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Geologic evaluation of plate kinematic models for the North American–Caribbean plate boundary zone

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ABSTRACT

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Four published plate kinematic models for the present-day North American–Caribbean plate boundary predict significantly different fault behavior along this dominantly strike-slip plate boundary zone (PBZ). Using a computer graphics system, we compare the deformational pattern predicted by the four kinematic models with geologic and seismic observations along the entire length of the PBZ from Central America to the northern Lesser Antilles. Our results indicate that none of the kinematic models predict all the geologic and seismic observations across the entire PBZ. However, all four models predict mapped fault character and observed earthquake focal mechanisms along certain segments of the PBZ. We conclude that the present-day deformation within the North American–Caribbean plate boundary zone cannot be described by rotation about a single pole. Instead, the Caribbean "plate" appears to be segmented into at least three major "sub-plates" or blocks, each of which requires an individual pole of rotation to describe its motion relative to the North American plate. Sub-plate boundaries correspond to two poorly studied zones of diffuse deformation within the Caribbean plate (Honduras Depression of Central America and Beata Ridge of the Caribbean Sea).

Introduction

The purpose of this paper is to evaluate the ability of four previously proposed kinematic models of present-day plate motion to explain post-Miocene tectonic deformation along the North American–Caribbean plate boundary zone (PBZ) (Fig. 1). By "plate kinematic models", we mean models that focus on the movement of plates with respect to one another.

Four previous plate kinematic models for the Caribbean–North American relative plate motion (MacDonald, 1976; Minster and Jordan, 1978; Sykes et al., 1982; Stein et al., 1988) have predicted significantly different rates and directions of plate movement between the North American (NOAM) and the Caribbean (CARIB) plates (Fig. 2 and Table 1). Differences between models result largely from the use of data sets emphasizing different aspects of the seismicity and geology of the complex PBZ.

The method of this paper is to graphically compare the geologic predictions made by each kinematic model and then compare these predictions to geologic and seismic constraints. Resolving the controversy about Caribbean relative plate motion is important for several reasons: (1) the assumption of a rigid Caribbean plate in Cretaceous and Cenozoic times may not be valid as suggested by paleomagnetic work in Central America (Gose, 1985) and the Greater Antilles (Vincenz and Dasgupta, 1978; Van Fossen and Channell, 1988); (2) an accurate plate kinematic model can predict fault character and rate of slip in poorly mapped on- and offshore areas; and (3) an accurate kinematic model is a prerequisite for

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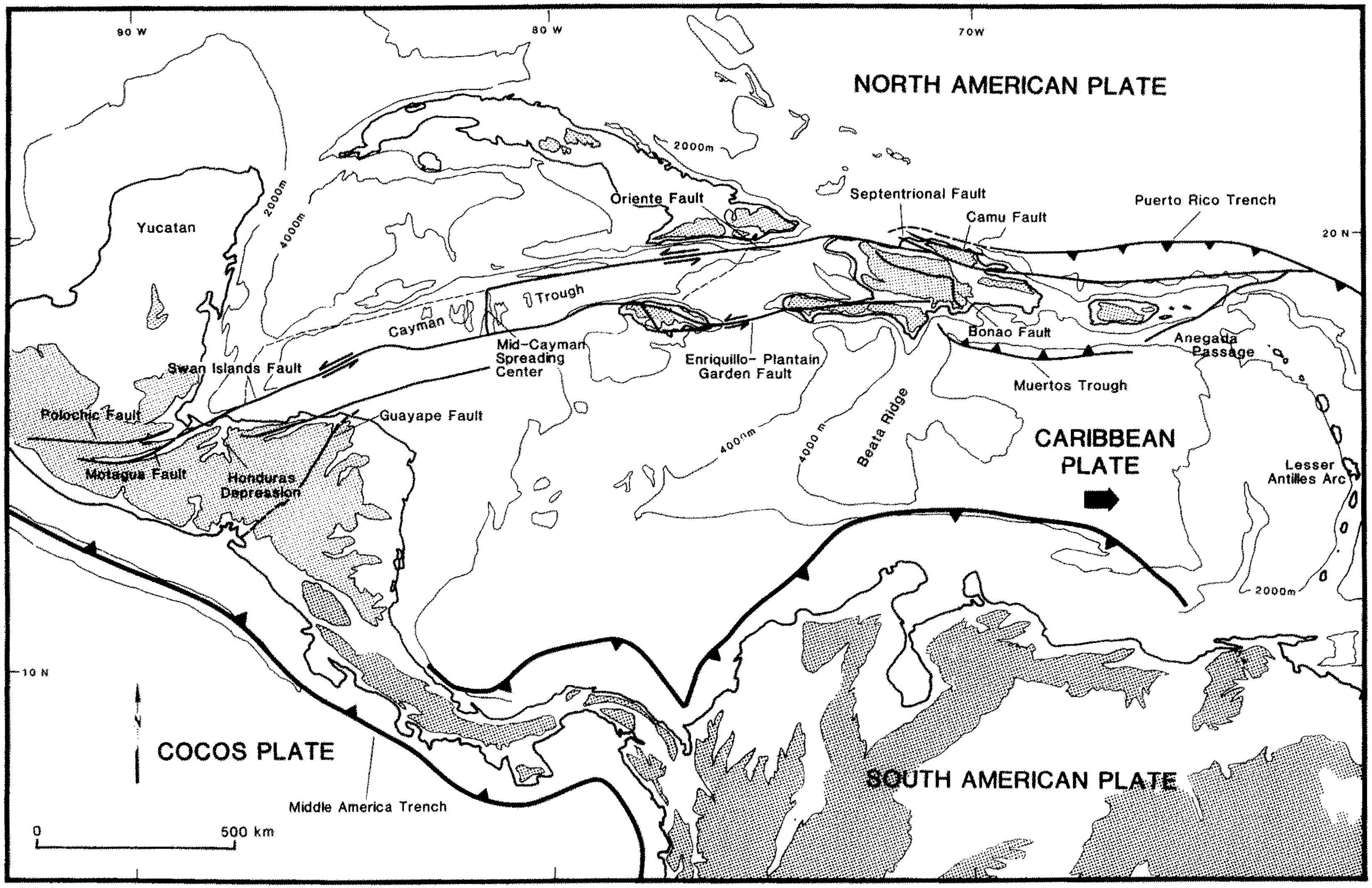

Fig. 1. Major fault structures around the Caribbean plate. The North America–Caribbean plate boundary zone (PBZ) is a dominantly left-lateral strike-slip boundary which accommodates the eastward motion of the Caribbean plate relative to the North American plate. Topography of the northern Caribbean above 200 m is shown in grey and is mostly produced by vertical movements along strike-slip zones. Bathymetry is from Case and Holcombe (1980).

more interpretative dynamic models that predict stress fields in PBZ's.

This paper is divided into four sections. In the first section, we summarize the techniques for locating poles of rotation and explain why previous kinematic models have yielded different results. In the second section, we describe our method for graphically comparing these models by using a three-dimensional computer graphics system. In the third section, we compile structural data from the northern Caribbean which is used to constrain plate kinematic models. In the final section, we evaluate the four kinematic models in the light of the geologic constraints.

Previous models and assumptions

The four previously proposed pole positions for NOAM–CARIB relative plate motion are summarized in Table 1 and plotted on a hemispherical map projection in Fig. 2. The large differences in pole positions can be attributed to the two types of data sets used to constrain the pole position. Data sets include the observed strikes of strike-slip faults in the Cayman Trough as determined from geologic and bathymetric maps, and azimuths of slip vectors from earthquakes occurring on interplate faults. Other types of data used to determine the pole positions are the rate of NOAM–CARIB relative motion that was derived using heat flow data and the spacing of dated marine magnetic anomalies from the Cayman Trough (Rosencrantz et al., 1988) and the configuration of the subducted seismic zone of the North American plate beneath the northeastern Caribbean (Sykes et al., 1982).

Transform fault data

The pole of rotation can be located using transform fault data by constructing great circles perpendicular to the strike of the transform. Great

TABLE 1

Rotation parameters for motion of the Caribbean plate relative to the North American plate

Reference	Euler vector		Rate (degrees/ m.y.)	Data used, listed in decreasing order of importance [a]
	Lat. (°N)	Long. (°E)		
MacDonald (1976)	−15	−75	0.4	Least-square fit of great circles along the Swan Island and Oriente Fault.
Minster and Jordan (1978) RM2 BFV [b]	−34.18	−70.40	0.225	(1) 1.9 cm/yr spreading rate of Cayman Trough based on magnetic anomalies. (2) three fault strikes each from the Swan island and Oriente Fault. (3) One slip vector each from the Motagua and the Oriente Fault.
Sykes et al. (1982)	66.0	132.0	0.36	Five slip vectors from the Puerto Rico Trench and the northern Lesser Antilles; one slip vector each from the Motagua and the Oriente Fault.
Stein et al. (1988) NUVEL-1 BFV [b]	−57.0	−59.8	0.14	(1) 1.5 cm/yr spreading rates of the Cayman Trough based on magnetic anomalies. (2) Three fault strikes each from the Swan Island and the Oriente Fault. (3) One slip vector each from the Motagua, the Swan Island, and the Oriente Fault; two slip vectors from the northern Lesser Antilles.

[a] See original papers for details; faults shown in Fig. 1; earthquake focal mechanisms shown in Fig. 5.

[b] BFV = Best Fitting Vector.

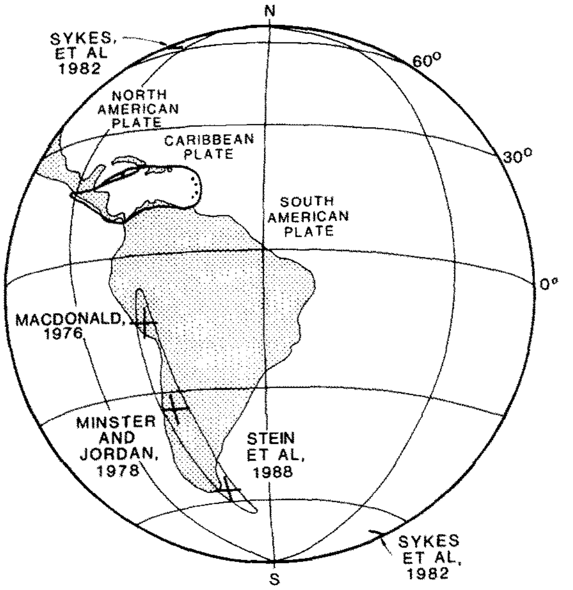

Fig. 2. Locations of published poles of rotation for the motion of the Caribbean plate relative to the North American plate. The ellipse encloses three poles based mainly on fault data from the Cayman Trough. The Sykes et al. (1982) pole is based mainly on earthquake data from the northeastern Caribbean. This pole lies at the periphery of this globe and is shown with its antipole.

circles, measured from localities at different transform faults, will all intersect in a single point—the pole of rotation (Fig. 3).

A major source of error in this method is the use of transform fault segments that are not "slip-parallel", that is, the transform faults may not be exactly parallel to small circles about the pole of rotation (Fig. 3, *A*). Whereas transform faults in oceanic regimes tend to be slip-parallel, those in lithologically heterogeneous island arc or continental lithosphere commonly accommodate a significant component of interplate divergence or convergence, resulting in "transtension" (Fig. 3, *B*) or "transpression" (Fig. 3, *C*), respectively. A second source of error in the transform method results when long transform segments are actually composed of shorter transforms that are connected by either shortening "restraining bends" (Fig. 4A), extensional "releasing bends" (Fig. 4B) or combinations of both types of bends (Fig. 4C). A final source of error occurs where faults of the plate boundary zone accommodate localized, internal plate deformation rather than interplate motion. Internal plate deformation may occur where active transform faults of the PBZ intersects previously deformed rock. Despite these three uncertainties, Minster and Jordan (1978) conclude that "the most precise estimate of relative motion direction are the azimuths of well-mapped transform faults".

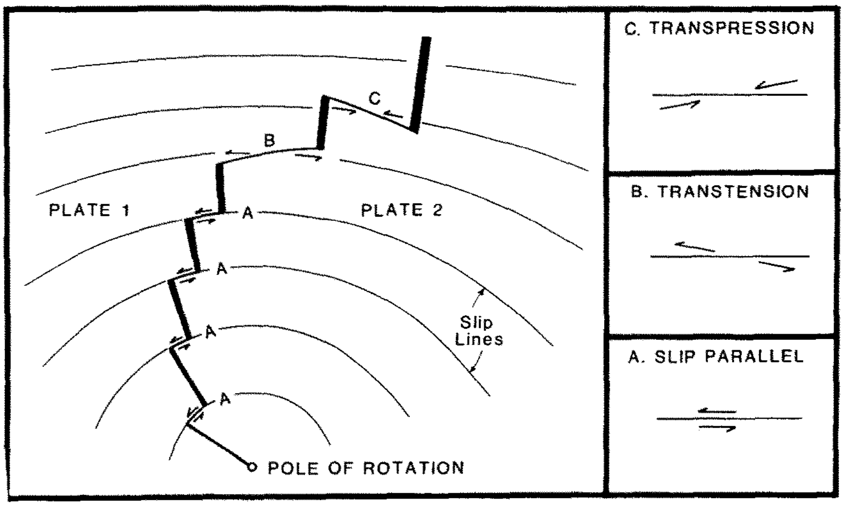

Fig. 3. Relationship between slip lines about a pole of rotation, strike-slip faults, and spreading ridges (heavy black lines). Letters *A*, *B*, and *C* indicate three types of strike-slip faulting determined by the angular relationship between the slip line about the pole of rotation and the strike of the strike-slip fault: *A* = slip-parallel fault in which slip is parallel to the fault; *B* = transtensional fault with a component of divergence caused by obliquity between the slip line and the fault; *C* = transpressional fault with a component of convergence caused by obliquity between the slip line and the fault.

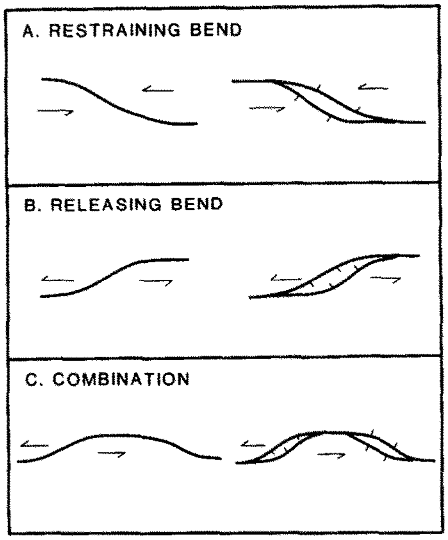

Fig. 4. Method used in this paper of plotting displacement along faults which are oblique to slip lines about the pole of rotation. Faults shown to the left are double, identical data sets. Rotation of one data set along the direction given by the slip lines (half arrows) results in (a) transpressional fault block overlap at a restraining fault bend; (B) transtensional fault block gap at a releasing fault bend; (C) fault block overlap and gap at a combination of restraining and releasing bends. Tickmarks indicate the downthrown side of faults.

Three of the four models under discussion (MacDonald, 1976; Minster and Jordan, 1978; and Stein et al., 1988) use transform fault data from the Cayman Trough (Table 1). All groups have avoided the use of transform fault strike data from Central America and Hispaniola because plate movement there is accommodated by several, simultaneously active sets of faults and folds over a zone up to 250 km wide (Mann and Burke, 1984a).

Slip vector data

The slip vector method requires earthquakes produced by motion between adjacent plates. Slip vectors of earthquakes produced by plate interaction along intraplate faults or at complex fault bends, rather than at simple, "plate to plate" contacts, produce an important source of error for this method. Therefore, careful selection of consistent sets of interplate seismic events and slip vectors is a critical step in using the slip vector method to constrain an accurate plate kinematic model.

In Fig. 5, we have compiled epicenter data of magnitude 3.0 and larger from the Caribbean region using a file provided by the National Earthquake Information Service. Focal mechanisms and slip vector data from other data files, unpublished dissertations, and published papers are also shown. The sources of slip vector data are listed in Table 2. As can be seen in Fig. 5, information on focal mechanisms and earthquake slip vectors is unevenly distributed along the PBZ. This uneven distribution reflects both poor station coverage on islands, such as Jamaica and Cuba, and small number of large earthquakes during the past 20 to 30 years. Nevertheless, a considerable number of earthquake focal mechanisms from the Cayman Trough and the Lesser Antilles have focal plane and slip vector orientations which are parallel to the overall strike of the PBZ. Therefore, the average slip vector for these earthquakes probably reflects the overall direction of interplate motion rather than local internal plate deformation at fault bends or reactivation of older, cross-cutting structures.

Of the four plate kinematic models, only the MacDonald (1976) model does not use slip vector data. The Minster and Jordan (1978) and Stein et al. (1988) models are similar in that they both use slip vector data from the Cayman Trough. In contrast, the Sykes et al. (1982) model omits earthquake data from the Cayman Trough while adding earthquake data from the eastern Greater Antilles. The selection of data by Sykes et al. (1982) results in their distinctively different pole position (Fig. 2).

Spreading velocity data

The Mid-Cayman Spreading Center (Fig. 1) provides the only direct data indicating the velocity of relative plate motion between the North American and the Caribbean plate for the past 45–50 Ma (Rosencrantz et al., 1988). The length of the Cayman Trough spreading ridge is only 110 km, and spreading is extremely slow (1.5 mm/yr for the last 5.5 Ma according to Rosencrantz et al., 1988). The shortness of the spreading ridge excludes the spreading velocity method using regional variations in spreading rate to determine a

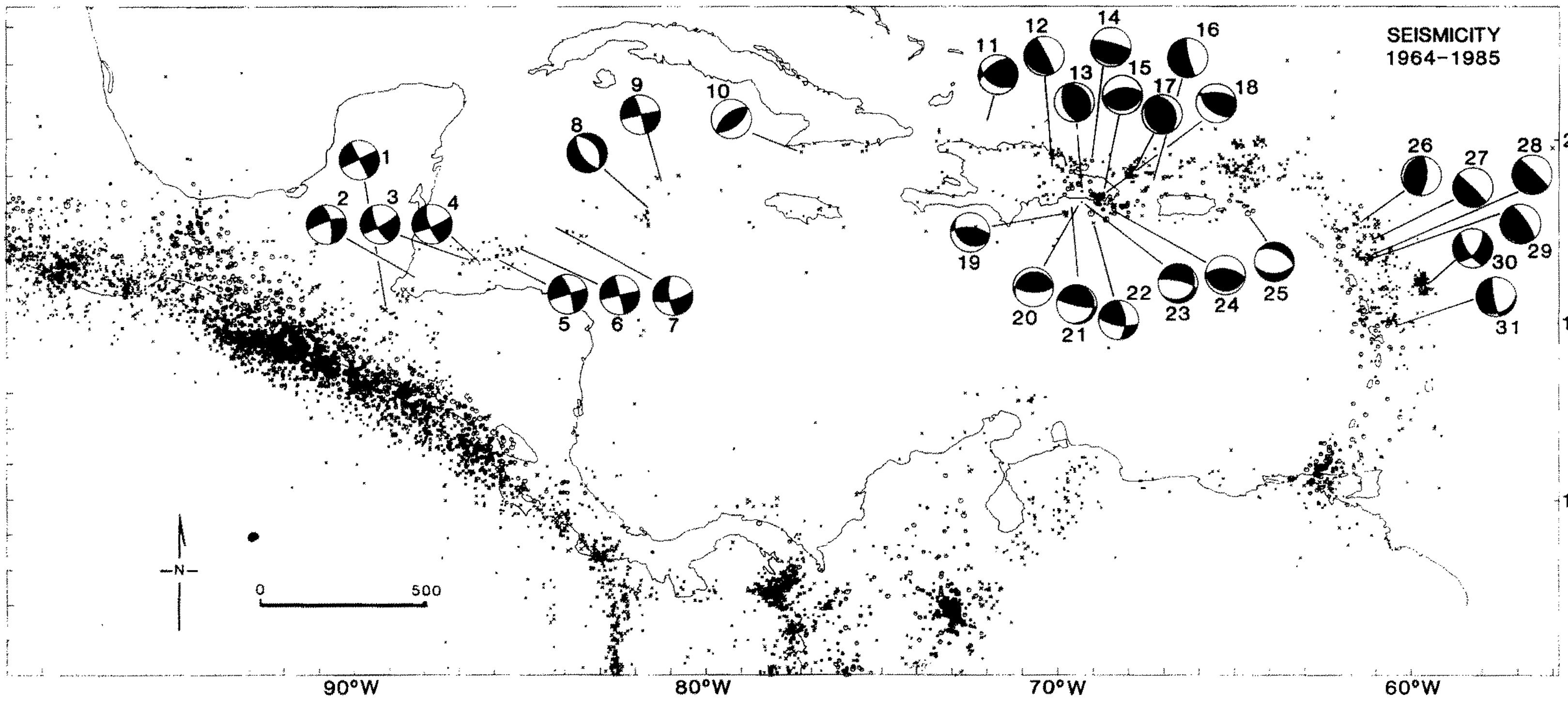

Fig. 5. Earthquakes with magnitude greater than 3 in the Caribbean for the period 1964–1985 (seismic data file provided by the National Earthquake Information Service). Numbers are keyed to published and unpublished sources for earthquake focal mechanisms which are listed in Table 2.

TABLE 2

Earthquake data from the North American–Caribbean Plate Boundary Zone

Event Number	Date (m/d/yr)	Depth (km)	M_b	Associated structure	Reference	Lat. (°N)	Long. (°E)
1	02/04/76	0-15	5.8	Motagua Fault	Kanamori and Stewart (1978)	15.27	−89.25
2	08/09/80	11		Swan Island Fault	Harvard Database	16.15	−88.27
3	08/20/77	38.2		Swan Island Fault	Harvard Database	16.71	−86.95
4	08/20/77	40.2		Swan Island Fault	Harvard Database	16.61	−86.65
5	03/23/66	9		Swan Island Fault	Molnar and Sykes (1969)	16.82	−85.90
6	09/12/57	12		Swan Island Fault	Molnar and Sykes (1969)	16.96	−85.60
7	04/10/82	10		Swan Island Fault	Harvard Database	17.72	−83.40
8	08/16/84	10		Mid-Cayman Ridge	Harvard Database	18.24	−81.62
9	07/25/62	10		Oriente Fault	Molnar and Sykes (1969)	18.90	−81.19
10	09/01/85	10		Oriente Fault	Harvard Database	19.67	−75.20
11	04/20/62	0		Bahamas Channel	Molnar and Sykes (1969)	20.50	−72.13
12	05/06/67	39		Septentrional Fault	Molnar and Sykes (1969)	19.3	−70.0
13	01/18/64	106		Eastern Hispaniola	Molnar and Sykes (1969)	18.66	−69.38
14	05/02/68	82	5.8	Samana Peninsula	Kafka (1980)	18.78	−69.64
15	09/01/84	38	5.2	Eastern Hispaniola	Harvard Database	18.31	−69.25
16	08/10/64	48		Puerto Rico Trench	Molnar and Sykes (1969)	19.03	−67.28
17	11/03/66	28		Puerto Rico Trench	Kafka (1980)	19.17	−67.92
18	12/22/64	117		Eastern Hispaniola	Molnar and Sykes (1969)	18.42	−68.73
19	09/13/71	55		Beata Ridge–Muertos Trough	Kafka (1980)	17.95	−69.73
20	06/25/84	42	5.5	Muertos Trough	Harvard Database	18.13	−69.35
21	06/24/84	33	5.2	Muertos Trough	Harvard Database	18.02	−69.64
22				Muertos Trough	USGS (1986)		
23	06/24/84	16	6.7	Muertos Trough	Harvard Database	18.09	−69.23
24	11/05/79	78	6.2	Muertos Trough	Harvard Database	17.96	−68.46
25	07/08/70	150		Anegada Passage	Kafka (1980)	17.96	−64.63
26	05/31/60	27		Lesser Antilles	Molnar and Sykes (1969)	17.72	−61.63
27	12/24/67	?		Lesser Antilles	Sykes (1982)		
28	05/15/69	50	5.7	Lesser Antilles	Kafka (1980)	16.75	−61.34
29	05/15/69	?		Lesser Antilles	Sykes (1982)		
30	12/25/69	7	6.4	Lesser Antilles	Kafka (1980)	15.77	−59.65
31	08/20/64	79		Lesser Antilles	Molnar and Sykes (1969)	14.87	−60.49

pole of rotation. The absence of this powerful constraint from the Mid-Cayman Trough spreading ridge is strikingly evident in Fig. 2, where the poles show up to 50° latitudinal variation. In the Minster and Jordan (1978) and Stein et al. (1988) models, rates of relative plate motion are constrained by the limited spreading velocity data from the Cayman Trough.

The location of the Sykes et al. (1982) pole is markedly different from the other three poles because transform strike and spreading velocity data from the Cayman Trough and the spreading ridge are not used to determine the pole position. The position of the Sykes et al. (1982) pole does not rely on earthquake slip vector data from the Cayman Trough but, instead, relies on slip vector data from the northeastern Caribbean (Table 1). The rate of relative plate motion is based mainly on calculations of the down-dip extent of the subducted slab beneath the northern Lesser Antilles and Puerto Rico. Stein et al. (1988) used the method of Sykes et al. (1982) to recalculate the rate (2.3 ± 0.3 cm/yr) and direction of plate movement from the seismicity associated with the subducted slab. Stein et al. (1988) concluded that the method of Sykes et al. (1982) is inadequate to determine the direction of movement.

Graphical comparisons of models

In order to compare the four kinematic models and explore their geologic implications, we have used an interactive 3-D computer graphics system with software developed by C. Scotese and M. Ross (see Ross and Scotese, 1988). The graphics system allows the rotation of tectonic elements such as plates or fault blocks on a spherical surface about a pole of rotation in real-time and avoids distortions inherent in two-dimensional map projections.

We digitized the active NOAM–CARIB plate boundary faults as depicted by Mann and Burke (1984a) (Fig. 1). We then rotated the Caribbean plate along these faults about poles given by the four plate kinematic models. In all reconstructions, the North American plate was held fixed. We include microplates which are postulated to exist within the plate boundary zone (Byrne et al., 1985), as part of the Caribbean plate because the seismic and geological evidence is presently not sufficient to define exact edges and motions of these blocks.

For each of the four kinematic models, we generated plate reconstructions for the times 2 m.y.b.p. (Late Pliocene) and 5 m.y.b.p. (Early Pliocene) (Figs. 6–9). For each reconstruction, the Caribbean plate was rotated about an angle given by the rate of relative plate motion in degrees per million years (Table 1). We chose these two Pliocene times for three reasons: (1) present-day plate motions are likely to have been broadly similar to Pliocene motions in most areas, although post-Miocene fault reorganizations have occurred locally (e.g., Calais and Mercier de Lépinay, 1989, 1990a); and (2) the geological data base of mapped folds and faults in the northern Caribbean can be greatly increased by extending the time span under consideration from the Quaternary into the Early Pliocene.

In the reconstructions of Figs. 6–9, three types of fault movement are observed. *Slip-parallel fault movement* occurs when the transform fault trace is parallel to the trace of a small circle about the pole of rotation (Fig. 3, *A*). *Transtensional fault movement* (Fig. 3, *B*) or *transpressional fault movement* (Fig. 3, *C*) occurs when the fault trace is slightly oblique to a small circle about the proposed pole of rotation. Transtensional fault movement results in extension, shown in our reconstruction as fault gaps between two fault blocks. Fault gaps are colored in green in Figs. 6–9. Transpressional fault movement results in convergence and produces an overlap between two fault blocks. Fault overlaps are colored in red. Where the fault trace is highly oblique to the slip direction, restraining bends (Fig. 4A) or pull-apart basins (Fig. 4B) are produced. These two types of bends commonly occur adjacent to one another (Fig. 4C). The tangent to a small circle can be constructed by connecting two originally adjacent points across any fault zone.

The fault pattern shown in Fig. 1 was compiled and published by Mann and Burke (1984a) after the MacDonald (1976) and Minster and Jordan (1978) models had been proposed. In particular, the Enriquillo–Plantain Garden fault zone (EPGFZ, Fig. 1) was not recognized as a continuous geologic feature from Jamaica to central Hispaniola until after all of the Caribbean plate models except Stein et al. (1988) were proposed. In the model of Sykes et al. (1982), half of the total rate of relative plate motion (3.7 ± 0.5 cm/yr) is suggested to occur on a diffuse zone of shallow seismicity (parallel to the EPGFZ) while the remainder of the motion was thought to be accommodated along the Septentrional–Oriente fault zone to the north (Fig. 8). The existence of the EPGFZ is consistent with the Sykes et al. (1982) model for partitioning of slip on two fault zones in the northeastern Caribbean and the presence of one or more microplates within the northeastern NOAM-CARIB strike–slip zone (Byrne et al., 1985).

Geologic evaluation of models

To evaluate the four kinematic models, we have compiled both published and unpublished data on major faults (that is, those with more than 1 km of measured offset) and folds of Pliocene or younger

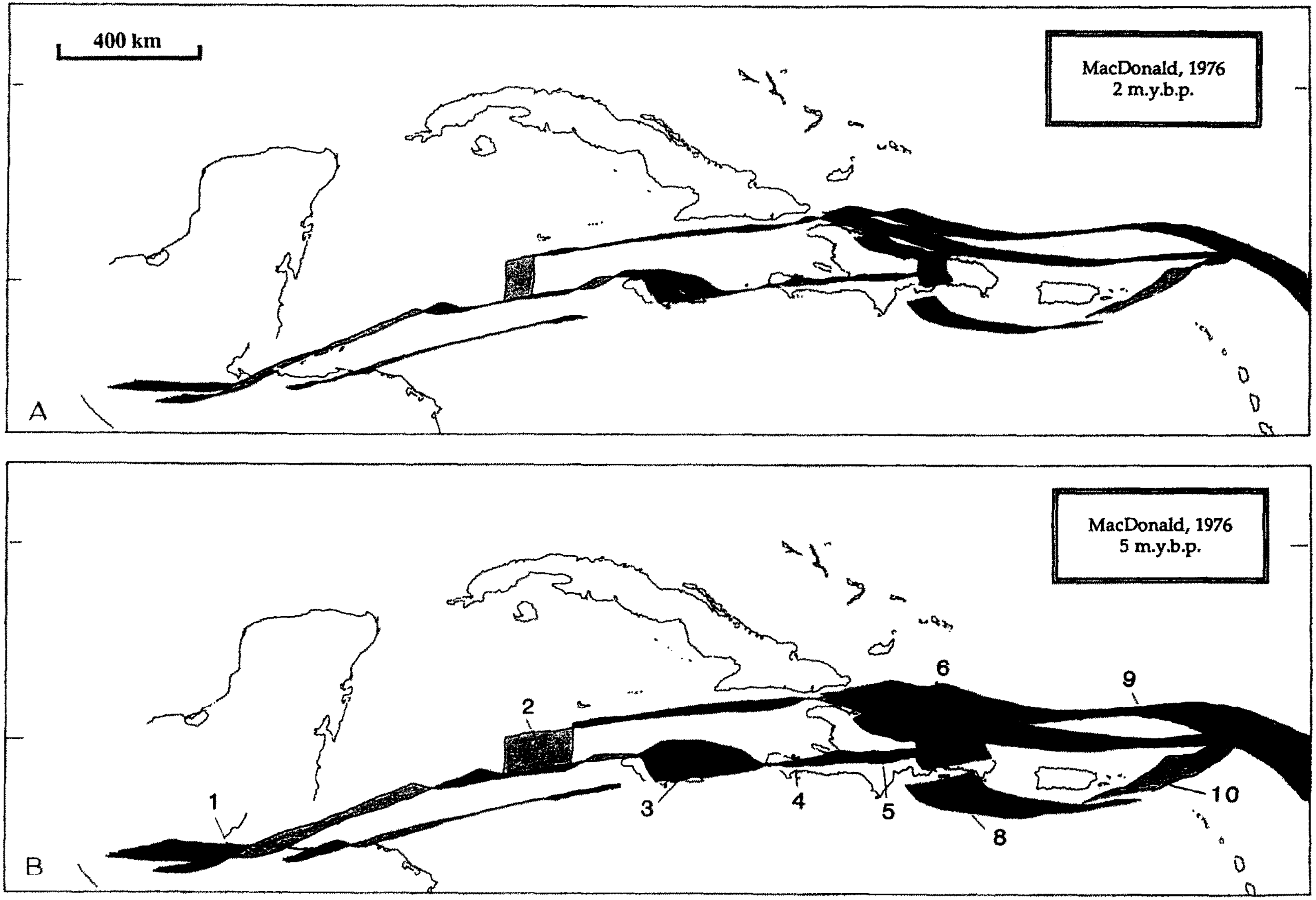

Fig. 6. (A) Reconstruction of the NOAM-CARIB plate boundary for 2 m.y.b.p. (Late Pliocene) using the pole of rotation published by MacDonald (1976). Colored regions represent overlaps (red) or gaps (green) between fault blocks produced when the Caribbean Plate is moved relative to the North American Plate from its position 2 m.y. ago to its present position. Fault overlaps should form the sites of crustal shortening and topographic uplift; fault gaps should form the sites of crustal stretching and topographic depression. Compare to the topographic map of Fig. 1. (B) Overlaps and gaps produced along fault systems when the Caribbean Plate is moved relative to the North American Plate from its position predicted 5 m.y. ago (Early Pliocene) using the pole of MacDonald (1976). Numbers refer to localities of Pliocene or younger deformation given in Table 3 and described in the text.

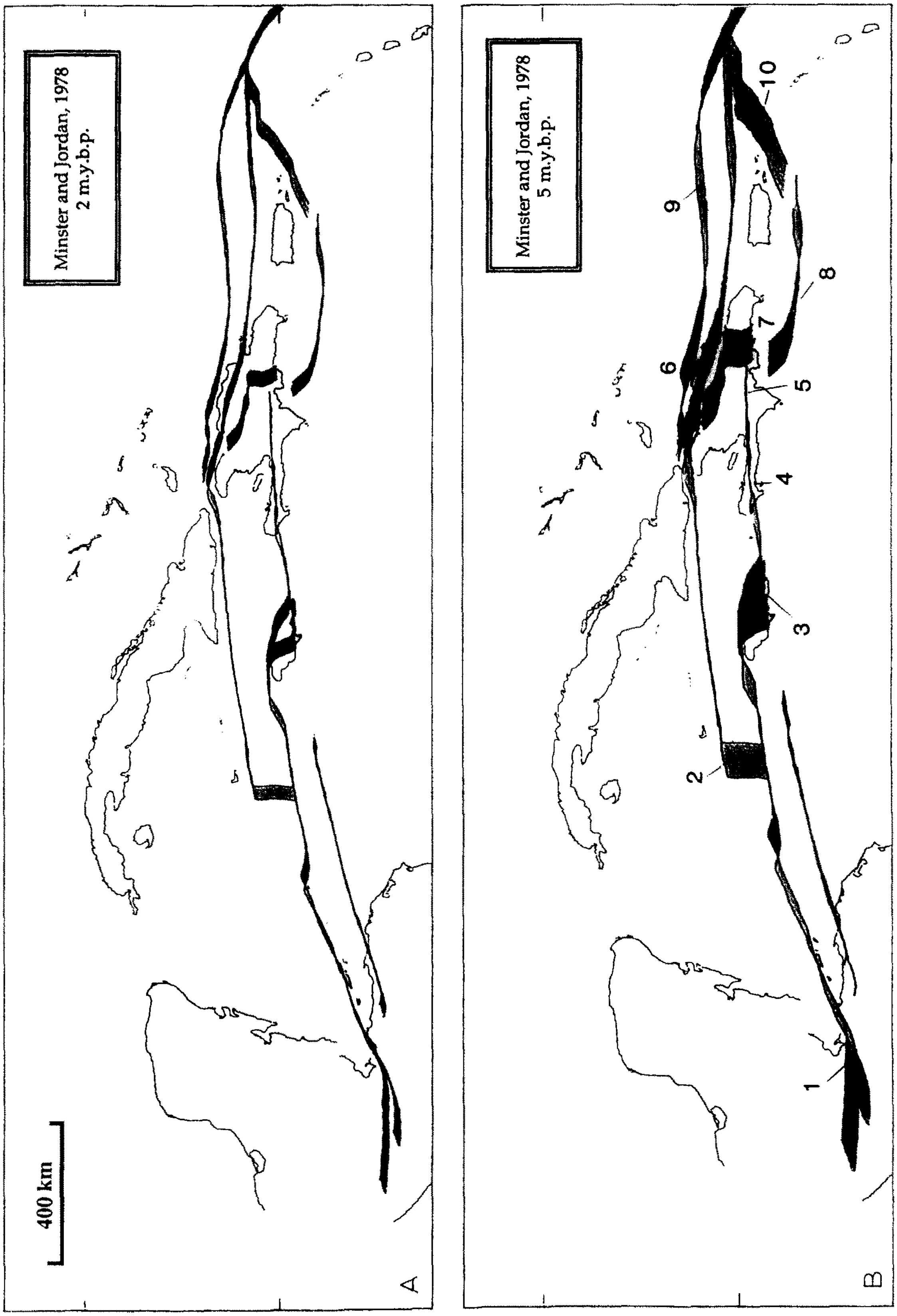

Fig. 7. (A) Overlaps and gaps produced along fault systems when the Caribbean Plate is moved relative to the North American Plate from its position predicted 2 m.y. ago (Late Pliocene) using the pole of Minster and Jordan (1978). (B) Overlaps and gaps produced along fault systems when the Caribbean Plate is moved relative to the North American Plate from its position predicted 5 m.y. ago (Early Pliocene) using the pole of Minster and Jordan (1978).

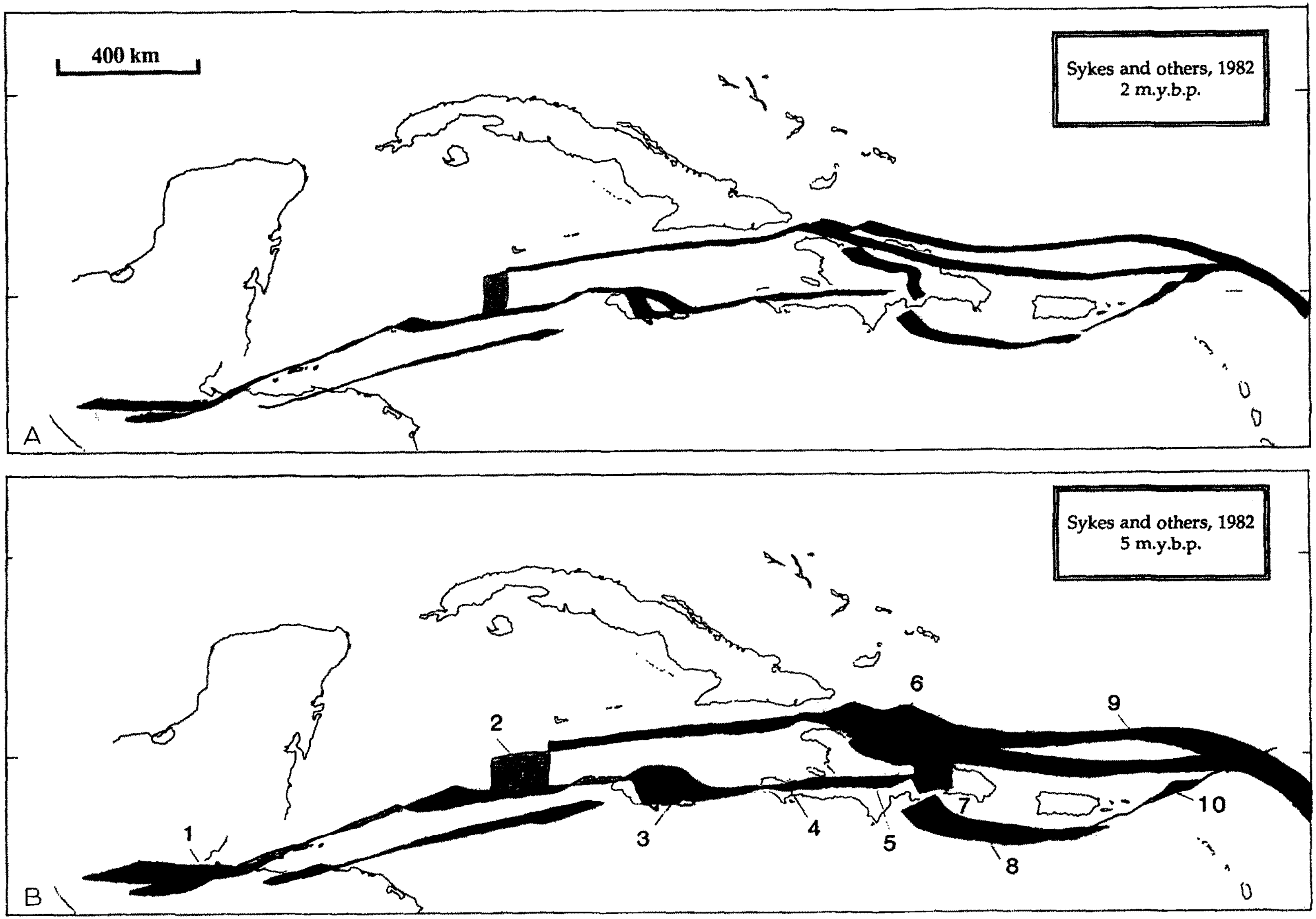

Fig. 8. (A) Overlaps and gaps produced along fault systems when the Caribbean Plate is moved relative to the North American Plate from its position predicted 2 m.y. ago (Late Pliocene) ago using the pole of Sykes et al. (1982). (B) Overlaps and gaps produced along fault systems when the Caribbean Plate is moved relative to the North American Plate from its position predicted 5 m.y. ago (Early Pliocene) using the pole of Sykes et al. (1982).

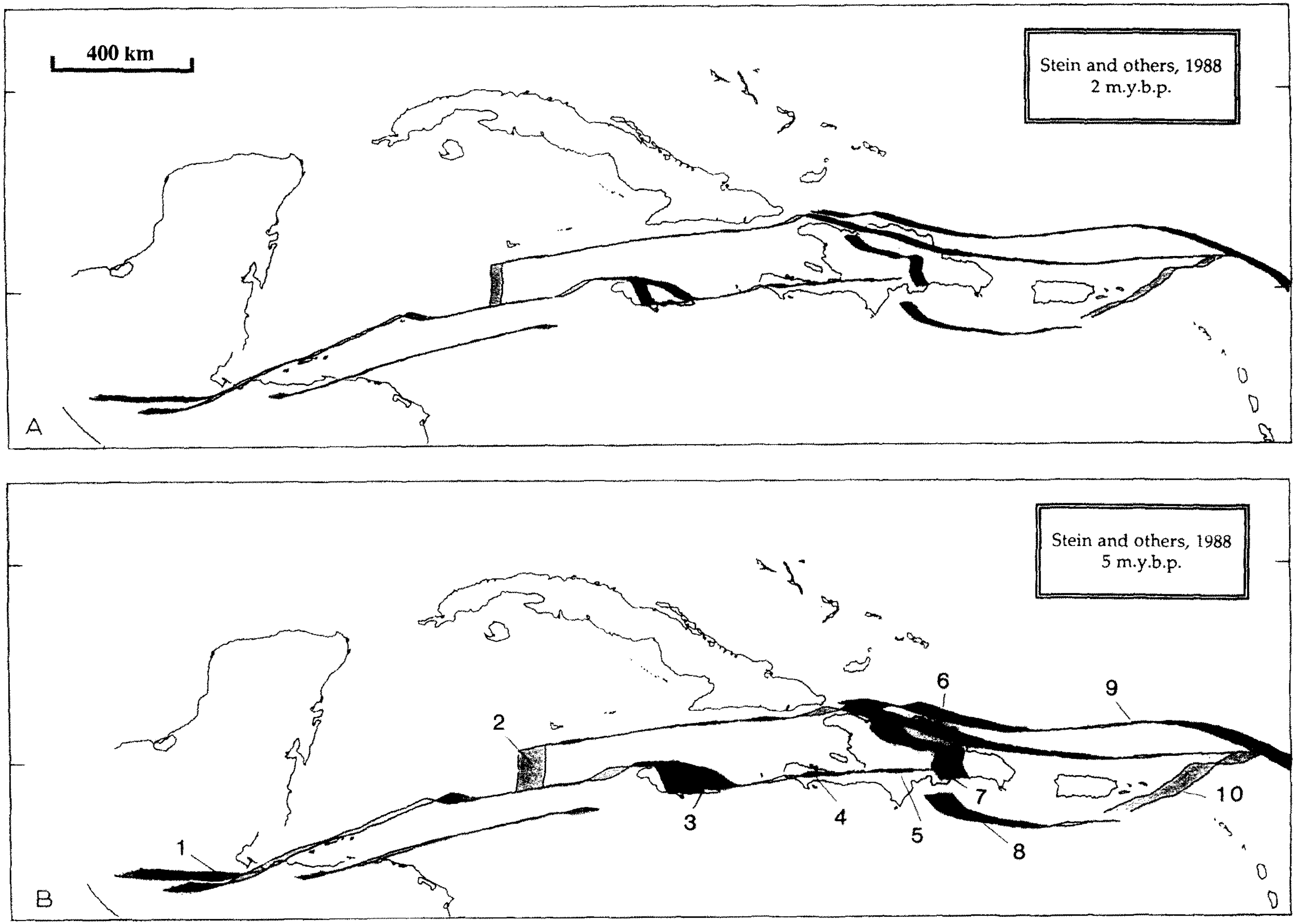

Fig. 9. (A) Overlaps and gaps produced along fault systems when the Caribbean Plate is moved relative to the North American Plate from its position predicted 2 m.y. ago (Late Pliocene) using the pole of Stein et al. (1988). (B) Overlaps and gaps produced along fault systems when the Caribbean Plate is moved relative to the North American Plate from its position predicted 5 m.y. ago (Early Pliocene) using the pole of Stein et al. (1988).

age. This structural information can then be directly compared to the slip-parallel, transpressional, or transtensional predictions made by the four kinematic models. Whereas the style of PBZ deformation can be determined from mapping and focal mechanism solutions, rates of active fault displacement are much more difficult to quantify. Neotectonic field studies and detailed bathymetric surveys in the northern Caribbean have not been emphasized in the past and, therefore, data are limited both in level of detail and geographic distribution. This limitation is particularly evident for northern Haiti, southernmost Cuba, and large offshore regions.

Fault data

Data from faults that affect post-Miocene rocks from ten localities in the northern Caribbean are summarized in Table 3. The data include information on the width, strike, and dip of the fault zone; the type of earthquake produced by slip on the fault as inferred from coseismic surface rupture and focal mechanism studies; the age of the youngest deformed sedimentary rock; the mapped structural style; and the observed slip rate of the fault as calculated from offset geologic features of known age.

In order to quantitatively compare these data to the plate kinematic models, we have also compiled a summary of the predicted fault types (that is, slip-parallel, transtensional, or transpressional), direction, and amount of relative block motion after 5 m.y. of movement about the poles given in each of the four models (Table 3). The direction of relative block motion was measured directly from the reconstructions in Figs. 6–9 by using a protractor. The amount of fault displacement was also directly measured from these figures. The error on the measured directions is estimated to be less than 5° while the error on the measured displacement is estimated to be less than 20 km. Below, we give a short description of the geology of each of the fault localities and compare these data to the predictions of the plate kinematic models. Both prediction and observations are summarized in Table 3.

1. Motagua and Polochic Fault zones, Guatemala

The Motagua and Polochic fault zones appear to accommodate much of the NOAM–CARIB slip through Central America. This interpretation is consistent with the fact that the Motagua fault zone forms the landward continuation of the Swan Islands fault zone which defines the southwestern margin of the Cayman Trough (Mann et al., 1989) (Fig. 1). The February 4, 1976, Guatemala earthquake ($M_s = 7.5$) produced about 1 m of left-lateral offset along a 230 km long, well-defined surface trace of the Motagua fault zone (Plafker, 1976). Despite the pronounced curvature of the fault trace, the 1976 surface rupture consistently formed right-stepping *en echelon* fractures and connecting low ridges that locally formed "mole tracks" diagnostic of left-lateral strike-slip faults. Offsets on late Pleistocene–Holocene terraces along the fault show left-slip and a vertical (up-to-the-north) slip that is about 5% of the lateral component of movement (Schwartz et al., 1979). Total post-5 Ma-offset on the Motagua fault zone is unknown because of lack of piercing points. Trenching across the Motagua Fault, however, indicates a maximum slip rate of 11 mm/yr over approximately the last 1870 yrs but stratigraphic relationships suggest this rate to be lower (Schwartz, 1985).

Total Neogene left-slip on the Motagua fault zone is likely to be greater than at the Polochic Fault zone (Schwartz, 1985; Schwartz, pers. commun., 1989). Deaton and Burkart (1984) argued that most of the 130 km of strike-slip displacement has occurred along the Polochic fault zone between 10.3 and 6.6 Ma. Offset soils which are dated as ~ 1460 A.D. indicate historic activity along the Polochic Fault (Schwartz, 1985). Because of significant Neogene offset and historical seismicity, we show predicted movement along both fault zones using the four models (Fig. 1).

Although none of the four kinematic models predict the observed arcuate strike-slip movement on the Motagua or the Polochic faults, the models do predict significant transpression, particularly along the western segments of both faults. Predicted transtension in the eastern Motagua Valley is consistent with the low topography and the thick alluvial fill of the Motagua Valley (B. Burkart,

TABLE 3

Comparison of predicted and observed fault structure at ten localities

	Predicted fault character after 5 m.y. of movement [a]				Predicted amount of fault displacement (km) full spreading rate (cm/yr)			
	MacDonald (1976)	Minster and Jordan (1978)	Sykes et al. (1982)	Stein et al. (1988)	MacDonald (1976)	Minster and Jordan (1978)	Sykes et al. (1982)	Stein et al. (1988)
1. Motagua/Polochic FZ, Guatemala	TT to the east, TP to the west; 77°	mostly TP [a] 72°	TP 76°	TP 75°	150/3	110/2	150/3	75/1.5
2. Mid-Cayman Spreading Center, Caribbean Sea	TT 88°	TT 82°	TT 72°	TT 84°	150/3	110/2	150/3	75/1.5
3. Wagwater FZ, Jamaica	TP 74°	TP 82°	TP 58°	TP 77°	150/3	100/2	75/1.5	75/1.5
4. Enriquillo–Plantain Garden FZ, Camp Perrin, Haiti	TP 80°	TP + TT 88°	TP 62°	TP + TT 82°	150/3	100/3	75/1.5	75/1.5
5. Enriquillo–Plantain Garden FZ, Lago Enriquillo Dominican Republic	TP 80°	SP 90°	TP 67°	SP 84°	150/3	100/2	75/1.5	75/1.5
6. Septentrional FZ, Arroyo Las Lavas, Dominican Republic	TP 81°	TP 90°	TP 68°	TP 85°	150/3	100/2	75/1.5	75/1.5
7. Bonao FZ, Dominican Republic	TP 81°	TP 90°	TP 76°	TP 85°	150/3	100/2	75/1.5	75/1.5
8. Muertos FZ, Caribbean Sea	TP 78°	TP + TT 86°	TP 68°	TP + SP 88°	150/3	100/2	75/1.5	75/1.5
9. Puerto Rico Trench, Atlantic Ocean	TP 79°	TT 90°	TP 59°	SP 85°	150/3	100/2	75/1.5	75/1.5
10. Anegada Passage FZ, Anegada Passage	TT 87°	TT 90°	TT 56°	TT 85°	150/3	100/2	75/1.5	75/1.5

[a] TT = transtension, TP = transpression, SP = slip-parallel.

TABLE 3 (Continued)

	Observed fault character					References
	mapped fault strike and width	youngest deformed sediments	mapped structural style	observed earthquake type	inferred slip rate	
1. Motagua/Polochic FZ, Guatemala	64–102° range 3–30 m wide	Holocene Alluvium and Terraces	64–102° ranging left-lateral strike-slip fault	left-lateral (2/4/1976)	0.45–1.8 cm/yr	Plafker (1976); Schwartz et al. (1979)
2. Mid-Cayman Spreading Center, Caribbean Sea	166° striking ridge axis, assuming orthogonal spreading	basalt	normal fault blocks	normal	12 mm/yr 35–40 km over 5.3 Ma	Rosencrantz et al. (1988)
3. Wagwater FZ, Jamaica	200–500 m wide	Pliocene related folding	reverse fault dips 57°	–	–	Green (1977)
4. Enriquillo–Plantain Garden FZ, Camp Perrin, Haiti	80° 1.5 km wide	Pliocene	vertical strike-slip faults and pull-aparts	–	–	Mann (1983)
5. Enriquillo–Plantain Garden FZ, Lago Enriquillo Dominican Republic	90° 1–3 km wide	Holocene	vertical strike-slip faults	–	–	Taylor et al. (1985) Mann (unpubl. data)
6. Septentrional FZ, Arroyo Las Lavas, Dominican Republic	90–117° 3 km wide	Quaternary–Pliocene	vertical strike-slip and steeply dipping reverse faults	–	–	De Zoeten (1988); Calais and Mercier de Lépinay (1989)
7. Bonao FZ, Dominican Republic	average 120° 1 km wide	seismically active	prominent unmapped lineament	–	–	Matumoto et al. (1981) Bowin (1966)
8. Muertos FZ, Caribbean Sea	103–86° 22 km	Pleistocene	accretionary wedge (dip 11°)	thrust (6/24/84); 40 km of under-thrusting	–	Byrne et al. (1985); Ladd et al. (1981)
9. Puerto Rico Trench, Atlantic Ocean	83°	Pleistocene?	high-angle block faults	shallow (< 50 km) thrusting	–	Sykes et al. (1982)
10. Anegada Passage FZ, Anegada Passage	10–30 km	Pleistocene?	right-lateral *strike-slip faults* with pull-aparts	–	–	Jany et al. (1987)

pers. commun., 1989). Slip rates inferred from geologic observations (0.45–1.8 cm/yr; Table 3) compare well with predicted offsets by Minster and Jordan (1978) and Stein et al. (1988).

2. *Mid-Cayman Spreading Center, Cayman Trough*

The active Mid-Cayman Spreading Center is a short (110 km) spreading ridge at a left-step between the Swan Island and Oriente fault zones (Fig. 1). The structure of the spreading ridge is typical of slowly spreading oceanic ridges and consists of a V-shaped axial valley that separates two areas of normal faulting (White and Stroup, 1979). Re-identification of magnetic anomalies, combined with age data derived from heat flow and depth to basement indicates very slow opening of the Cayman Trough at rates as slow as 1.5 mm/yr for an average rate over the last 25–30 Ma (Rosencrantz et al., 1988).

All four of the kinematic models predict various amounts of opening at the Mid-Cayman Spreading Center during the past 5 Ma (Table 3). Spreading of 15 mm/yr at the spreading center (Rosencrantz et al., 1988) is consistent with 75 km of left-lateral offset predicted by the model of Stein et al. (1988). In addition to opening at the Mid-Cayman Spreading Center, the models of Sykes et al. (1982) and MacDonald (1976) predict about 40 km of shortening along the southern edge of the Cayman Trough spreading ridge since the earliest Pliocene (Figs. 6 and 8). Holcombe and Sharman (1983) proposed convergence along the entire length of the Cayman Trough over the last 5 m.y. based on the trend of structural fabric as observed on marine geophysical surveys. According to their data, convergence at an angle of 12° and 7° relative to the spreading direction in two periods since the Early Pliocene has resulted in a cumulative shortening of approximately 15 km, compared to approximately 160 km of spreading. Using GLORIA side-scan data, Edgar et al. (1988) found no evidence for the changes in spreading-generated topography at the Mid-Cayman Spreading Center as predicted in the model of Holcombe and Sharman (1983). Calais et al. (1989) and Calais and Mercier de Lépinay (1990b) have described transpressional deformation of Late Pliocene–Recent age along the Oriente fault zone south of Cuba. The orientation of folds and thrust faults suggests their origin by left-lateral strike-slip faulting along the Oriente fault rather than north-south closure of this segment of the Cayman Trough.

The models of Minster and Jordan (1978) (Fig. 7) and Stein et al. (1988) (Fig. 9) predict pure strike-slip motion along the Oriente Fault along the northern edge of the Cayman Trough and for most of the Swan Islands fault zone at the southern edge of the Cayman Trough. Both of these models predict a fault overlap near Swan Islands in the central segment of the Swan Islands fault zone. The area of the Swan Islands has been recently mapped using SeaMARC II side-scan sonar as a large right-stepping restraining bend complex (Mann et al., 1989). Both the models of Minster and Jordan (1978) and Stein et al. (1988) predict a slight component of fault opening on the Swan Islands fault to the southwest of the Swan Islands bend complex. In this area, the fault has a more southwest strike than the fault to the east of the bend. The models of MacDonald (1976) and Sykes et al. (1982) predict much larger amounts of fault overlap at the Swan Islands bend complex and fault opening to the west of the bend (Table 3).

3. *Wagwater Fault Zone, Jamaica*

This fault is a well exposed zone of reverse faulting that juxtaposes Cretaceous to Early Eocene rocks against Middle Eocene to Pliocene rocks (Green, 1977). Green (1977) estimates a maximum reverse throw of about 8000 ft (about 2700 m). Uplift of the northwestern side of the fault zone is attributed to shortening at a major restraining bend structure developed in eastern Jamaica (Mann et al., 1985). Folding affects rocks as young as Pliocene in age in the Long Mountain anticline adjacent to the Wagwater fault zone.

All four kinematic models predict transpression along the Wagwater fault zone (Table 3).

4. *Enriquillo–Plantain Garden Fault Zone, Camp Perrin, Haiti*

The Enriquillo–Plantain Garden fault zone (EPGFZ) in this area juxtaposes terrestrial Pliocene clastic rocks against Eocene marine carbonates along a 1.5 km wide zone of closely spaced, subvertical strike-slip faults (Mann, 1983). To the east and west of the Camp Perrin area, the existence of small pull-apart basins (maximum dimensions 15 km length by 5 km width) suggests that the EPGFZ is transtensional in this area (Mann et al., 1984).

All models predict transpression along the eastern sector of the EPGFZ (Table 3). The models of Minster and Jordan (1978) (Fig. 7) and the Stein et al. (1988) (Fig. 9) predict transtension and the opening of a small pull-apart basins in the segment from central Hispaniola to eastern Jamaica.

5. *Enriquillo–Plantain Garden Fault Zone, Lake Enriquillo, Dominican Republic*

Mapping and unpublished industry seismic reflection data in and around Lake Enriquillo indicate an E–W trending, 1–3 km wide zone of faulting and fault-related folding affecting sediments as young as Holocene (Taylor et al., 1985). The seismic reflection data also indicate the existence of a vertical fault zone to a depth of about 2 km.

The kinematic models predict either slip-parallel or transpressional displacement (Table 3) which is in good agreement with the geologic observations.

6. *Septentrional Fault Zone, Cordillera Septentrional, Dominican Republic*

The Septentrional fault zone (SFZ) in the northern Dominican Republic is the direct landward extension of the Oriente fault zone of the Cayman Trough (Calais and Mercier de Lépinay, 1989) (Fig. 1). In the western Cordillera Septentrional, the Septentrional fault zone consists of a 3–5 km wide zone of south-verging reverse faults and folds which deforms rocks of Pliocene to Quaternary age (Calais and Mercier de Lépinay, 1989). The Septentrional fault zone in the Arroyo Las Lavas area is marked by a 3 km wide zone of subvertical to steeply northeast dipping strike-slip faults with a reverse throw component (De Zoeten, 1988). Carbonate rocks of Late Miocene to Pliocene age are locally intensely sheared and fractured in this zone. Unpublished industry seismic data across the fault zone 50 km to the east of the Arroyo Las Lavas indicates that the SFZ has at least 3 km of vertical throw and dips 75–80° beneath the Cordillera Septentrional (M. Nemec, pers. commun., 1988; T. Edgar, pers. commun., 1989). These observations are consistent with the interpretation of Mann et al. (1984) and Calais and Mercier de Lépinay (1989) that the SFZ is a north to northeast-dipping, left-lateral transpressional fault along which the Cordillera Septentrional has been uplifted in post-Miocene time.

All four models predict varying amounts of transpression across the SFZ (Table 3). These predictions are in accord with geologic observations.

7. *Bonao Fault Zone, Dominican Republic*

This structure forms a prominent topographic escarpment bounding the eastern margin of the Cordillera Central. The fault was mapped in a reconnaissance fashion by Bowin (1966) who concluded: (1) the fault is vertical or steeply dipping; (2) the fault is not a thrust because a younger formation crops out at its topographically higher side; and (3) movement on the fault must have occurred prior to the deposition of unfaulted Oligocene–Miocene sediments overlying it. Bowin speculated, based on these observations, that the topographic scarp is an exhumed fault zone.

More recent work on the local seismicity of the region by Matumoto et al. (1981, unpublished report; see summary in McCann and Sykes, 1984) defines a northwesterly striking band of hypocenters parallel to the Bonao fault zone and suggests a southeastwardly dipping seismic zone beneath the Cordillera Central. Hypocenters range in depth from 50 km to 120 km and define a near-vertical zone of seismic activity. Based on this seismic data and the prominent topographic expression of the Bonao Fault, Mann et al. (1984) speculated that the Bonao fault zone (and possibly also the Hispaniola and Hatillo fault zones to the east—Bowin, 1966) may represent the surface expression of this seismic zone and thus be active zones of reverse faulting and crustal subduction within the Hispaniola restraining bend area.

All four kinematic models predict at least 75 km of overlap since 5 Ma ago (Table 3). This motion could be partly accommodated along the Bonao Fault.

8. Muertos Trough, Caribbean Sea

The Muertos fault zone is a zone of active underthrusting marked by the 5200 m deep Muertos Trough. Multichannel seismic profiling by Ladd and Watkins (1978) across the Muertos Trough revealed features similar to those seen on some reflection profiles from other convergent margins, including: (1) landward-dipping slope basins; (2) landward-dipping reflecting horizons within a sedimentary accretionary wedge at the base of the landward slope; and (3) reflectors of Caribbean ocean floor which can be traced for at least 40 km underneath the slope north of the Muertos Trough. An earthquake (M_b 5.2) on June 24, 1984, beneath the landward slope of the Muertos Trough exhibited a thrust focal mechanism at a depth of 32 km (Byrne et al., 1985). This event was interpreted to represent active northward subduction of Caribbean crust beneath the northern Caribbean.

All four kinematic models predict shortening within the western Muertos Trough. The rate of shortening decreases to the east where transtensional (Minster and Jordan, 1978; Fig. 7) and slip-parallel kinematics (Stein et al., 1988; Fig. 9) are predicted (Table 3).

9. Puerto Rico Trench, Atlantic Ocean

Like the Muertos Trough, the 8200 m deep Puerto Rico Trench displays many features of active convergent margins, including an outer rise, an outer gravity highs a negative gravity anomaly along the trench and a Benioff seismic zone dipping southward to a depth of 140 km beneath eastern Puerto Rico (McCann and Sykes, 1984). These observations indicate that the Puerto Rico Trench marks the site of subduction of Atlantic Ocean lithosphere beneath eastern Puerto Rico. Results of side-scan sonar surveys and seismic reflection profiles across the Puerto Rico Trench indicate that both strike-slip and normal faults are widespread on the northern and southern slopes of the Puerto Rico Trench (Maley et al., 1974; Scanlon et al., 1988; Larue, 1990).

Sykes et al. (1982) used focal mechanisms and the configuration of the downgoing slab in the Puerto Rico Trench area to deduce a west-southwesterly subduction of Atlantic seafloor beneath the northeastern Caribbean (Fig. 8). Oblique convergence is also implied by the plate kinematic model of MacDonald (1976; Fig. 6). The other kinematic models predict either a strike-slip movement along the Puerto Rico Trench (Stein et al., 1988; Fig. 9) or even a slight transtensional component of plate motion (Minster and Jordan, 1978; Fig. 7) that results in up to 40 km of extension since 5 Ma (Table 3).

10. Anegada Passage Fault Zone, Anegada Passage

The Anegada Passage fault zone extends for 375 km in a northeast direction between the Virgin Islands and the northern Lesser Antilles. Recent high-resolution Seabeam and seismic reflection data indicate the fault zone may be an active right-lateral strike-slip fault along which the St. Croix and Sombrero Basins have formed as late Neogene pull-apart basins (Houlgatte, 1983; Jany et al., 1987). All four kinematic models predict between 80 and 150 km of left-lateral transtensional offset (Table 3).

Fold data

Fold data are listed from Pliocene and younger sedimentary rocks at ten localities in Jamaica, Hispaniola and Puerto Rico (Fig. 10A; Table 4). We have selected localities which are well mapped and precisely dated using microfossils. We have not included fold data from offshore regions because of the lack of age control and we have not included fold data from the PBZ in Central America because the youngest reported sedimentary rocks folded by strike-slip movements are Miocene or older in age (Manton, 1987).

We compiled the orientations of post-Miocene fold axes from the islands of Jamaica and Hispaniola, an area extending about 700 km in length and 300 km in width. The fold axes have a consistent NW-SE trend (Fig. 10A). This consistency suggests a uniform post-Miocene strain pattern over a large region of the active plate boundary zone. The strain pattern illustrated in

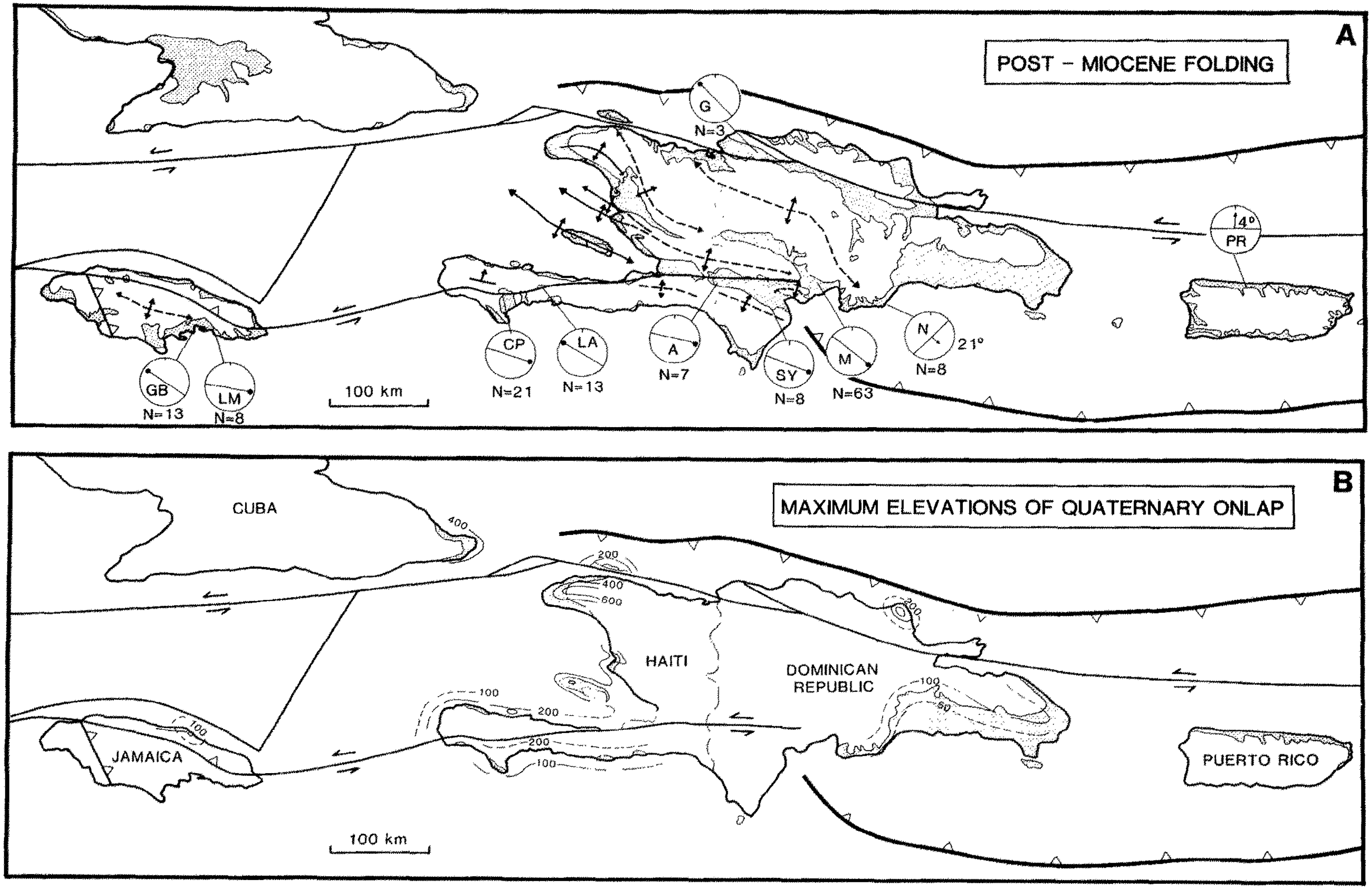

Fig. 10. (A) Post-Miocene folds in Jamaica and Hispaniola. Fold axes are drawn as solid lines where post-Miocene folds are mapped and as dashed lines where post-Miocene folds in older rocks are inferred in unmapped areas or zones of older rocks. Area in grey is Quaternary alluvium. Lower hemisphere stereographic projection showing orientation of fold axial plane and plunge of fold axis from ten localities including: *GB* = Green Bay, Jamaica; *LM* = Long Mountain, Jamaica; *CP* = Camp Perrin, Haiti; *LA* = L'Asile, Haiti; *A* = Aculadero, Dominican Republic, *SY* = Loma Sal y Yeso, Dominican Republic; *M* = Maleno, Dominican Republic; *G* = Guayabin, Dominican Republic. Tilted post-Miocene beds are recorded from the Rio Nizao Region (*N*) and the north coast of Puerto Rico (*PR*). Sources of fold data are listed in Table 3. (B) Maximum elevation of Quaternary marine sediments (grey areas) in the Greater Antilles. Contours show elevation of base of Quaternary section above sea level in meters. See text for discussion.

TABLE 4

Summary of post-Miocene fold data from the Northeastern Caribbean

Locality	Age of youngest exposed folded beds	Maximum dip in degrees	References
Green Bay, Jamaica	Pliocene	40	Chubb (1958); Coates and Williams (1970)
Long Mountain, Jamaica	Pliocene	50	Green (1974)
Camp Perrin, Haiti	Pliocene	80	Mann (1983)
L'Asile, Haiti	Pliocene	24	Mann (1983)
Aculadero, Dominican Republic	Pliocene	70	Mann (1983)
Loma Sal y Yeso, Dominican Republic	Pliocene	80	Mann (unpublished field notes)
Maleno, Dominican Republic	Early Pliocene	85	Mann (unpublished field notes)
Rio Nizao, Dominican Republic	Late Miocene–Pleistocene (?)	21	Heubeck (1988)
Guayabin, Dominican Republic	Pliocene	60	Dohm (1942); De Zoeten (1988); Mann (unpublished field data)
North Coast, Puerto Rico	Early Pliocene	4 (avg.)	Moussa et al. (1987)

Figs. 10A and 10B is consistent with the pattern of E–W striking left-lateral strike-slip earthquake slip vectors from the Cayman Trough and N–S striking thrust faults from the northern Lesser Antilles. This pattern is also consistent with an interpretation of left-lateral strike-slip motion along E–W-striking faults or NW-striking restraining bends within the plate boundary zone (Mann and Burke, 1984a).

Quaternary onlap data

Horsfield (1975) first pointed out the regional tectonic significance of variable elevations of raised Quaternary marine deposits and coral terraces in the Greater Antilles. Based on his compilation study, he noted that Quaternary terraces are highest and most numerous in northwestern Haiti and southeastern Cuba. Elsewhere in the Greater Antilles, the Quaternary terraces are tilted away from the area of northwestern Haiti and southeastern Cuba and lie at lower elevations.

In Fig. 10B, we have plotted the elevations of the base of the Quaternary onlapping coastal limestone and coral reefs using published geologic maps. We conclude that the Quaternary structural "dome", proposed by Horsfield (1975) to extend as a regional feature from Puerto Rico to Central America, is instead an anticlinorium of NW-striking folds of shorter wavelengths. This conclusion was reached because the elevation of the Quaternary beds is closely related to the pattern of post-Miocene folding shown in Fig. 10A. We interpret the patterns in Figs. 10A and 10B as representing progressive Pliocene–Quaternary folding in response to active crustal shortening. The most extensive area of folding within the Greater Antilles is localized in the Hispaniola restraining bend (Mann et al., 1984).

Discussion

In this section, we attempt to answer the following questions: (1) Can kinematic models based on plate tectonic principles describe the observed deformation pattern in the North American–Caribbean strike-slip zone?; (2) Which of the four models tested here predicts the observations best?; and (3) What implications for the kinematic behavior of the Caribbean plate arise from the four conflicting plate kinematic data sets?

Comparison of kinematic models to geologic data

Three of the models (MacDonald, 1976; Minster and Jordan, 1978; Stein et al., 1988) rely heavily on fault-strike, slip-vector, and spreading-velocity data from the Cayman Trough to constrain the direction and rate of Caribbean relative plate motion. An alternative model (Sykes et al., 1982) does not emphasize Cayman Trough data but instead relies on earthquake focal mechanisms and geometry of the seismic zone in the northeastern Caribbean. We will discuss the models by comparing their predictions to the data of three regions which are the best studied: Central America, the central Cayman Trough region, and the northeastern Caribbean.

At the western end of the North American–Caribbean PBZ in Central America, neither group of models predicts the observed pattern of slip-parallel strike-slip faulting, such as the observed left-lateral offset along the 1976 Motagua fault surface rupture or its left-lateral strike-slip focal mechanism. On the contrary, both sets of models predict largely transpressional overlaps along the Motagua and the Polochic fault zones.

In the region from the Cayman Trough to Puerto Rico, the models emphasizing Cayman Trough data are all roughly consistent with areas of observed transpression, transtension and slip-parallel strike-slip displacement. Of these three models, the models of Stein et al. (1988) and Minster and Jordan (1978) show only subtle differences in predicted geology (Table 3). The MacDonald (1976) model, which only uses the curvature of the Cayman Trough faults and no additional constraints on the pole position, is the least successful of the three models in predicting observed fault structures in the Cayman Trough area (Fig. 6B). In both the Stein et al. (1988) and Minster and Jordan (1978) models, there is good agreement between (1) predicted areas of transpression with observed areas of late Neogene uplift and folding such as Jamaica and Hispaniola; (2) predicted areas of transtension such as the Mid-Cayman Spreading Center and the Enriquillo–Plantain Garden fault zone in Haiti; and (3) predicted areas of slip-parallel fault movement such as along the Oriente and the eastern Enriquillo–Plantain Garden fault zone. The model proposed by Sykes et al. (1982) which does not emphasize Cayman Trough data does not predict fault character, orientation, and earthquake focal mechanism in the Cayman Trough region (Fig. 8B). In fact, the Sykes et al. (1982) model predicts mainly transpressional faulting in the Cayman Trough (Table 3), as shown by large fault overlaps in Figs. 8A and 8B.

At the eastern end of the PBZ, the first group of models based on data from the Cayman Trough is not successful in modeling the observed pattern of underthrusting along the Muertos Trough and the Puerto Rico Trench. The Stein et al. (1988) and the Minster and Jordan (1978) models predict a strike-slip and a transtensional fault behavior along the Puerto Rico Trench. In contrast, the Sykes et al. (1982) model, which heavily relies on seismicity data from this region, and the MacDonald (1976) model, which relies only on fault strikes in the Cayman Trough, predict convergence. None of the models predicts right-lateral motion on the Anegada Passage fault zone.

Interpretation of overall plate kinematics

None of the four kinematic models based on plate-tectonic principles can completely describe the observed deformational pattern along the North American-Caribbean PBZ. What is the reason for the lack of a single kinematic model that adequately describes the deformation across the entire length of the plate boundary? The demonstrated predictive power of the kinematic models for certain regions along the plate boundary zone indicates that the underlying approximation of plate rigidity is valid for large regions along the PBZ.

In Fig. 11, we suggest a possible explanation. In Figs. 11B and 11C, the northern Caribbean plate boundary is generalized as a single fault with one pull-apart basin (the Cayman Trough) and two restraining bends (Central America—Mann and Burke, 1984a, and Hispaniola-Puerto Rico area—Mann et al. 1984). This fault trace defines three arcuate segments which can be fitted to three individual poles: the largest, central arc along the plate boundary outlines the Cayman Trough. This arc has been used by MacDonald (1976), Minster and Jordan (1978), and Stein et al. (1988) to define pole positions for the relative Caribbean–North American plate motion in the southern hemisphere (see Fig. 2). Likewise, the bend defined by the Hispaniola–Puerto Rico–Lesser Antilles plate boundary zone has been indirectly

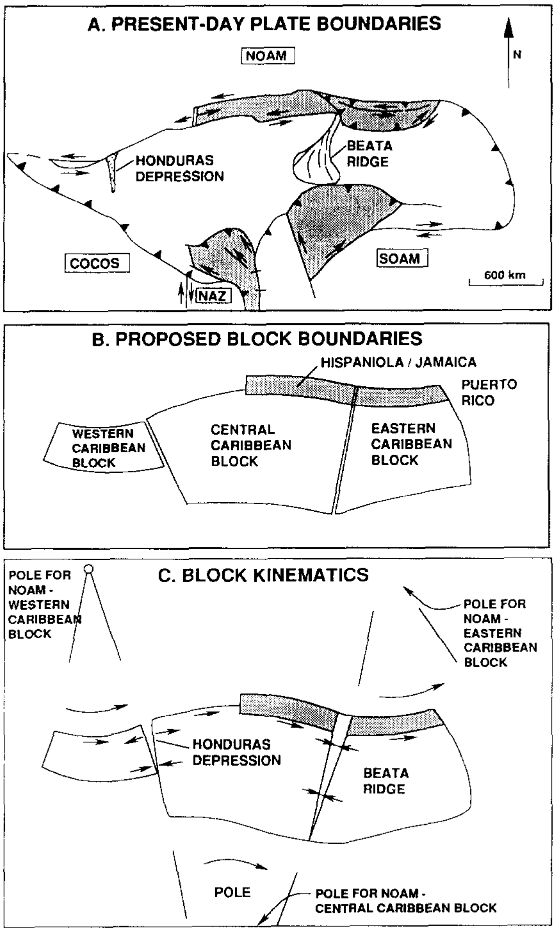

Fig. 11. (A) Schematic tectonic map of the Caribbean PBZ showing major strike-slip faults (arrows indicate sense of motion), thrust faults (barbs indicate hanging wall), possible microplates (shaded), and zones of possible intraplate deformation (Honduras Depression and Beata Ridge). (B) Proposed block boundaries within the Caribbean plate; possible microplates within the NOAM–CARIB plate boundary zone are shaded). (C) Geometric consequences of the simultaneous rotation of three Caribbean blocks rotating about different poles (position of poles is schematic). Zones of intraplate deformation (Beata Ridge and Honduras Depression) coincide with block boundaries independently determined from results of kinematic models. Gap between western and central Caribbean blocks would produce extension and subsidence at the Honduras depression; overlap between the central and eastern Caribbean blocks would produce shortening and uplift at the Beata Ridge. The presence of Hispaniola and Puerto Rico microplates and convergence between the South American plate and the Beata Ridge complicates this simplified model of NOAM–CARIB plate kinematics.

used by Sykes et al. (1982) to locate the pole for this segment from focal mechanisms and the geometry of the subducted North American plate. No pole has been published based on the arc defined by the Polochic and Motagua faults, but preliminary plate reconstructions using rotation of Central American structural blocks have been presented by Gordon (1987). His results indicate that Late Neogene rigid rotation of several fault-bounded blocks in central America along the arcuate Motagua–Polochic fault system is geometrically possible.

The simultaneous rotation of a Caribbean plate about three poles is geometrically impossible without significant internal plate deformation within either the North American or the Caribbean plate. The geological and seismological data presented for the Central America and the Cayman Trough region suggest that the Caribbean plate moves along arcuate strike-slip faults around the bend defined by the Motagua–Polochic fault system and the western Cayman Trough. There is abundant evidence for active faulting, volcanism, large Cretaceous–Cenozoic tectonic rotations and seismicity within the western Caribbean plate (Fig. 5) (see, for example, compilation by Mann and Burke, 1984a). In Central America, we predict interaction of the Western Caribbean block (western "Chortis block" of Gordon, 1990), rotating counterclockwise about a pole north of the PBZ, with a Central Caribbean block (eastern "Chortis block" of Gordon, 1990, plus Nicaraguan Rise and Colombian basin), rotating clockwise about a pole south of the PBZ (Figs. 11B and 11C). One possibility for the resulting scissor-like motion along the block boundary is schematically illustrated in Fig. 11C. The simplified model of Fig. 11C shows maximum extension and normal faulting along N–S oriented faults just south of the "inflection point" of the faults bounding the Western Caribbean block and the Central Caribbean block to the north. The Honduras Depression (Figs. 1 and 11A) and associated N–S trending graben structures form active, normal-fault bounded structures near the predicted void shown in Fig. 11C. The Honduras Depression widens to the north. In this model, we do not attempt to explain the growing amount of evidence for internal deformation of the North American plate to the north of the bend region in Guatemala and southern Mexico (Guzmán-Speziale et al., 1989).

In the Beata Ridge area, we predict a triangular zone of crustal overlap with its apex pointing south. This zone is formed at the contact of the Central Caribbean block, rotating clockwise, and the Eastern Caribbean block, rotating counterclockwise.

Comparison of predicted intraplate deformation with previous work

There have been several previous models for the intraplate deformation of the Caribbean plate in Central America which include: (1) secondary extension by differential movement along the Polochic and Motagua fault zones (Dengo and Bohnenberger, 1969); (2) "pinning" of the Central American segment of the Caribbean plate by increased underthrusting of the Cocos plate at the Middle America Trench (Malfait and Dinkelman, 1972); (3) fault termination structures along the Motagua fault zone (Langer and Bollinger, 1979); (4) internal deformation resulting from eastward movement around the bend (Wadge and Burke, 1983; Mann and Burke, 1984b); (5) decoupling between the volcanic arc and the rest of the Caribbean Plate (Burke et al., 1984; Burkart and Self, 1985).

There has been less speculation on the origin of the Beata Ridge because it has not been studied in detail. Using seismic profiles, Ladd et al. (1981) were unable to confirm whether the east flank of the Beata Ridge is a series of fault blocks or whether it consists of parallel volcanic ridges. Field studies in southern Hispaniola indicate that the northern end of the Beata Ridge has collided with and indented the south-central margin of Hispaniola since the Late Miocene (Matthews and Holcombe, 1976; Heubeck, 1988). Mann and Burke (1984a) previously suggested that the uplift of the Beata Ridge may reflect shortening related to the Neogene northward movement of the Maracaibo block from northwestern South America. The existence of microplates in the Hispaniola and Puerto Rico areas to the north of the Beata Ridge (Byrne et al., 1985; Stephan et al., 1986) may further complicate the proposed relation of the plate edge bending mechanism and the intraplate deformation.

Our interpretation of Caribbean intraplate deformation which is derived from the results presented in this paper are shown in Fig. 11C. Our results support a model that calls for internal deformation of Central America as it moves around a bend in the strike-slip plate boundary. In the Beata Ridge–Hispaniola area, we invoke a similar mechanism of bend-related deformation. Internal deformation is required in this area because the relative Caribbean plate motion as indicated by transform fault azimuths and slip vector data from the Cayman Trough does not agree with the slip vector data from the Puerto Rico Trench.

The northern part of this predicted zone of intraplate deformation in Hispaniola coincides with the seismologically defined boundary between the Cayman Trough-related strike-slip tectonics and the Puerto Rico Trench underthrusting near latitude 71° W in central Hispaniola (Sykes et al., 1982; McCann and Sykes, 1984). This seismic boundary extends into the Caribbean plate along the Beata Ridge, a zone of high-angle faulting (Ladd et al., 1981; Fox and Heezen, 1975). Our model predicts a triangular-shaped crustal overlap with the maximum overlap to the north near Hispaniola. The bend-related deformation may be modified by northward movement of the Maracaibo block from northwestern South America (Mann and Burke, 1984a; Heubeck, 1988). Direct tests of this model of a segmented Caribbean plate await further field, seismic, and geodetic studies at proposed block boundaries in Central America and the Caribbean Sea.

Conclusions

(1) Plate kinematic models for the North American-Caribbean PBZ can be divided into two types: those based on fault orientation, earthquake slip vectors, and spreading data from the Cayman Trough (MacDonald, 1976; Minster and Jordan, 1978; Stein et al., 1988), and those based mainly on earthquake data from the northeastern Caribbean (Sykes et al., 1982). Within the limits of the available geological and seismological data, the models of Minster and Jordan (1978) and Stein et al. (1988) match fault character and earthquake focal mechanism in the area of the Cayman

Trough, Jamaica, and western Hispaniola. The model of Sykes et al. (1982) predicts earthquake focal mechanism in the area of eastern Hispaniola and the Puerto Rico Trench. Neither model is adequate for completely predicting the pattern of deformation across the entire northern Caribbean plate boundary zone.

(2) The demonstrated predictive ability of plate kinematic models for some regions of the North American-Caribbean PBZ suggests that large segments of the PBZ behave in a rigid rather than in a plastic manner.

(3) The failure of all kinematic models to predict deformation pattern equally well along the entire length of the PBZ suggests that the kinematics of the northern Caribbean PBZ could also be modeled by the movement of three rigid blocks within the Caribbean plate. Predicted zones of intraplate deformation coincide with poorly studied zones of intraplate deformation in Central America and along the Beata Ridge and are suggested as priority areas for future onland and marine studies.

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References

Bowin, C.O., 1966. Geology of the Central Dominican Republic: a case history of part of an island arc. In: H.H. Hess (Editor), Caribbean Geological Investigations. Geol. Soc. Am., Mem., 98: 11–64.

Burkart, B., and Self, S., 1985. Extension and rotation of crustal blocks in northern Central America and effect on the volcanic arc. Geology, 13: 22–26.

Byrne, D.B., Suarez, G. and McCann, W.R., 1985. Muertos Trough subduction—microplate tectonics in the northern Caribbean? Nature, 317: 420–421.

Calais, E. and Mercier de Lépinay, B., 1989. Données nouvelles sur la Cordillère Septentrionale d'Hispaniola: ses relations avec la limite de plaques décrochante nord-Caraibe. C. R. Acad. Sci., Paris, Sér. II, 309: 409–415.

Calais, E. and Mercier de Lépinay, B., 1990a. Tectonique et paléogéographie de la cote sud de l'Oriente cubain: nouvelles contraintes pour l'évolution géodynamique de la limite de plaques décrochante nord-caraibe de l'Eocene à l'Actuel. C. R. Acad. Sci., Paris, Sér. II, 310: 293–299.

Calais, E. and Mercier de Lépinay, B., 1990b. A natural model of active transpressional tectonics: The en échelon structures of the Oriente Deep along the northern Caribbean transcurrent plate boundary (southern Cuban margin). Rev. Inst. Fr. Pét., 45: 147–160.

Calais, E., Mercier de Lépinay, B., Renard, V., and Tardy, M., 1989. Géométrie et régime tectonique le long d'une limite de plaques en coulissage: la frontière nord-Caraibe de Cuba à Hispaniola, Grandes Antilles. C. R. Acad. Sci., Paris, Sér. II, 308: 131–135.

Case, J.E. and Holcombe, T.L., 1980. Geologic-tectonic map of the Caribbean region. U.S. Geol. Surv., Misc. Invest. Ser., I-1100, scale 1 : 2,500,000.

Chubb, L.J., 1958. Field meeting at Green Bay and Port Henderson Hill, Jamaica. Proc. Geol. Assoc., 69: 182–187.

Coates, A.G. and Williams, J.B., 1970. Geology of the Hellshire Hills Quadrangle: Explanation to Geological Sheet 23, 1 : 50,000. Jamaica Geological Survey Department, Kingston, Jamaica.

Deaton, B.C. and Burkart, B., 1984. Time of sinistral slip along the Polochic Fault of Guatemala. Tectonophysics, 102: 297–313.

Dengo, G. and Bohnenberger., O., 1969. Structural development of northern Central America and the western Caribbean. In: A.R. McBirney (Editor), Tectonic Relations of Northern Central America and the Western Caribbean—The Bonacca Expedition. Am. Assoc. Pet. Geol., Mem., 11: 203–220.

De Zoeten, R., 1988. Structure and stratigraphy of the central Cordillera Septentrional, Dominican Republic. M.A. Thesis, Univ. of Texas at Austin, 299 pp.

Dohm, C.F., 1942. Report of a geological reconnaissance of the Guayabin Anticline, Cibao Valley, Dominican Republic. Unpublished Report of Seaboard Petroleum Company, 6 pp.

Edgar, T., Parson, L., Dillon, W., Jacobs, C., Scanlon, K., and Hill, G., 1988. Gloria survey of the Cayman Trough: a preliminary report. Trans. 11th Caribb. Geol. Conf., Barbados, 31: 1–31: 8

Fox, P.J. and Heezen, B.C., 1975. Geology of the Caribbean crust. In: A.E.M. Nairn and F.G. Stehli (Editors), The

Ocean Basins and Margins. Vol. 3. The Gulf of Mexico and the Caribbean, Plenum Press, New York, pp. 421–466.

Gordon, M.B., 1987. Cenozoic migration of strike-slip faulting in Central America. Eos, Trans. Am. Geophys. Union, 68: 1483.

Gordon, M.B., 1990. The Chortis block is a continental, pre-Mesozoic terrane. Trans. 12th Caribb. Geol. Conf., St. Croix, U. S. Virgin Islands, in press.

Gose, W., 1985. Caribbean tectonics from a paleomagnetic perspective. In: F.G. Stehli and D. Webb (Editors), The Great American Biotic Interchange. Plenum Press, New York, N.Y., pp. 285–301.

Green, G.W., 1974. Map and explanation of the geology–Geological Sheet 25, Kingston, 1:50,000. Jamaica Geological Survey Department (London: Overseas Development Administration, Directorate of Overseas Surveys).

Green, G.W., 1977. Structure and geology of the Wagwater Belt, Kingston, Jamaica. Overseas Geol. Miner. Resour. (London: Her Majesty's Stationery Office), 48: 22 pp.

Guzmân-Speziale, M., Pennington, W.D. and Matumoto, T., 1989. The triple junction of the North America, Cocos, and Caribbean plates: seismicity and tectonics. Tectonics, 8: 981–997.

Heubeck, C.E., 1988. Geology of the southeastern termination of the Cordillera Central, south-central Hispaniola. M.A. Thesis, Univ. of Texas at Austin, 333 pp.

Holcombe, T.L. and Sharman, G.F., 1983. Post-Miocene Cayman Trough evolution: a speculative model. Geology, 11: 714–717.

Horsfield, W.T., 1975. Quaternary vertical movements in the Greater Antilles. Geol. Soc. Am. Bull., 86: 933–938.

Houlgatte, E., 1983. Etude d'une partie de la frontière nord-est de la plaque Caraibe. Diplome d'Etudes Approfondies, Univ. de Bretagne Occidentale, Brest, 69 pp.

Jany, I., Mauffret, A., Bouysse, P., Mascle, A., Mercier de Lépinay, B., Renard, V. and Stéphan, J.-F., 1987. Relevé bathymétrique Seabeam et tectonique en décrochement au sud des Iles Vierges (Nord-Est Caraibes). C.R. Acad. Sci., Paris, Sér. II, 304: 527–532.

Kafka, A.L., 1980. Caribbean tectonic processes: seismic surface wave source and path property analysis. Ph.D Thesis, State Univ. of New York at Stonybrook, 298 pp.

Kanamori, H. and Stewart, G.S., 1978. Seismological aspects of the Guatemala earthquake of February 4, 1976. J. Geophys. Res., 83: 3427–3434.

Ladd, J.W. and Watkins, J.S., 1978. Active margin structures within the north slope of the Muertos Trench. Geol. Mijnbouw, 57: 255–260.

Ladd, J.W., Shih, T.C. and Tsai, C.J., 1981. Cenozoic tectonics of central Hispaniola and adjacent Caribbean Sea. Am. Assoc. Pet. Geol. Bull., 65: 466–489.

Langer, C.J. and Bollinger, G.A., 1979. Secondary faulting near the terminus of a seismogenic strike-slip fault: Aftershocks of the 1976 Guatemala earthquake. Bull. Seismol. Soc. Am., 69: 427–444.

Larue, D.K., 1990. Toa Baja drilling project, Puerto Rico. Eos, Trans. Am. Geophys. Union, 71: 233–234.

MacDonald, W.D., 1976. Cretaceous–Tertiary evolution of the Caribbean. Trans. 7th Caribb. Geol. Conf., Guadeloupe, pp. 69–81.

Maley, P.S., Sieber, F.D. and Johnson, B.L., 1974. Topography and structure of the western Puerto Rico Trench. Geol. Soc. Am. Bull., 85: 513–518.

Malfait, B.T. and Dinkelman, M.G., 1972. Circum-Caribbean tectonic and igneous activity and the evolution of the Caribbean plate. Geol. Soc. Am. Bull., 83: 251–272.

Mann, P., 1983. Cenozoic tectonics of the Caribbean: structural and stratigraphic studies in Jamaica and Hispaniola. Ph.D Thesis, State Univ. of New York at Albany, 688 pp.

Mann, P. and Burke, K., 1984a. Neotectonics of the Caribbean. Rev. Geophys. Space Phys., 22: 309–362.

Mann, P. and Burke, K., 1984b. Cenozoic rift formation in the northern Caribbean. Geology, 12: 732–736.

Mann, P., Burke, K. and Matumoto, T., 1984. Neotectonics of Hispaniola: plate motion, sedimentation, and seismicity at a restraining bend. Earth Planet. Sci. Lett., 70: 311–324.

Mann, P., Draper, G. and Burke, K., 1985. Neotectonics of a strike-slip restraining bend system, Jamaica. In: K.T. Biddle and N. Christie-Blick (Editors), Strike-slip Deformation, Basin Formation, and Sedimentation. Soc. Econ. Paleontol. Mineral., Spec. Publ., 37: 211–226.

Mann, P., Rosencrantz, E., Tyburski, S.A., Mercier de Lépinay, B. and Calais, E., 1989. SeaMARC II survey of the North America-Caribbean plate boundary zone between western Jamaica and eastern Guatemala. Eos, Trans. Am. Geophys. Union, 70: 1346.

Manton, W.I., 1987. Tectonic interpretation of the morphology of Honduras. Tectonics, 6: 633–651.

Matumoto, T., Rabb, L., Perez, M.J., Luciano, F., Sanchez, J. and Pennington, W., 1981. Seismology in the Dominican Republic as inferred from a local network. Eos, Trans. Am. Geophys. Union, 62: 324.

Matthews, J. and Holcombe, T.L., 1976. Possible Caribbean underthrusting of the Greater Antilles along the Muertos Trough. Trans. 7th Caribb. Geol. Conf., Guadeloupe, pp. 235–242.

McCann, W.R. and Sykes, L.R., 1984. 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.

Minster, J.B. and Jordan, T.H., 1978. Present-day plate motions. J. Geophys. Res., 83: 5331–5354.

Molnar, P. and Sykes, L.R., 1969. Tectonics of the Caribbean and Middle America regions from focal mechanisms and seismicity. Geol. Soc. Am. Bull., 80: 1639–1684.

Moussa, M.T., Seiglie, G.A., Meyerhoff, A.A. and Taner, I., 1987. The Quebradillas Limestone (Miocene–Pliocene), northern Puerto Rico, and tectonics of the northeastern Caribbean margin. Geol. Soc. Am. Bull., 99: 427–439.

Plafker, G., 1976. Tectonic aspects of the Guatemala earthquake of 4 February 1976. Science, 193: 2101–2108.

Rosencrantz, E., Ross, M.I. and Sclater, J.G., 1988. Age and spreading history of the Cayman Trough as determined from depth, heat flow and magnetic anomalies. J. Geophys. Res., 93: 2141–2157.

Ross, M.I. and Scotese, C.R., 1988. A hierarchical tectonic model of the Gulf of Mexico and Caribbean region. Tectonophysics, 155: 139–168.

Scanlon, K.M., Masson, D.G. and Rodruguez, R.W., 1988. GLORIA sidescan-sonar survey of the EEZ of Puerto Rico and the U. S. Virgin Islands. Trans. 11th Caribb. Geol. Conf., Barbados, pp. 31: 1–32: 9.

Schwartz, D.P., 1985. The Caribbean–North American plate boundary in Central America: new data on Quaternary tectonics. Earthquake Notes, 55: 28.

Schwartz, D.P., Cluff, L.S. and Donnelly, T.W., 1979. Quaternary faulting along the Caribbean-North American plate boundary in Central America. Tectonophysics, 52: 431–445.

Stein, S., DeMets, C., Gordon, R.G., Brodholt, J., Argus, D., Engeln, J.F., Lundgren, P., Stein, C., Wiens, D.A. and Woods, D.F., 1988. A test of alternative Caribbean Plate relative motion models. J. Geophys. Res., 93: 3041–3050.

Stéphan, J.F., Blanchet, R. and Mercier de Lépinay, B., 1986. Northern and southern Caribbean festoons (Panama, Colombia–Venezuela and Hispaniola–Puerto Rico), interpreted as pseudosubductions induced by the east–west shortening of the pericaribbean continental frame. In F.-C. Wezel (Editor), The Origin of Arcs. (Develop. Geotectonics, 21) Elsevier, Amsterdam, pp. 401–422.

Sykes, L.R., McCann, W. and Kafka, A.L., 1982. Motion of Caribbean Plate during last 7 million years and implications for earlier Cenozoic movements. J. Geophys. Res., 87: 10,656–10,676.

Taylor, F.W., Mann, P., Valastro, S. and Burke, K., 1985. Stratigraphy and radiocarbon dating of a subaerially exposed Holocene coral reef, Dominican Republic. J. Geol., 93: 311–332.

United States Geological Survey, 1986. Catalog of first motion focal mechanisms 1984-1985. Open File Rep., 86-520 A.

Van Fossen, M.C., and Channell, J.E.T., 1988. Paleomagnetism of Late Cretaceous and Eocene limestones and chalks from Haiti: tectonic interpretations. Tectonics, 7: 601–612.

Vincenz, S.A. and Dasgupta, S.N., 1978. Paleomagnetic study of some Cretaceous and Tertiary rocks on Hispaniola. Pure Appl. Geophys., 116: 1202–1210.

Wadge, G. and Burke, K., 1983. Neogene Caribbean plate rotation and associated Central American tectonic evolution. Tectonics, 2: 633–643.

White, G.W. and Stroup, J.B., 1979. Distribution of rock types in the Mid-Cayman Rise, Caribbean Sea, as evidence for conjugate normal faulting in slowly spreading ridges. Geology, 7: 32–36.