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A simpler plate-tectonic history for the Caribbean

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With 8 figures and 1 table in the text

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Abstract: Evolution of the Caribbean Plate can be modeled by motions about six successive rotation poles. Opening of Cayman Trough has occurred since 49.5 Ma through westward motion of the Caribbean Plate, eastern Greater Antilles and Chortis Block. Before 49.5 Ma, the eastern Greater Antilles were west of Cuba, and the southeastern margins of Yucatan and the Nicaragua Rise (Chortis) were aligned. From 67.5 to 49.5 Ma the Caribbean Plate rotated clockwise, opening the Yucatan Basin. From 100 Ma to 67.5 Ma, the Caribbean Plate, with Cuba attached, moved along the southeastern margin of Yucatan-Chortis. At 130 Ma it was attached to northwestern South America.

Zusammenfassung: Die Entstehung der Karibik kann mit Hilfe sechs aufeinanderfolgender Rotationspole modelliert werden. Die Öffnung des Caymantrogs findet seit 49,5 Ma statt, mit westlicher Bewegung von der Karibikplatte, den östlichen Großen Antillen und dem Chortismassiv. Vor 49,5 Ma lagen die gesamten östlichen Großen Antillen westlich von Kuba, und die südöstlichen Ränder von Yukatan und die Nicaraguaschwelle (Chortis) bildeten eine fast gerade Linie. Zwischen 67,5 Ma und 49,5 Ma rotierte die Karibikplatte im Uhrzeigersinn und öffnete das Yukatan-Bekken. Zwischen 110 Ma und 67,5 Ma bewegt sich die mit Kuba verbundene Karibikplatte nordöstlich parallel zur Spur des Südostrandes von Yukatan-Chortis. Um 130 Ma läßt sich eine sehr enge Anpassung zwischen der Karibikplatte und dem südamerikanischen Rand vermuten.

Resumen: La evolución de la Placa del Caribe puede ser modelada utilizando seis polos de rotación sucesivos. La apertura de la Fosa de Caymán hasta 49.5 Ma involucró un movimiento de rotación hacia el este de la Placa del Caribe, de las Antillas Mayores orientales y el bloque de Chortis. Antes de 49.5 Ma las Antillas Mayores orientales estaban localizadas al occidente de Cuba y los márgenes surorientales de Yucatán y el Nicaragua Rise (Chortis) estaban alineados. Desde 67.5 hasta 49.5 Ma la Placa del Caribe rotó dextralmente, abriéndose así la Cuenca de Yucatán. De 100

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a 67.5 Ma la Placa del Caribe con Cuba adherida se movieron a lo largo del margen suroriental de Yucatán-Chortis. Hace 130 Ma la Placa del Caribe estaba unida al borde noroccidental de Sur América.

Introduction

PINDELL & BARRETT (1990) reviewed 12 models of the evolution of the Caribbean that had been suggested by earlier investigators, and proposed a new one. Their 1990 model has been subsequently slightly modified by PINDELL (1993). We refer the reader to the useful tabulation of similarities and differences and discussion of the development of models up to 1988 by PINDELL & BARRETT (1990). The earliest reconstructions reflected belief that the Caribbean Plate had been generated in situ, whereas most later reconstructions assumed it had been formed as an oceanic platform in the Pacific, only later entering the space between North and South America. Most of the reconstructions shown in the literature have been done as sketches, fitting the blocks into different frameworks of the North American-African-South American plates. Exceptions are the models of ROSS & SCOTESE (1988) and STANEK & VOIGT (1993) that used rotations about Euler poles. All of these models imply plastic deformation of the Caribbean Plate proper (Venezuelan Basin, Beata Ridge, Colombian Basin) as well as the smaller peripheral entities (Greater and Lesser Antilles, Chortis, Panama-Costa Rica, etc.), as shown in the figures of PINDELL & BARRETT (1990) and PINDELL (1993). The "plasticity" of the region shown in these reconstructions requires ad hoc rotations for every block. If the evolution of the Caribbean region can be explained by plate tectonics with rigid plates, few rotations should be required, and the same rotations should apply to most blocks.

Some of the reconstructions suggesting entry of the Caribbean Plate from the Pacific show the Greater Antilles on the narrow (now the eastern) leading edge of the plate, but do not explain how they have come to be along the long northern side of the plate at present. Other reconstructions show the Caribbean Plate entering sideways, with the present northern margin being the leading edge. In these reconstructions the Lesser Antilles are shown as being alongside the Greater Antilles on what was then the leading edge of the entering plate. They do not explain the mechanism of later translation by which the Lesser Antilles have come to occupy their present position on the modern leading (eastern) edge of the plate.

The PINDELL & BARRETT (1990) reconstruction required Chortis to "back out" from its position in Central America into the Pacific to allow the Caribbean Plate to enter; then the Chortis Block returns to its present Central Americal location, while subduction occurred simultaneously on both the leading and trailing edges of the Caribbean Plate. The "swinging door" motion of the Chortis Block is a strictly ad hoc solution to the problem of the space apparently needed for entry of the Caribbean Plate. Subduction on opposite sides of a plate is uncommon if occurring at all today.

Recently, MONTGOMERY et al. (1994) have cited the presence of Early Jurassic (~195 Ma) Radiolaria on Hispaniola as conclusive evidence for a Pacific origin of the Caribbean Plate, because these fossils were deposited in deep waters before the opening of the Central Atlantic and the Proto-Caribbean Seaway between North and South America.

The deformation of the blocks peripheral to the Caribbean Plate proper is unquestionable, being evident in their complex structure discussed in many investigations. However, the extent of their compression is not known, and the sediments eroded from them are not a major component of the fill of the adjacent basins.

Except the Beata Ridge, there is little evidence for deformation of the Caribbean Plate proper. The surface of the flood basalts underlying the pelagic sediments of the Venezuelan and Colombian Basins is remarkably horizontal, especially when isostatic adjustment for the sediment load is taken into account (EDGAR et al. 1973, MATTHEWS & HOLCOMBE 1976). The Colombian and Venezuelan Basins have behaved as rigid blocks and have been only slightly warped while the peripheral terranes underwent extensive deformation.

We initiated this study to determine whether the history of the Caribbean region can be described in terms of plate tectonics, i. e. as rotations of rigid plates about Euler poles. We were concerned that there might not be sufficient space between North and Central America and South America for the entry of the Caribbean Plate and its peripheral elements from the Pacific. We found that the formation of the Caribbean Sea can be modeled more simply by six successive rotation poles for a single rigid Caribbean Plate consisting of the Grenada Trough, Aves Swell, Venezuelan Basin, Beata Ridge, and Colombian Basin.

Evolution of the North and Central American, African, and South American framework

In the following discussion, the "Caribbean Plate" refers to a rigid arrangement of the following elements in their present-day configuration: Lesser Antilles Arc, Grenada Trough, Aves Ridge, Venezuelan Basin, Beata Ridge, Colombian Basin. The blocks were digitized from the Geologic World Atlas (CHOUBERT & FAURE-MURET 1976). The northern and southern margins of the Caribbean Plate blocks were taken to be at the base of the continental slopes of northern South America, Nicaragua Rise, and Greater Antilles; approximately the 2000 m isobath. The reconstructions in Figs. 2-8 were prepared with the ATLAS™ Program of Cambridge Paleoservices Ltd. The total rotations (from the present to the age cited) are given in Table 1. Each of the rotations is relative to another block, and the rotations for different blocks are chained together. Rotations for one block may be relative to more than one other block at different times.

The Greater Antilles move with the Caribbean Plate, but are not rigidly attached to it. The Chorotega and Choco Blocks also move with the Caribbean Plate, but have undergone deformation.

We assume that the motions of the Caribbean Plate must fit into the North American-African-South American framework described earlier (HAY & WOLD 1992). Relative motions of North America and Africa are based on KLITGORD & SCHOUTEN (1987). Relative motions of South America to Africa are based on the rotations of NÜRNBERG & MÜLLER (1991) with an adjustment prior to Anomaly 34 (83 Ma), so that motion

Table 1. Total rotations used in reconstructions.

EASTERN NORTH AMERICA RELATIVE TO THE PALEOMAGNETIC REFERENCE FRAME

AGE	LAT	LONG	ANGLE	SOURCE
20	0	61.1	4.1	1
30	0	67.7	5.3	1
40	0	75.4	6.6	1
50	0	88.2	6.9	1
60	0	93.8	10	1
70	0	98.4	13.4	1
80	0	105.1	19.4	1
90	0	102	21.1	1
100	0	96.1	20.9	1
110	0	92.2	20.5	1
120	0	89.1	22	1
130	0	74.3	23.8	1
140	0	66.5	24	1
150	0	67.8	23.4	1

NORTH AFRICA RELATIVE TO NORTH AMERICA

AGE	LAT	LONG	ANGLE	ANOM	SOURCE
9.59	80.12	50.8	-2.52	A5	2
19.08	79.57	37.84	-5.29	A6	3
33.05	75.37	1.12	-10.04	A13	2
46.28	75.3	-3.88	-15.25	A21	2
55.98	79.68	-0.46	-18.16	A25	2
66.6	82.9	4.94	-20.76	A30	2
71.72	81.35	-9.15	-22.87	A32	3
73.78	80.76	-11.76	-23.91	A33y	3
78.78	78.3	-18.35	-27.06	A33o	3
83	76.55	-20.73	-29.6	A34	3
90	74.33	-22.65	-33.86		4
94	72	-24.39	-36.49		4
99.5	69.42	-23.52	-40.46		4
106	68.08	122.66	-45.36		4
116.5	66.21	-21	-53.19		4
124.32	66.09	-20.17	-54.45	M0	5
125.36	65.97	-19.43	-56.63	M4	5
135.87	66.14	-18.72	-58.03	M11	5
142.76	66.24	-18.33	-59.71	M16	5
149.3	66.24	-18.33	-62.14	M21	5
154.76	66.7	-15.85	-64.9	M25	5

CENTRAL SOUTH AMERICA RELATIVE TO AFRICA

AGE	LAT	LONG	ANGLE	ANOM	SOURCE
4.03	60	-39	1.21	A3	6
9.59	60	-39	3.15	A5	6
11.85	59.5	-38	4.05	A5A	6
16.03	59.5	-38	5.75	A5C	6
19.08	59.5	-38	7.05	A6	6
20.55	59.5	-37.75	7.6	A6A	6
23.35	59.5	-37	8.8	A6C	6
24.72	59	-36	9.5	A7	6
27	58	-35	10.55	A9	6
29.37	57	-34.5	11.6	A11	6
33.05	57.5	-34	13.38	A13	6
35.37	57	-33.25	14.4	A16	6
38.5	57.5	-32.5	15.8	A18	6
42.63	57.5	-31.75	17.6	A20	6
46.28	58.5	-31.5	19.07	A21	6
48.95	59	-31.5	20.1	A22	6
52.24	60	-32	21.2	A24	6
55.98	61.5	-32.5	22.3	A25	6
61.56	62.5	-33	23.55	A27	6
64.91	63	-33.3	24.3	A29	6
66.6	63	-33.3	24.7	A30	6
71.72	63	-33.5	26.6	A32	6
73.78	63	-33.5	27.9	A33	6
78.78	63	-34	31	A33R	6
118	42.02	329.51	54.72		NEW
129	44.38	329.55	57.17		NEW

WESTERN NORTH AMERICA RELATIVE TO EASTERN NORTH AMERICA

AGE	LAT	LONG	ANGLE	SOURCE
49.50	0.00	0.00	0.00	
67.50	15.00	-92.00	2.00	NEW

Table 1. Total rotations used in reconstructions (continued).

NORTHERN SOUTH AMERICA RELATIVE TO CENTRAL SOUTH AMERICA

AGE	LAT	LONG	ANGLE	SOURCE
123.00	0.00	0.00	0.00	
125.00	68.20	15.05	0.30	NEW

CORDILLERAS OCCIDENTAL, CENTRAL AND ORIENTAL RELATIVE TO CENTRAL SOUTH AMERICA

AGE	LAT	LONG	ANGLE	SOURCE
24.70	0.00	0.00	0.00	
67.50	-3.46	-78.92	15.00	NEW

NORTHEASTERN VENEZUELAN MARGIN RELATIVE TO CENTRAL SOUTH AMERICA

AGE	LAT	LONG	ANGLE	SOURCE
24.70	0.00	0.00	0.00	
35.50	0.00	30.00	-0.30	NEW

SOUTH SIDE OF CAYMAN TROUGH RELATIVE TO NORTH AMERICA

AGE	LAT	LONG	ANGLE	SOURCE
24.70	-77.15	1.65	3.33	NEW
49.50	-77.15	1.65	11.36	NEW

CHORTIS RELATIVE TO SOUTH SIDE OF CAYMAN TROUGH

AGE	LAT	LONG	ANGLE	SOURCE
24.70	0.00	0.00	0.00	

CHORTIS RELATIVE TO WESTERN NORTH AMERICA

AGE	LAT	LONG	ANGLE	SOURCE
49.50	-36.48	87.22	25.72	NEW

CUBA RELATIVE TO EASTERN NORTH AMERICA

AGE	LAT	LONG	ANGLE	SOURCE
67.50	0.00	0.00	0.00	
84.00	-16.32	88.82	23.20	NEW
100.00	-27.68	73.53	26.83	NEW

CARIBBEAN PLATE RELATIVE TO SOUTH SIDE OF CAYMAN TROUGH

AGE	LAT	LONG	ANGLE	SOURCE
49.50	0.00	0.00	0.00	NEW
				NEW

CARIBBEAN PLATE RELATIVE TO CUBA

AGE	LAT	LONG	ANGLE	SOURCE
67.50	5.54	284.91	75.86	NEW
100.00	4.89	285.01	70.92	NEW

CARIBBEAN PLATE RELATIVE TO THE CORDILLERA OCCIDENTAL

AGE	LAT	LONG	ANGLE	SOURCE
120.00	-4.04	292.99	61.72	NEW
130.00	-1.11	294.74	61.57	NEW

SOURCES

1 Harrison & Lindh, 1982
2 Müller et al., 1991
3 Klitgord & Schouten, 1986
4 Roest, 1987
5 Roest et al., 1992
6 Nürnberg & Müller, 1991

of the northeast South American and Guinea margin of Africa is transform. The latitude-longitude grid is for the paleomagnetic reference frame with respect to North America of HARRISON & LINDH (1982). Except for Cuba, we interpreted the motions of the Greater Antilles with respect to each other and with respect to the Caribbean Plate as left-lateral shear along the northern margin of the Caribbean Plate. We considered the Lesser Antilles an an integral part of the Caribbean Plate proper. The blocks taken into account in our model are shown in Fig. 1, and total rotation poles for most of them are given in Table 1.

Fig. 1. Map of the Caribbean Region at present, showing the blocks and terranes used in the plate-tectonic reconstructions.

In the following discussion the evolution is described as four successive stages. The more recent history is better documented than the more speculative earlier history, so we discuss them from youngest to oldest.

Stage 1: Opening Cayman Trough

Cayman Trough is a wide left-lateral transform fault. The traces of the east-west trending walls of the trough are arcs that represent small circles about the pole of rotation to the south. The north side of Cayman Trough is fixed relative to North America. The Caribbean Plate and Chortis form the south side. There are no older reliable magnetic anomalies in the region to guide reconstruction of the region prior to Anomaly 20 (42.6 Ma), but by extrapolation the opening of Cayman Trough is thought to have started at 49.5 Ma (earliest Middle Eocene). Timing of the motion is based on ROSENKRANTZ et al. (1988); they found the rate of opening to be ~1.5 cm yr^{-1} between 0 and Anomaly 7. The age of Anomaly 7 used by ROSENKRANTZ et al. (1988) was 25.5 Ma, but we have corrected it to 24.7 Ma, following the time scale of CANDE & KENT (1992), =

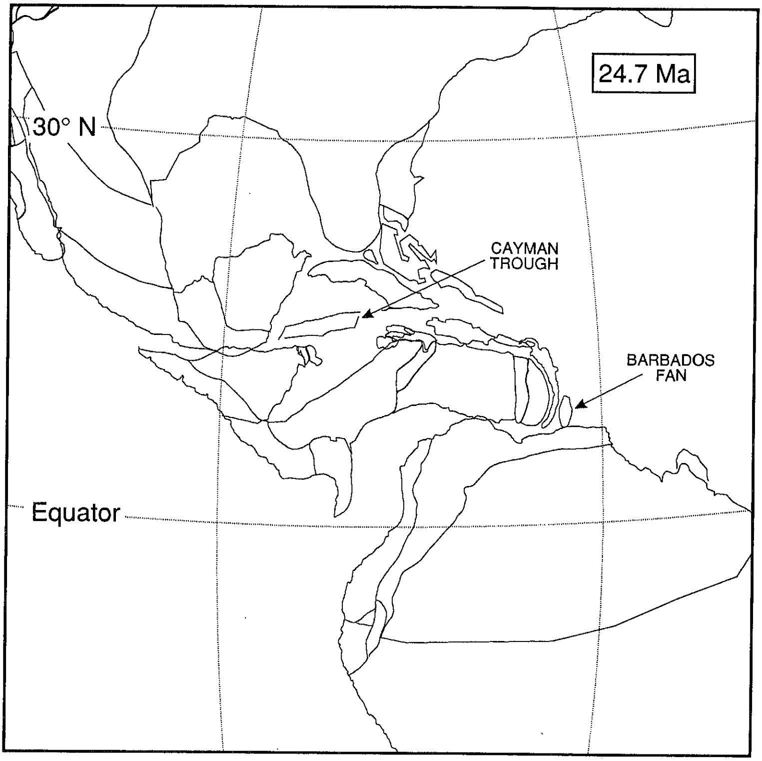

Fig. 2. Plate-tectonic reconstruction of the Caribbean Region at 24.7 Ma.

latest Oligocene. ROSENKRANTZ et al. (1988) found that the earlier opening, from 24.7 to 49.5 Ma (Middle Eocene-latest Oligocene) occurred at twice that rate. We use a single pole to describe the motion of the south side of Cayman Trough during the interval 0-49.5 Ma (Table 1).

The position of the various blocks at 24.7 Ma (latest Oligocene), when the motion abruptly slowed, is shown in Fig. 2. The southern end of the Lesser Antilles arc was north of present Isla Margarita. SAUNDERS (1978) suggested that the turbidites of Barbados Ridge were originally a submarine fan that had been situated north of Barcelona, Venezuela, and was scraped off by the westward movement of the Caribbean Plate. Fig. 2 shows Barbados Ridge as a fan at that location. Since 24.7 Ma the Caribbean Plate has been sliding along the E-W northern margin of South America; the additional friction along the longer contact may account for its slower motion.

Cayman Trough opened more rapidly between 49.5 and 24.7 Ma than since then. From 49.5 to 24.7 Ma the Caribbean Plate was converging at a very low oblique angle with South America. Fig. 3 shows Cayman Trough completely closed at 49.5 Ma (earliest Middle Eocene).

The Polochic and Motagua faults of Central America form the western prolongation of the Cayman transform (AZEMA et al. 1986). Making slight

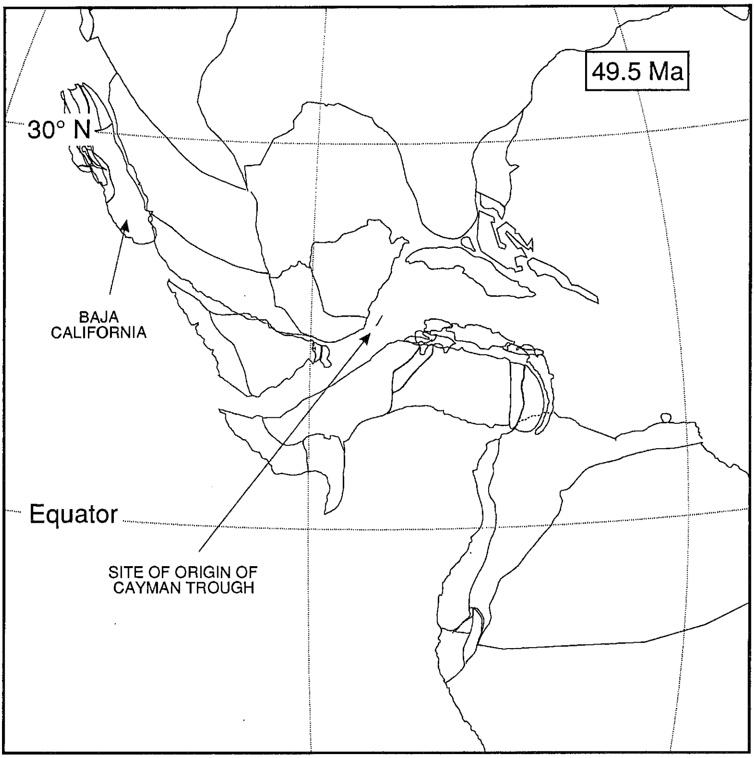

Fig. 3. Plate-tectonic reconstruction of the Caribbean Region at 49.5 Ma. Overlap of the present Grenada Trough and southern Lesser Antilles arc with the reconstructed position of the Guajira Peninsula promontory is shown as a dashed line.

adjustments to the Cayman Trough rotation to follow the traces of these faults, the northern margin of Chortis Block becomes juxtaposed to southwestern Mexico and Guatemala, as suggested by RATSCHBACHER et al. (1991).

At 49.5 Ma the eastern Greater Antilles are south of Cuba, and the southeastern margins of the Maya Block, Meseta Central de Chiapas, and the Nicaragua Rise (SE margin of Chortis) are aligned, forming an arcuate trace concave to the northwest.

There are no unambiguous seafloor magnetic anomalies to guide the older reconstructions.

Stage 2: Opening of the Yucatan Basin

Although there is evidence from heat flow studies that the Yucatan Basin formed in the Early Cenozoic (ROSS & SCOTESE 1988), it can be argued purely on geometric considerations that the Yucatan Basin formed

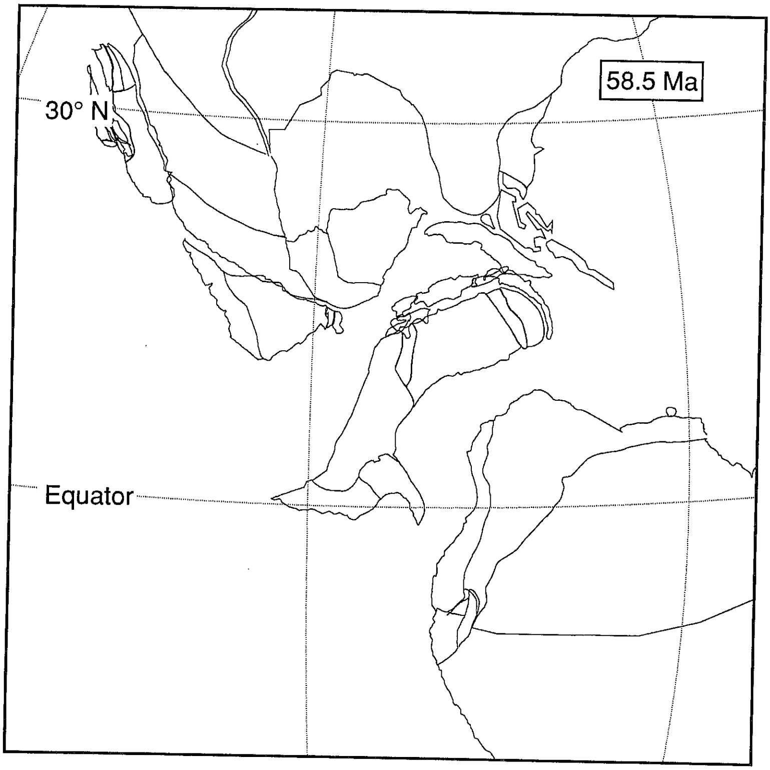

Fig. 4. Plate-tectonic reconstruction of the Caribbean Region at 58.5 Ma. This is the mid-point of the total rotation from 67.5 to 49.5 Ma.

as the Caribbean Plate rotated clockwise like a pinwheel about a pole (Table 1) near the mid-point of its southern margin, as shown in Figs. 3-5. We interpret the concave southern margin of Cuba as a transform, representing a small circle about this pole. We assume that this motion started at the end of Cretaceous (67.5 Ma), when Cuba collided with the Bahama Platform and Florida Block and ended at 49.5 Ma. The maximum deformation in Cuba occurred at the end of the Cretaceous (MacGILLAVRY 1970, JUDOLEY & FURRAZOLA-BERMUDEZ 1971, PINDELL & BARRETT 1990). The subsequent minor deformations in Cuba can be understood in terms of effects of irregularities as the Caribbean Plate rotated, shearing past Cuba. The rotary motion opening the Yucatan Basin occurred throughout the Paleocene and ended at the end of the Early Eocene. The maximum rate of motion during this rotation (≈4 cm/yr) would have been along the transform that developed between Cuba and the Lesser Antilles arc, which remained on the leading edge of the Caribbean Plate. As shown in Fig. 5, the Lesser Antilles arc fits remarkably well into the concave south side of Cuba. As Fig. 5 shows, the eastern Greater Antilles would have been located between the Venezuelan Basin and the Maya Block during the latest Cretaceous and Paleocene.

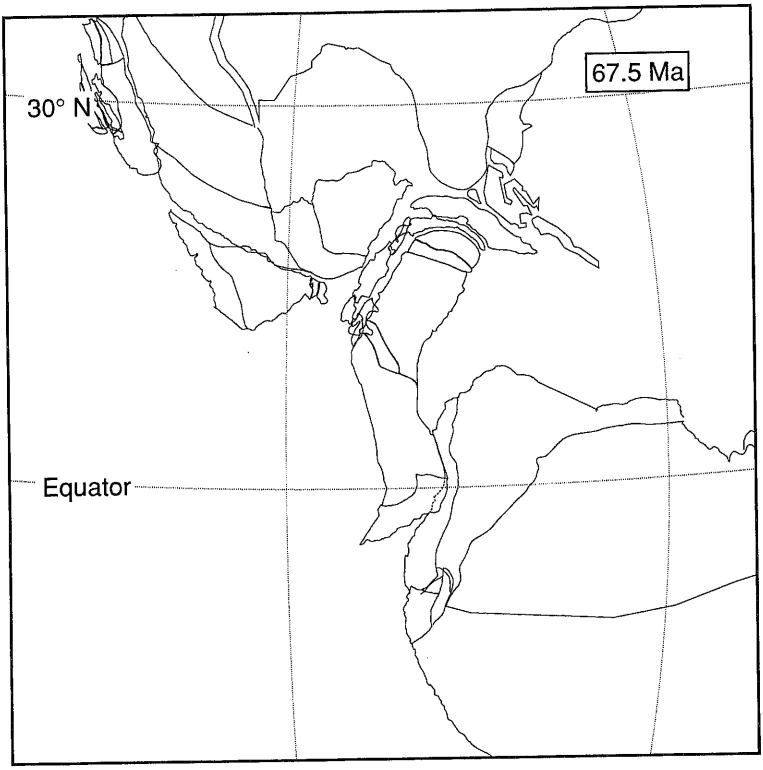

Fig. 5. Plate-tectonic reconstruction of the Caribbean Region at 67.5 Ma. The Choco Block has been removed, although it must have existed at this time. The overlap of the present Corotega Block with the reconstructed position of the Cordillera Occidental is shown as a dashed line.

The pinwheel motion requires that as the Venezuelan Basin moved away from the Maya Block and toward South America, the Colombian Basin moved away from South America and toward Chortis, opening a basin that was the mirror image of the Yucatan Basin to the west of Colombia. It would have had a fan-shaped magnetic anomaly pattern similar to the fan of 0-15 Ma anomalies containing the Siqueiros Fracture Zone west of Mexico. No trace of such a basin remains. The oldest magnetic anomaly west of Colombia is 6A (20 Ma); all older ocean crust has been subducted beneath South America.

Following suggestions by T. VILLAMIL (pers. comm. 1995), the northern margin of South America had a different shape at this time, as shown in Figs. 4 and 5. The E-W margin of eastern Venezuela is shown moved to the north to remove the effect of 30 km of compression that occurred in the Serrania del Interior Oriental during the mid-Cenozoic. Fig. 4 shows part and Fig. 5 all of 200 km of Paleogene compression of the Cordillera Central and Cordillera Oriental restored. If these restorations are correct, and the pinwheel motion is correct, the present southwestern margin of the Colombian Basin should have been in close proximity to, or in contact with, the western margin of Colombia at 67.5 Ma (Fig. 5).

The coincidence of the asteroid impact at Chicxulub on the Maya Block (HILDEBRAND 1991), maximum deformation in Cuba, climax of the Laramide Orogeny in western North America, and changes in direction of spreading reflected in bends in the fracture zones of the North Atlantic and elsewhere is intriguing. Is it possible that the impact event triggered plate reorganization?

Stage 3: Passage of the Caribbean Plate through the gap between Central and South America

Motion of the Caribbean Plate prior to 67.5 Ma is more speculative but is constrained by the changing size of the opening between the Central American blocks and South America. We believe that it is most likely that the Caribbean Plate arrived at the position shown in Fig. 5 by sliding along the southeastern margins of Chortis, the Meseta Central de Chiapas

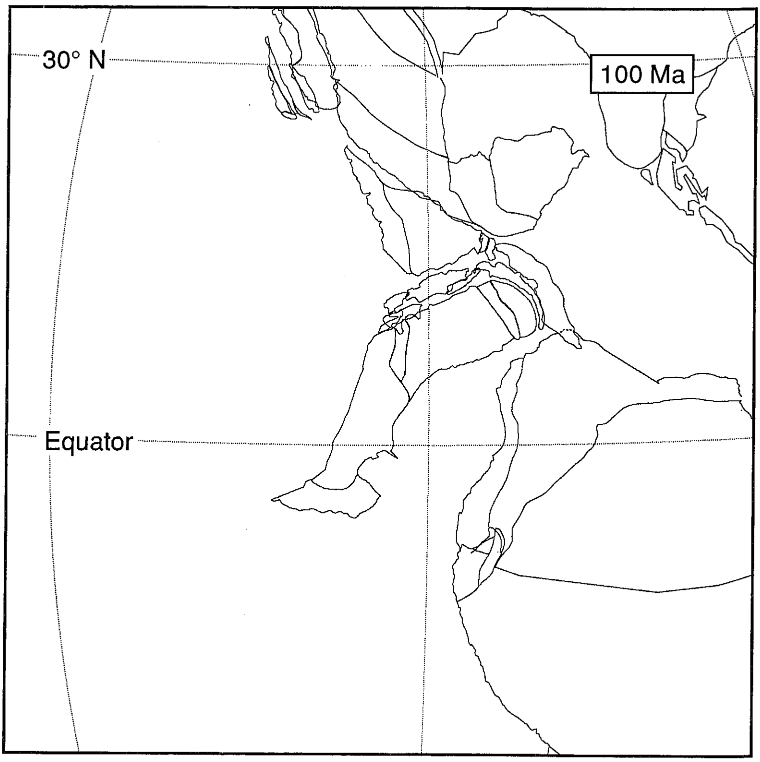

Fig. 6. Plate-tectonic reconstruction of the Caribbean Region at 100 Ma. Overlap of southeastern Cuba with the reconstructed position of the Guajira Peninsula promontory is shown as a dashed line.

and the Maya Block. Although the trace of these margins is arcuate and might represent a transform, the shape of the northern margin of the Caribbean Plate is very different. Accordingly, we think it most likely that the Caribbean Plate entered the Caribbean from the Pacific, first colliding with and then sliding along the southeast (Nicaragua Rise) margin of Chortis. Fig. 6 shows a speculative reconstruction when, while sliding along the margin of Chortis, the Caribbean Plate collided with Cuba. This would have been the cause of the first of the major deformations of Cuba at 100 Ma. Cuba was added to the leading (Lesser Antilles) edge of the Caribbean Plate. Cuba could have picked up the fragments of the Yucatan Platform now incorporated into its southwestern terranes (ITURRALDE-VINENT 1992) as it moved along the margin of the Maya Block. The velocity of the Caribbean Plate during the interval 100 to 67.5 Ma would have been about 2.75 cm/yr.

The space between Chortis and South America is defined by the motions between North America, Africa and South America. In the reconstruction shown here, the space is further constrained by removing the effects of Cenozoic deformation in northwestern South America, as described above. Even in its narrowest orientation, the Caribbean Plate could not have passed through the gap between Chortis and South America earlier than 105 Ma. If oriented sideways to the gap (i. e. long axis of the Venezuelan Basin NW-SE), as shown in many sketched reconstructions, the Venezuelan Basin alone could not pass through the gap before 70 Ma. There has never been enough room for the entire Caribbean Plate to pass sideways through the gap.

The site where the basement of Cuba formed is unknown. We suggest that the basement of Cuba formed in the space between Chortis and South America as they spread apart. This was a region where ocean crust must have been created to fill the widening gap. It is possible that the Cuban basement grew from a hot spot, analogous to the modern Greenland-Scotland Ridge. The length of Cuba and the length of the Iceland-Faeroes segment of the Greenland-Scotland Ridge are almost the same. We place the site of formation at the junction between the Meseta Central de Chiapas and Chortis with no justification other than that is a particularly complex area. Obviously, Cuba did not have its present form at that time, but its length closely approximates the width of the gap between Chortis and South America at 100 Ma. If Cuba was obducted and (temporarily) added to the Caribbean Plate as it moved northeastward, the same hypothetical hot spot could account for the ~90-86 Ma flows that cover the floors of the Venezuelan and Colombian basins as they moved over it. Such a hot spot might also be responsible for the younger lavas that now cover the southern half of the Chortis Block.

Stage 4: The Caribbean Plate in the Pacific

The motion of the Caribbean Plate before the collision with Cuba is even less certain. If it originated as a massive outpouring of basalt (Caribbean Cretaceous Basalt Province) at the Galapagos hot spot (DUNCAN & HARGRAVES 1984) about 88 Ma (SINTON & DUNCAN 1992) and carried Cuba to its present site by 67.5 Ma, it traveled about 2500 km in 20 Ma, or an average speed of 12.5 cm/yr. DUNCAN & HARGRAVES

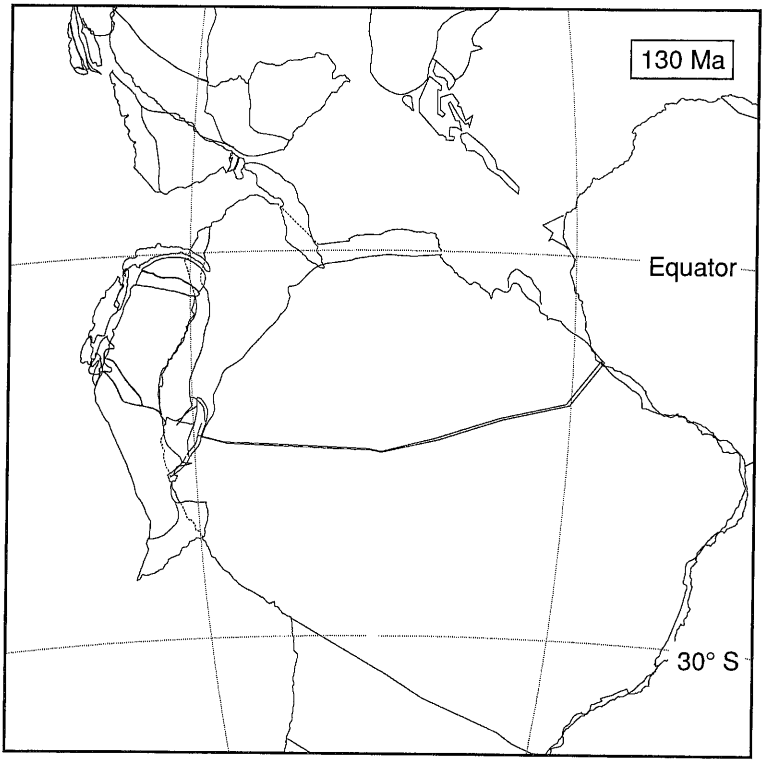

Fig. 7. Plate-tectonic reconstruction of the Caribbean Region and surrounding areas at 130 Ma. Overlaps of eastern Cuba with the reconstructed position of the Cordillera Oriental and of the Grenada Trough, southern Lesser Antilles Arc, Colombian Basin, and Chorotega Block with the Cordillera Occidental are shown as dashed lines.

(1984) had assumed an age of 80 Ma for the basalts and also assumed that Cuba did not reach its present site until about 40 Ma. This still requires an unusual high rate of motion of 6 cm/yr.

We experimented with a possible range of rates of motion of the Caribbean Plate between South America and Chortis and noticed that not only the earliest time of passage through the gap is tightly constrained, but that the northwestern margin of South America has the same shape as the present southern margin of the Caribbean Plate.

Very tight fits are possible between the present southern margin of the Caribbean Plate and the Mesozoic rocks of the Cordillera Occidental that form the western margin of northern South America (Fig. 7). Fig. 7 shows the reconstructed margin of South America created by expanding the Cordillera Central and Cordillera Oriental, but the fit is just as good along the present margin of South America. This suggests that at least the south side of the Venezuelan and Colombian basins might be thinned continental material, as has been suspected from a seismic section in

Aruba Gap showing dipping reflectors interpreted as sediments beneath horizontal basalts (HOPKINS 1973). Further studies suggest that layered rocks beneath the basalts may be extensive (STOFFA et al. 1991).

Fig. 7 also shows an overlap of the southern parts of Grenada Trough and Lesser Antilles Arc with the Cordillera Occidental. Multichannel seismic investigation of the Grenada Basin by PINET et al. (1986) suggests that only the southern part of the basin, a region almost exactly the size and shape of the overlap shown in Fig. 7, is underlain by typical ocean crust. The Lesser Antilles Arc contains Jurassic rocks, especially in its northern part (CASE & HOLCOMBE 1980, MONTGOMERY et al. 1994), indicating that it was in existence before the Caribbean Plate passed through Central America. BOUYSSE et al. (1980) give evidence that the islands from Guadelope to the north rest on an island-arc system that was in existence in the Mesozoic. This can be recognized morphologically by the breadth of the Lesser Antilles Arc. The islands from Dominica to the south are younger (Neogene?), and the Lesser Antilles Arc is much narrower. The dividing line between Guadeloupe and Dominica is approximately where the Lesser Antilles Arc begins to overlap the Cordillera Occidental in Fig. 7. Note that Fig. 3 shows a similar overlap of the same regions, supporting the notion that this part of the plate did not come into existence until after the Middle Paleogene.

For the motion from the 130 Ma position shown in Fig. 7 to the position shown for 100 Ma (Fig. 6) we used two consecutive rotation poles to avoid overlaps at intermediate times not shown here. We assumed that the initial separation (from 130 to 120 Ma) is orthogonal, i. e. to the west, and that the subsequent motion rotates the Caribbean Plate as it moves northward.

Fig. 8 shows the position of the different blocks at 150 Ma. At this time the northern margin of South America is beginning to separate from Chortis, and the Chortis-South America gap is about to be initiated. In reconstructions for earlier times, with a closed Gulf of Mexico, the Caribbean Plate attached to South America, as shown in Figs. 7 and 8, does not interfere with required motions of the Chortis and Oaxaca-Guerrero blocks.

Summary and conclusions

Evolution of the Caribbean Sea region can be modeled by six successive rotation poles for a single Caribbean Plate consisting of the Lesser Antilles Arc, Grenada Trough, Aves Swell, Venezuelan Basin, Beata Ridge, and Colombian Basin as rigid elements. Hispaniola and the Puerto Rico-Virgin Islands Block were deformable elements along its present northern margin. A tight fit between this Caribbean Plate and the South American margin at 130 Ma suggests that at least the south side of the Venezuelan and Colombian basins are thinned continental material. This has long been suspected from seismic sections in Aruba Gap that show a thick section of dipping reflectors, interpreted as sediments, beneath the horizontal flood basalts of the Venezuelan Basin.

After rifting orthogonally from the South American margin at 130 Ma and drifting 300 km westward until 120 Ma, the Caribbean Plate drifted northward to collide with the southern margin of the Chortis Block. It

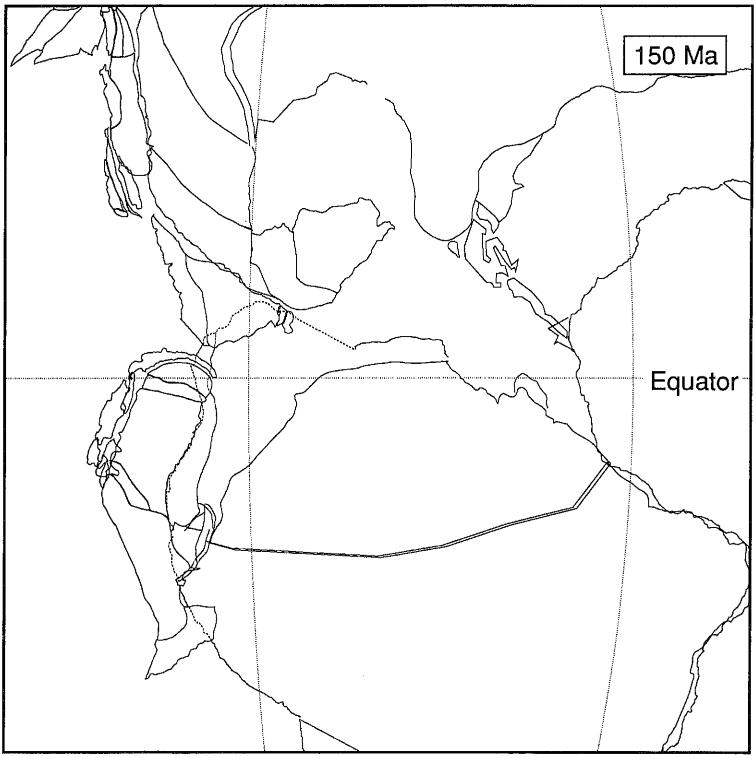

Fig. 8. Plate-tectonic reconstruction of the Caribbean Region and surrounding areas at 150 Ma.

then slid northeastward along the margin to collide with Cuba, which was located between Chortis and South America, at about 100 Ma. From 100 Ma to 67.5 Ma the Caribbean Plate, with Cuba attached to it, moved northwest, parallel to the trace of the southeastern margin of Yucatan. At 67.5 Ma, the Caribbean Plate, with Cuba on its leading edge, collided with the Florida Block and Bahama Platforms. During this time the eastern Greater Antilles were between the Venezuelan Basin and Yucatan. From 49.5 to 67.5 Ma the Caribbean Plate rotated like a pinwheel clockwise, opening the Yucatan Basin. This caused convergence of the southern margin of the Venezuelan Basin with the northwestern margin of South America and convergence of the northern margin of the Colombian Basin with the Chortis Block. At 49.5 Ma the eastern Greater Antilles were south of Cuba. From 49.5 until 24.7 Ma, the Cayman Trough opened rapidly, with the eastern Greater Antilles sliding eastward south of Cuba. The Caribbean Plate converged slowly with the northern margin of South America. At 24.7 Ma the Caribbean Plate ceased to converge and began to slide along the northern margin of South America. The leading edge of the Caribbean Plate, the Lesser Antilles Arc, sheared off the sediments of a submarine fan that had formed north of Barcelona, Venezuela, to form Barbados Ridge. Since 24.7 Ma the movement of the Caribbean Plate has been tied to the slower opening of Cayman Trough.

The advantage of this reconstruction is its simplicity: No deformation of the Caribbean Plate is required to get around the corner of northern South America. Subduction occurs only on the leading edge of the plate until Cuba collides with the Bahamas, thereafter it occurs on both leading and trailing edges of the plate. The eastern Greater Antilles have always been near their present location with respect to the Venezuelan Basin, and their complex geology is explained as the result of their having been in shear zones between the Caribbean Plate and Chortis-Yucatan, Cuba, and the Bahama Platform.

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References

AZEMA, J., BIJU-DUVAL, B., BIZON, J. J., CARFANTAN, J. C., MASCLE, A. & TARDY, M. (1986): Le Honduras (Amérique centrale nucléaire) et le bloc de Oaxaca (sud du Mexique): Deux ensembles comparables du continent Nord-Américain séparés par le jeu décrochant sénestre des failles du système Polochic-Montagua. - Géodynamique des Caraibes. Symposium Paris 5-8 Février 1985: 427-438; Paris (Ed. Technip).

BOUYSSE, P., ANDRIEFF, P. & WESTERCAMP, D. (1980): Evolution of the Lesser Antilles island arc: new data from submarine geology. - Trans. IXth Caribb. Geol. Conf., **1**: 75-88; Santo Domingo.

CANDE, S. C. & KENT, D. V. (1992): A new geomagnetic polarity time scale for the Late Cretaceous and Cenozoic. - J. Geophys. Res., **97**: 13917-13951; Richmond, Va.

CANDE, S. C., LABRECQUE, J. C., LARSON, R. L., PITMAN, W. C. III, GOLOVCHENKO, Y. & HAXBY, W. F. (1989): Magnetic lineations of the World's Ocean Basins. - Amer. Assoc. Petrol. Geol., Map; Tulsa.

CASE, J. E. & HOLCOMBE, T. L. (1980): Geologic-tectonic map of the Caribbean region. Scale 1 : 2,500,000. - U. S. Geol. Surv. Misc. Investig. Ser. Map I-1100; Washington.

CHOUBERT, G. & FAURE-MURET, A. (1976): Geological World Atlas. - 22 sheets with explanations; Paris (UNESCO).

DUNCAN, R. A. & HARGRAVES, R. B. (1984): Plate tectonic evolution of the Caribbean region in the mantle reference frame. - In: BONINI, W. E., HARGRAVES, R. B. & SHAGAM, R. (eds.): The Caribbean - South America Plate Boundary and Regional Tectonics. Geol. Soc. Amer. Mem., **162**: 81-94; New York.

EDGAR, N. T., HOLCOMBE, T., EWING, J. & JOHNSON, W. (1973): Sedimentary hiatuses in the Venezuelan Basin. - In: EDGAR, N. T. & SAUNDERS, J. B. (eds.): Initial Reports of the Deep Sea Drilling Project, **XV**: 1051-1062; Washington, D. C. (U. S. Governm. Print. Off.).

HARRISON, C. G. A. & LINDH, T. (1982): A polar wandering curve for North America during the Mesozoic and Cenozoic. - J. Geophys. Res., **87**: 1903-1920; Richmond, Va.

HAY, W. W. & WOLD, C. N. (1992): The fit of North America, Africa and South America about the site of the future Gulf of Mexico and Caribbean. - VIII Congr. Españ. Geol. y XII Congr. Latinoamer. Geol., 22-26 June, 1992, Actas, **4**: 122-126; Salamanca.

HILDEBRAND, A., PENFIELD, G. T., KRING, D. A. M., PILKINGTON, A., CAMARGO, Z., JACOBSEN, S. B. & BOYNTON, W. V. (1991): Chicxulub crater: a possible Cretaceous/Tertiary boundary impact crater on the Yucatan Peninsula. - Geology, **19**: 867-871; Boulder, Co.

HOPKINS, H. R. (1973): Geology of the Aruba Gap Abyssal Plain near DSDP Site 153. - In: EDGAR, N. T. & SAUNDERS, J. B. (eds.): Initial Reports of the Deep Sea Drilling Project, **XV**: 1039-1050; Washington, D. C. (U. S. Governm. Print. Off.).

ITURRALDE-VINENT, M. A. (1992): Cuban geology and tectonics. - VIII Congr. Españ. Geol. y XII Congr. Latinoamer. Geol., 22-26 June, 1992, Actas, **4**: 294-295; Salamanca.

JUDOLEY, C. M. & FURRAZOLA-BERMUDEZ, G. (1971): Geología del area del Caribe y de la costa del Golfo de Mexico. - 288 pp.; La Habana (Inst. Cubano del Libro).

KLITGORD, K. D. & SCHOUTEN, H. (1986): Plate kinematics of the Central Atlantic. - In: VOGT, P. R. & TUCHOLKE, B. E. (eds.): The Geology of North America, **M**: The Western Atlantic Region: 351-378; Boulder, Co. (Geol. Soc. Amer.).

MacGILLAVRY, H. J. (1970): Geological history of the Caribbean. - Konink. Nederl. Akad. Wetensch., Proc., Ser. B, **73** (1): 64-96; Amsterdam.

MONTGOMERY, H., PESSAGNO, E. A. & PINDELL, J. L. (1994): A 195 Ma terrane in a 165 Ma sea: Pacific origin of the Caribbean Plate. - GSA Today, **4** (1): 1-6; New York.

MÜLLER, R. D., SANDWELL, D. T., TUCHOLKE, B. E., SCLATER, J. C. & SHAW, P. R. (1991): Depth to basement and geoid expression of the Kane Fracture Zone. - Marine Geophys. Res., **13**: 105-129; Dordrecht.

NÜRNBERG, D. & MÜLLER, R. D. (1991): The tectonic evolution of the South Atlantic from Late Jurassic to present. - Tectonophysics, **191**: 27-53; Amsterdam.

PINDELL, J. L. (1993): Regional synopsis of Gulf of Mexico and Caribbean evolution. - Gulf Coast Section SEPM (Soc. for Sediment. Geol.) Foundation, 13th Ann. Res. Conf., Proc., July 1, 1993: 251-274; Tulsa.

PINDELL, J. L. & BARRETT, S. F. (1990): Geologic evolution of the Caribbean Region: A plate-tectonic perspective. - In: DENGO, G. & CASE, J. E. (eds.): The Geology of North America, **H**: Caribbean: 405-432; Boulder, Co. (Geol. Soc. Amer.).

PINDELL, J. L., CANDE, S. C., PITMAN, W. C., ROWLEY, D. B., DEWEY, J. F., LaBRECQUE, J. & HAXBY, W. (1988): A plate-kinematic framework for models of Caribbean evolution. - Tectonophysics, **155**: 121-138; Amsterdam.

PINET, B., LAJAT, D., LE QUELLEC, P. & BOUYSSE, P. (1986): Structure of Aves Ridge and Grenada Basin from multichannel seismic data. - Géodynamique des Caraibes, Symp. Paris, 5-8 Février 1985: 53-64; Paris (Ed. Technip).

RATSCHBACHER, L., RILLER, U., MESCHEDE, M., HERRMANN, U. & FRISCH, W. (1991): Second look at suspect terranes in southern Mexico. - Geology, **19**: 1233-1236; Boulder, Co.

ROEST, W. R. (1987): Seafloor spreading pattern of the North Atlantic between 10° and 40° N. - Geologica Ultraiect., **48** (1): 101-121; Utrecht.

ROEST, W. R., DANOBEITIA, J. J., VERHOEF, J. & COLETTE, B. J. (1992): Magnetic anomalies in the Canary Basin and the Mesozoic evolution of the central North Atlantic. - Marine Geophys. Res., **14**: 1-24; Dordrecht.

ROSENCRANTZ, E., ROSS, M. I. & 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; Richmond, Va.

ROSS, M. I. & SCOTESE, C. R. (1988): A hierarchical tectonic model of the Gulf of Mexico and Caribbean region. - Tectonophysics, **155**: 139-168; Amsterdam.

SAUNDERS, J. (1980): The development of the Caribbean with special reference to the southern margin of the Venezuela basin. - In: AUBOIN, J., DEBELMANS, J. & LATREILLE, M.: Géologie des Chaines Alpines issues de la Téthys: De la Téthys aux mers Intra-Alpines actuelles. Bur. Rech. Géol. Min., Mém., **115**: 237-243; Paris.

SINTON, C. W. & DUNCAN, R. A. (1992): Temporal evolution of the Cretaceous basalt province: results of $^{40}Ar/^{39}Ar$ dating. - EOS Trans. Amer. Geophys. Union, **73**: 532; Washington.

STANEK, K.-P. & VOIGT, S. (1994): Model of Meso-Cenozoic evolution of the northwestern Caribbean. - Zbl. Geol. Paläont. Teil I, **1993** (1/2): 499-511; Stuttgart.

STOFFA, P. L., MAUFFRET, A., TRUCHAN, M. & BUHL, P. (1981): "Sub-B" layering in the southern Caribbean: The Aruba Gap and Venezuelan Basin. - Earth Planet. Sci. Lett., **53**: 131-146; Amsterdam.

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