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Arguments for and against the Pacific origin of the Caribbean Plate and arguments for an *in situ* origin

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ABSTRACT. **This paper discusses arguments presented in support of the Pacific model of Caribbean Plate origin. They do not stand up to close scrutiny. The paper continues with a series of arguments, supported by known geology, for the *in situ* origin of the plate.**

1. INTRODUCTION

Debate on the origin of the Caribbean Plate considers possible *in situ* and Pacific origins, also known as the 'fixist', or 'stabilist', and 'mobilist' models (Fig. 1). The Pacific model dominates modern literature (e.g., Edgar *et al.*, 1971; Malfait and Dinkleman, 1972; Pindell and Dewey, 1982; Duncan and Hargraves, 1984; Bouysse, 1988; Pindell *et al.*, 1988; Ross and Scotese, 1988; Pindell and Barrett, 1990; Lebron and Perfit, 1993; Tardy *et al.*, 1994; Kerr *et al.*, 1999). A minority support the *in situ* model (e.g., Ball *et al*, 1969; Meyerhoff and Meyerhoff, 1971; James, 1990, 1997, 2000, 2005a; Frisch *et al.*, 1992; Meschede, 1998a; Meschede and Frisch, 1998; Cobiella-Reguera, 2000). This paper examines arguments quoted in support of the Pacific model and then considers those that point to the *in situ* origin of the Caribbean Plate. I begin with a summary of the Pacific and *in situ* models. For details and illustrations of the former, see the references quoted above. For illustrations of the latter, see figures in this paper.

Pacific models have always been complex, postulating spreading ridges that no longer exist (Farallon-Phoenix), hotspots that 'burst into activity' and die (Duncan and Hargraves, 1984) producing an oceanic plateau of just the right width and length to subsequently occupy the Caribbean area (e.g., Duncan and Hargraves, 1984; Bouysse, 1988), 'flips' of subduction along the 'Caribbean Great Arc' (e.g., Duncan and Hargraves, 1984, Mattson, 1984, Pindell, 1993) and major rotations of arcs (Fig. 1A), continental blocks (Chortis and Maya, Fig. 2) (Burke *et al.*, 1984; Bouysse, 1988; Pindell, 1993; Pindell, *et al.*, 1988) and of the Caribbean Plate itself (Pindell *et al.*, 1998). The models have become increasingly complex ('refined') in response to data that call into doubt details of earlier models. Mantle plumes have joined (Hall *et al.*, 1995) or replaced hotspots (Kerr *et al.*, 1996; Lapierre *et al.*, 1999; Hauff *et al.*, 2000) to explain oceanic plate thickening.

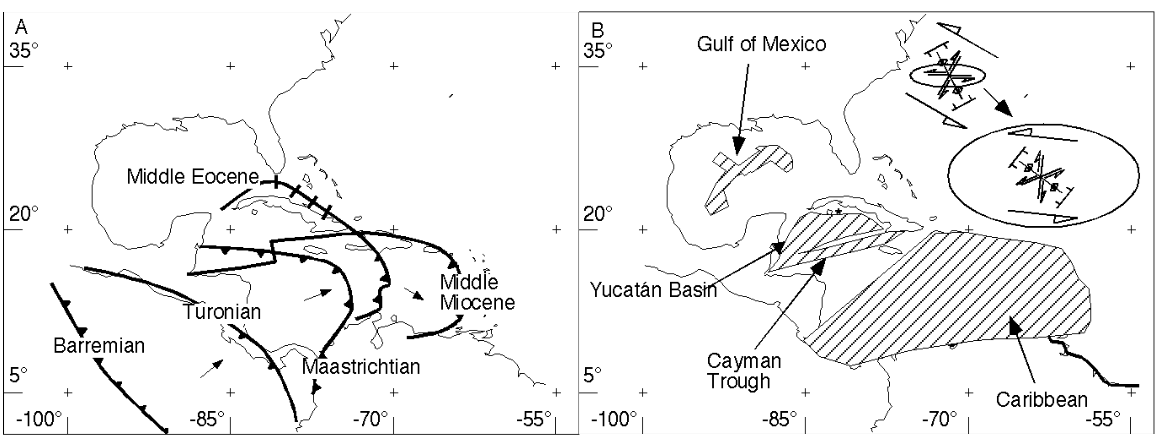

Figure 1. Pacific (A) and *in situ* (B) concepts for the origin of the Caribbean Plate. For simplicity, both are shown in the context of a modern map. A shows stages of arc migration, at the leading edge of the Caribbean Plate as it migrated from the Pacific. B shows formation of oceanic areas (cross 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.

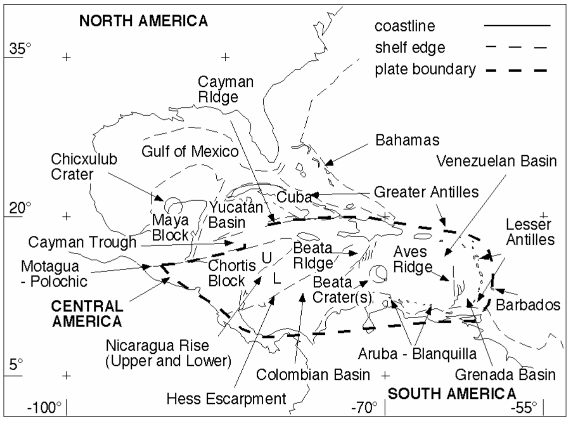

Figure 2. Middle America, geographic elements referred to in text.

2. Pacific Model Summary

Pacific models begin with palaeogeographic reconstructions showing the Maya (Yucatán) Block lying along the northern coast of South America, between North and South America, and the Chortis Block lying on the west side of Mexico (Ross and Scotese, 1988; Pindell and Kennan, 2003). The 'proto-Caribbean' and the Gulf of Mexico formed in the Jurassic to Early Cretaceous as North America drifted away from Pangea. Maya rotated counterclockwise (ca. 50˚) to its present orientation at this time (e.g., Pindell and Kennan, 2003). An east-facing island arc ('proto Antilles' or 'Caribbean Great Arc') trended NW-SE across the western end of the proto-Caribbean, extending alongside Mexico and NW South America. The Caribbean Plate formed west or south of this, with a west-facing volcanic arc (in early papers; a 'proto Costa Rica – Panam' arc) on its west flank. The Caribbean Plate thickened to form a Large Igneous Province/Ocean Plateau, either as it migrated northeastward across the Galapagos Hot Spot (early papers, e.g. Duncan and Hargraves, 1984; Bouysse, 1988) or above a rapidly melting mantle plume head (or both) (Hall *et al*., 1995; Kerr *et al*., 1997), or above two plumes, Sala y Gomez and Galapagos. The plate then entered the gap between North and South America, overriding 'proto-Caribbean' oceanic crust (Fig. 1A), after a reversal of subduction direction below the leading edge of the 'Great Arc' (Fig. 3). Chortis rotated southeastward into its Central American location at the same time (Fig. 4). Further plate thickening resulted from decompression melting (Révillon *et al*., 2000). Volcanic activity ceased along the northern and southern Great Arc segments after they had rotated and collided with North and South America in the Palaeocene-Middle Eocene. The Yucatán Basin opened as a Maastrichtian-Middle Eocene intra-arc or back-arc basin behind Cuba (e.g., Sigurdsson *et al*., 1996; Pindell, 2001). Spreading drove Cuba northward to collide with the Florida-Bahamas platform. Cuba and the Yucatán Basin then accreted to the North American Plate. The Caribbean Plate assumed an eastward migration direction relative to North and South America from the Oligocene onwards. Sinistral and dextral offset of 1,100 to 1,300 km occurred along the northern and southern plate boundaries since Cayman Trough opening began in the Eocene. The defunct northern and southern segments of the Great Arc extended in an E–W direction, forming the Greater and Netherlands - Venezuelan Antilles. The remnant, N–S trending segment of the arc formed the Aves Ridge and northern Lesser Antilles. The latter arc segment jumped eastward in the Eocene to the southern Lesser Antilles, when the back-arc or inter-arc Grenada Basin formed (Bouysse, 1988; Pindell and Barrett, 1990; Bird *et al*., 1999). The Lesser Antilles is the last active segment of the Great Arc. Volcanic-arc activity linked the continental Maya and Chortis blocks to South America via Costa Rica and Panama.

3. *In Situ* Model Summary

The *in situ* model begins with reconstructions that do not later involve large-scale rotations of elements such as the Maya and Chortis blocks (Fig. 2) and evolves largely through sinistral transtension between North and South America (Fig. 1B)

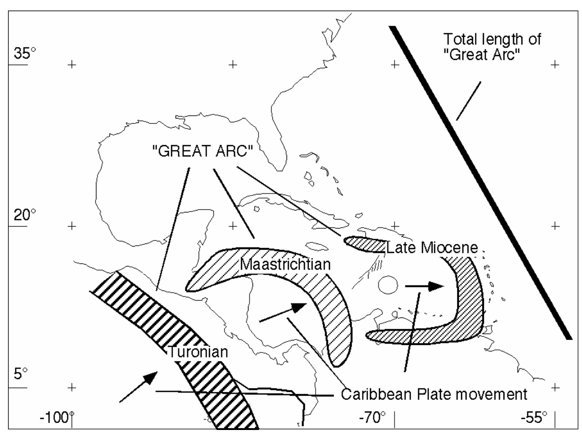

Figure 3. Models of the entering 'Great Arc', at the leading edge of the Caribbean Plate. The solid line to the right of the diagram is the measured length of the Greater Antilles - Lesser Antilles - Aruba-Blanquilla Antilles, with pull-apart extension removed. For this arc to have changed from a linear, NW trending feature to the curved arcs shown in the Maastrichtian and Miocene, either the Caribbean Plate would be intensely folded behind the arc or the arc would be decoupled from the plate.

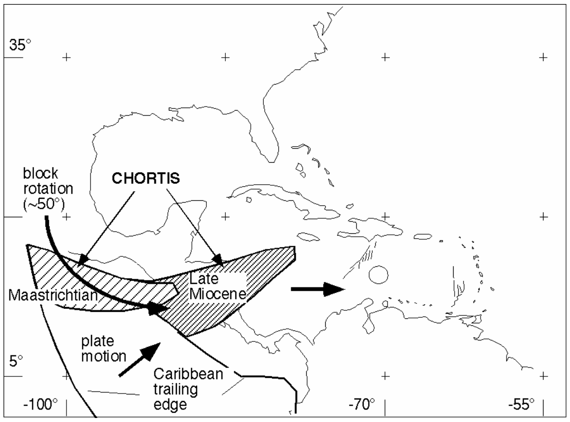

Figure 4. Models of the Chortis Block rotating to follow the trailing edge of the Caribbean Plate into a Central American location. The diagrams imply that the block moved SE along the trailing edge of the NE migrating plate and somehow added itself to the NW part of the plate. This is unrealistic (and the mechanism is never explained in Pacific models).

(James, 2005a). The Caribbean Plate is part of the oceanic province that formed when North America drifted NW from Gondwana in the Jurassic-Early Cretaceous. Continental fragments (Maya and Chortis) bordered the plate to the west. Thickening of ocean crust in areas of the present-day Venezuelan, Yucatán and Colombian basins occurred as a result of extension, possibly over triple junctions heralding spreading jumps to the Atlantic and Pacific in the Aptian (James, 2005a). Interaction between the Caribbean area and the new spreading centres resulted in outward facing island-arcs along the boundaries of the newly identified plate to the east and southwest. N-S growth of the Mid Atlantic Ridge to the east resulted in Caribbean Plate extension and further decompression-related extrusion. Continued westward movement of the North American Plate relative to the South American Plate (and the Caribbean) resulted in continued subduction in the Lesser Antilles. In the Palaeogene, flysch/wildflysch deposits containing very large olistoliths of Mesozoic continental margin sedimentary rocks, volcanic-arc rocks, serpentinites and ophiolites formed along the plate margins. This event culminated in the Middle Eocene with regional shallow-marine carbonate development above a regional unconformity. Subsequently, the plate remained stationary relative to the westward moving North and South American plates. Strike-slip along the northern and southern plate boundaries resulted in thrusting and complementary foreland basins and pull-apart extension, all becoming younger to the east. Continued convergence between the Pacific Cocos Plate (earlier, the Farallon Plate) and the Atlantic Plate resulted in continued volcanic-arc activity along the southwestern and eastern plate boundaries.

4. Arguments in Support of a Pacific Origin for the Caribbean.

Pindell (1991, 1993) and Pindell and Barrett (1990) listed arguments supporting the Pacific model, concluding that the evidence was overwhelmingly in favour of such an origin. Some of these have been modified or abandoned and new arguments have evolved (Pindell, 2001; Pindell and Kennan, 2003). For completeness I consider both old and new arguments. I then move on to my own arguments for the *in situ* origin of the Caribbean Plate. In the next sections, I paraphrase the arguments (Pindell, 1991, 1993; Pindell *et al*., 2002; Pindell and Kennan, 2003) in ***bold italics*** and follow with my discussion in plain text.

Pindell and Barrett (1990) and Pindell (1991, 1993) arguments:

The Aves Ridge and the Lesser Antilles together represent an upper Cretaceous - Recent (ca. 90 Ma) record of subduction of the Atlantic Plate beneath the eastern Caribbean. Minimum relative plate migration has been ca. 1000 km.

Most papers (Freeland and Dietz, 1972; Meyerhoff and Meyerhoff, 1971; Bouysse, 1988; Maury *et al*., 1990; Bouysse *et al*., 1990; Pindell, 1991, 1993; Bird *et al*., 1999; Iturralde-Vinent and MacPhee, 1999) discuss the Aves Ridge (Fig. 2) in terms of a Late Cretaceous volcanic arc that became abandoned in the Eocene, either as subduction jumped to the southern Lesser Antilles or when the back-arc or inter-arc Grenada Basin formed. Pindell (1993) surmised that the Aves 'arc' was east-facing because of its convex-eastward shape and absence of an accretionary prism along its west flank. Note that there is no evidence of an accretionary prism to the east, either, and there is no indication of a subduction trench.

The Aves Ridge crosses the eastern Caribbean from the Venezuelan shelf margin towards the Virgin Islands. It originates in the south as a narrow, NE trending ridge. Its eastern flank continues this trend to around 14˚N whence it runs north, parallel to its remarkably linear western flank. North and east of 15˚, the topographic high broadens into a volcaniclastic fan, with NE-SW structural and magnetic grain (Bird *et al*., 1999), derived from the northern Lesser Antilles. The eastern and western flanks seem to be fault controlled (Holcombe *et al*., 1990, fig. 12).

In 1984, Bouysse wrote that the Aves Swell had long been enigmatic, but there was broad agreement that the ridge was an ancient island arc structure.

However, there is no proof that the ridge is a volcanic arc. It has been directly sampled only by dredging and two DSDP holes (Fox *et al*., 1971; Nagle, 1972; Bouysse *et al*., 1985). The latter penetrated only Plio-Pleistocene sediments. Fox *et al*. (1971) described dredge samples of diabase, basalt and meta-basalt that gave dates of 60 Ma. Granodiorite also occurred amongst these samples, with K-Ar ages of lower Senonian, upper Senonian, and upper Palaeocene. Fox *et al*. (1971) considered that this material indicated the northern margin of South America. The ridge was underlain by granitic rocks of late Mesozoic age and bore pedestals of volcanic origin (basaltic dredge samples). Bouysse *et al*. (1985) reported that dredging on the 15 banks or ridges of the ridge recovered volcanic material only from three of them. Holcombe *et al*. (1990) summarized that the crustal structure and the types of igneous rocks found strongly suggest that the Aves Ridge is primarily an extinct island arc.

The 'inter-arc' or 'back arc' Grenada Basin separates the ridge from the Lesser Antilles. There are at least five models for the origin of this basin (see Bird *et al*., 1999). They all invoke spreading ridges. Depending on which model, these range in orientation from E-W to N-S. In fact, there is no evidence for either spreading or ridges. Bouysse (1988) pointed out that magnetic anomalies in the basin are low in amplitude and have no clear pattern. The age of the basin is not known, it is only calculated to be Palaeogene on the bases of heat-flow measurements and depth to basement (e.g., Bouysse *et al*., 1990).

The Grenada Basin (like the Aves Ridge) is divisible into northern and southern parts at around latitude 15˚N, the approximate latitude of contact between North and South America in the Atlantic realm. The NE trending southern basin contains 2 to 9 km of sediment, that thickens to the south. Bouysse (1988) remarked that the Grenada Basin formed through extensional tectonics that also structured the Aves Swell, which has a step-like eastern flank. He concluded that the southern basin was oceanic, while the northern area was probably rifted arc. All data suggested the existence of a late Mesozoic, single arc system (the Mesozoic Caribbean Arc) that included the Greater, Lesser and the Netherlands-Venezuelan Antilles and the Aves Ridge. He proposed that the northward propagating back-arc Grenada Basin separated the Ridge from the Lesser Antilles. However, such a basin should narrow northwards and the Grenada Basin is symmetrical.

Fox *et al*. (1971) observed that the Aves Ridge appeared to be a thickened part of part of the 2-3 km thick 6.3 km/s layer of the Venezuela Basin. Bouysse (1988) recalled that Venezuelan and Colombian basin crust is three layered, with the following velocity structure: 3.2-5.0 km/s, 6.0-6.3 km/s and 7.0-7.3 km/s. Grenada Basin crust is also three layered, with velocities of 5.3, 6.2 and 7.4 km/s. The similar patterns do not support models of a young, inter-arc/back-arc Grenada Basin.

In summary, the Aves Ridge and Grenada Basin both have uncertain origins. In no way do they provide evidence of a Pacific origin of the Caribbean Plate.

The Cayman Trough oceanic component and reassembly of (extended) Cuba, Hispaniola, Puerto Rico and the Aves Ridge indicate at least 1000 km of sinistral movement between the Caribbean and North and South America (and hence the Atlantic Plate).

Movement between the Caribbean Plate and North America today occurs along a sinistral strike-slip E-W boundary from the Greater Antilles to Central America. The Cayman Trough is generally seen as a sinistral pull-apart basin.

For some, the Cayman Trough is pivotal in discussions of Caribbean Plate history. Pindell and Barrett (1990) stated "*A large amount of offset along the Cayman Trough (more than 800 km) is especially important in constraining models for the evolution of the Caribbean. The concept of the Caribbean Plate originating within the Pacific realm and entering the North-South American gap prior to the Eocene depends on this interpretation. If smaller estimates of offset are assumed, an* in situ *formation of the Caribbean Plate (between North and South America) is required*." Since little relative movement has occurred between North and South America since the Eocene, Cayman sinistral displacement implies equal, dextral offset along the southern plate boundary.

Estimates of displacement related to the Trough range from 150 to 1400 km (Kesler, 1971; White and Burke, 1980; Pindell and Dewey, 1982; Sykes *et al*., 1982, Wadge and Burke, 1983; Pindell and Barrett, 1990). Depths typical of oceanic crust characterize 980 km of the Trough (Pindell and Barrett, 1990). An additional 70–100 km of extension relates to block faulted zones (arc or continental material) in the west and east.

Bowin (1968) and Dillon and Vedder (1973) thought that the eastern part of the Trough began to form during Late Cretaceous or Palaeocene time. Later papers emphasize Eocene opening. Rosencrantz *et al*. (1988) proposed that trough opening quantified movement along the northern Caribbean Plate boundary zone and constrained plate movement relative to surrounding plates. Depth-to-basement and heat flow studies indicated that opening began in the Eocene. However, ages from heat flow measurements are inconclusive and Rosencrantz *et al*. (1988) stated: "*We suggest that the question of Cayman Trough heat flow be shelved until new and better measurements are obtained*". In 1993, Rosencrantz suggested that Cayman Trough opening recorded local rather than regional plate movements and could not be used to track Caribbean-North American relative plate motion (a modified view overlooked by subsequent literature).

The western extension of Cayman sinistral offset crosses Central America.

Here, the Maya and Chortis blocks are separated along the Malpaso, Motagua - Polőchic Megashear: a system of faults in Honduras, Guatemala and adjacent Mexico (Anderson and Schmidt, 1983; Guzm n-Speziale, 1989). Sinistral movement along these variously occurred from the Jurassic onwards, migrating southwards (Santa Cruz Fault, Jurassic, Malpaso Fault Late Cretaceous - Viniegra, 1971; Motagua Fault, mid Tertiary; Burkart, 1983). Burkart *et al*. (1987) restored Laramide structures sinistrally offset by 130 km along the Polőchic Fault of Guatemala (displacement began around 10 Ma; rate approximately 1.3 cm/y).

These observations suggest that most sinistral offset between the Caribbean and North America (Cayman Trough) occurred prior to 'Laramide' folding. In a separate paper (James, 2005a) I emphasize that most of the E-W relative displacement between North and South America developed during the Jurassic-Early Cretaceous, distributed over Caribbean latitudes. The Cayman Trough may have been the locus of much of this displacement.

Ten Brink *et al*. (2001) interpreted the thin crust in the distal part of the trough as transitional, formed by extreme attenuation without organized sea floor spreading, whereas the proximal part formed by crustal accretion at a slow spreading mid-ocean ridge. The only identified spreading ridge in the Caribbean area lies in the centre of the Trough. Rosencrantz (1993) and Leroy *et al*. (2000) recognized two main sets of magnetic anomalies in the trough. A younger set is perpendicular to and is associated with the spreading centre; it fits present-day plate movements and records these back to anomaly 6 (Early Miocene). Older sets of anomalies to the east and west do not fit current plate movements.

Anomalies associated with the (slow) ridge vary greatly in shape and amplitudes are low, prompting Leroy *et al*. (2000) to write: "*Thus the characteristic magnetic anomaly shapes are hardly recognizable here, which makes the recognition of certain anomalies questionable*". In summary, Cayman anomalies do not reveal when opening began.

The Cayman Ridge and the walls of the Cayman Trough lie south of the Cuban segment of the Cretaceous volcanic arc. Pacific models would have these following the arc from an oceanic setting. Dillon and Vedder (1973) conclude that acoustic basement of the ridge consists of continental rocks. The western Cayman Ridge has crustal thicknesses of near-continental proportions and a low magnetic susceptibility, similar to the rift blocks of the margin of British Honduras. Perfit and Heezen (1978) reported clastic rocks dredged from the walls of the trough. They include volcanic breccias, conglomerates, sandstones, argillites, red bed material, greywacke and arkose. The presence of continental material in the Cayman Ridge and along the walls of the Cayman Trough rule out the Pacific origin of this area.

To summarize: most Cayman offset occurred between North America and the Caribbean region during the Jurassic - Early Cretaceous, it does not imply 1000 km offset along the southern Caribbean Plate boundary.

Seismicity and seismic tomography show a distinct west-dipping Atlantic Benioff zone extending at least 1200 km beneath the eastern Caribbean.

McCann and Pennington (1990) summarized seismicity studies in the Caribbean region. Intermediate-depth seismicity indicates penetration of American lithosphere to at least 200 km below the Lesser Antilles.

Van der Hilst (1990) summarized that his tomographic studies imaged the Lesser Antilles subduction zone well below the seismic zones to a depth of 600 km. He also stated "... *the results necessarily have a preliminary character and discussions and conclusions should be considered tentative*." His interpretation "o*f inclined, slab-like velocity anomalies as transections through the blurred image of the Atlantic lithosphere subducted below the eastern Caribbean*" was 'a working hypothesis'. Seismic tomography does not prove any amount of subduction.

There is a boundary between the North and South American plates in Caribbean latitudes. Since North America has continuously moved west relative to South America (and the Caribbean) since the Albian, subduction has occurred in the Lesser Antilles for a long time. This does not translate into eastward migration of the Caribbean Plate.

The Cretaceous stratigraphy of the Caribbean area is divisible into a Proto-Caribbean suite, comprising pre-Mesozoic basement with Jurassic

rift sediments, Cretaceous shelf sediments and foredeep clastics (no volcanics) and a volcanic Caribbean suite. The two are presently juxtaposed across circum-Caribbean ophiolite belts but they must have formed in spatially separate locations.

Two provinces, of continental and oceanic/volcanic origins, certainly do exist. It is patently true that they formed in different locations. This does not require that one formed in the Pacific.

As the Caribbean Plate moved into place diachronous flysch basins formed (Guatemala, Campanian; northern Cuba, Latest Cretaceous-Eocene; Maracaibo area, Eocene; Eastern Venezuela, Miocene).

In 1997 I emphasized that coeval flysch/wildflysch deposits formed across the northern margin of South America during the Palaeogene. An expanded version of that paper (James, 2005b) summarizes widespread occurrence of such deposits in the Caribbean and in Colombia, Ecuador and Peru. They record regional, coeval compressional interaction between the Caribbean Plate that emplaced Caribbean volcanic arc and oceanic rocks along with continental margin rocks. This was not related to diachronous passage of a migrating Caribbean Plate. Diachronous interaction between the Caribbean and neighbouring plates occurred only from the Oligocene - Recent and is recorded by eastward migrating compression, foreland basin subsidence and pull-apart (James, 2000; Draper, 1999).

The pre-Albian space between North and South America was too small to have housed a (probably) Jurassic Caribbean Plate.

This observation is premised by two assumptions. First, that the Jurassic Caribbean area had the same dimensions as the present plate and second, that the modelled pre-Albian area is correct. Diebold *et al*. (1999) presented seismic evidence that the Venezuela Basin comprises extensionally thinned oceanic crust, thickened by two phases of volcanic extrusion, the latest producing the smooth floor Horizon B". Bowland and Rosencrantz (1988) presented similar data from the Colombian Basin where a western plateau, locally capped by volcanic knolls, has a smooth character. Horizon B" is tightly dated at 88-90 Ma; DSDP Leg 15 Sites). Therefore, while the original Caribbean crust may have formed during the Jurassic, extension may have continued until the Late Cretaceous. In a separate paper (James, 2005a), I show that Cretaceous N-S extension of the Mid Atlantic Ridge probably had significant extensional consequences for the Caribbean. My reconstructions of plate movements (James, 2005a) indicate that the present day Caribbean Plate would have been accommodated sometime between the end of the Jurassic and the Late Cretaceous.

Truncated structural trends and a truncated Palaeogene arc (Sierra Madre Occidental) of SW Mexico (Oaxaca) are continued, across sinistral offset, in the Chortis Block of Central America. The latter rotated into a position south of, and sutured, to the Maya Block along with the Caribbean Plate in the Cenozoic.

Donnelly *et al*. (1990) discussed the Maya (Yucatán) and Chortis blocks of northern Central America. They are joined along the Motagua Fault Zone, along strike from the southern margin of the Cayman Trough. Mainly phyllites and schists of greenschist facies are known from this area. Donnelly *et al*. (1990) emphasized that most models of this region do not admit the small amount of data available to constrain possibilities. Various models show the Chortis Block originating in: the central Gulf of Mexico, against the Yucatán Peninsula in the Gulf of Honduras; in its present position, along the SW coast of Mexico; off the NW coast of South America; or in the Pacific Ocean. The SW coast of Mexico model had most credibility because the basement and the Mesozoic stratigraphy show clear affinities between the Chortis and Oaxaca (Mexico) blocks.

According to Donnelly *et al*. (1990), suturing occurred in the Late Cretaceous - Early Eocene, recorded by Sepur Group flysch/wildflysch (actually Palaeocene-Middle Eocene in age; see James, 2005b). Pacific models show the Caribbean Plate migrating NE into the Caribbean region at this time. It is geometrically impossible for the Chortis Block to have migrated southeastward and then eastward to enter the Central America region at the same time (Fig. 4). In a separate paper (James, 2005a), I show that Maya and Chortis are simply sinistrally offset remnants of Pangean, continental middle America. This does not deny the geologic affinities of Oaxaca and Chortis. It does deny rotation of Chortis and passage of the Caribbean Plate through the Central American area.

Shelfal faunal provinces in the Mexican-Caribbean region were separate until the Campanian (Johnson and Kauffman, 1989) when they merged as a result of tectonic juxtaposition, presumably during relative eastward migration of the Caribbean Plate between the Americas (a bottleneck between Colombia and Yucatán).

The concept here is that the Great Arc formed a topographic link between continental Central and South America as it entered the Caribbean region.

Mattson (1984) summarized several unconformities, including a Campanian event, that occur around the Caribbean (see also, Beets *et al*., 1984; Bowland and Rosencrantz, 1988; Donnelly *et al*., 1990; Echevarria-Rodriguez *et al*., 1991; Iturralde-Vinent *et al*., 1996; Khudoley and Meyerhoff, 1971; Lundberg, 1983).

The Pacific model cannot account for these regional events shared by the Caribbean Plate and its neighbours.

Montgomery (1992) identified cold water Late Jurassic radiolaria that can only have come from the Pacific.

In 1994, Montgomery *et al*. noted that the radiolarian genera *Praeparvicingula* and *Parvicingula* signify minimum palaeolatitudes of 22-30˚ N or S of the equator. Their presence in two Jurassic Caribbean fragments (basement complex; La Dásirade; Bermeja Complex, Puerto Rico) suggested significant translation of these components. A third Jurassic fragment (Duarte Complex, Hispaniola) had an equatorial origin, shared also by the Bermeja Complex. The oldest material (Pliensbachian) occurs on Puerto Rico. It is stated to have formed in open-ocean environment before oceanic crust existed between North and South America.

Montgomery *et al*. (1994) concluded that radiolarian palaeogeography is totally incompatible with any fixist Caribbean model. This would appear to leave the choice of either rejecting the fixist model or modifying radiolarian palaeogeography. More rational would be to recognize that oceanic crust in the Gulf of Mexico - Yucatán Basin - Cayman Trough - Caribbean has never been sampled in place and remains undated. The radiolaria occur on islands on the northeastern margin of the Caribbean, adjacent to Central Atlantic Jurassic crust. Finally, radiolaria are planktic and may be transported great distances.

Stainforth (1969) discussed the significance of deep (3 to 8 km) early Mesozoic trenches in Venezuela and postulated Triassic to early Cretaceous separation of North and South America. According to Viniegra (1971) the Mexican and Gulf of Mexico salt basins probably came into existence during the Triassic. Salvador (1987) suggested that the thickest Louann Salt was accommodated by a major graben trending E-NE across the gulf, on trend with the Late Triassic - early Jurassic grabens of southeastern North America. Bartolini and Larson (2001) estimated that the oldest Central Atlantic oceanic crust is not much younger than 200 ± 4 Ma - supercontinent separation began in the Pliensbachian-Toarcian (190 - 180 Ma). Iturralde-Vinent (2001, 2002) noted that similarities among several groups of Jurassic animals in western Tethys and the southwestern Pacific suggest marine connections since the Sinemurian.

The material studied by Montgomery *et al*. (1994) suggests that oceanic crust existed between the Americas in the early Jurassic.

Pindell (2001) arguments [Meetings in Rio de Janeiro and Stuttgart (2000), Havana and Leicester (2001) and Guatemala (2002) discussed the Caribbean debate. Summaries on Internet Web pages provide updates on arguments supporting the Pacific model. Pindell *et al*. (2002) also provide such an update] – again, I summarize the arguments in italics and discuss in plain text.

Models deriving the Caribbean from the Pacific explain regional Caribbean geology far better than models deriving the Caribbean Plate from between the Americas. There are two primary lines of evidence. First, the Greater Antilles Arc (Great Arc) is older than the Central American Arc, which is predicted by Pacific but not by Intra-American models. Second, Caribbean tectonic interaction and control of stratigraphic development in northern Colombia and southern Yucatán began in the Campanian, which requires a more southwestward (Pacific) position of the Caribbean Plate until that time.

It is not correct to state that the Great Arc is older than the Central American Arc. Calvo and Bolz (1994) concluded that subduction occurred in the Central American arc since at least the Albian (Loma Chumico Formation island arc sedimentary section, Upper Nicoya Complex, contains radiolarites, radiolarian claystone) and Holcombe *et al*. (1990) noted that earliest arc activity occurred in the Late Jurassic in Honduras.

The Stuttgart meeting summary records a debate on this subject, noting that geochemical and geological investigations by Hoernle and Astorga in the Nicoya Complex did not confirm the Calvo and Botz findings. This does not mean that Calvo and Bolz were wrong. These authors emphasize (personal communication, 2003) that the oldest pyroclastic deposits in northwestern Costa Rica are intercalated with hemipelagic sediments dated as late Albian by Azema *et al*. (1979) on the basis of the ammonite *Neokentroceras* sp. In southwestern Nicaragua, the oldest hemipelagic sediments containing tephra deposits have been dated as late Albian-Cenomanian on the basis of the planktic foraminifer *Rotalipora appenninica* (Renz) (see Calvo and Bolz, 1994).

Calvo and Bolz (1994) also noted that palaeomagnetic data from the Loma Chumico Formation indicate an equatorial latitude of formation, consistent with *in situ* (Central American) formation, and postulated that subduction may have begun already in the Jurassic.

The latest models claim to have refined earlier Pacific-derived Caribbean evolutionary models to new levels of kinematic and palinspastic precision and conclude:

The Galapagos Hotspot has nothing to do with Caribbean evolution; **and** ***the Panama - Costa Rica arc formed at Equatorial paleolatitudes;***

These two points concede to data and arguments presented by Frisch *et al*. (1992), Meschede (1998b) and Meschede and Frisch (1998). With respect to the Galapagos hotspot, the Stuttgart summary noted two fundamental positions regarding its role in the geology of the Caribbean. One holds that the Galapagos hotspot has nothing to do with the proto-Caribbean crust or the Caribbean Plate, because it was always positioned to the west; the Caribbean Plate arrived from the south, travelling up the west coast of South America inboard of the 'Hotspot' (note, here, that the Pacific model maintains that the northward migrating Caribbean Plate interacted in the Campanian with both Colombia, to the south, and Maya, to the north).

The other interpretation holds that the hotspot produced the Caribbean plateau basalts (Hoernle *et al*., 2002). Galapagos hotspot activity is known only as far back as the Oligocene (Lonsdale and Klitgord, 1978). Meschede (1998) summarized that the oldest Galapagos rocks relate to the time when the Farallon Plate split into the Cocos and Nazca plates (15 - 20 Ma; Christie *et al*., 1992), whereas magnetic and stratigraphic data (Kimura *et al*., 1997) show that the Cocos Ridge is an abandoned spreading system (not a hotspot track).

High-P/low-T metamorphic assemblages in the Caribbean pertain to Aptian-Early Albian onset of west-dipping subduction beneath Great Caribbean Arc after Aptian arc polarity reversal, which then allowed the crust of the Caribbean Plate to enter the Proto-Caribbean realm during Upper Cretaceous-Cenozoic;

The central Cuban Arc comprises mainly forearc elements of the Great Arc, and Sierra Maestra is more representative of the Great Arc itself;

Campanian cessation of magmatism in central Cuba pertains to shallowing of subduction angle as the Great Arc approached southern Yucatán, and the central Cuban forearc remained ahead of the magmatic axis as the Yucatán intra-arc opened in the Maastrichtian-early Paleogene;

The Yucatán intra-arc basin formed in two phases. Maastrichtian and Paleocene NW-SE extension was driven by slab rollback of Jurassic proto-Caribbean lithosphere along eastern Yucatán, and Early and Middle Eocene NNE migration of central Cuba was driven by rollback of Proto-Caribbean crust toward the Bahamas, facilitated by northward propagation of a NNE-trending east-Yucatán tear fault, during which western and northern Cuban terranes were accreted to the front of the central Cuban forearc;

Middle Eocene collision of all Cuban terranes with the Bahamas, and rapid uplift of the orogen as the Proto-Caribbean slab detached from the south-dipping Benioff Zone.

These points are attempts to explain reported geology via increasingly complex modelling. There is, for example, no evidence of 'slab rollback' of proto-Caribbean lithosphere to the NW and NE during the opening of the Yucatán Basin. At least six models for the development of this basin appear in the literature (e.g., Lara, 1993). Rosencrantz (1990) concluded that the oldest crust in the eastern Yucatán Basin is at least Late Cretaceous and could be Aptian-Albian. The basin possibly formed during Jurassic separation of North and South America (James, 2005a).

Eocene onset of Cayman Trough pull-apart allowed for the well-known subsequent migration of Caribbean Plate to its present position relative to the Americas, and the late? Oligocene onset of separation of Hispaniolan arc assemblages from Oriente, Cuba.

As I have argued above, Cayman Trough opening is not proven to have commenced in the Eocene. To state that something is 'well-known' when it is only modelled is not science. Most of the sinistral offset of the trough developed much earlier.

4. Arguments Against the Pacific Model

Geometric improbability of entry of the Mesozoic island arc into the Caribbean area.

According to the Pacific model, the Greater, Lesser, and Netherlands-Venezuelan Antilles are the remains of an approximately NW trending (NE according to some models), Mesozoic volcanic arc that entered the Caribbean (undergoing a polarity flip in the process, see Pindell, 1993) in the late Cretaceous. Summation of the present day components of this supposed arc (the islands and their submarine extensions/shelfal areas) amounts to around 3,000 km (about the distance from the NW coast of Colombia to the Texas coast in the Gulf of Mexico). The gap through which the arc is supposed to have passed is half this wide. If the Netherlands - Venezuelan Antilles used to be the western continuation of the Villa de Cura - Margarita - Testigos - Lesser Antilles (see section on Oligocene movement, below), then the arc had a total length of around 4,000 km, making the space problem even more difficult (Fig. 3). Once in the Caribbean area, the northern and southern parts are supposed to have rotated, anticlockwise and clockwise, respectively, to become the E-W trending Greater and Netherlands-Venezuelan Antilles, leaving only 850 km of north-trending arc in the Lesser Antilles.

Rotation of such an arc is geometrically impossible. A subduction arc is rooted in the plate it rides upon. The rotating sections would either have to be decoupled from and slipped back over narrowing Caribbean Plate or the plate would have to undergo intense internal folding. The Caribbean Plate is not folded, it is highly extended (Diebold *et al*., 1999; Driscoll and Diebold, 1999). Decoupling would require subduction of up to 3,000 km of Caribbean Plate formerly beneath the rotating arc segments. There is no evidence of large amounts of subducted plate north and south of the Greater and Netherlands-Venezuelan Antilles. There was no volcanism to record such activity.

Geometric improbability of entry of the Caribbean Plate between the Americas.

Some 70 km of north-south convergence between North and South America is supposed to have occurred in the Maastrichtian-Middle Eocene (Pindell *et al*., 1998), implying that the Caribbean entered a narrowing gap. Diagrams illustrating the entry of the Caribbean Plate between the Americas show NE movement in the late Cretaceous - Palaeocene, followed by eastward movement (Pindell and Dewey, 1982) and strong NW-SE convergence with South America since the Eocene (Pindell and Barrett, 1990; Pindell, 1993). This involves up to a 90˚ change in direction of plate movement (Fig. 1A). In detail, the diagrams show the plate progressively taking up the change of direction upon entry into the inter-American location; the trailing edge of the plate retains its NW trend and NE migration while the leading edge is moving east. That is not possible without major internal plate deformation (NW trending extension followed by compression). Data show that the plate has experienced only NE trending extension.

Pindell *et al*. (1998, fig. 11) also showed the pole of Caribbean rotation moving S-SE from 0.5˚S (Middle Eocene), to 20˚S (Late Oligocene) to 68˚S (Late Middle Miocene). Unless the plate behaves in a plastic manner, this is not possible without northerly trending interplate extension and/or marked changes in the manner of interaction with adjacent plates. Pindell *et al*. (1998, fig. 12) shows north-south convergence between the Caribbean and northeastern South America of almost 700 km. Since South America is drifting westward (see transform faults in the Atlantic, James, 2005a, fig. 7), this implies that the Caribbean Plate moved strongly to the southeast (above) relative to South America. GPS data show only eastward relative movement.

Geometric improbability of Chortis rotation.

Diagrams illustrating the entry of the Caribbean Plate between the Americas show the unlikely southeastward Chortis migration to join the northeasterly migrating trailing edge of the Plate (Fig. 4). The N35˚E Guayape Fault of Honduras and the Rio Hondo Fault are associated with Jurassic rift sediments (Mills *et al*., 1967). They parallel regional (inter-American) Jurassic strain and argue against rotation of the blocks. When the faulted eastern margin of the Maya Block is lined up with the San Andreas Lineament east of Chortis (around 900 km of sinistral offset), the Jurassic faults also line up. The offset resulted from westward motion of North America (Maya included), rather than eastward movement of Chortis (James, 2005a). These continental blocks, Maya and Chortis, have always been at the western end of the Caribbean region and a gap wide enough for Caribbean Plate to pass through the Central American region never existed.

Continental margin sequences of Cuba show that all island components were in the Caribbean during the Jurassic.

Cobiella-Reguera (2000) emphasized the similarity of stratigraphy and magmatism in Jurassic continental margin sequences on Cuba. Two sections (the Guaniguanico mountains, the Maisj area of eastern Cuba and the Southern Metamorphic Belt of the Isle of Youth and Escambray in the south, and the evaporite-bearing section of north-central Cuba) show a simple Jurassic palaeogeography deepening southwards from the Bahamian shelf. According to Pacific models, the first section was picked up by the migrating Caribbean Arc as it passed by the southern (Pindell and Kennan, 2002b) or eastern (Iturralde-Vinent, 1994, 2000, Pszczolkowski, 1999) margin of Yucatán.

Albian shallow-water limestones above an unconformity characterize both Caribbean and neighbouring continental areas (Fig. 5), indicating a shared history.

Meyerhoff and Hatten (1974) reported that the Andros-1 well (Bahamas) bottomed in Albian backreef carbonates. Mattson (1984) noted a regional Albian unconformity in the Caribbean. It is recorded in Cuba, Hispaniola and Puerto Rico as a time of metamorphism, deformation and intrusion. A coeval break exists along the southern plate boundary in the Caribbean Mountains, Santa Marta Massif and on the Colombia-Caribbean coast. In

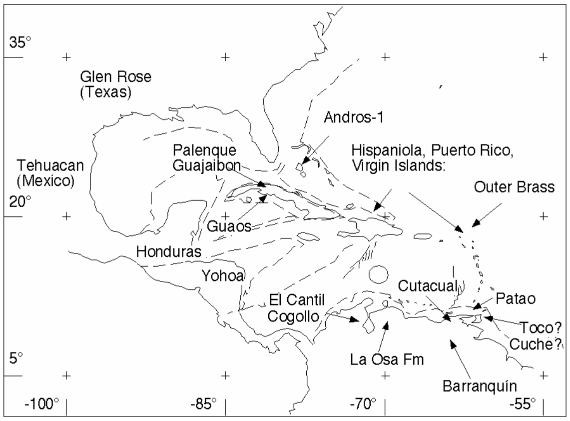

Figure 5. Regional distribution of Albian shallow-water limestones in the Caribbean region. They occur above a regional unconformity. They indicate a shared geologic history between continental and volcanic arc elements and indicate that the Caribbean Plate was *in situ* at this time.

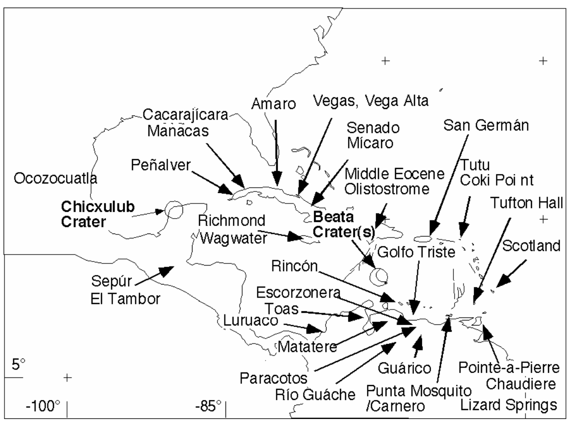

Figure 6. Regional distribution of Palaeocene - Middle Eocene flysch/wildflysch deposits. They record the regional interaction of the Caribbean Plate with neighbouring elements.

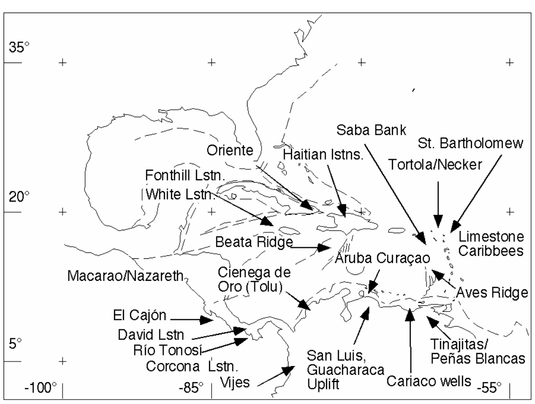

Figure 7. Regional distribution of Middle Eocene shallow-water limestones in the Caribbean region. They indicate regional geological uplift at the culmination of Palaeocene - Middle Eocene convergence. Like the deposits of Figure 6, they indicate an inter-American location of the Caribbean Plate at the time of deposition.

central Puerto Rico and eastern Hispaniola lower, Primitive Island Arc rocks are separated from upper calc-alkaline rocks by an unconformity (Lebron and Perfit, 1993). These are overlain by shallow-water, Aptian-Albian limestones.

Donnelly (1989) summarized that early Cretaceous sections around the Caribbean consist mostly of thin units of diverse lithologies, dominated by carbonates. The lower limit in most areas is Albian, characterized by thick limestones. Tardy *et al*. (1994) described the rocks of the Guerrero suspect terrane of western Mexico and discussed these in relation to Caribbean rocks. Whatever the basement, oceanic or continental, on which the arc rocks were built, they are capped by Albian limestones with reef faunas similar to those on the North American craton.

Shallow water Albian limestones occur in Cuba both in the North American passive margin section of north Cuba (Palenque and Guajaibon formations) and in the volcanic arc terrane in the south (Guaos Formation) (Cobiella-Reguera, 2001, personal communication). Albian limestones occur across Venezuela (Cogollo Group in the west, El Cantil Formation in the east).

Lewis (2002) discussed Albian unconformities in the Dominican Republic (overlain by Hatillo Formation limestone), Cuba (overlain by La Provincial limestone), Puerto Rico (overlain by Barrancas and Rjo Matőn limestones).

The unconformity/shallow-water limestone couplet formed at a time when transgression was beginning (Villamil *et al*., 1999). It therefore records tectonic uplift and erosion followed by carbonate formation. This affected Caribbean and adjacent continental areas and shows a shared history.

Organic-rich Cretaceous sediments indicate Caribbean-Atlantic affinities and a Caribbean/Pacific barrier.

Organic-rich sediments occur in several widely separated sites in the Caribbean and Atlantic (Saunders *et al*., 1973). They indicate that the late Cretaceous Caribbean had a much greater affinity to the Atlantic than to the Pacific. Absence of carbonaceous material in Pacific cores of the same age demands a barrier between the Pacific and Caribbean separating the bottom water regime of the two basins.

Palaeocene - Middle Eocene flysch/wildflysch deposits are regionally developed in the Caribbean area (Figs. 6, 7).

Coeval flysch and wildflysch deposits occur in south Central America (Rivas, Las Palmas and Brito formations); between the Maya and Chortis blocks

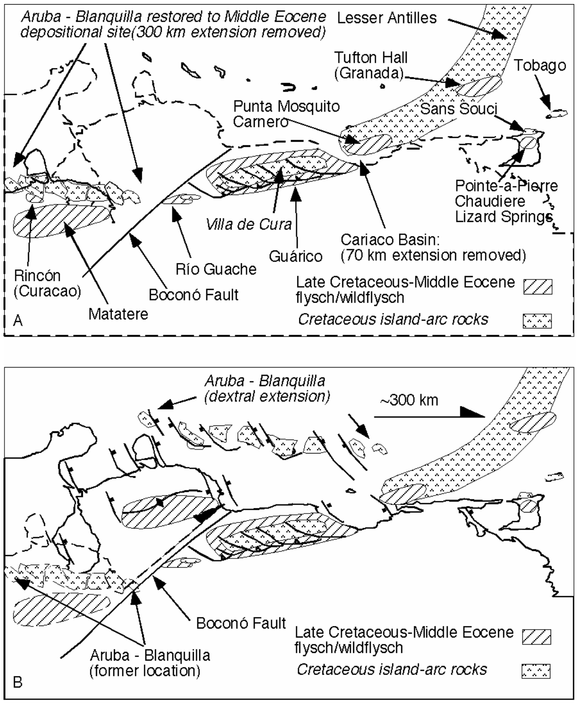

Figure 8. A. Detail of the Middle Eocene distribution of flysch/wildflysch deposits and the Aruba - Blanquilla - Villa de Cura - Margarita - Lesser Antilles island-arc complex. B, same area after NE translation of the Bolivar - Bonaire blocks, driven by the Pacific Nazca Plate. The Bonaire Block transgressed 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.

(Sepur Formation) in the Guaniguanico Cordillera (Manacas Formation) and in north central Cuba Vegas and Vega Alta formations (Cobiella-Reguera, 2001, personal communication), on Jamaica (Richmond Formation) and Puerto Rico (San German Formation), in NW Colombia (Luruaco Formation; Maco Conglomerate, Aleman, 1997, personal communication), in western and central Venezuela (Matatere, Rjo Guache, Guárico, Paracotos formations, in Trinidad (Pointe-a-Pierre, Chaudiere and Lizard Springs formations), offshore Venezuela on Bonaire (Rincőn Formation) and Margarita (Punta Mosquito/Carnero formations) and in Golfo Triste wells, on Grenada (Tufton Hall Formation) and on Barbados (Scotland Group) (see James, 1997, 2005b, for discussion of these units). They also occur in Peru (Talara Formation; Doreen, 1951), Ecuador (Clay Pebble Bed; Marchant, 1956; San Eduardo Formation, Daly, 1989), SE Mexico (Ocozocuautla Formation, Dengo, 1968), in the Parras and Chicontepec basins of N-NE Mexico (Tardy *et al*., 1974).

The deposits include Cretaceous and older continental rocks, along with volcanic-arc and ophiolitic material derived from the Caribbean Plate (thick ‘Plateau’ basalts). They show regional and coeval interaction between the Caribbean Plate and adjacent areas of North and South America (James, 2005b).

Lithologic continuity between autochthonous deep Caribbean and Venezuelan allochthonous units show that the Caribbean Plate was in place during the Palaeocene-Middle Eocene event

At Site 146/149, (Joides leg 15, Venezuela Basin, Saunders *et al*., 1973), aphanitic limestones and claystones of Campanian age are followed by siliceous limestones and black cherts with Maastrichtian claystones and Palaeocene laminated claystones interbedded with siliceous limestones. The same sequence occurs in the Rjo Chávez Formation (Vivas and Macsotay, 2002), a klippe, and in the Mucaria Formation of the Piemontine Nappe in northern Venezuela. The abyssal sediments remained in their original position, while the Mucaria and Rjo Chávez formations were thrust above the South American passive margin. This occurred during the Palaeocene-?Middle Eocene event noted in the preceding paragraph.

The Caribbean Plate is thickened over large areas into a ‘Plateau’ (Donnelly, 1973). Parts of this appear accreted in the Greater Antilles and along northern South America from Trinidad to Guajira. Accretion occurred in the Palaeocene - Middle Eocene. The deposits show that the Caribbean was in place at this time.

Middle-Late Eocene, shallow-water limestones are widespread in the Caribbean area (Fig. 7), recording coeval uplift. In Central America they are known from Costa Rica (Limőn Sur area - reefs on middle Eocene highs; Barbosa *et al*., 1997; Osa Peninsula and Terraba Basin; Escalante, 1990) and Panam (Chiriquj basins, Escalante, 1990).

In the Greater Antilles Middle Eocene limestones occur on Jamaica (Robinson, 1967; James and Mitchell, 2002), Cuba (Iturralde-Vinent, 1994), Haiti (Pubellier *et al*., 2000), St. Barts (St. Bartholomew Formation, Christman, 1953; Tomblin, 1975), Tortola and Virgin Gorda (Lewis and Draper, 1990).

In the Lesser Antilles, Maury *et al*. (1990) noted that the northeastern branch of low-lying Lesser Antillean islands is called the Limestone Caribees because of extensive middle Eocene - Pleistocene calcareous cover. Tomblin (1970) described siliceous limestones with Middle - Early Eocene foraminifers on Mayreau and upper Eocene, reefal limestones on Carriacou.

Hunter (1995) described a line of late Middle

Eocene algal/foraminiferal limestones from the Central American Isthmus, through Colombia to eastern Venezuela. They cap highly deformed flysch and other deep-water sediment and are best developed on frontal thrusts. Middle Eocene limestones are present on Aruba (Helmers and Beets, 1977; Fig. 8), Curaçao (Beets, 1977) and in the Cariaco Basin (exploration drilling).

Middle Eocene limestone also occurs at locations within the Caribbean Plate on the Aves Ridge (Fox *et al*., 1971; Nagle, 1972; Bouysse *et al*., 1990), Saba Bank (Pinet *et al*., 1985) and the Beata Ridge (Fox *et al*., 1971).

These limestones record the culmination of Palaeocene - ?Middle Eocene compression that brought nappes and other highs into the photic zone (e.g., Kugler, 1953; Hunter, 1995: Escalante, 1990; Sageman and Speed, 2002). This well defined event throughout the Caribbean and neighbouring areas proves a shared history.

A regional Late Eocene hiatus characterizes many circum-Caribbean sections.

Bandy and Casey (1973) noted that a hiatus covers most of the Late Eocene - early Oligocene interval in eastern Panama, with deep-water sedimentation occurring again in the middle Oligocene. Barbosa *et al*., (1997) described how broad continental areas formed in the arc in the Middle-Late Eocene in Costa Rica. Calais and Mercier de Lepinay (1991) noted tectonic unconformities on land and at sea in the Late Eocene of Cuba and Hispaniola. Ave Lallement and Gordon (1999) reported isotopic data indicating exhumation of metamorphic rocks on Roatan Island, Honduras, in the Late Eocene - Early Oligocene. Hunter (1974) noted that in northern South America only the Cerro Mision Formation of Falcőn and the San Fernando Formation of Trinidad yield conclusive evidence of Late Eocene age. Several authors refer to a synchronous tectonic event in northern South America. Bell (1972) recognized a Middle Eocene orogeny, involving crustal shortening, overthrusting, uplift and strike-slip faulting in Venezuela and Trinidad. Guedez (1985) noted late middle Eocene uplift of the Monay-Carora area. Chigne and Hernandez (1990) stated that Andean uplift in Venezuela began in the Middle Eocene. Audemard (1991, 1993) reported seismic evidence of uplift of the Perij in the Eocene. Maresch *et al*. (1993) and Kluge *et al*., (1995) reported (K/Ar) radiometric data indicating uplift of Margarita Island at 50 - 55 Ma. Apatite fission track data indicate Middle Eocene deformation in the Serranja del Interior of eastern Venezuela (Aleman, 2001, personal communication).

The Scotland Group of Barbados; not a far-traveled deposit.

The Barbados accretionary prism includes the Middle Eocene Scotland Group (Fig. 6). This almost pure quartzite includes blue quartz. It resembles the Lower - Middle Eocene Mirador and Misoa formations of Colombia and Venezuela. Early Pacific Caribbean models showed the migrating plate picking up these sands from a site north of the Maracaibo Basin (Dickey, 1980; Beck *et al*., 1990; Pindell, 1993). Pindell *et al*. (1998) changed this model, showing the sands accumulating in the Lesser Antilles trench when it lay north of the Araya Peninsula during the Oligocene. However, the sands are interbedded with hemipelagic units that contain Middle and Late Eocene radiolaria (Cuevas and Maurasse, 1995). DSDP Site 672, on the Atlantic Plate to the east, encountered correlative Middle and Upper Eocene sands (Mascle *et al*., 1986).

The Barbados Ridge dies out at the Tiburőn Rise (Dolan *et al*., 1990) where Middle Eocene - Oligocene (Middle Eocene peak) ‘coarse’ (very fine silt to medium and - rare - coarse sand) sediment was penetrated by Site 162. Mineralogy suggests a South American source. Absence of these sediments from Site 543 just 19 km to the north supports the idea that the rise stopped Barbados prism sediment flow.

Exotic rocks on Barbados indicate that the Scotland Group came from the eastern part of northern South America. Kugler (1953) and Tomblin (1970) identified rocks like the Naparima Hill (the unit occurs in Trinidad and areas to the east). Meyerhoff and Meyerhoff (1971) reported large exotic blocks of Albian limestone bearing faunas identical to those of Trinidad and eastern Venezuela (Vaughan and Wells, 1945; Douglas, 1961).

Driscoll *et al*. (1995) described a fan of probably Cretaceous - Eocene turbidites in the southern part of the Venezuela Basin. It suggests that the eastern Caribbean region was the site of a large amount of Eocene deposition which was subdivided into sites west of the Aves Ridge, in the Grenada Basin, and in front of the Lesser Antilles. Sediments could only have arrived west of the Aves Ridge if the latter were already in a Caribbean location during the Cretaceous - Eocene.

Dextral displacement of only 300 km has occurred between the Caribbean and South America since the Oligocene (Figs. 9A, B).

In Figure 9A, I show that the Aruba-Blanquilla chain used to be the westward continuation of the

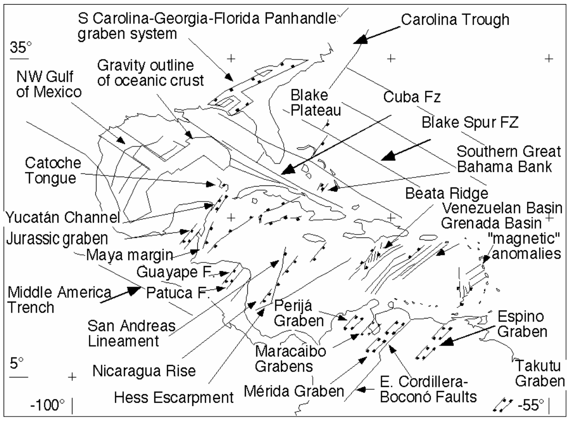

Figure 9. NE trending extensional strain in Middle America includes Triassic-Jurassic rifts in the southern United States and in northern South America, extended continental crust in the Gulf of Mexico, eastern offshore North America, eastern Yucatán, the Nicaragua Rise and western Venezuelan Basin/Beata Ridge. Parallelism of Jurassic rifts on Yucatán and in Honduras with the regional Middle America strain show that the Maya and Chortis Blocks have not rotated.

Villa de Cura, emplaced along northern Venezuela during Palaeocene - Middle Eocene convergence. The eastern continuation is the Tobago Terrane (Snoke, 1990), which links the Villa de Cura nappes, via Margarita and Los Testigos, with the Lesser Antilles. Beets *et al*. (1984) and Donnelly *et al*. (1990) noted the similarity in chemistry of the Bonaire and Curaçao volcanic rocks and those of the Villa de Cura Group. Igneous rocks of the Netherlands Antilles consist of 3 - 5 km thick, Middle Albian to Coniacian arc lavas and a Santonian tonalite-gabbro batholith. The Villa de Cura Group is a 4-5 km thick sequence of ‘Caribbean Plateau basalts’, volcanic arc volcanic and volcaniclastic rocks.

Following the regional Palaeocene - Middle Eocene compressional event northwestern South America (the Bolivar Block; James, 2000) moved NE along faults that parallel Colombia’s Eastern Cordillera and Venezuela’s Mérida Andes. The northern part of the block (the Maracaibo - Bonaire Block) delaminated and crossed the Caribbean - South American plate boundary (literature commonly refers to this overthrusting as subduction of the Caribbean below NW South America). From the Oligocene onwards, E-W dextral relative motion characterized the plate boundary. As a result, major pull-apart basins bounded by NW-SE oblique slip faults formed in the Maracaibo - Bonaire Block. These were the Falcőn Basin (now inverted), the Gulf of Venezuela, Urumaco Trough, La Vela Bay, Golfo Triste and the depressions that separate the Netherlands and Venezuela Antilles. Lake Maracaibo is a younger pull-apart in the same system.

Dextral transtension also separated the Aruba-Blanquilla islands. Drilling adjacent to Aruba penetrated an Oligocene - Recent record of rapid subsidence of weathered Cretaceous basement overlain by a possible basal conglomerate of volcanic, metamorphic and granitic rocks and red claystone (Curet, 1992). The Cayosal-1x well in the Golfo Triste encountered Oligocene coarse-grained siliclastic rocks above Eocene shelf deposits. The Falcőn Basin suffered Oligocene extension prior to Miocene inversion. Moderate to very deep marine shales of the Pecaya Formation lie unconformably on lightly metamorphosed Eocene. Alkaline basaltic intrusion occurred in the Oligocene - Miocene (Muessig, 1978). La Vela Bay is an offshore extension of the Falcőn Basin. The Urumaco Trough subsided in the Oligocene. Oligocene Carbonera sandstones overlie middle Eocene section in the Maracaibo Basin. These data show that pull-apart extension began in the Oligocene (35–30 Ma).

Removal of extension between the Aruba - Blanquilla islands restores Blanquilla approximately 300 km westward to the present location of Las Aves. Here, it lay along the strike of the Bocoнő Fault, the pathway of its NE translation. From the Oligocene to Present, only 300 km or so of dextral displacement has occurred between the Caribbean and northern South America (average rate around 1 cm/y).

Today, Blanquilla lies some 600 km west of the leading edge of the Caribbean Plate. In the Oligocene, therefore, the latter must have been north of Trinidad (the presence of island-arc and oceanic plateau rocks on Trinidad and Tobago, and the Palaeocene - Eocene flysch/wildflysch of Trinidad provide evidence of this; see James, 2005b).

The following estimates of displacement along the (currently recognized) main plate boundary faults provide some degree of check on this figure. Estimates of dextral displacement on the Oca Fault range from 25 km (Aleman, Lugo, pers. comm.) to 50 km (Erlich and Barrett, 1990) or 90 km (Kellogg and Bonini, 1982). Villamil (pers. comm.) determined a minimum offset of 65–70 km between schists of the Santa Marta massif and similar rocks encountered by the well Perico-1 on the Sinamaica Platform. Where the fault crosses the Falcőn area, Audemard (1991) estimated 100 km of dextral displacement. Estimates of dextral displacement on the E-W El Pilar Fault range from

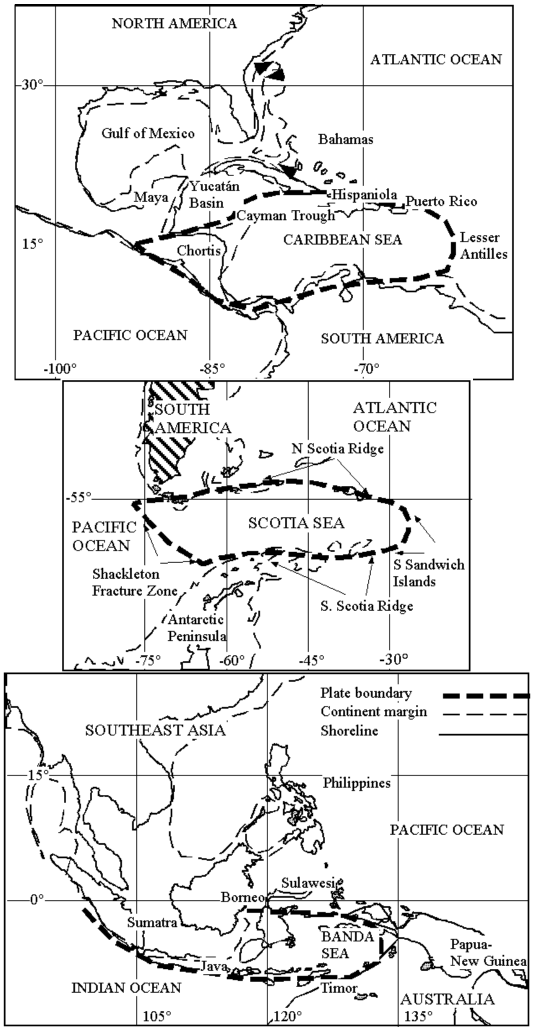

Figure 10. The Caribbean, Scotia and Banda areas are remarkably similar in form and dimension. Scotia and Banda oceanic crust is known to have formed in place.

10-15 km (Metz, 1968) to 475 km (Alberding, 1957). Vierbuchan (1984) proposed possible 150-300 km dextral displacement. Giraldo (1993) deduced that dextral displacement of some 150 km had occurred in the last 10-15 My, while Audemard and Giraldo (1997) concluded that this would be a maximum and that a more likely figure is around 60 km.

Middle America shows a regional pattern of NE trending extensional faults (Fig. 9) formed during regional, Jurassic-Cretaceous sinistral offset between North and South America. They show that the Caribbean Plate was in place when they developed.

Regional extensional strain in Middle America is expressed by faults that downthrow to the SE in the NW Gulf of Mexico and along the SE margin of the Nicaragua Rise, by the basement structure of the Yucatán Basin, and by faults and grabens in the Venezuelan Basin (Case and Holcombe, 1980; Diebold *et al.*, 1999). The faults have the same orientation as Jurassic grabens in northern South America, in the SE United States and on the Maya Block.

Diebold *et al.* (1999) provided seismic evidence that extension in the Venezuelan Basin occurred prior to formation of smooth Horizon B" (pre-Senonian extension). Holcombe *et al.* (1990) noted the undisturbed nature of upper Cretaceous - Recent sediments next to the Hess Escarpment, indicating that the latter is at least as old as late Cretaceous. Driscoll and Diebold (1997) noted that the character of reflections in the Venezuelan crust resembles wedges elsewhere in the world that are associated with the cessation of continental rifting and the onset of seafloor spreading (see also, Rosendahl *et al.*, 1992).

The regional extension relates to regional sinistral stress generated by offset of North America relative to South America (James, 2005a). It indicates an *in situ* origin for the Caribbean Plate. The parallel faults also argue against any association of the Caribbean with a mantle plume, since that would have produced radial strain (e.g., Glen and Ponce, 2002).

Postulated, major (ca. 50˚), anticlockwise rotation of the Maya Block (e.g., Dengo, 1985; Ross and Scotese, 1988; Pindell and Kennan, 2003) is also denied by the orientation of a Jurassic graben along the eastern margin of the block and of the Catoche Tongue, at the tip of the block. Equally, the parallel Triassic-Jurassic trough of the Chortis Block (Mills *et al.*, 1967) negates rotation of that block. Line up of the Jurassic grabens of Yucatán and Chortis and of the eastern margin of the Yucatán with the San Andreas lineament (Fig. 9) supports a Pangean restoration of around 900 km of sinistral offset between the blocks (James, 2005a).

Satellite-derived isostatic gravity anomaly data presented by Bain and Hamilton (1999) indicate that the Gulf of Mexico oceanic crust is defined by N40˚E trending boundaries (parallel to Jurassic grabens in North and South America) and by N45˚W 'segment boundaries' (parallel to Jurassic transform faults). Had the Maya Block rotated, Gulf of Mexico oceanic crust would have widened to the west; it actually widens to the east (Fig. 9).

Palaeomagnetic data from Central America and western Cuba negate major differential movement of the Caribbean relative to South America.

Palaeomagnetic data from ophiolite complexes of Costa Rica and western Panama indicate an equatorial position of formation and a subsequent northward movement of approximately 10˚ (Frisch *et al*., 1992). This conforms to the movement of South America but not that of the Pacific.

Di Marco *et al*. (1995) concluded that the Chorotega Terrane, which forms most of southern Central America and was the western edge of the Caribbean Plate during the Late Cretaceous-Palaeocene, originated close to its present latitude and has not rotated relative to South America.

Alva-Valdivia *et al*. (2000, 2001) studied palaeomagnetism in rocks of the Guaniguanico Terrane, western Cuba, and found that no important latitudinal tectonic movements have occurred since Jurassic time.

***Similarity between the Scoti, Banda and Caribbean plates agues for a similar origin. The Scotia and Banda Plates formed by spreading* in situ** (Fig. 10).

The Scotia, Banda and Caribbean plates are 800 km wide, 3,000 km long, east-west elongate plates situated between major continental blocks. They have N-S trending subduction-related volcanic arcs at their eastern ends and NW trending highs at their western ends. Northern and southern boundaries are characterized by strike-slip and pull-apart. The Scotia and Banda oceanic crusts are known to have formed in place.

While the spreading fabric of the Caribbean plate has been masked by overlying basalts, that of the Scotia and Banda Plates is evident and shows NE trending spreading ridges in the west and N-S spreading ridges in the east. The Scotia Plate analogy suggests that Caribbean Beata and Aves highs were spreading ridges.

An* in situ *origin of the Caribbean Plate offers a simple account of regional geology.

An important argument for the *in situ* origin of the Caribbean Plate is that it accommodates regional geology in simple terms (James, 2005a). The Caribbean shared its history with its present neighbouring areas. The simple, *in situ* story requires no changes of subduction polarity, no hot spot or plume, no major rotations of island-arcs or continental blocks, no major (1000s km) plate migration and no major changes in migration direction. It contrasts sharply with the geometrically improbable and needlessly complex Pacific models.

5. CONCLUSIONS

Arguments proposed to support a Pacific origin for the Caribbean Plate do not hold up to close scrutiny. Entry of a Pacific-derived plate would have involved unlikely, geometrically complex and highly diachronous events. These would have included changes in direction of subduction, changes in direction of plate migration, major (1000s km) plate migration, major rotation of large parts of an island arc, major rotations of the Maya and Chortis blocks and diachronous development of flysch/wildflysch deposits as the entering plate interacted with neighbouring elements. The internal structural conformity of the Caribbean Plate with regional geology of Middle America shows that no major rotations have occurred. Coeval, regionally developed deposits of Albian shallow water limestones, Palaeocene - Middle Eocene flysch/wildflysch deposits, Middle Eocene limestones, and a regional Late Eocene hiatus are more likely to have developed in an inter-American location than in a changing Pacific-Caribbean location. Neogene displacement of the Caribbean relative to North and South America amounts to no more than 300 km. The *in situ* model is simple and feasible. The Pacific model is complex and, at least, improbable.

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