectonics*, 1, 251-276, 1982.
- Kellogg, J. N., and W. E. Bonini, Reply to "Comments on 'Subduction of the Caribbean Plate and basement uplifts in the overriding South American plate' by J. N. Kellogg and W. E. Bonini" by C. Schubert *Tectonics*, 4, 785-790, 1985.
- Ladd, J. W., J. L. Worzel, and J. S. Watkins, Multifold seismic records from the northern Venezuela Basin and the north slope of the Muertos Trench, in *Island Arcs, Deep-sea Trenches, and Back-arc Basins, Maurice Ewing Ser.*, 1, edited by M. Talwani and W. C. Pitman, pp. 41-56, AGU, Washington, D.C., 1977.
- Macdonald, K. C., and T. L. Holcombe, Inversion of magnetic anomalies and sea-floor spreading in the Cayman Trough, *Earth Planet. Sci. Lett.*, 40, 407-414, 1978.
- Mann, P., and K. Burke, Neotectonics of the Caribbean, *Rev. Geophys.*, 22, 309-362, 1984.
- McCann, W. R., and L. R. Sykes, Subduction of aseismic ridges beneath the Caribbean Plate: Implications for the tectonics and seismic potential of the northeastern Caribbean, *J. Geophys. Res.*, 89, 4493-4519, 1984.
- McKenzie, D. P., Speculations on the consequences and causes of plate motions, *Geophys. J. R. Astron. Soc.*, 18, 1-32, 1969.
- McKenzie, D. P., Temperature and potential temperature beneath island arcs, *Tectonophysics*, 10, 357-366, 1970.
- Minster, J. B., and T. H. Jordan, Present-day plate motions, *J. Geophys. Res.*, 83, 5331-5354, 1978.
- Minster, J. B., T. H. Jordan, P. Molnar, and E. Haines, Numerical modeling of instantaneous plate tectonics, *Geophys. J. R. Astron. Soc.*, 36, 541-576, 1974.
- Molnar, P., and L. R. Sykes, Tectonics of the Caribbean and middle America regions from focal mechanisms and seismicity, *Geol. Soc. Am. Bull.*, 80, 1639-1684, 1969.
- Molnar, P., D. Freedman, and J. S. F. Shih, Lengths of intermediate and deep seismic zones and temperatures in downgoing slabs of lithosphere, *Geophys. J. R. Astron. Soc.*, 56, 41-54, 1979.
- Perez, O. J., and Y. P. Aggarwal, Present-day tectonics of the southeastern Caribbean and northeastern Venezuela, *J. Geophys. Res.*, 86, 10791-10804, 1981.
- Pindell, J. L., and J. F. Dewey, Permo-Triassic reconstruction of western Pangea and the evolution of the Gulf of Mexico/Caribbean region, *Tectonics*, 1, 179-211, 1982.
- Plafker, G., Tectonic aspects of the Guatemala earthquake of 4 February 1976, *Science*, 193, 1201-1208, 1976.
- Rosencrantz, E., and J. G. Sclater, Depth and age in the Cayman Trough, *Earth Planet. Sci. Lett.*, 79, 133-144, 1986.
- Schubert, C., Are the Venezuelan fault systems part of the southern Caribbean plate boundary?, *Geol. Rundsch.*, 70, 542-551, 1981.
- Silver, E. A., J. E. Case, and H. J. MacGillivray, Geophysical study of the Venezuelan borderland, *Geol. Soc. Am. Bull.*, 86, 213-226, 1975.
- Sleep, N. H., Teleseismic P-wave transmission through slabs, *Bull. Seismol. Soc. Am.*, 63, 1349-1373, 1973.
- Speed, R. C., Cenozoic collision of the Lesser Antilles Arc and

- continental South America and the origin of the El Pilar Fault, *Tectonics*, 4, 41-69, 1985.
- Speed, R. C., G. K. Westbrook, B. Biju-Duval, J. W. Ladd, A. Mascle, J. C. Moore, J. B. Saunders, J. E. Schoonmaker, and S. Stein, *Atlas 10, Ocean Margin Drilling Program, Lesser Antilles and Adjacent Ocean Floor*, Marine Science International, Woods Hole, Mass., 1984.
- Stein, S., J. Engeln, D. Wiens, K. Fujita, and R. Speed, Subduction seismicity and tectonics in the Lesser Antilles Arc, *J. Geophys. Res.*, 87, 8642-8664, 1982.
- Stein, S., J. Engeln, D. Wiens, R. Speed, and K. Fujita, Slow subduction of old lithosphere in the Lesser Antilles, *Tectonophysics*, 1988, 139-148, 1983.
- Stein, S., D. Wiens, J. F. Engeln, and K. Fujita, Comment on "Subduction of aseismic ridges beneath the Caribbean Plate: Implications for the tectonics and seismic potential of the northeastern Caribbean" by W. R. McCann and L. R. Sykes, *J. Geophys. Res.*, 91, 784-786, 1986.
- Sykes, L. R., W. R. McCann, and A. L. Kafka, Motion of Caribbean Plate during last 7 million years and implications for earlier Cenozoic movements, *J. Geophys. Res.*, 87, 10656-10676, 1982.
- Vierbuchen, R. C., Jr., The tectonics of northeastern Venezuela and the southeastern Caribbean Sea, 193 pp., Ph.D. thesis, Princeton Univ., Princeton, N.J., 1979.
- Vierbuchen, R. C., The geology of the El Pilar fault zone and adjacent areas in northeastern Venezuela, in *The Caribbean-South American Plate Boundary and Regional Tectonics*, edited by W. E. Bonini, R. B. Hargraves, and R. Shagam, pp. 189-212, Geological Society of America, Boulder, Colo., 1984.
- Wadge, G., and K. Burke, Neogene Caribbean Plate rotation and associated Central American tectonic evolution, *Tectonics*, 2, 633-643, 1983.
- Westbrook, G. K., A. Mascle, and B. Biju-Duval, Geophysics and the structure of the Lesser Antilles forearc, *Initial Rep. Deep Sea Drill. Proj.*, 78A, 23-38, 1984.
- Wortel, M. J. R., Seismicity and rheology of subducted slabs, *Nature*, 296, 553-556, 1982.
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