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A simple synthesis of Caribbean geology

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ABSTRACT. **The complex area between the continental masses of North and South America is a collage of many continental, stretched continental, island arc and oceanic elements described by numerous works. Some areas are poorly exposed and not well known. Others are intensely explored and well documented. Syntheses of this geology popularly derive the Caribbean Plate from the Pacific and require major rotation of island arc elements and continental blocks along with major changes in plate migration direction. These models are complex and geometrically unlikely. This paper suggests a simple, *in situ* evolution from a Pangean configuration principally via regional (North - South America), Jurassic-Late Cretaceous, WNW oriented sinistral transtension, followed by a Palaeocene–Middle Eocene compressional event and Oligocene-Recent, E-W strike-slip between the Caribbean and American Plates.**

1. INTRODUCTION

The Middle America area of this paper lies between the continental masses of North and South America (Fig. 1). The present-day Caribbean Plate interacts with Atlantic plates to the north, south and east and with the Nazca and Cocos plates to the west. Atlantic elements are moving westward relative to the Caribbean Plate, carrying with them the continental Americas. Broad (ca. 250 km) zones of east-west sinistral and dextral strike slip on the northern and southern Caribbean boundaries, respectively, accommodates these relative motions. Pacific elements are moving NE and E relative to the Caribbean Plate. Subduction and arc activity along the Lesser Antilles and Central America reflect convergent interaction between the Caribbean Plate and the Atlantic and Pacific areas.

The northern Caribbean boundary corresponds approximately to the northern margin of the Greater Antilles in the east, to the north flank of the Cayman Trough west of Cuba to the Cayman spreading centre (Oriente Fault), and to the south flank (Swan Fault) of the Trough from the spreading centre to the Central American Isthmus. Across the latter, a system of roughly E-W sinistral faults (Motagua Fault Zone, Fig. 1) documents dispersed (geographic and temporal) surface expression of the boundary. In the south, the plate boundary runs approximately E-W along the northern limit of South America.

Continental crust forms North and South America, parts of southern Mexico, the Yucatán Peninsula and the Central American area of southern Guatemala, Honduras, Nicaragua and El Salvador. Extended continental crust forms the northern part of the Gulf of Mexico, the eastern margin of Mexico, the eastern and western margins of the Florida Platform, the eastern Bahamas Platform and the Nicaragua Rise/Jamaica and the Guyana Platform.

Volcanic-arc material forms the Greater, Lesser and Netherlands-Venezuelan Antilles and the southern part of the Central American Isthmus. It also occurs obducted in the Interior Range of central Venezuela. In Cuba (and ?Hispaniola), obducted island-arc lies above continental basement.

Oceanic crust floors the deep Gulf of Mexico, the Yucatán Basin, the Cayman Trough and the interior of the Caribbean Plate. The Beata Ridge divides the latter into the western Colombian Basin and the eastern Venezuelan Basin (contiguous south of the ridge) while the Aves Ridge separates the Venezuelan and Grenada basins.

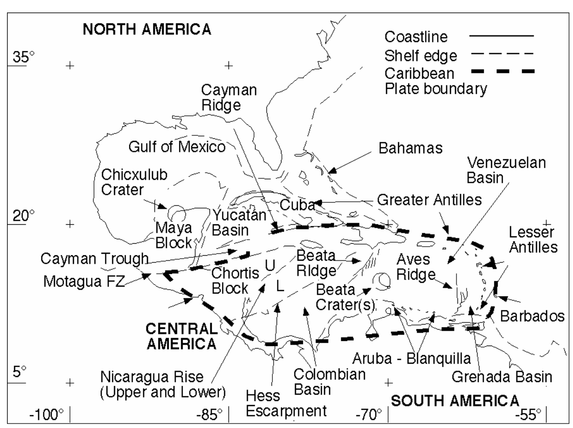

Figure 1. Middle America, geographic elements referred to in text.

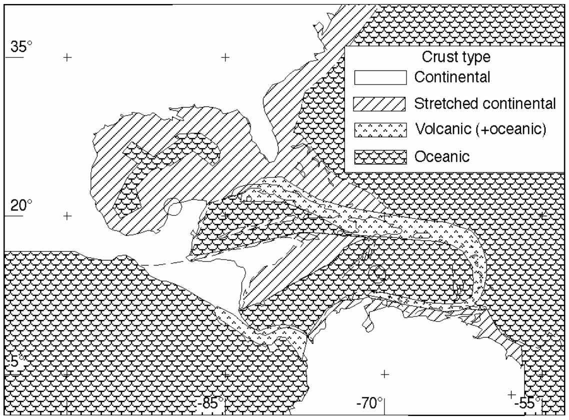

Figure 2. Middle America crustal types.

2. A Complicated Vision

The written geology of the area, and of the Caribbean especially, appears complicated for the following reasons.

Geographic diversity and wide range of data quality. Middle America includes continental, stretched continental, oceanic and island arc rocks (Fig. 2) dispersed among a large number of geographic elements. Poor accessibility and severe weathering obscure data in remote and tropical areas. The Florida-Bahamas platform, northern Yucatán, Nicaragua, the Greater Antilles and offshore northern South America have large submarine extensions that are not known as well as onshore areas. The large submarine areas of the Lower Nicaragua Rise and the Aves and Barbados Ridges (Barbados excepted) are poorly sampled. Thus data in the area are disparate, ranging from well-documented contiguous geology known from onshore northern South America and North America, to the less well-documented, contiguous geology of Central America and the highly discontinuous geology of the Caribbean islands.

Comprehensive regional knowledge is required. Regional geological synopsis of the above requires synthesis of a large volume of literature ranging from local to regional focus and from academic to industrial (mainly hydrocarbon) interest. Local studies (unpublished theses, Spanish/French language publications, local industry publications) may not be easily available or even known to the world at large, while international literature may not be readily accessible to some local centres. Works range across the spectrum of geological studies, but generally are specialized. Sedimentologists and palaeontologists, for example, seldom are interested in igneous and volcanic petrologists and *vice versa*. Some authors base their conclusions on comprehensive synthesis of available information (e.g., Pindell, in many papers, see references). The majority simply quote 'generally accepted' Pacific models and unjustifiably propagate unproven concepts. Mantle plume discussions of the Caribbean Plate are recent examples (e.g., Kerr *et al*., 1995, 1996a, b). They do not present original syntheses of regional Caribbean geology, they fail to acknowledge the conceptual nature of mantle plumes (Smith and Lewis, 1999) and they do not consider multiple working hypotheses.

Complex thinking. Complex models that derive the Caribbean Plate from the Pacific (Fig. 3A) dominate the literature (e.g., Malfait and Dinkleman, 1972; Pindell and Dewey, 1982; Bouysse, 1988; Pindell *et al*., 1988; Ross and Scotese, 1988; Pindell and Barrett, 1990; Lebron and Perfit, 1993; Tardy *et al*., 1994). They postulate spreading ridges that no longer exist (Farallon-Phoenix); hotspots that 'burst into activity' (Duncan and Hargraves, 1984) to produce an oceanic plateau (Burke *et al*., 1984) of just the right width and length to subsequently occupy the Caribbean area (illustrations in Duncan and Hargraves, 1984; Bouysse, 1988; Hoernle *et al*., 2002); 'flips' of subduction polarity along the Caribbean Great Arc (Duncan and Hargraves, 1984; Mattson, 1978, 1984; Pindell, 1993); major rotations of arcs (Greater and Netherlands-Venezuelan Antilles: Pindell *et al*.; 1988; Mann, 1999) and of large continental blocks (Yucatán/Maya and Chortis: Anderson and Schmidt, 1983; Dengo, 1985; Marton and Buffler, 1999; Pindell and Kennan, 2003) and changes in Caribbean Plate migration direction from NE to E (maps of Bouysse, 1988; Pindell *et al*., 1988; Ross and Scotese, 1988; Lebron and Perfit, 1993). Complexity increases in 'refined models' that respond to data and discussion challenging earlier versions (Pindell, 2001; Pindell *et al*., 2001). A mantle plume replaces, or joins, the Galapagos hotspot to explain the thickened part (oceanic plateau) of the Caribbean Plate. The plume was so heterogeneous that the small island of Gorgona exhibits most of the chemical and isotopic compositions seen within the Caribbean oceanic plateau (Kerr *et al*., 1996a, b). A new arc (aborted and largely eroded away) and a new model for the Caribbean are derived from analyses of just 25 samples (yielding six lava types) from Cuba - an area of "*poorly exposed, badly weathered rock*" (Kerr *et al*., 1999). While the Galapagos Hotspot seems to be going out of fashion (discussions of the Leicester meeting of the Caribbean Research Group, 2001), a summary of 'hotspot-or-not' discussion in Stuttgart noted that 'divergence of opinions is determined by the kind of general plate framework' chosen (Iturralde-Vinent, 2000).

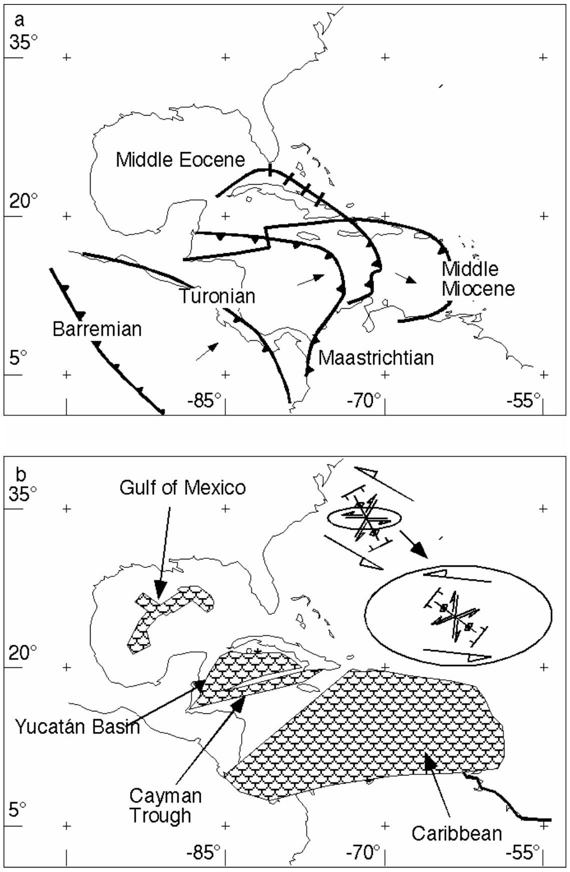

Figure 3. Pacific (A) and *in situ* (B) concepts for the origin of the Caribbean Plate. For simplicity, both are shown in the context of a modern map. Diagram A shows stages of arc migration, at the leading edge of the Caribbean Plate as it migrated from the Pacific, see references for detailed palaeogeographic reconstructions. The *in situ* diagram shows formation of oceanic areas (cross hatched) between WNW, sinistrally diverging North and South America in the Jurassic - Early Cretaceous. The Caribbean Plate was defined by island arcs in the Greater - Lesser - Aruba-Blanquilla Antilles and in southern Central America. From the Late Eocene the northern Caribbean boundary follows the Cayman Trough.

Circular/inverted reasoning. Révillon *et al.* (2000) concluded that although Beata Ridge gabbros and dolerites aged 88-90, 76 and 55 Ma are identical and could have resulted from melting related to *in situ* lithospheric thinning, the older ones must have formed over a plume in the Pacific, because most authors think the Caribbean Plate came from there.

White *et al.* (1999) noted that tonalitic batholiths are generally associated with continental margins. The Aruban tonalite batholith formed shortly after the Aruban volcanic rocks, which formed in a Pacific setting. The Aruban tonalite therefore offers a model for primitive continent formation.

Draper *et al.* (2002) regarded a garnet peridotite (normally associated with deep subducted continental rock) in Hispaniola as unusual because it occurs at an ocean-ocean convergent plate boundary. They suggest it came from the asthenosphere. It should be seen to indicate that the Florida-Bahamas continental crust, seen in Cuba, continues below Hispaniola.

Unquestioning/unqualified propagation of complex, Pacific models. Many papers quote Pacific models as ‘accepted’ explanations of Caribbean Plate origin without consideration of alternative possibilities. Unquestioning propagation of such models fails to consider multiple working hypotheses or to recognize unreliability or absence of data. The Pacific-origin model was built upon a series of arguments (Duncan and Hargraves, 1984; Pindell *et al.*, 1988; Pindell and Barrett, 1990; Pindell, 1991; Pindell, 1993) that have not received proper scrutiny until recently (James, 2005a). New arguments are introduced to ‘refine’ the concept (Pindell, 2001; Pindell and Kennan 2003) and add to complexity. Science demands discussion of alternatives (multiple working hypotheses), but few papers provide this. Discussion should consider whether there are any essential arguments that require a complex Pacific origin or whether a simple, *in situ* model suffices. In a separate paper (James 2005a), I examine arguments, old and new, quoted in support of a Pacific origin and I suggest arguments that indicate an *in situ* origin (Fig. 3B). There is no essential reason for the Caribbean to have its origin in the Pacific, and such models are geometrical impossible. There are several lines of evidence that suggest a simple, *in situ* origin of the Caribbean Plate. I present them in this paper.

Prejudiced research. Popularity of the Pacific model results in continued application of research to support them, with an unsurprising level of success. For example, Skerlec and Hargraves (1980), Stearns *et al.* (1982) and Molina Garza *et al.* (1992) sought and found palaeomagnetic support for rotation of the Netherlands and Venezuelan Antilles (90˚) and the Maya Block (50˚). The former did not consider rotation of local elements about vertical axes (e.g., dextral strike-slip as in the Perij Mountains of Venezuela, Gose *et al.*, 1993; sinistral strike-slip along the northern Caribbean boundary Gestel *et al.*, 1999). Molina Garza *et al.*, (1992) extrapolated data from local (Chiapas Massif) to regional (Maya Block) scale.

Hoernle *et al.* (2002) looked for and found the missing history of the Galapagos Hotspot track and ‘confirmed’ that the Caribbean formed there. Notwithstanding that their data may be accommodated by other models, they fail to show

how the Cocos, Malpelo, Coiba and Carnegie ridges all formed above the same hotspot. They overlook evidence that the Cocos Ridge is an abandoned spreading centre (Kimura *et al*., 1997; Meschede, 1998).

Lack of data on the age and origin of older Caribbean oceanic crust. Four oceanic provinces record the large amount of extension that occurred between North and South America: the Gulf of Mexico, the Yucatán Basin, the Cayman Trough and the Caribbean (Colombian, Venezuelan and Grenada basins). The age of first crust formation is uncalibrated by *in situ* sampling. Obducted oceanic basement, interbedded with cherts bearing Jurassic radiolaria, occurs at several localities in the area (Cuba - Northern Ophiolitic Belt, Hispaniola - Duarte Complex, Puerto Rico - Virgin Islands - Bermeja Complex, La Désirade basement complex). It may represent the oldest Middle American oceanic crust (e.g., Donnelly *et al*., 1990).

Palaeogene ages quoted for the Yucatán and Grenada basins and for the Cayman Trough derive solely from heat-flow and depth-to-basement estimates (Rosencrantz *et al*., 1988). A Callovian age for the Gulf of Mexico ocean crust is based upon data from the NE basin margin (Marton and Buffler, 1999).

Submarine volcanoes and lava flows form smooth crust above rough crust in parts of the Caribbean area (western Venezuelan Basin and the Beata Ridge, the eastern Yucatán Basin and the western Colombian Basin: Bowland and Rosencrantz (1988), Rosencrantz (1990), Diebold *et al*. (1999). DSDP samples of the upper crust indicate at least two phases (130 - 120 Ma, 90 - 88 Ma) of basaltic outpourings (Donnelly, 1989; Diebold *et al*., 1999), though extrusion continued at least until 77 Ma (Sigurdsson *et al*., 1996) or 55 Ma (Révillon *et al*., 2000). Donnelly (1973) and Donnelly *et al*., (1973) suggested that the Caribbean was the site of a large, Cretaceous flood basalt event that thickened parts of the Caribbean Plate. The idea evolved into the concept of an oceanic plateau, similar to the Iceland, Manihiki and Ontong Java oceanic plateaus. However, Diebold *et al*. (1999) remarked that while the idea that the Colombian and Venezuela basins are capped uniformly by a Cretaceous igneous body persists 'The concept of the Caribbean Plate as a monolithic allochthon of crust thickened by Cretaceous flood basalts is laid to rest by multichannel seismic data'. They emphasized that the Caribbean Sea includes crust of thickness from normal (6-8 km) to abnormally thin (3-5 km), as well as thick (up to 12 km, Diebold *et al*., 1999, or even 20 km, Révillon *et al*., 2000).

Albian–Cenomanian, tholeiitic arc lavas (Primitive Island Arc of Donnelly *et al*., 1990), coeval with the Basalt Province, occur around the Caribbean in Puerto Rico (Pre-Robles), the Virgin Islands (Water Island Formation), Hispaniola (Los Ranchos Formation and Maim¢n Schists), Dominican Republic (El Seybo), Jamaica (Lower Devil's Racecourse Formation), La Désirade, Tobago (North Coast Schist), Bonaire (Washikemba Formation), Venezuela (Villa de Cura Nappe: El Caco, El Chino, El Carmen and Santa Isabel formations). Kerr *et al*. (1997) saw these as accreted remnants of an arc that was peripheral to the plateau. However, seismic data from the Colombian and Venezuelan basins show submarine volcanoes associated with the basalt flows (Bowland and Rosencrantz, 1988; Diebold *et al*., 1999). Volcanoes occur throughout the area of the Lower Nicaragua Rise (Holcombe *et al*., 1990). Some extrusive activity occurred in shallow water (vesicularity in basalts of the Washikemba Formation, Bonaire; DSDP Sites 1001, Cayman Ridge and 1003, Hess Escarpment). The volcanic material may have had a shallow, regional intraplate, rather than a peripheral, development.

Absence of dated spreading ridges and magnetic anomalies. Well-defined, symmetrical spreading anomalies are notably absent from Middle America except in the central part of the Cayman Trough (dated back to Anomaly 6, Early Miocene; Case *et al*., 1990). Uncalibrated magnetic anomalies reported from the Colombia, Grenada, Venezuela and Yucatán basins (Christofferson, 1976; Ghosh *et al*., 1984, Rosencrantz, 1990; Bird *et al*., 1995, 1999; Hall, 1995; Hall *et al*., 1995) are suspect; they may be reflections of structure and topography rather than records of spreading (Driscoll and Diebold, 1997; Diebold *et al*., 1999).

Uncalibrated extension of the Caribbean Plate. Cretaceous basaltic flows cover much of the deeper, original crust in the Colombian and Venezuelan basins (see section on magmatic history, below). Where the deeper crust occurs uncovered it is stretched and thin. This (?Jurassic–Cretaceous) extension is unquantified and is not considered in most models of the area. Driscoll and Diebold (1997, 1999) discussed seismic data showing divergent wedges, above shallowed MOHO, of reflections below Horizon B" (88-90 Ma) of the Caribbean Plate. At other sites, such wedges reflect large igneous events at or immediately prior to the cessation of continental rifting and the onset of seafloor spreading (see also Rosendahl *et al*., 1992). If the Caribbean fabric is related to continental rifting, it clearly formed between the Americas and

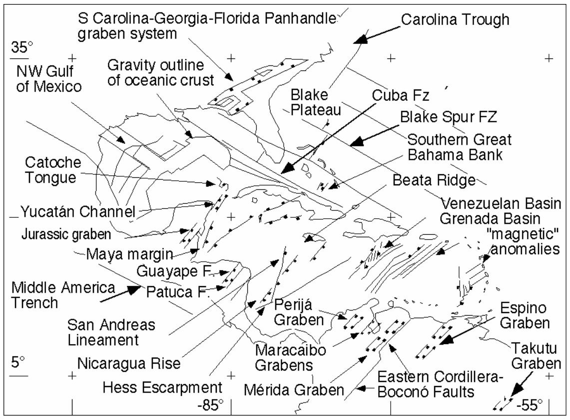

Figure 4. NE trending extensional strain in Middle America includes Triassic-Jurassic rifts in the southern United States and in northern S America, extended continental crust in the Gulf of Mexico, eastern offshore North America, eastern Yucatán, the Nicaragua Rise and western Venezuelan Basin/Beata Ridge. Parallelism of rifts on Yucatán with the regional strain shows that the Maya Block has not rotated. There is no indication of radial (plume activity) deformation in the area.

not in the Pacific.

Extension in the western Venezuela Basin and Beata Ridge occurred along westward-downthrowing, NE trending faults (Driscoll and Diebold, 1999). This direction parallels regional Jurassic extensional strain in southern North America - northern South America (Fig. 4) and also argues for an intra-American origin (James, 2005b). Extension is also emphasized by Case *et al*. (1990), who noted that gabbroic material dredged from the walls of the Cayman Trough indicated anomalously thin crust, and by Ten Brink *et al*. (2001), who interpreted thin crust in the distal part of the Cayman Trough as transitional, formed by extreme attenuation without organized sea floor spreading.

Debatable estimates of strike-slip along plate boundary faults. Strike-slip displacements characterize the northern and southern boundaries of the Caribbean Plate. There are widely differing estimates of offset. Sinistral movement of around 1,100 km seems to have occurred between the Caribbean and North America along the Cayman Trough and its extension through Central America. This figure is frequently transposed to estimate displacement along the southern margin of the plate. This is not justified. There is a (?diffuse) boundary between the North and South America plates in the Atlantic in the region of latitude 15˚N (see also, next paragraph).

Uncalibrated age of Cayman displacement. Heat-flow and depth-to-basement studies conclude that Cayman Trough displacement began in the Eocene (Rosencrantz *et al*., 1988). This remains the commonly quoted age of Trough opening (e.g., Mann, 1999) even though Rosencrantz (1993) later suggested that the Cayman Trough recorded local rather than regional plate movements and could not be used to track Caribbean-North American relative plate motion.

An overview of the western Atlantic shows that North America has moved westwards by some 1,500 km with respect to South America. Most of this distance is accounted for by Jurassic-early Cretaceous oceanic crust that is present in the North Atlantic and absent from the Equatorial Atlantic. The additional crust is present north of the northern Caribbean Plate boundary (see later). 'Laramide' structures in Central America require only 130 km of restoration along the Motagua Fault Zone (Polóchic Fault, westward continuation of the Swan Fault, Fig. 1) (Burkart *et al*., 1987; Burkart and Scotese, 2001). Therefore, most of the Cayman Trough sinistral displacement occurred in the Jurassic-early Cretaceous, while South America was still attached to Pangea. It relates only to the Caribbean - North America plate boundary.

Uncalibrated shortening along northern and southern boundaries of the Caribbean Plate. Shortening along the northern and southern margins of the plate could sum to several hundred kilometres. Pindell *et al*. (1998, fig. 12 and its inset) show around 400 km of N–S shortening between the Caribbean and northeast South America since 54 Ma (the present paper maintains that no convergence occurred). Shortening along the plate margins resulted from Oligocene - Recent transpression that produced eastward migrating thrust/foredeep couples. Rossi *et al*. (1987), Daal (1992) and Chevalier and Spano (1996) estimated that 40 to 49 km of shortening occurred in the trusted/folded Interior Ranges of Venezuela. Folds in the Jurassic of the Coastal Ranges of Venezuela record further shortening. Bally *et al*. (1995) estimated total shortening as high as 250 km.

Relative motions of major plates were poorly defined. Until the advent of satellite-derived data, fracture patterns in the equatorial Atlantic were poorly known. Magnetic anomaly data in the equatorial Atlantic remain poorly known (a blank area on the magnetic anomaly map of Cande *et al*., 1989). As a result, published flow path models for North and South America are based upon fracture and magnetic data from the central North and Southern Atlantic regions (e.g., Ladd, 1976; Pindell *et al*., 1988; Müller *et al*., 1999). Such data reflect the relative movements of North America and southern South America. Fracture patterns in the

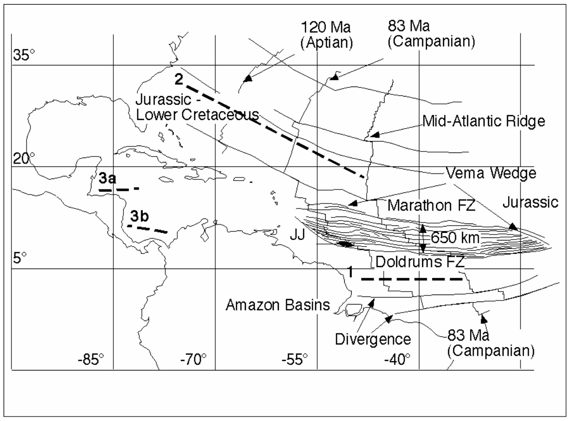

Figure 5. Fracture zones of the Central and Equatorial Atlantic and detail of the Vema Wedge. The former indicate the the Jurassic - Early Cretaceous drift of N America from Pangea (1,000 km of E–W offset and around 850 km of N - S extension). The latter shows approximately 650 km of Cretaceous N–S extension between the North and South American plates. Divergence between transforms in the Equatorial Atlantic, offshore from the Amazon Basins, shows that northern South America has moved differentially with respect to southern South America (see text for significance to drift reconstructions). Dashed lines 1 and 2 indicate the mid-Atlantic Ridge to continental edge distances of South and North America. The greater length of 2 relates to Jurassic crust in the Central Atlantic that is absent from the South Atlantic, together with a broader lower Cretaceous crust. This distance (2 minus 1) corresponds to offsets between Maya and Chortis and Chortis and NW South America (3a + 3b).

western South Atlantic diverge in the equatorial region (Fig. 5); the Amazon Basins are the continental extension of this divergence. Northern and southern South America have moved differentially. For the Caribbean region, relative motions of North America and northern South America are required. I address this problem below.

Intra-plate deformation of North and South America and Africa not entirely quantified. Stretched continental crust borders eastern North America (Klitgord *et al*., 1984) and the SE Gulf of Mexico (Marton and Buffler, 1999). Major grabens probably formed in the Gulf of Mexico area in the Late Triassic - Early Jurassic (Salvador, 1987). Anderson and Schmidt (1983) suggested that 700 – 800 km of sinistral offset occurred along the Mojave-Sonora megashear, 300 km along the Mexican Volcanic belt and 1,300 km along the Guatemala megashear (Jurassic-Cretaceous). Sedlock *et al*. (1993) concluded that at least 1000 km of NW-SE offset developed between North and South America occurred during spreading and stretching in the Gulf of Mexico region.

Unternehr *et al*. (1988) suggested up to 95 km of sinistral offset along the Benoué Trough of West Africa and 150 km of dextral offset along the Rio Grande Rise - Andean Cochabamba-Santa Cruz bend in South America.

Unknown age of volcanic-arc activity in the Lesser Antilles. Convergence and tectonic inversion have exposed deeper geology of the Greater and Netherlands - Venezuelan Antilles and drilling in the eastern Greater Antilles has penetrated volcanic flows (Water Island Formation) beneath Albian deposits (Donnelly, 1970). The Lesser Antilles are tips of undisturbed edifices with some 3,000 m of relief. Deeper geology has not been exhumed for age dating and it is not drilled. Some authors continue to propagate the notion that the southern islands have only Eocene or Oligocene origins (e.g., Macdonald *et al*., 2000; Pindell, 2003). However, proprietary seismic data, tied to well data, show the Jurassic basement-Middle Eocene section pinching out against the Antilles in the western Tobago Trough. The arc probably formed when spreading jumped from the Caribbean area to the Atlantic (see later).

3. RECONSTRUCTION

3.1. Relative movements of North and South America

Pindell *et al*. (1988) described the following relative movements between North and South America. Divergence occurred from the Late Triassic to the Late Cretaceous. From the Early Campanian to the Eocene there was little relative movement. Since the Eocene slow N–S convergence has occurred. Müller *et al*. (1999) showed sinistral transtension/strike-slip between the two Americas until the end of the Palaeocene, followed by NE-SW convergence until the end of the Eocene.

Müller *et al*. (1999) studied the relative motions of North and South America since chron 34 (83 Ma). They used information from the central North Atlantic, where good magnetic data are available, and from fracture patterns south of latitude -10˚. There are no magnetic data between latitudes 8 and 15˚ N. Müller *et al*. (1999) noted that the fracture zones in the equatorial Atlantic constrain South America-Africa plate motions; yet absence of magnetic data means that one cannot determine which part of a fracture is relevant for a particular age.

Both Pindell (1991) and Müller *et al*. (1999) derived their relative motion vectors from transform fault patterns in the Central and South Atlantic. Flow lines in the South Atlantic indicate movement

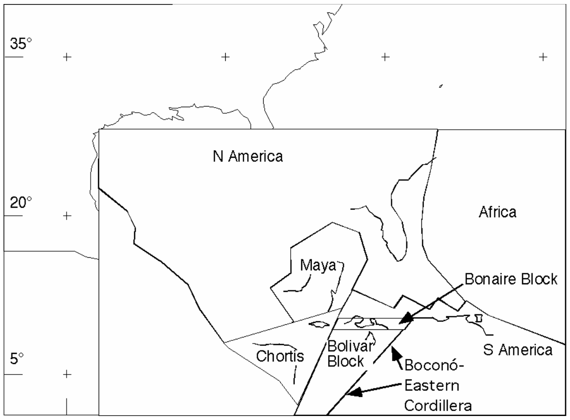

Figure 6. Suggested Pangean reconstruction of North and South America and intervening continental areas. This reconstruction involves removal of volcanic arcs, of oceanic crust in the Atlantic, the Gulf of Mexico, the Yucatán Basin, the Cayman Trough and the Caribbean, simple restoration of sinistral offset of North America and continental elements of the Maya and Chortis blocks (no rotations) and removal of continental crust extension in the Bahamas, the Florida Peninsula, the Gulf of Mexico and the Lower Nicaragua Rise. The Bolivar and Bonaire blocks of NW South America are restored SW along the Boconó/Eastern Cordillera Faults of Venezuela and Colombia.

of South America in a direction south of west. However, flow lines in the South Atlantic diverge at the latitude of the Amazon basins (Fig. 5). Those just north of this latitude indicate movement of South America to the west. It is the latter that should be used to indicate the movement of northern South America, not the pattern further south.

Overview of the western Atlantic region (Fig. 5) shows that the American continent margin - Mid Atlantic Ridge distance north of the Marathon/Fifteen-Twenty Fracture Zones is markedly wider (ca. 1,600 km) than that at the Sierra Leone/Doldrums Fracture Zones (Stainforth noted 1,000 miles of offset in 1969). N–S separation of North and South America (northern continental margin of South America to southern edge of the Florida Platform) is also around 1,500 km.

The offset developed primarily along WNW trending Atlantic Ocean fractures and along sinistral faults within North America (Fig. 3B). Secondary (synthetic) offset occurred along an approximately E–W zone today marked by the Cayman Trough. Most of the extensional strain (NE-SW normal faults) in middle America reflects this (Fig. 4): normal faults in NW Gulf of Mexico, north Yucatán Fault, Hess Escarpment, western Venezuelan Basin and Beata Ridge; Triassic-Jurassic grabens of Georgia-Florida, Yucatán and northern South America.

The additional continent-spreading ridge distance (1,600 km) relates largely to Jurassic crust in the Central Atlantic that is absent in the south, together with a wider lower Cretaceous zone. The sinistral offset between the continents therefore developed largely at that time, along with some 850 km of N–S separation.

In addition, Atlantic fracture patterns between latitudes 7 to 15˚N (east of the Caribbean) were poorly seen until satellite-derived bathymetry revealed the Vema Wedge (Fig. 5) (e.g., James *et al*., 1998). This complex area indicates N–S elongation of the Mid Atlantic Ridge (as predicted by Ball *et al*., 1969) by some 650 km. From south to north, the Mid-Atlantic spreading ridge is offset some 1,000 km westwards across the wedge. Fracture zones north of the wedge trend north of west while those to the south trend westward. The wedge separates once-contiguous (Demerara, Guinea) Jurassic crust in the Central Atlantic, so N-S offset must have formed largely during the Cretaceous. However, short, young transform faults indicate that N–S separation continued late into the Cenozoic.

In summary, Middle America, including the Caribbean area, has suffered considerable sinistral stress and N–S extension.

3.2. Pre-drift configuration of Middle America and drift progress.

Pre-drift restoration of Middle America requires little more than removal of extension and sinistral offset that occurred between North and South America. The Bolivar and Bonaire blocks of NW South America also have to be restored along the Boconó Fault (James, 2000) and volcanic-arc elements have to be removed. Figure 6 shows a simple Pangean reconstruction based on these premises.

Analysis of fracture zones and reported magnetic anomalies in the Central Atlantic (North America Plate), in the Central Atlantic at around 0 to 5˚N (South America) and in the Vema Wedge indicates the plate migration history shown in Figure 7. Magnetic anomaly definition is poor in the Equatorial Atlantic and Vema areas, so this history is a suggested one. The illustrations indicate that relative movements between North and South America were NW extension and sinistral offset followed by narrowing of their E-W separation. No significant convergence has occurred. Later figures illustrate details of the Middle America development. Beforehand, I consider how the Caribbean area became thickened and isolated

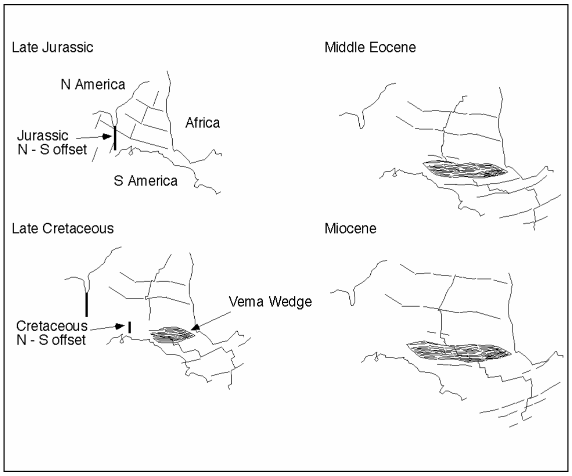

Figure 7. Schematic drift reconstructions as North America and South America move west from the Pangean reconstruction of Figure 6. Bold vertical lines show N - S offset between the continents that occurred in the Jurassic, while South America remained attached to Africa, and again in the Cretaceous, when the Vema Wedge developed and South America moved westward, catching up, longitudinally, with North America. Note that there has been no N - S convergence between North and South America.

as a separate plate bordered by subduction island-arcs. The Iceland and Manihiki plateaus are possible models.

3.3. Isolation of the Caribbean Plate and development of thickened oceanic crust (plateau development) - the 'Iceland Model'

Iceland is an oceanic plateau (cf. the Caribbean plateau) astride the Mid-Atlantic spreading ridge between the continental masses of Greenland and Europe (cf., North America and Pangea) (Fig. 8a). If spreading jumped to the east and west (Fig. 8b), Iceland would become isolated between two new spreading ridges. The plateau would become a newly defined plate, bounded by subduction of normal oceanic crust and volcanic arcs.

The Manihiki oceanic plateau formed in the interval 125 - 120 Ma (coeval with first plateau thickening in the Caribbean). It became subdivided by Tongareva triple junction, preceded by transtensional rifting (Larson *et al*., 2002). An early phase (130 - 120 Ma; Diebold *et al*., 1999) of Caribbean plateau thickening may have been associated with triple junction spreading (Manihiki model) that heralded the spreading move from the Caribbean to the Central Atlantic. Following the development of Atlantic spreading towards the south, spreading convergence between the Caribbean plateau and normal, Atlantic ocean crust resulted in subduction and island-arc volcanism. The Caribbean Plate became bounded by subduction zones to the east and west in the Albian and assumed its own identity.

Thickened oceanic crust (plateau) occurs also in the western part of the Colombian Basin (Bowland and Rosencrantz, 1988) and in the eastern part of the Yucatán Basin (Rosencrantz, 1990). It is tempting to consider that these once were contiguous with the plateau of the Venezuelan Basin/Beata Ridge before they were offset by rifting, triple junction and subsequent offset, similar to the breakup of the Manihiki Plateau (Larson *et al*., 2002). However, ODP Hess Escarpment Site 1001 penetrated mid Campanian basalt (77 Ma) (Sigurdsson *et al*., 1996) beneath Maastrichtian sediments, thus activity of the west Colombian plateau seems to have continued later than in the Beata area. In addition, thick, lower Cretaceous oceanic basalts occur in western Ecuador and Colombia. It makes more sense to consider that thickening occurred in several areas (Larson, 1991), not necessarily linked as one vast Caribbean province. It is also noteworthy that no plateau thickening occurred in the Gulf of Mexico, a more isolated ('intracontinental') oceanic development, coeval with the other Middle America oceanic provinces.

4. Tectonic Evolution (Figs. 9, 10, 11, 12)

Triassic-Jurassic rifting (Fig. 9) occurred along lineaments that were to become the continental margins of NW Africa, eastern North America, southern North America and northern South America and along grabens within the continent peripheries.

Jurassic to early Cretaceous drift of North America from Gondwana (Fig. 10) left South America attached to Africa. More than 1,000 km of E–W offset and around 850 km of N–S extension (NW-SE extension of around 1500 km) separated North and South America. The area between the Americas was extended along NE trending normal faults (extrapolations of Triassic to Jurassic rifts, Fig. 4), developing transitional (continental margin) and oceanic crust. Fragments of continental crust, the Maya and Chortis blocks (Fig. 2), bordered the Caribbean area to the west. Maya moved west relative to Chortis by around 500 km at this time. The spreading ridge between North and South America trended NE–SW and remnants occur today at the Beata Ridge.

Early Cretaceous separation of South America from Africa occurred and South America began to drift to the west (Fig. 11).

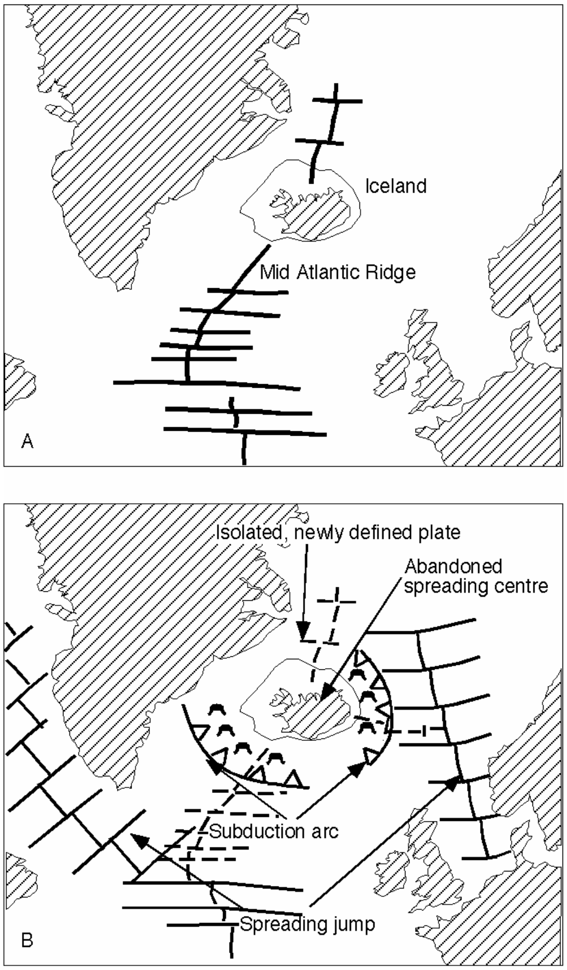

Figure 8. A, Present day configuration of the Iceland oceanic plateau and the Mid-Atlantic Ridge. B, hypothetical jump of spreading to the east and west resulting in abandonment of Mid-Atlantic spreading in the Iceland region, subduction, arc volcanism and isolation/definition of a new 'Iceland Plate'.

Early Cretaceous definition of the Caribbean Plate occurred as seafloor spreading moved to its Atlantic and Pacific neighbours. Northern South America separated from Africa in the Aptian?/Albian and the central and southern Atlantic became united. Triple junctions in the Middle America area heralded the change of spreading pattern (Fig. 11). Related crustal extension resulted in decompression melting and plate thickening in areas of today's eastern Yucatán Basin, western Venezuelan Basin/Beata Ridge, western Colombian Basin and offshore Ecuador and Colombia. Spreading in the Atlantic and the Pacific drove subduction of normal ocean crust below the thickened Caribbean. Subduction-related arc magmatism commenced in Central America and in the Lesser Antilles and the Caribbean Plate assumed its identity (Fig. 12).

Around 650 km of N–S Cretaceous divergence of the Americas occurred as the Atlantic spreading ridge became extended in latitudes 5 - 15°N (Fig. 5). Internal NW-SE extension along NE-SW oriented faults, focussed in part on the Beata Ridge area (Fig. 4), allowed further, regional basaltic outpouring on the Caribbean Plate in the late Turonian. Back-arc extension in the east of the Caribbean region was marked by the Aves Spreading Ridge.

Palaeocene through Middle Eocene convergence between the Caribbean oceanic plate and surrounding elements led to uplift and flysch/wildflysch sedimentation (Fig. 13) (James, 2005a) around the Caribbean margins. Extremely large olistoliths of Caribbean oceanic and volcanic material and continental material were thrust onto the western Greater Antilles (Cuba) and along northern South America. Among these were the 250 km long Villa de Cura Nappe (Venezuela) and its former, western extension, the Aruba - Blanquilla island chain (Fig. 14A). Well-sorted, quartzose sands (Scotland Group, Barbados) accumulated on the Atlantic Plate some 300 km north of NE South America. Clasts of local material define their provenance in the Trinidad area (Guppy, 1911; Senn, 1940; Renz, 1942). Coeval sands on the Tiburón Rise (Atlantic Plate) (Dolan *et al*., 1990), which blocked their further northward progress, proves the site of deposition (and disproves models of deposition further to the west).

Oligocene to Recent strike-slip occurred along the northern and southern boundaries of the Caribbean plate, while subduction and related volcanism occurred along its western and eastern boundaries. The northern and southern boundaries of the Caribbean Plate experienced pull-apart extension followed by, in some areas (e.g., the Falcón Basin of western Venezuela), later inversion. Oligocene volcanic rocks occur in Falcón and La Vela Bay. Thermal gradient in the Yucal Placer area of the Oligocene Guárico Basin is the highest in eastern Venezuela.

Interaction of NW South America with its NE moving Pacific neighbour drove the Bonaire Block northwards across the South America - Caribbean Plate dextral boundary (Fig. 6). Pull-apart extension separated the Aruba - Blanquilla islands, formerly the western continuation of the Villa de Cura nappe. Restoration of this extension shows that the Caribbean has moved some 300 km east relative to South America since the Oligocene (Fig. 14B). Similar offset occurred along the northern plate boundary.

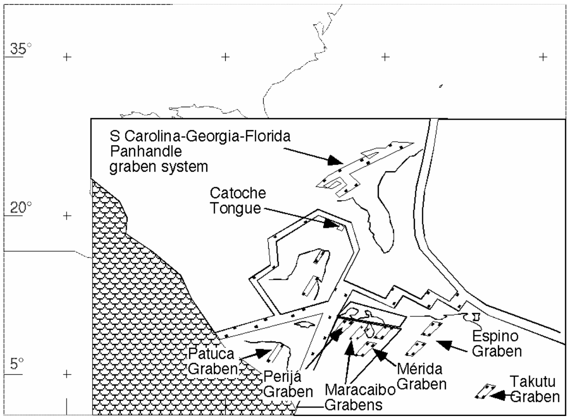

Figure 9. Schematic Triassic-Jurassic reconstruction. Rifting in Middle America trends NE, sinistral offset begins along WNW faults. Note the orientation of Jurassic rifts and the Catoche Tongue of the Maya Block remains unchanged (Fig. 4), showing that the block has not rotated.

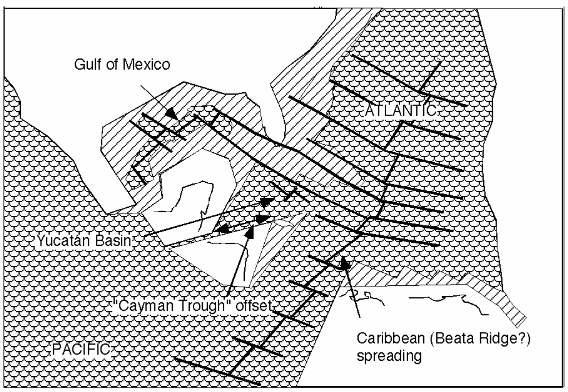

Figure 10. Schematic Callovian-Berriasian reconstruction. Ocean crust forms in the Gulf of Mexico, Yucatán Basin and the area of the future Caribbean Plate. Extended continental crust forms along the northern coast of South America, in the Gulf Coast, Florida-Bahamas, eastern seaboard of North America and Nicaragua Rise.

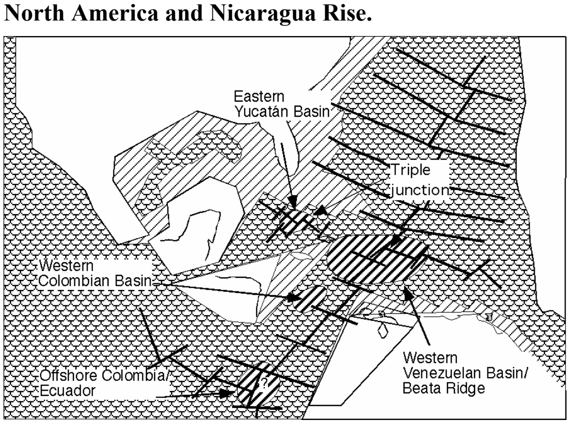

Figure 11. Schematic Aptian reconstruction. Spreading has ceased in the Gulf of Mexico. Triple junction spreading in the Yucatán and 'Caribbean' areas heralds abandonment of those areas. Related extension allows basalt extrusion and eventual thickening of extended original ocean crust.

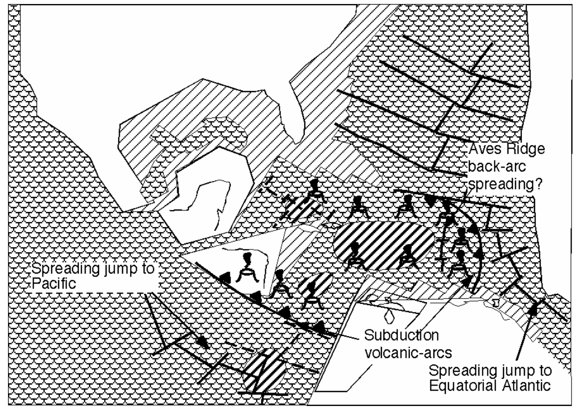

Figure 12. Post Aptian-spreading jump. Spreading has jumped to the Equatorial Atlantic and Pacific. The Caribbean area is isolated between spreading westwards from the Atlantic and eastwards from the Pacific. Resultant convergence causes subduction and related volcanic. The Caribbean Plate is born.

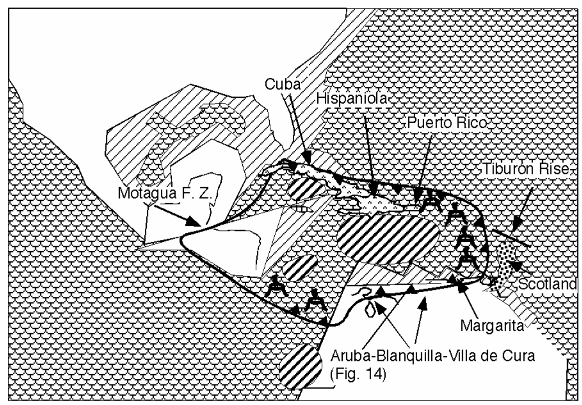

Figure 13. Schematic Middle Eocene reconstruction. Compression between the Caribbean and surrounding plates results in cessation of subduction-related arc volcanicity along the northern and southern Caribbean Plate boundaries and violent uplift of marginal areas, producing flysch and wildflysch (Fig. 14). Huge olistostromes of Caribbean oceanic and volcanic material occur along with continental margin material in the western Greater Antilles and along northern South America. Quartz sands of the Scotland Group (Barbados) are deposited on the Atlantic Plate, more than 300 km offshore northern S America. Their progress is halted by the Tibur¢n Rise.

5. CONCLUSIONS

All Caribbean geology may be simply and elegantly accommodated by its evolution *in situ* between North and South America. Models that derive the plate from the Pacific, invoking hotspots/mantle plumes for plate thickening, reversal of subduction direction and major rotations of arc and continent elements are geometrically unlikely and needlessly complex.

Following Triassic-Jurassic rifting along the future North America - South America - Africa

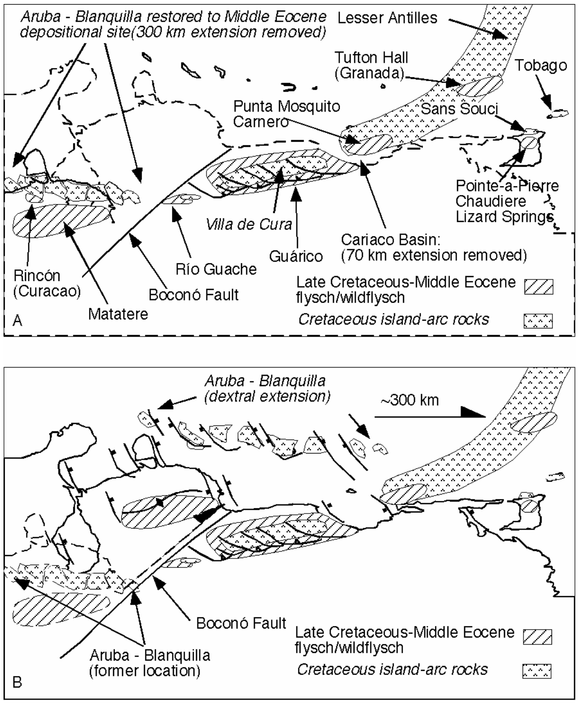

Figure 14. A. Detail of the Middle Eocene distribution of flysch/wildflysch deposits and the Aruba - Blanquilla - Villa de Cura - Margarita - Lesser Antilles volcanic-arc complex. B. the same area after NE translation of the Bolivar - Bonaire blocks, driven by Pacific spreading. The Bonaire Block transgressed the dextral Caribbean - South America plate boundary and became internally deformed by pull-apart extension since the Oligocene. Summation of this extension indicates 300 km of dextral plate movement.

boundaries, and within North and South America, North America drifted to the NW. Major extension occurred in the southern part of the continent. Oceanic crust formed in the Gulf of Mexico, the Yucatán Basin and in the area of today's Caribbean Plate. N–S separation of around 950 km and sinistral offset of at least 1,000 km developed between North and South America. The latter offset was distributed across the Caribbean area and offset the remnant continental blocks of Maya and Chortis ('Cayman' offset) and separated Chortis from NW South America. Caribbean crust was highly faulted and extended. In the early Cretaceous triple junctions in the Caribbean heralded a spreading jump to the Equatorial Atlantic. Related decompression melting generated a first phase of basaltic outpouring, thickening parts of the Venezuelan, Yucatán and Colombian Basins. Spreading in the Equatorial Atlantic and the Pacific drove convergence of normal ocean crust with the thickened Caribbean, leading to subduction and volcanism in the Lesser Antilles and Central America. The Caribbean Plate assumed its identity. A regional compressional event in the Palaeocene - Middle Eocene, produced regional flysch/wildflysch, with extremely large olistoliths and mixtures of oceanic, volcanic and continental material, along the southern and northern Caribbean plate boundaries. From the Oligocene to Recent, sinistral and dextral strike-slip characterized the northern and southern Caribbean Plate boundaries, respectively. The Caribbean Plate moved some 300 km eastward relative to the Americas in this interval.

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