The Caribbean Ocean Plateau – an overview, and a different understanding

Keith H. James

Inst. Geography and Earth Sciences, University of Wales, Aberystwyth, Wales, UK.

khj@aber.ac.uk

Introduction

This article summarises evolution of data and thought about the Caribbean oceanic plateau (Fig. 1). It concludes by suggesting an origin quite different from popular understanding.

Geology of the Caribbean plateau is inextricably linked to the geology of the plate it rides upon. The Caribbean Plate is widely believed to be oceanic (apart from a single accreted continental block), to have formed in the Pacific and to have migrated eastwards to its current location. The paradigm strongly influences the way data are explained. For example, while andesites used to signal subduction below continent, their presence in southern Central America, supposedly an intra-oceanic arc on the trailing edge of the plate, is used to call this into question. High silica ignimbrites in that area are interpreted as indicating "continentalization". However, continental thicknesses, negative Bouguer gravity anomalies, Albian quartz sands, granulite xenoliths and high silica ignimbrites and granitoids together show that southern Central America is underpinned by continental fragments (James, 2007a). They lie beneath accreted/obducted oceanic/arc rocks and young extrusive rocks. In fact, high silica rocks (andesites, tonalites) are common around Caribbean plate margins and indicate widespread continental presence (James, 2007b). This article therefore sees both the plate and plateau forming between N and S America, with strong continental inheritance.

Since the Caribbean Plateau must be seen in its geological context as part of the Caribbean Plate, relevant aspects of regional geology are included here. Key references in chronological order allow the reader to trace evolution of plateau data/understanding. Donnelly *et al*. (1990) provide the most comprehensive discussion of Caribbean magmatism. Kerr *et al.* (2003) summarise additional methodology and data (Table 2 and Fig. 17 are useful compilations of ages and rock types). Diebold *et al*., (1999) summarised the history of seismic investigation in the Caribbean area, described the internal (seismic) aspects of the Caribbean Plateau and discussed possible origins of unusually thin Caribbean crust. For recent discussions of allocthonous and in-situ understanding of the Caribbean, see Pindell *et al*., (2005, 2006) and James (2005a, 2006), respectively. For a summary of a recent conference (Sigüenza, Spain, 2006) on the area see Episodes, v. 39/4, 2006, or kjgeology.com. A Geological Society of London Special Publication will present conference papers, including compiled data indicating the plate's in-situ origins and a simple description of its evolution (James, 2007b, c).

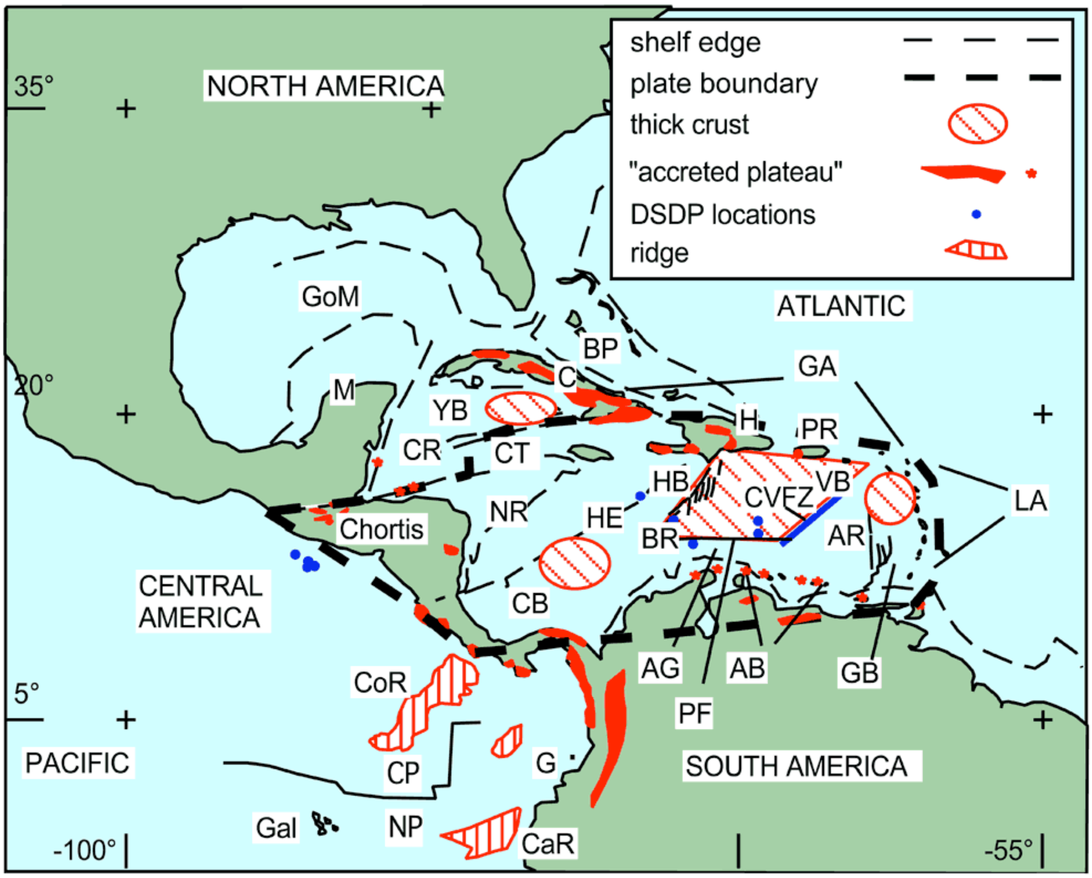

Figure 1. Middle America, with the Caribbean Plate outlined by the heavy dashed line. The 20 km thick "original" Caribbean Plateau (rhomboid area) lies in the western Venezuela Basin, centred on the NE trending Beata Ridge, bounded to the SE by the NE trending Central Venezuelan FZ (blue line) and to the south by the Flamingo – Pecos Fault. Thick crust also occurs in the Colombia, Yucatán and Grenada basins. Accreted rocks distributed around the area are commonly attributed to the plateau, though many clearly lie on different plates. AB – Aruba-Blanquilla, AG – Aruba Gap, AR - Aves Ridge, BP – Bahamas Platform, BR - Beata Ridge, C – Cuba, CB – Colombia Basin, CP – Cocos Plate, CR – Cayman Ridge, CT – Cayman Trough, CVF – Central Venezuelan Fault Zone; G – Gorgona Island, GA – Greater Antilles, Gal – Galapagos Islands, GB – Grenada Basin, GoM – Gulf of Mexico, H – Hispaniola, HE – Hess Escarpment, LA – Lesser Antilles, M – Maya, NP – Nazca Plate, NR – Nicaragua Rise, PFF – Pecos – Flamingo F., PR – Puerto Rico, VB – Venezuela Basin, YB – Yucatán Basin. Locations of Mesozoic plateau rocks in red (after Donnelly *et al.*, 1990).

The Caribbean Plate

The Caribbean Plate extends some 3,000-km east-west and 800 km north-south between North and South America (Fig. 1). Northern and southern plate boundaries, around 300 km wide, are sinistral and dextral strike-slip, respectively. Cretaceous – Cenozoic volcanism along these boundaries largely died out in a Middle Eocene convergent event. In the east and west oceanic crust subducts below the Lesser Antillean (at least Albian – Recent) and Central American (Jurassic – Recent) volcanic arcs. According to literature only the Chortis Block on the northwestern corner of the Caribbean Plate has continental basement. Chortis extends towards Jamaica as the Upper Nicaragua Rise, generally 200 m deep but crossed by deeper channels. The Caribbean plate is subdivided by the Aves (2000m) and Beata (3000m) ridges into the Grenada (2000 - 3000m), Venezuela (5000m in SE) and Colombia (3000m) basins (the latter two contiguous at the Aruba Gap). Origins of the ridges are not known. The Aves Ridge is generally seen as a Cretaceous arc, abandoned when the

Grenada Basin formed by back- or intra-arc spreading, but neither the ridge nor the basin is dated by drilling. The "original" Caribbean Plateau (4000m) is the largest area of thick crust on Figure 1. It lies in the western part of the Venezuela Basin, bounded by major faults to the NW and SE and limited to south by the E-W Pecos-Flamingo F. (Hopkins 1975). Later works have added accreted oceanic rocks and extended the plateau to western Colombia, western Central America and Cuba.

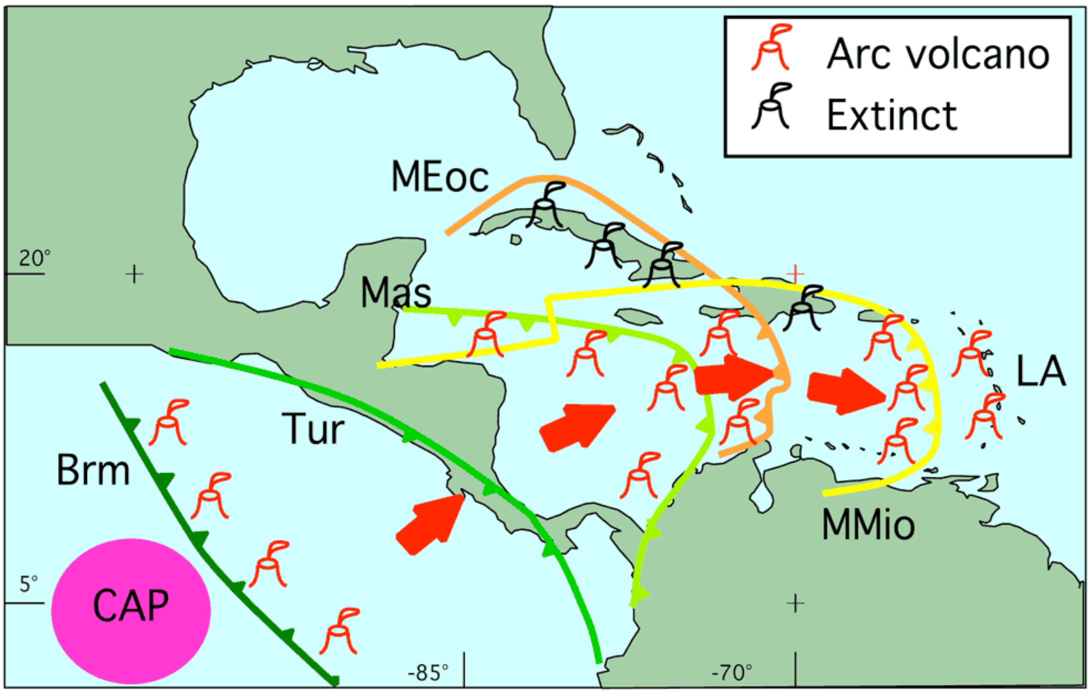

Figure 2. The popular model for the Caribbean Plate (CAP) maintains that it formed during the Jurassic in the Pacific, west of a west-facing inter-oceanic arc (the Caribbean Great Arc, colour coded for age). Albian plateau thickening occurred over the Galápagos hotspot (Fig.1). The plateau collided with the arc in the Aptian or Albian, causing subduction to reverse polarity and change chemistry from primitive to calc-alkaline. The plateau then drove the arc between N and S America. Northern and southern arc arms rotated and accreted to N and S America, where volcanism ceased. The northern plate boundary jumped from Cuba to the Cayman Trough (observe the MEoc/MMio change). The remaining active arc continued moving east. Back- or inter-arc spreading in the south opened the Grenada Trough, leaving the extinct southern part of the arc (the southernmost part of the MEoc arc) as the Aves Ridge. The Lesser Antilles arc is the remaining active part of the Great Arc. Brm – Barremian, Tur – Turonian, Mas – Maastrichtian, Meoc – middle Eocene, Mmio – middle Miocene, LA – Lesser Antilles.

A great obstacle to deciphering Caribbean Plate geology is the lack of spreading anomalies and fractures (Fig. 3 explains their absence – there is little true oceanic crust in the area). Oligocene-Recent spreading (Fig. 3, red) in the centre of the Cayman Trough is part of a large (900 km) pull-apart within the sinistral, northern Caribbean Plate boundary. On the Caribbean Plate itself, Donnelly (1973a) identified linear magnetic anomalies in the area of the original plateau (Figs.1, 4) and Edgar *et al.* (1973) described a structural grain of buried scarps and seismic isopachs. Diebold *et al.* (1981) related anomalies and structure in a unified map. Christofferson (1973) and Ghosh *et al.* (1984) attributed magnetic anomalies in the Colombia and Venezuela basins to early Cretaceous spreading but Donnelly (1989) and Diebold *et al*., (1999) disputed this, relating them instead to the deep structures.

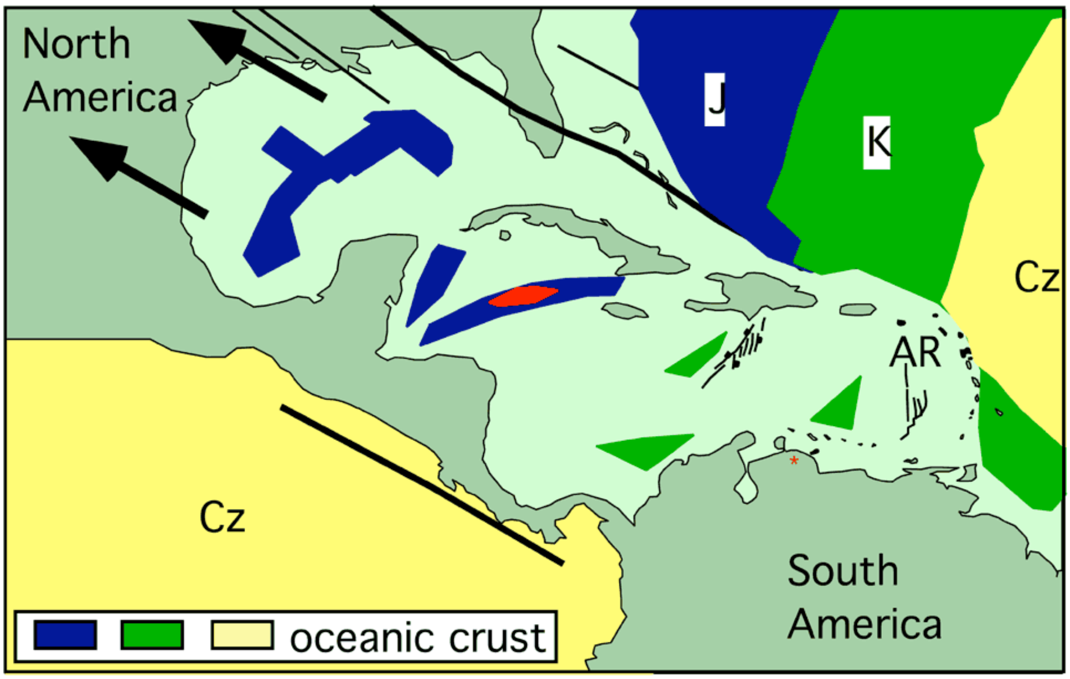

Figure 3. Middle America, in-situ model. Jurassic, Cretaceous and Cenozoic Atlantic and Pacific crust is colour coded. The area suffered rifting and extension as N America pulled away from S. America, following the direction (arrows) indicated by Jurassic fractures (heavy black lines). It is easy to assume that submarine (light green) = ocean, but calibrated areas of oceanic crust in the Gulf of Mexico (gravity data; Bain & Hamilton, 1999) and the Cayman Trough (seismic) give an idea of the very limited amount of true oceanic crust in the area. Most crust is extended continental/transitional, distributed by extension and back-arc spreading. Small oceanic areas are indicated by seismic character (James, 2007b). In the Gulf of Mexico, Yucatán Basin and early Cayman Trough oceanic crust is probably middle Jurassic in age, maybe older; in other areas possibly Cretaceous. The only known spreading ridge and anomalies (red area), Oligocene-Recent, in the whole of middle America occur in the centre of the Cayman Trough, a plate boundary pull-apart. Younger (late Cretaceous) back-arc spreading, focussed on the Aves Ridge (AR), and slab rollback beneath the Lesser Antilles extended the Caribbean Plate into the Atlantic realm.

Crustal thickness of the Caribbean Plate varies from normal, 6-8 km, west of the Beata Ridge, to thick, 20 km, between the Central Venezuelan Fz. and the western part of the Beata Ridge, to abnormally thin, 3-5 km, in the south east of the Venezuela Basin (Diebold *et al*., 1999). Crust is also thick in the Yucatán Basin (8-9 km, Hall 1995) and in the Colombian and Grenada Basins (10 - 22 km; 18 km; Case *et al*., 1990).

Caribbean seismic data show two regional markers, Horizons A" and B" (see, for example, seismic line 1293, Driscoll & Diebold, 1999). They are calibrated by DSDP drilling (Saunders *et al*. 1973). Horizon A" marks the contact between unconsolidated Eocene-Miocene oozes and lithified, Lower Eocene cherts and siliceous limestones. It correlates with Atlantic Horizon Ac, an early to middle Eocene chert within a variety of sediments (Mountain & Tucholk, 1985; Mountain, personal communication, 2006). It crops out in NW Puerto Rico as laminated siliceous and calcareous mudstones and bedded chert (McIntyre & Aaron, 1972).

Horizon B" marks the top of dolerite sills or basalt flows, overlain by Late Turonian to Campanian limestone, seen as the last phase of volcanic/intrusive activity on the Caribbean Plateau. It is important to note that the plateau has been tested by very few drill holes, all located in crestal positions. Shallow penetrations do not calibrate a 20 km thick section. Data from other locations show younger extrusion in the area. Horizons smooth B" and A" are not seen in the Yucatán Basin.

Horizon B" is smooth over the Caribbean plateau. This contrasts with thin, rough crust seen in the southeastern Venezuela and western Colombia basins (Bowland & Rosencrantz, 1988; Diebold *et al*., 1999). Rough crust is not calibrated by the drill. Obducted oceanic rocks on Cuba, Hispaniola, Puerto Rico, La Désirade, in Costa Rica, Nicaragua and northwestern Venezuela suggest Jurassic onset of spreading in the Caribbean region but there is good reason (below) to suspect that more eastern crust formed later.

The Caribbean plateau is popularly attributed to a mantle plume (*e.g*. Kerr *et al*., 1997, 2003). Kerr *et al*. (1997) maintain that the "Caribbean-Colombian Large Igneous Province" (CCLIP) is one of the world's best-exposed example of a plume-derived oceanic plateau. The hotspot/plume that generated the plateau is commonly thought to be the Galápagos hotspot, around 3000 km to the southeast in the Pacific. The Cocos Ridge (2000 m), which trends N35° towards Central America, is supposed to be the related hotspot track.

History of understanding

Officer *et al*. (1957) contrasted Caribbean and Atlantic oceanic floors, noting that Caribbean crust is thicker than normal. The Atlantic has thin sediments underlain by 4-5 km thick crust, velocity 6.5 km/s (basalt), and the Moho, below which velocity is 8 km/s (peridotite). The Caribbean has 4 km sediment underlain by thicker crust with velocity 6.1 - 6.5 km/s (intermediate, basic - acidic rocks -- andesitic material) and a major discontinuity below which velocity is 7.4 km/s.

Edgar *et al*. (1971) observed an anomalous velocity structure in the Caribbean from seismic refraction data. Oceanic velocities characterise the Beata Ridge and the Nicaraguan Plateau but the thickness is 2.5 times greater than in normal oceanic basins. Velocities of refraction profiles recording the mantle were converted to densities and the total mass/sq cm was summed to a depth of 32 km. The values were low (light) compared with standard ocean section and possibly reflected low-density mantle.

Edgar & Saunders *et al.* (1973) stated that crustal layers of the Caribbean are thicker than typical oceanic crust and have a totally different seismic velocity structure. The Nicaragua Rise and the Beata Ridge have oceanic velocities but almost continental thicknesses.

In 1973 (a) Donnelly linked basalts on land and in the Colombia and Venezuela basins as a large igneous province. Donnelly (1997b) also observed that magnetic basement in the eastern Caribbean lies considerably deeper than igneous rocks encountered by drilling.

In 1975, Ludwig *et a*l. reported on seismic Horizons A" and B" detected on airgun-sonobuoy profiles. They calculated 3 km depression of Venezuela Basin normal crust by flood basalts.

Talwani *et al*. (1977) distinguished between smooth and rough Horizon B" east of the plateau.

Maurasse *et al*. (1979) described the Dumisseau Fm intercalated mafic and pelagic rocks of Cretaceous age exposed at the Southern Peninsula of Haiti as an ophiolite equivalent to the crust below Horizon B". The unit is built of interbedded pillowed and nonpillowed basalts, dolerites, pelagic limestones, intrabasinal volcanogenic and biogenic turbidites, cherts and siliceous siltstones. It records magmatic eruptions and intrusions that occurred as more than a single event also (not a "flood basalt event") and may have spanned at least 40 Ma in the Cretaceous.

Bowland & Rosencrantz (1988) reported a regional topographic rise interpreted to be a large oceanic plateau in the western Colombia Basin. It has a generally smooth upper surface and local, sub-parallel internal reflections - seen as inter layered basalt flows and sediments. The highest crest, Mono Rise, is crowned by rough basement with mounded internal structure seen as volcanic knolls. Smooth crust in the western Colombian Basin has acoustic characteristics similar to the Upper Cretaceous basement complex below Horizon B" in the central Venezuela Basin and Bowland & Rosencrantz (1988) suggested correlation. An area of apparently typical ocean crust lies east of the plateau.

Donnelly *et al*. (1989) summarised that DSDP Leg 15 sampled Horizon B" at five sites, showing the presence of a vast area (3,000 by 1,000 km) of shallow basaltic sills intruding sediment of about 88 Ma in age, probably formed as an oceanic flood basalt plateau (like Ontong Java). Cretaceous basalts in Panamá, Costa Rica, Guatemala, central Hispaniola, Jamaica, Belize, Trinidad, Aruba, Curaçao and northern and western Colombia are stratigraphically and petrologically linked to this plateau. They were emplaced during compression at the end of the Santonian. Fossils within the complex are dated mainly Albian through Santonian, but there are Campanian ages for Hispaniola and Nicaraguan Rise sites and some Pacific coast sites show minor volcanicity into the Paleogene. In general, magmatism stopped abruptly at 88 Ma.

According to Donnelly *et al*. (1990) some (onshore) plateau occurrences are dominantly serpentinite, others basalt. Many consist of highly deformed and scattered mafic lithologies in a serpentinite matrix. The dominant mafic lithology is basalt, generally pillowed, less commonly hyaloclastic and rarely pyroclastic. Less widespread lithologies are dolerite (rare sheeted dykes), cumulate gabbro, peridotite and plagiogranite. Amphibolite of basaltic composition is abundant at many localities; eclogite is relatively rare. Associated sedimentary rocks are radiolarian cherts and pelagic limestones or thick and coarse, terrigenous or epiclastic mafic igneous debris. Ages (fossil and radiometric) are mostly Aptian - Cenomanian, some earlier, a few later. Termination of the event seems regionally coeval - Campanian sediments overly the basalt. Donnelly *et al*. (1990) described the Dumisseau Fm. (Maurasse *et al*., 1979) as 500 m of pillow and massive basalts interlayered with cherts and fine-grained turbidites overlain by Maastrichtian limestones. They noted that intrusive facies were not reported so Wadge *et al.* (1984) did not include the unit in a list of Caribbean ophiolites. The upper basalts are interlayered with Campanian sediments; the lower units contain late Santonian to Cenomanian or Early Cretaceous fauna. Donnelly *et al*. (1990) quote Woodring *et al*. (1924) as reporting Albian rudists in beds intercalated with the basalts. The tectonic environment of emplacement is not clear; the unit is highly faulted. The deepwater pelagic environment of later Cretaceous sedimentary rocks shows considerable vertical uplift and the overlying, unconformable Maastrichtian - Palaeocene shallow-water limestones provide a minimal date for emplacement. Gravity indicates several a thickness of several kilometres.

In 1996 Sigurdsson *et al.* reported Leg 165 drilling results. Site 1001 on the Hess Escarpment found mid-Campanian volcanic rocks below the basement-sediment contact, probably recording the waning stages of Caribbean basaltic plateau. Large vesicules in the basalts and benthic foraminifera in limestones between the flows suggest neritic depths. Magnetic directions recorded by the flows indicate that the plateau was near the palaeo-equator in the mid-Campanian.

Arndt *et al*., (1997) noted that high Mg spinifex komatiites on Gorgona (Fig. 1), a small (8x3 km) island off the Pacific coast of Colombia, have a wide range of trace-element compositions, from moderately enriched basalts (La/SmN ~ 1.5) to extremely depleted ultramafic tuffs and picrites (La/SmN ~ 0.2). These authors concluded that neither fractional crystallisation nor partial melting of a homogenous mantle source could account for this large variation so the source must have been chemically heterogeneous. The wide range of incompatible trace-element characteristics in the D-basalts, komatiites and tuffs, from moderate to extreme depletion, resulted from intra-plume differentiation. Kerr *et al*. (1997)

wrote: "Because most of the range of chemical and isotopic compositions seen within the CCLIP has been found within the small island of Gorgona, this heterogeneity must be on a relatively small scale.

Sinton *et al*. (1998) provided further age data, but noted imprecision (few papers qualify age dating with the necessary statistical control noted by Baksi, 2005). Basalts from Gorgona, Costa Rica, Haiti and Curaçao yield Ar/Ar ages of 88 - 90 Ma. According to Sinton *et al*., (1998) the Caribbean Plate was located over the Galapagos Hot Spot at 90 Ma. Widespread but apparently smaller volume magmatism occurred at ~76 Ma with still younger volcanism occurring locally in the Dominican Republic. The 76 Ma magmatism may have been the result of extension during tectonic emplacement of the plateau between N and S America. Younger volcanics (western Colombia, 72 Ma; Quepos Peninsula of Costa Rica, 63 Ma) may have formed over the Galapagos plume and later became accreted. Magmatism occurred in short, large volume pulses with individual massive flows erupting over a few days. Ninety Ma magmatism was compositionally heterogeneous, showing that a range of mantle sources and melting conditions were involved in forming the vast initial phase of plateau construction. In some localities (Curaçao, Nicoya Peninsula) rock compositions are strikingly uniform, in others (Haiti, Gorgona), rocks show a range of parental compositions.

Diebold *et al*., (1999) and Diebold & Driscoll et al. (1999) reported on a Venezuela Basin seismic investigation effected in 1995. The data presented were brute stacks, except for Line 1293, which is discussed later. In these papers they remark: "The concept that the Colombia and Venezuela basins are capped uniformly by a Cretaceous igneous body persists (Caribbean Plateau). In fact, the Caribbean Sea includes crust of thickness from normal (6-8 km) to abnormally thin (3-5 km)." Thickest crust, at least 20 km, lies between the north western, faulted margin of the Beata Ridge and a parallel fault (Central Venezuela Fault Zone, Fig. 2) to the southeast. Reflection profiles image structures within the entire thickness of the Caribbean oceanic plateau. Large amounts of extrusive material form two distinct, vertically stacked sequences. A lower sequence consists of local highs and ridges, flanked by wedges of dipping flows. These source Venezuela Basin magnetic anomalies. The upper sequence is more homogeneous, with widespread flows that fill morphological and extensional lows in the lower sequence. Dipping sequences of volcanic flows extend from 20 km to over 100 km. The flows appear to be of submarine origin and maintain their primary sense of dip. The top of the upper high-volume sequence forms the smooth B" horizon sampled by DSDP and ODP drilling. Palaeontology and Ar/Ar dating both indicate an igneous event occurred at 90 – 99 Ma but this terminated plateau formation; it was not the initial event. Detailed surveying of the south-eastern edge of the plateau revealed a 100-km-wide sequence of flows forming gently dipping wedges above thinned oceanic crust (similar to the Colombian data described by Bowland & Rosencrantz, 1988). In this article, Diebold *et al.* (1999) note that basement fabric predated volcanic emplacement, that the mantle beneath thin crust southeast of the plateau has low velocities (serpentinization?) and shows possible extended (listric faulted) continental crust. Basalt flows of the plateau (smooth B") overlap the deeper oceanic crust (rough B") by 20 – 30 km beyond the plateau boundary. Diebold *et al*., (1999) remarked that the morphology of smooth B" is reminiscent of continental flood basalts.

Hauff et al. (2000) presented data from 40 samples of extrusive rocks from Costa Rica, Colombia and Curaçao and from Caribbean DSDP sites. The lavas have uniform incompatible element patterns and initial Nd-Pb isotopic compositions. Linear correlations exist between isotope ratios and between isotope and highly incompatible trace element ratios. Sr-Nd-Pb isotope and trace element signatures of the chemically enriched lavas are compatible with derivation from recycled oceanic crust. The depleted lavas are derived from a highly residual source. This could be oceanic lithosphere left after ocean crust formation or gabbros with interlayered ultramafic cumulates of the lower oceanic crust. Mantle plume heads may provide a mechanism for transport of large volumes of possibly young recycled oceanic lithosphere in the lower mantle back to the shallow, MORB source mantle.

Révillon *et al.* (2000) discussed of plume/no plume/hotspot/lithospheric extension origins of various Caribbean basalt events. This is an intricate, somewhat confusing paper (please check this précis). It reveals the tormented thinking the Pacific paradigm provokes.

The authors note that oceanic plateaux have more extended periods of magmatism (than continental plateaux) with two or more pulses extending over 30 - 40 Ma. New data from Ontong Java show major peaks at 120 and 90 Ma and less important activity at 60 and 30 Ma. A similar picture is emerging for the Caribbean ocean plateau. Radiometric ages indicate two major events at 90-88 Ma and at 76 Ma (Kerr *et al.*, 1977; Sinton *et al.*, 1998). New data in this paper show activity over a period of 30 Ma, extending to 55 Ma. There is also evidence of a 120 Ma event.

The magmas retain similar petrologic and chemical compositions, indicating derivation from a mantle source of similar composition and conditions. The findings raise questions about the validity of mantle-plume models for the formation of oceanic plateaux. It is commonly assumed that they result from melting in mantle plumes. This should only occur once. This paper considers two and three headed plumes, multiple plumes, a serial plume and melting due to processes unrelated to plumes such as extension of the lithosphere and adiabatic decompression melting of upwelling mantle. "When we consider the oldest 90 - 88 Ma event (the 120 Ma event seems forgotten), there is, in our opinion, no credible alternative to the plume hypothesis". This is justified by chemistry - high Mg content, picritic or komatiitic composition - and the idea that only a plume could supply the large volumes involved.

The paper then considers the two younger events. Chemistry indicates plumes. Since compositions of Ontong Java, Manihiki, Naturaliste and Kerguelen are similar, in terms of both trace elements and isotopes, it is seen that different plumes can produce the same rocks, in different places and at different times. If a different mechanism for the younger events is sought, such as lithospheric extension, then how could such a process also produce the same properties? Modelling indicates that 20% thinning of the lithosphere could produce the same melting conditions.

A serial plume model is only consistent with an in-situ model for the Caribbean. "Since most authors think the Caribbean came from the Pacific this can't be true." Thus the first episode of magmatism occurred over a plume south of Galapagos and the second occurred over Galapagos. Alternatively, Galapagos was responsible for episodes 1 and 2 OR Galapagos was responsible for episode 1 and lithospheric thinning drove episode 2. Since Farallon Plate velocity was around10 cm/y magmas of 1 and 2 should be separated by 1500 km and there should be an age progression in the 1500 km long Caribbean Plateau. This is not observed. Also, a cause of thinning in the second event is not known. Thus the plume responsible for episode 1 must have been 200 km to the south. It was the Sala y Gomez hotspot.

Alternatively, the Caribbean was between the Americas during episodes 2 and 3. A serial plume cannot have been involved. A multiple plume is also ruled out because there is no evidence of a plume in the Caribbean. Lithospheric extension is possible. Whatever, the youngest (55 Ma) magmas must have formed in-situ. This might have been a plume, associated just with the Beata Ridge or the unknown Caribbean plume responsible for event 2. Because this magmatic event was small, a plume is ruled out.

The paper concludes that plumes are the best explanation for events 1 and 2 and extension explains event 3.

Kerr *et al*. (2003, Table 2) summarised occurrences and ages of plateau rocks in the Pacific and the Caribbean. Ages group at 91-88 Ma and 78 - 59 Ma (actually, rocks with the latter ages come mainly from the western margin of Central America). Activity also occurred at 124 - 112 Ma, coeval with Ontong-Java. Data compiled by Kerr *et al*. (2003) seem to indicate a wide range of age and chemistry (*e.g*. Duarte complex of Hispaniola ranges in Ar/Ar age from 86 – 69 Ma but Jurassic radiolaria occur locally. In this paper Kerr *et al*. (see also Kerr *et al.,* 2000) discuss means of identifying oceanic plateaux. Indicators are occurrence of basalts and high Mg lavas, La/Nb ratios around 1 (less than arc rocks), flat rare earth element patterns and narrow radiogenic isotope ranges. While these parameters individually do not identify a plateau, in conjunction they provide "a powerful set of discriminants." Kerr *et al*. (2003) note that basalts of marginal basins of island and continental arcs are potentially the most difficult to distinguish from oceanic plateaux, but these should include more tephra and temperatures lower than those above mantle plumes should result in uncommon high MgO lavas. Kerr *et al*., (2003) regard oceanic rocks accreted to the Pacific side of Colombia as part of a single Caribbean-Colombia plateau.

In 2005, Kerr & Tarney suggested that the Caribbean-Colombian oceanic plateau represents the remnants of two different oceanic plateaux, both dated *ca*. 90 Ma. The Caribbean Plateau formed in the vicinity of the present-day Galapagos hotspot. North-eastward movement of the Farallon plate caused this to collide with the proto–Caribbean arc and north western South America <10 my after its main phase of formation (the Farallon Plate is now split into the Cocos and Nazca plates, Fig. 1). The Gorgona Plateau (Gorgona Island, Fig. 1) formed at 26°–30°S, possibly at the Sala y Gomez hotspot. Over the next 45 my it travelled north eastward on the Farallon plate to collide with the proto–Andean subduction zone in north western South America in the middle Eocene. Kerr & Tarney (2005) noted that at least two and possibly three (90, 120 and 140 Ma) ages of plateau material exist in the Caribbean area. Limited occurrence of the older one possibly indicates significantly smaller volumes while the 90 Ma oceanic plateau events (Caribbean and Gorgona) were voluminous.

Flores *et al*. (2006) described a pre-Cretaceous, subduction-related melange in northeastern Nicaragua as marking a major suture between the Chortis Block and the Caribbean Large Igneous Province.

Kerr & Hastie (2006), for whom a plume origin of the plateau is unequivocal, consider the petrological origin of the Caribbean plate to be fundamental. Failure to correctly address this is at the root of much of the disagreement about the geographic provenance and tectonic history of the Caribbean Plate. They list the following facts:

1. The Caribbean plate is significantly thicker than normal oceanic crust over much of its area.
2. The margins of the Caribbean plate have been uplifted and exposed around its edges.
3. High-MgO lavas (>14 wt.% MgO) are found in many of these accreted sections.
4. In marked contrast to other oceanic plateaux (extant and accreted to continents) there is no chemical evidence of any input from continental crust or components derived from a subducted slab or a back arc basin. There is also little evidence for derivation from ambient upper mantle (MORB-source).
5. Although there are older and younger phases, the vast bulk of Ar-Ar ages cluster around ~90Ma.

From these they deduce:

1. The thickness of melt forming the Caribbean plate cannot be produced only by extension and decompression melting of ambient relatively anhydrous upper mantle, under any reasonable geological conditions. Melting of mantle with either elevated Tp and/or a significant volatile content is required.
2. Absence of geochemical signature of subduction in the Caribbean oceanic plateau basalts, combined with a relative lack of evidence for explosive volcanism in its accreted and drilled sections firmly rules out a hydrated source mantle and a suprasubduction zone origin for the plateau.
3. It has been suggested by some that because high-MgO lavas can occasionally form in arc settings, the occurrence of these lavas around the Caribbean plate margins is testament to a subduction-related origin for the plateau. However, high-MgO arc lavas also display clear geochemical and petrological evidence for derivation from a subduction-related and hydrated mantle source region. Plateau picrites and komatiites do not have a subduction-related signature.
4. Parameterisation of experimental phase data and mantle melt modelling reveals that the high-MgO lavas of the COP were derived from a mantle source region with potential temperatures >100° C hotter than ambient upper mantle.
5. The volume of melt produced and the relative rapidity of eruption of the main phase of plateau volcanism, in conjunction with the evidence for elevated mantle Tp from high MgO lavas, means that by far the most petrologically plausible formational model is one involving a hot mantle plume.

Discussion

Magnetic data show that that the plateau was near the palaeo-equator in the mid-Campanian (Sigurdsson *et al.* 1996). Magnetic data from Pacific coast Cretaceous ophiolites of Costa Rica and Panama also formed in an equatorial position (Frisch *et al.* 1992). Both areas have moved approximately 10° since, conforming with the movement of South America.

Rocks on Cuba, Jamaica, Hispaniola, Puerto Rico, Aruba, Curaçao, Trinidad and Tobago, in Costa Rica, Guatemala, Panama, Venezuela and Colombia (and Gorgona) are seen as uplifted parts of the Caribbean plateau. However, except for Hispaniola and Puerto Rico, all these occurrences are removed from the actual (in-situ) plateau. Cuba lies on the North American Plate and is separated from the Caribbean by the Cayman Ridge and Nicaragua Rise, both with continental basement rocks (Holcombe et al., 1990; Dillon & Vedder, 1973; Malin & Dillon, 1973; Muñoz et al. 1997).). Trinidad and Tobago lie beyond the Lesser Antilles arc, not behind it, on the South American Plate. Even the Hispaniolan rocks lie on the SW peninsula of Haiti, west of the Beata Ridge and north of normal oceanic crust (undated) in the Haiti Basin. These data suggest several areas of igneous activity, rather than one Large Igneous Province.

Besides the Caribbean Plateau (of the western Venezuela Basin), thick crust is reported from the Colombia, Grenada and Yucatán basins. The western Yucatán Basin shares the regional NE tectonic trend and shows the same periodicity as the Caribbean Plateau. It parallels the major Río Hondo fault zone that crosses the Yucatán Peninsula (Fig. 4) and repeats the periodicity of basement blocks along the faulted eastern Yucatán margin (Case, 1975, Fig. 24). A slightly more easterly trend obtains in the east/southeast, where bathymetric morphology suggests tilted fault blocks of extension and rifting (Holcombe *et al.*, 1990). Implications are that the basin shares history with the Caribbean Plateau and the Gulf of Mexico. The basin lies north of the Cayman Ridge, which is underpinned by continental crust. It clearly did not come from the Pacific; it was not part of a large plateau. The Jurassic ophiolites and Cretaceous arc rocks obducted northwards onto Cuba came from the basin, which must have originated in the Jurassic, coeval with its neighbour, the Gulf of Mexico, not in the Palaeogene.

There are at least six different models for formation of the Grenada Basin. Most invoke Palaeogene back- or inter-arc spreading (Aves Ridge – Lesser Antilles). Crust in the south is 9 – 11 km thick km thick (Christeson *et al*., 2004) and clearly is not ordinary oceanic crust The Tobago Trough, outboard of the Lesser Antilles arc, has similar crustal thickness; (Christeson *et al*., 2004). Grenada Basin crustal thickness and width of 150 km are not compatible with rifting of an 18 – 24 km thick volcanic arc. In the north the basin 18 km thick and displays a NE structural trend (Fig. 4).

Sigurdsson *et al.* (1996) wrote that Caribbean Oceanic Plateau volcanism continued at least until 77 Ma and may have persisted to 74 Ma (end Campanian) and does not conform to any model of extremely rapid outpouring in 88 - 90 Ma interval. Maurasse *et al*. (1979) made a similar point with respect to the Dumisseau Fm (Hispaniola), which records eruption and intrusion as more than a single event (not a "flood basalt event") possibly over at least 40 Ma in the Cretaceous. Different ages of gabbros and dolerites sampled on the Beata Ridge show that they not belong to the same magmatic sequence (Révillon *et al*., 2000). These authors noted that uniform compositions could record repeated tapping of the same source in an extensional setting.

The Cocos Ridge, supposed hotspot track of the Caribbean plateau, does not extend to the Galápagos "Hotspot" (Harpp *et al*., 2002), which, in any case, lies on the opposite side of a spreading ridge (Fig. 1). Galápagos activity began 22 – 17 Ma (Lonsdale & Klitgord 1978); it is not likely to have generated a Cretaceous plateau. Volcanism on Cocos Island, on a segment of ridge supposedly Miocene in age, is dated at 2 Ma (Castillo *et al*., 1989). Lavas on the northern Galápagos Islands, closest to the ridge, range in chemical composition from enriched to depleted (Harpp *et al*., 2002).

While Kerr *et al*. (2003) attribute parts of the upper Jurassic – lower Cretaceous North Coast Schist of Tobago and the Albian Sans Souci Formation of Trinidad to the Caribbean Plateau this is at odds with their location southeast (*i.e*. outboard) of the volcanic arc the plateau is supposed to have followed into place. Kerr & Hastie (2006) state that there is no continental signal in plateau rocks. The North Coast Schist contains metatuffs, graphitic siliceous schist, graphitic quartzose phyllite, shows continental input from the Albian and suffered tonalitic intrusion at that time (Snoke, 1990 *et al*., 1990). The Sans Souci Fm. is a series of volcanic tuffs, tuff breccias, agglomerates and andesitic lavas (Kugler 1953) erupted onto the passive margin of South America during the Aptian – Santonian (Wadge & MacDonald, 1985). Associated sediments are limestones, black, carbonaceous shale, quartz sandstones and conglomerates with continental provenance (Wadge & MacDonald, 1985). Both the North Coast Schist and the Sans Souci formed close to continental crust. The Siuna Terrane of northeastern Nicaragua is an ocean island-arc active from early to middle late Cretaceous (Venable 1993). It is seen as the leading edge of the entering Caribbean Plate. Strata include conglomerates, limestones and interbedded volcanic rocks. Conglomerates contain abundant quartz and fragments of schists and quartzite, indicative of a nearby continental source.

The subduction-related mélange in northeastern Nicaragua, interpreted as part of the Caribbean large igneous province (Flores *et al*. 2006), contains Middle and Late Jurassic Radiolaria. It is overlain unconformably by calcareous hemipelagites with Aptian/Albian planktonic foraminifera. It is not part of a Cretaceous plateau.

At least 400 km of thinned crust lie southeast of the limit of the Caribbean Plateau mapped by Diebold & Driscoll (1999). This does not support the idea that the thick plateau collided with and choked an early Cretaceous volcanic arc and then drove the "Caribbean Great Arc" (Aves-Lesser Antilles) between the Americas. It does not support a resulting subduction reversal.

Bowland & Rosencrantz (1988) and Diebold & Driscoll (1999) observe flows associated with smooth Horizon B" lapping onto rough Horizon B" in the Colombia and Venezuela basins. For this article this indicates that the two horizons are close in age, so small areas of spreading occurred in the late Cretaceous.

Drill samples of smooth B" are variously described as basalt and fine-grained dolerite (Donnelly *et al*. 1984) or coarse-grained basaltic flows (Sinton *et al.*, 1998). Donnelly *et al.* (1984) reported that all the basalts appear to be intrusives. Others describe smooth Horizon B" units as flows (Diebold & Driscoll *et al*, 1999). Submarine sampling of the Beata Ridge recovered alternating magmatic and sedimentary rocks, probably with tectonic contacts (Révillon *et al*. 2000). The main constituents are gabbros and dolerites, possibly as sills. Volcanic rocks are rare, as pillowed lavas. Textures range from coarse-grain gabbros to very fine-grain dolerites, indicating large differences in cooling rates during emplacement and crystallization. Fine-grained rocks are more abundant and most show doleritic textures (*Révillon et al*., 2000).

Diebold (in preparation) suggests that the 5 km thick Albian – Cenomanian Curaçao Lava Fm. is analogous to the upper 5 km of the (seismic) upper volcanic sequence of the Caribbean Plateau. The Curaçao Fm. has a presumed palaeosol at its top (Beets *et al*, 1977) and a palaeosol occurs above weathered basalt on the correlative Aruba Lava Fm. of the neighbouring island (Snoke, 1990). Vesicularity of drilled Caribbean plateau mid Campanian basalts and benthic foraminifera in sediments resting on the flows suggest shallow origins (Sigurdsson *et al.* 1996). Spheroidal weathering of some gabbros and dolerites from the Beata Ridge indicates subaerial weathering (Révillon *et al*, 2000). Shallow marine fauna occurs also in Cretaceous volcanic and sedimentary shale, sandstone, tuff, thin limestone and chert above Jurassic oceanic material in the Siuna mining district of Honduras (Chortis) (Venable, 1993). Andesitic flows were eroded in a high energy/beach environment that gave way to a shallow carbonate bank (Flores *et al*. 2006). Reduced velocities in the upper sub-B" sequence of the plateau could indicate vesicles, brecciation, weathering or interbedded sediments (Diebold *et al*., 1999). These are indications that flows could have been subaerial, which is a reasonable explanation for the great lateral extent/continuity and character of smooth Horizon B". Diebold et al., (1999) observed that smooth Horizon B" is reminiscent of a continental flood basalt.

The Venezuela Basin plateau seems to be related to the N35°E trending Beata Ridge. Its margins are the linear, faulted flank of the ridge in the NW and the parallel Central Venezuela Fault Zone in the SE (Fig.1). This trend parallels Triassic-Jurassic rifts and faulted continental margins formed during Pangean rift/drift in Middle America. This suggests that the plateau was the focus of late Jurassic – early Cretaceous spreading, coeval with or slightly younger than opening of the Gulf of Mexico and the Yucatán Basin as North America drifted northwest from Gondwana. Location above a spreading ridge would be similar to Iceland's location. An Albian shift of spreading from the Caribbean to the South Atlantic must have involved a Caribbean triple junction as it began (perhaps accounting for 120 Ma extrusion). That phase of extrusion therefore might show location and age similarities to Ontong Java and Manihiki.

Basement highs below the plateau are 30 – 40 km wide and are modelled by Diebold *et al*. (1999, fig. 15) as formed by vertical dykes. At the same time, Diebold *et al*. (1999, p. 583) remarked that reflections (on the highs), "if any, are horizontal". Almost horizontal reflections are visible on line 1293 (CDP 9000 – 10000) and slightly more steeply dipping reflections occur on line 1298 (CDP22000 – 23000) (figs. 2, 3 of Diebold *et al*., 1999). The upper wedge of Diebold *et al*. (1999) thickens from 400 to 5000 m over a distance of 62.5 km, while the Moho remains at a constant depth. This clearly is a growth wedge related to extension between massive basement blocks. Diebold *et al*. (1999) note that the thickness supports an Aptian age for the beginning of this section, which includes "an appreciable amount of metamorphosed sedimentary layers".

Hess (1938) observed a circum-Caribbean belt of serpentinized peridotite across Guatemala, the whole length of Cuba, through northern Hispaniola and across Puerto Rico. In the south it runs from Margarita through Orchila and El Roque to Cabo Vela on Guajira and southward into the serpentinite belt of the Cordillera Central of Colombia. Serpentinites also occur in northeastern (Flores *et al*. 2006).

Rigassi-Studer (1961) noted that serpentinite encountered by drilling in the Cuban Jarahueca oilfield passed abruptly to almost unaltered peridotite. Serpentinization occurred post Neocomian and pre Maastrichtian and resulted from influx of hydrothermal, silica-rich water. Hess (1966) suggested that serpentinized peridotite in the Caribbean region is hydrated upper mantle. Hopper *et al.* (2004) reported data from the Galicia Bank and Iberian margins suggestive of detachments near the base of the continental crust. Extreme crustal thinning results in exhumation and serpentinization of upper mantle to form a layer with crust-like seismic velocities. Distal parts of the Cayman Trough probably have similar origins (Ten Brink *et al*. 2003).

The foregoing indicates late Cretaceous Caribbean extension, tying subaerial plateau extrusion (smooth B") to serpentinitic crust generation (rough B"), with both possibly involving continental crust.

Arc volcanism, HP/LT metamorphism and some geology that does not fit Pacific origins of the plateau.

Most models of the Caribbean plateau maintain that a "Caribbean Great Arc" formed in the Pacific in the early Cretaceous above an east-dipping subduction zone (e.g. Pindell & Barrett, 1990). However, palaeontological and zircon U-Pb dating show calc-alkaline quartz diorite and rhyolites on La Désirade, Lesser Antilles, to be upper Jurassic in age. Precambrian and Palaeozoic zircons in Cretaceous calc-alkaline volcanic arc rocks in central and eastern Cuba (Rojas-Agramonte *et al*., 2006) show they formed above continental crust. Permian granite intrudes the Miralejos gneiss and schist of the Paraguana Peninsula

Arrival of the east migrating Caribbean plateau is supposed to have choked the (Pacific) subduction zone in the Aptian/Albian, changing subduction polarity and chemistry from primitive to calc-alkaline (Lebrón & Perfit, 1994). The arc then entered between North and South America, ahead of the plateau, and mostly accreted, diachronously from the Middle Eocene on, to the Greater Antilles and northern South America, with the active remains lying in the Lesser Antilles. It picked up pieces of continental crust from Yucatán and NW Colombia (*e.g*., Pindell *et al*., 2005; Stanek & Maresch, 2006), burying them as deep as 80 km where they suffered HP/LT metamorphism. These were then exhumed in Cuba and from Aruba-Blanquilla to Tobago by extension as the arc collided diachronously from the middle Eocene with N and S America (Avé Lallement 1997, Stanek *et al*., 2006). This exhumation is never illustrated but implies unrealistic extension and disappearance of 80 km of overburden.

The continental rocks supposedly picked up from Yucatán by the "Great Caribbean Arc" as it entered between the Americas extend 2,500 km from Cuba, through northern Hispaniola to the south wall of the Puerto Rico Trough (a trench north of Puerto Rico) and as far as the Lesser Antilles. The continental rocks on Cuba are in palaeogeographic continuity with the southern margin of North America. Inter-tidal to subtidal rocks on the Silver-Navidad Banks, easternmost Bahamas Platform, and Puerto Rico link these areas from the Albian to the early Miocene (Schneidermann *et al*. 1972). Both the Cuban and Puerto Rican suites are in place.

Pardo (1975) noted that metamorphism in the Organos Belt of Cuba was slight in general, but extreme along the Pinar Fault. Goncalvesa *et al*. (2002) remarked that HP/LT rocks occur close to strike-slip faults along the north Caribbean margin. There is geographic continuity from lower – upper Cretaceous, sedimentary to metamorphic continental rocks approaching major strike-slip faults along northern South America (James, 2007b). HP/LT metamorphism should be explained by transpressional faulting/tectonics, not by improbable great burial and tensional exhumation.

The Pacific model also invokes Palaeocene-middle Eocene opening of the Yucatán Basin by two episodes, in different directions, of slab roll back and a Caribbean Plate boundary jump from Cuba to the Cayman Trough. However, Rosencrantz (1990) concluded that the eastern Yucatán Basin is at least Late Cretaceous in age and could be Aptian-Albian or even Late Jurassic in age. Northward obducted Jurassic ophiolites on Cuba support the last date. Continental rocks on the Cayman Ridge further south show that obducted rocks on Cuba did not come from the Pacific.

Recent data show that more than one arc existed in Cuba (Iturralde-Vinent, 1995; Blein et al 2003) and that the change from primitive to calc-alkaline chemistry did not always occur in the Albian and was not always abrupt (Kerr *et al*., 2003). PIA and CA rocks crop out within metres of each other on Cuba (Iturralde-Vinent *et al*. 2006). Also on Cuba, arc volcanism ceased along a 1,000 km length in the Cenomanian and resumed 15 my later in a Danian arc oriented 45° to the earlier one. This does not support the (Pacific model) middle Eocene arrival of the arc and its diachronous collision with Cuba, Hispaniola and Puerto Rico.

Origin of the Plateau, significance of obducted oceanic/arc rocks

This article earlier noted the internal structural grain of Middle America, including the Caribbean Plate (Fig. 4). It trends N35°E and parallels precisely Triassic-Jurassic rifts in southern North America, northern South America, Central America and the Beata Ridge. Thus Middle America shows a regional structural integrity related to Triassic-Jurassic-early Cretaceous rift/drift. The rifts on Maya and Chortis negate large (80°) rotations postulated and required by models deriving the Caribbean Plate from the Pacific.

In the absence of spreading magnetic anomalies and fractures James (2005a, 2006, 2007) used the striking analogy with the Scotia and Banda Plates to support an in-situ origin for the Caribbean Plate. The plates are remarkable similar in form and dimension. (Fig. 5). Each lies between large continental masses to the north and south. Each carries a curved volcanic arc to the east. Oceanic fractures to the east and west diverge towards the plates, suggesting extensional settings.

Scotia and Banda carry calibrated magnetic anomalies and both are known to have formed in place. They also have internal spreading ridges. Scotia and Banda formed by episodic spreading, extending eastward through time (Barker, 2001; Milsom, 2007, in preparation). The analogy suggests that the Caribbean Plate also formed in place by back-arc spreading, focussed firstly on the NE trending Beata Ridge (= W. Scotia Ridge) and later on the N-S trending Aves Ridge (= E. Scotia Ridge), extending eastward above the Atlantic Plate.

Dispersed continental blocks rim Scotia and Banda. Data indicating continental material below southern Central America were listed earlier. Crustal thicknesses below Puerto Rico (30 km, Talwani, 1964) and the Virgin Islands (29 km, Shurbet *et al.* 1956) and black marbles on Hispaniola (Nagle, 1974) and the south wall of the Puerto Rico Trough (Fox & Heezen, 1975) indicate continental crust below these islands. They lie hidden beneath obducted volcanic arc and oceanic rocks, carbonate platforms and Cenozoic volcanic and volcaniclastic rocks.

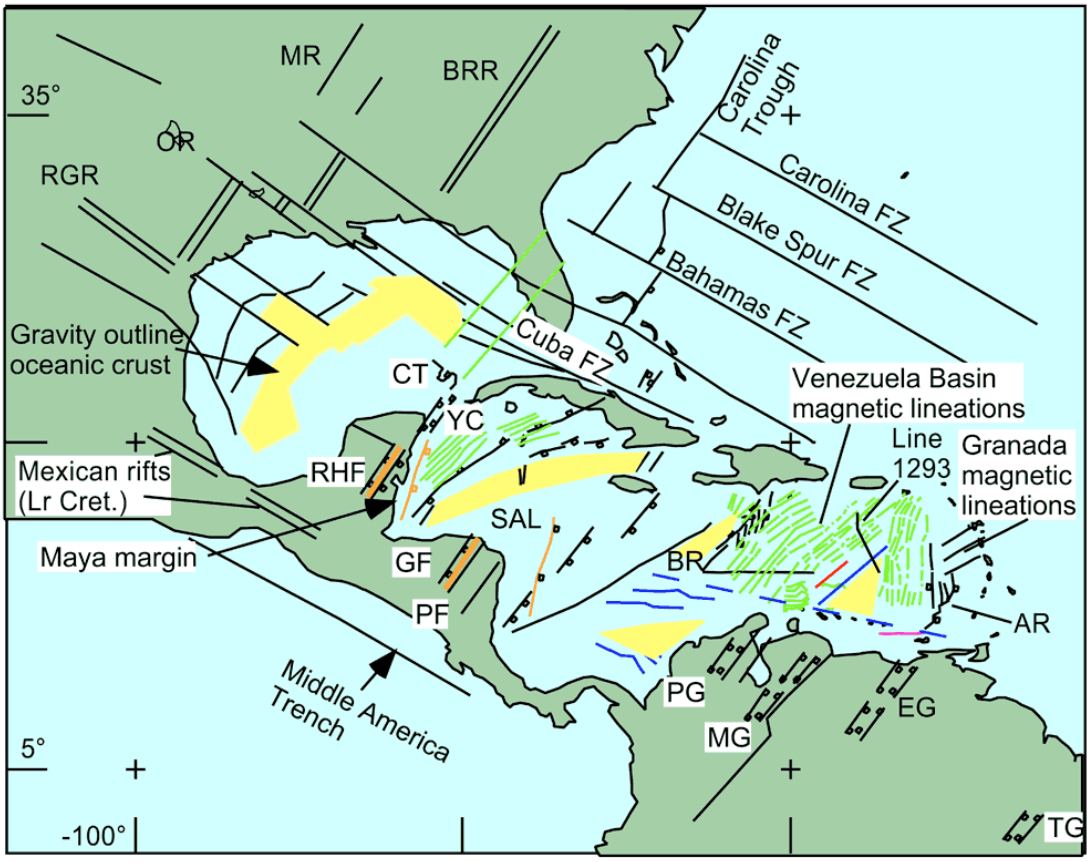

Figure 4. Middle America is bracketed by N60°W fractures (Cuba Fz., Middle America Trench) and shows in internal regional tectonic pattern of N35°E and N60°W faults. They reflect Triassic-Jurassic rifting and Jurassic-Cretaceous drifting. The Caribbean Plate shares this regional pattern and shows no radial signature expected of a plume. When Maya and Chortis are restored, removing some 900 km of sinistral offset (Cayman Trough offset), aligning the Maya margin with the San Andrés lineament (*i.e*., the main, Caribbean margins of the blocks - orange lines) the Río Hondo and Guayape faults (also orange) also line up, suggesting a regional Jurassic rift. Offset occurred in the Jurassic-Cretaceous (James, 2005c). The red line marks the mapped SE limit of Caribbean Plateau (Diebold & Driscoll, 1999) – the Central Venezuela FZ. Green lines are magnetic anomalies (Caribbean: Ghosh *et al*., 1984; Gulf of Mexico: Gough, 1967; Yucatán Basin: Hall & Yeung, 1980); magenta (Peter, 1972), blue – this study. The NE trend over the "plateau" area reflects basement structures (*e.g*., Diebold *et al.,* 1981). Similar anomalies in the Yucatán Basin probably have the same origin. Magnetic anomalies in the east, parallel to the Aves Ridge, support the idea that it was a back arc spreading centre, analogous to the East Scotia Ridge (see below). BR - Beata Ridge, BRR - Blue Ridge Rift, CT - Catoche Tongue, EG - Espino Graben, GF - Guayape F., MG - Mérida Graben, MiG - Mississippi Graben, OR - Oachita Rift, PF- Patuca F., PG - Perijá Graben, RGR - Río Grande Rift, RHF - Río Hondo F., SAL - San Andrés Lineament, TF - Ticul F., TG - Takutu Graben, TT - Texas Transform, YC- Yucatán Channel.

Geochemistry also evidences widespread presence of continental crust on Caribbean margins. Tonalites, a chemical signal of continental crust (*e.g.,* White *et al.* 1999) are common. Many date in the region of 86-80 Ma, close to the age of basalts/dolerites found on the Caribbean plateau. Tonalites dredged from the Cayman Trough (Perfit & Heezen, 1978) have a geochemistry typical of continental arc granitoids (Lewis *et al.* 2005). Silica content of plutonic rocks in the northeast Caribbean (Puerto Rico - northern Lesser Antilles) ranges 45 - 78% weight (Smith *et al.,* 1998). Andesites, dacites, diorites and granodiorites, also continental signals, occur in Panamá (Case, 1974), on the Nicaragua Rise (Arden, 1975), on Jamaica (Jackson *et al*., north Yucatán (Banks, 1975), Cuba (Lewis, 1990; Blein *et al*., 2003), Hispaniola (Butterlin, 1956) on Saba Bank (Despretz *et al*, 1985) and Mariner Bank (Bouysse *et al*., 1985) and in the Virgin Islands (Donnelly, 1966; Lidiak, 1970; Lewis & Draper, 1990).

Analogy with Scotia and Banda also suggests that unrecognised blocks of continental crust lie within the Caribbean Plate (James, 2007a, b). Internal Banda ridges are interpreted as continental slivers from New Guinea (dredged sedimentary and metamorphic rocks) and oceanic crust forms only a small part of the Flores Sea (Milsom, pers. comm., 2007). Parts of the Scotia Sea are more elevated than normal ocean floor and may be continental crust thinned by extension (Barker, 2001).

These discussions suggest that extended continental crust lies beneath the Caribbean plateau. Granitic basement occurs in the Seychelles, the Parcel Islands, on the Kerguelen and Agulas plateaux and continental crust may be present below Iceland (Foulger *et al*. 2005).

Diebold *et al.* (1999) interpreted that seismic data show large (30 – 40 km wide) volcanic highs sourcing flows in large, adjacent wedges. Diebold (in preparation) suggests that the 5 km thick Albian – Cenomanian Curaçao Lava Fm. (Klaver, 1987) is analogous to the upper 5 km of the upper volcanic sequence of the Caribbean Plateau.

The Curaçao Fm. is dated Albian (ammonites, Weidmann, 1978) – Turonian (radiometric dates). Kerr et al. (1997) questioned the Curaçao ammonite data but they were upheld by Snoke et al, (2001); moreover, other sections of "plateau" rocks around the Caribbean have Albian – Turonian ages. Maurasse et al. (1979) described the Dumisseau Fm., exposed on southern Haiti, as 1.5 km of interbedded pillowed and nonpillowed basalts, dolerites, pelagic limestones, intrabasinal volcanogenic and biogenic turbidites, cherts and siliceous siltstones. The unit records magmatic eruptions and intrusions that occurred as more than a single event and may have spanned at least 40 Ma in the Cretaceous. The complex is an ophiolite equivalent to the crust below Horizon B". For Maurasse et al., (1979), this was not a "flood basalt event".

Seismic line EW9501-1293 of Driscoll *et al.* (1999) shows the contact (CDP 19000) between the Plateau and thin, rough crust of the southeast Venezuela Basin. A deep normal fault abruptly places the top of rough crust to the SE against a SE dipping wedge of reflections to the NW. This dips and widens away from a horst below CDPs 9000 – 10000. If the upper part of Diebold's upper sequence is equivalent to the Curaçao Fm., then the lower part of the upper sequence must be Albian or older. The underlying sequence has to be yet older, and the basement highs, away from which the wedge sections dip, have to be older still.

The southeastern Gulf of Mexico, between Yucatán and Florida, which also manifests the regional NE tectonic grain (Fig. 4), offers an analogue for these data. Calibrated by 8 drill sites, this area was described by Phair & Buffler (1983). DSDP Site 537, at the mouth of the Catoche Tongue (Fig. 1) encountered 500 ± my old phyllite, Site 538A reached 500 ± my old gneiss amphibolite intruded by 160 - 190 my (Pliensbachian – Bathonian) diabase dykes. Upper Triassic-lower Jurassic (early rift), fills large, NE - SW trending graben systems with beds tilted to the SE. (tilted fault blocks tested by DSDP sites have Palaeozoic basement). The Middle Jurassic (supposed age) section is up to several kilometres thick. It may be partly shallow marine (a shallow marine dolomite of unknown age was penetrated by DSDP 635). High amplitudes indicate rocks such as salt, volcanic rocks, alluvial fans and lacustrine beds.

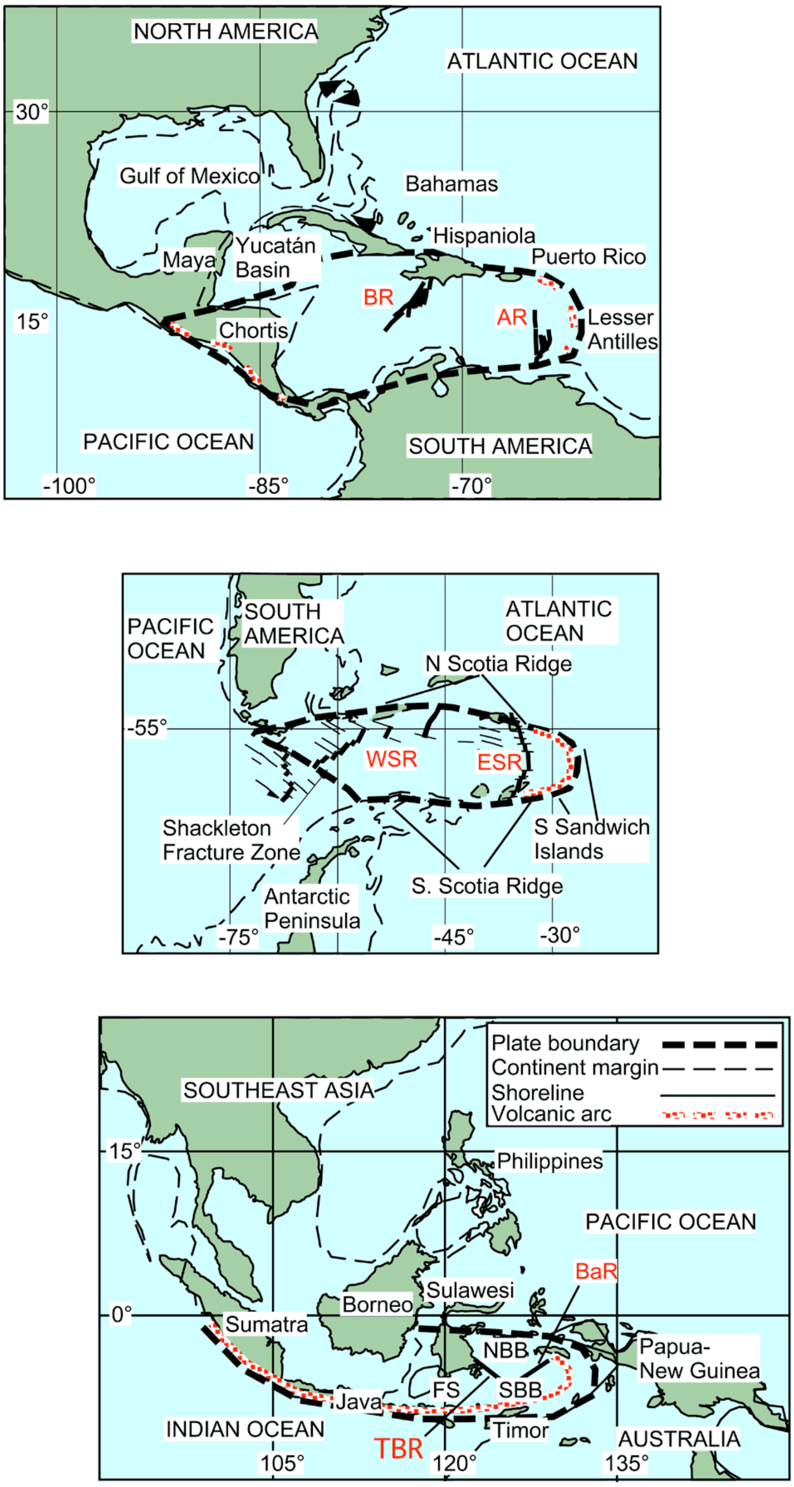

Figure 5. Caribbean, Scotia and Banda Plates (outlined in heavy dashed lines). The plates have similar shapes and dimensions, are located between large continental masses to the NW and SE and have active arcs in the east. Scotia and Banda are known to have formed in place. They are rimmed by continental fragments. Note the coincidence of the Aves Ridge/East Scotia Ridge, Beata Ridge/West Scotia Ridge. The Tukang Besi and Banda Ridges are continental. AR – Aves Ridge, BaR – Banda Ridges, BR – Beata Ridge, ESR – East Scotia Ridge, FS – Flores Sea, NBB – North Banda Basin, SBB – South Banda Basin, TBR – Tukang Besi Ridge, WSR – West Scotia Ridge.

The Upper Jurassic fills and onlaps the Middle Jurassic and possibly is transitional between shallow to deeper marine. The Lower Cretaceous is up to 2 km thick (deep water carbonates were found in DSDP holes 535 and 540). It is truncated by a prominent regional unconformity traceable throughout the GOM. In the SE it represents a large, variable hiatus that at Site 540 spans the entire upper Cretaceous. It suggests Late Cretaceous shallow depths /exposure.

Figure 6 is an alternative interpretation (this study) of their line 1293, suggesting that the Caribbean shared the history of the SE Gulf of Mexico described by Phair & Buffler (1983). Triassic/older basement blocks flanked by Jurassic rift deposits are overlain by Cretaceous carbonates. This assemblage was shallow in the late Cretaceous, at the time when smooth B" basalts were extruded.

If Jurassic rift deposits are present beneath the Caribbean plateau, they could include salt. The "volcanoes" of Diebold *et al*. (1999), at CDPs 2200 and 5900 of line 1293, might be salt diapirs. The Caribbean might even have its own "Sigsbee Knolls" (Gulf of Mexico salt diapirs). The features push up sea-floor sediments, rather than building up as cones. Reflections dipping towards the diapirs below Horizon B" ("moats" of Diebold *et al*., 1999) might be rim synclines formed by salt withdrawal. There is even a suggestion of convex up reflectors within the diapir, which could be velocity pull-up of deeper reflections (however, the condensed data - every fifth trace shown - are not migrated). Diebold et al. (1999) note that seamounts in the Venezuela Basin align NE-SW or E-W and parallel magnetic anomalies. The diapir at CDP 2000 coincides with a NE magnetic high, diapir 6000 does not. The CDP 2000 feature seems to be associated with an important fault, with major downthrow to the northwest. Salt walls and stocks commonly follow underlying tectonic grain.

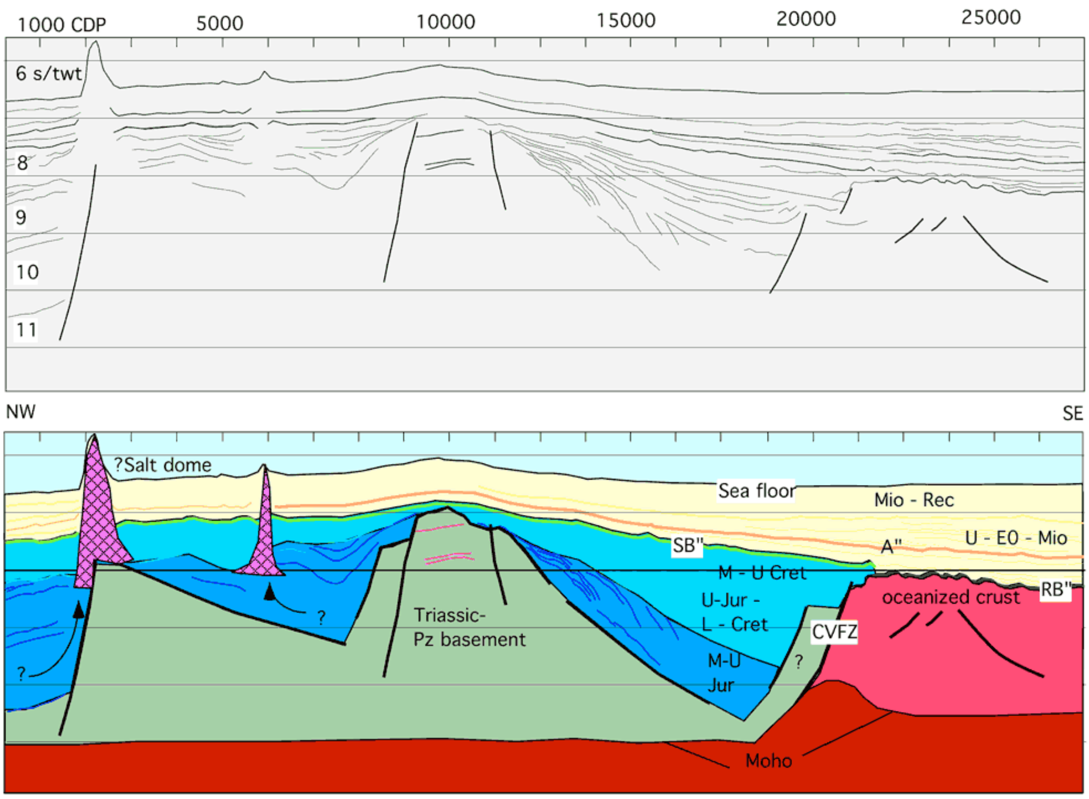

Fig. 6 Interpretation, line drawing and geology, this study, of Line 1293 (located on Fig.4) from Diebold & Driscoll (1999, Fig. 2). The interpretation suggests that Caribbean and Gulf of Mexico histories were similar. Triassic-Jurassic rifting accommodated continental – shallow marine sediments (including salt?) and volcanic flows. Drifting introduced open marine Jurassic – Cretaceous sediments. Late Cretaceous extension resulted in

shallow marine (subaerial?) flows over the plateau, forming smooth Horizon B" (SB") and serpentinization of adjacent mantle, forming rough Horizon B" (RB"). Horizon A" is the Middle Eocene contact between chert and unconsolidated sediments. CVFZ – Central Venezuelan Fault Zone.

Conclusions

1. The Caribbean plateau formed has a long history, from Triassic- Jurassic rift – drift, reactivating ancient basement lineaments, through Cretaceous extension to Cenozoic subsidence and deep-sea sedimentation.
2. It is underpinned by and surrounded by extended continental crust.
3. "Plateau" extrusion resulted from adiabatic decompression melting in an extensional setting between separating continents and above triple junctions.
4. Smooth B" is subaerial, rough B" is more or less coeval, serpentinized crust.
5. Thick crust in the Yucatán, Colombia and Grenada Basins has similar origins.
6. Oceanic crust might form as little as 20% of middle America (Fig. 7, James, 2007, in preparation).
7. The presence of continental crust below the whole of Central America and the fact that Chortis has not rotated mean that there never was a gap through which a migrating plate/plateau could pass. The Caribbean Plate did not come from the Pacific.
8. The Pacific "Caribbean Great Arc" never existed. Caribbean volcanic rocks formed *in-situ*.
9. The change from PIA to CA reflects input from continental crust that rims much of the plate.
10. HP/LT metamorphism resulted from compression related to transpression and nappe emplacement.
11. If the Caribbean plateau does involve continental crust, and if other oceanic large igneous provinces do as well, then accepted geochemical/isotopic discriminant signals of these provinces need re-thinking.

Tailpiece – some wider observations

This article makes much of N35E trending lineaments in Middle America. They are ancient basement structures. A new paper on Central America (James, 2007a) notes their possible control of fractures and the Cocos Ridge in the Pacific and even spreading rates at the East Pacific Rise.

Szatmari (1983) described the Pisco-Juruá Fault, a major, N40E trending Palaeozoic normal, lineament that crosses South America from the Guyana Basin on the Central Atlantic coast to Pisco on the Pacific coast, a distance of around 3,000 km (Fig. 8). The Nazca Ridge continues this trend into the Pacific, where Szatmari suggested that deep hydration serpentinization, density loss and uplift of ocean floor basalts occurred. Szatmari proposed that the Pisco-Juruá lineament was the Mesozoic continuation of the North Atlantic rift. Some 100 km of sinistral offset occurred at this time according to Szatmari (I suggest 350 km). On its route it intersects the E-W trending Amazon Fault that runs along the Amazon Rift (late Proterozoic-early Palaeozoic), separating the Guayanan and Brazilian shields. One hundred thousand km3 of Jurassic diabase intruded upper Palaeozoic evaporites in the eastern Amazon Basin, coeval with North Atlantic rifting. While South Atlantic met Central Atlantic in the Equatorial Atlantic only in the early-mid Cretaceous, something was afoot in the Jurassic.

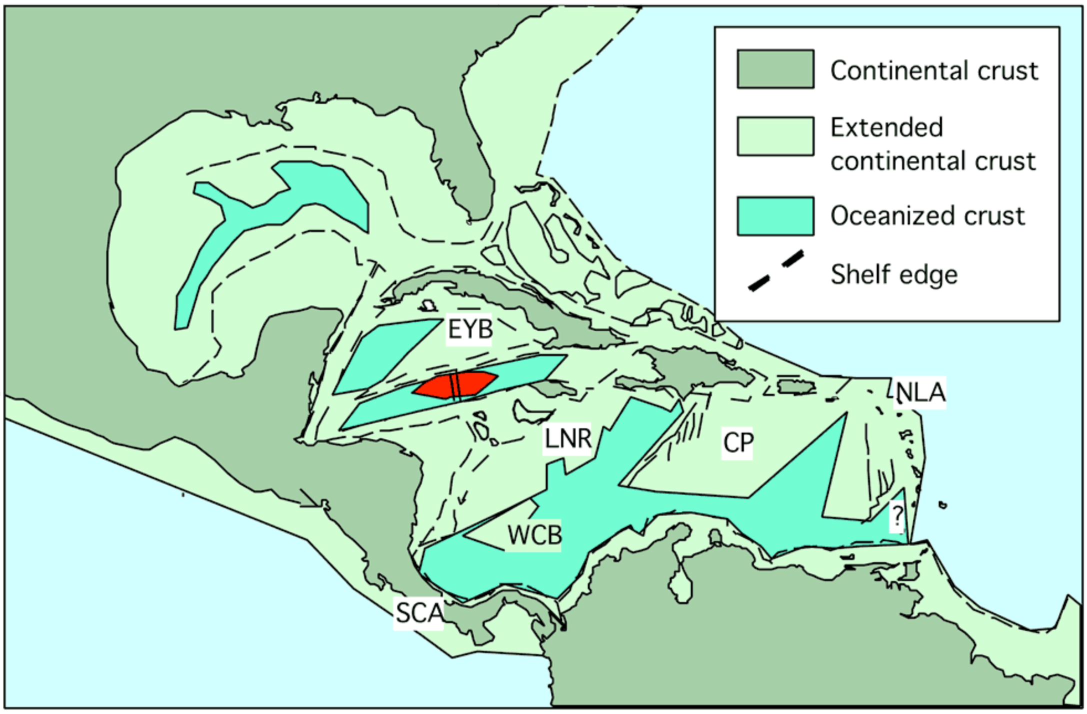

Figure 7 Middle America crustal types/distribution. This illustration differs dramatically from conventional wisdom. Continental blocks, indicated by crustal thickness (gravity, seismic), high silica rocks, dredge samples, beneath southern Central America (SCA) and the Greater Antilles - northern Lesser Antilles (NLR) are hidden beneath obducted volcanic arc/oceanic crust. The Lower Nicaragua Rise (LNR), eastern Yucatán Basin (EYB), Caribbean "Plateau" (CP) and west Colombia Basin (WCB) thick crustal areas are underpinned by highly extended continent. The "oceanized" crust also might involve extremely extended continent and serpenitized upper mantle. The red area in the Cayman Trough is Oligocene-Recent spreading crust. It might be the only true oceanic crust in the area.

Differential movement between northern and southern South America is recorded by diverging fractures in the south Atlantic east of the Amazon Basin (Fig. 8 and James, 2005b, 2006). Fairhead & Wilson (2005) illustrate this in their Figures 4D and 5. They also define (their Fig. 8) the African Kandi Fault and Trans-Brazilian Lineament - major, NE trending sinistral shears related to the Equatorial Atlantic (Fig. 8), parallel to the Pisco – Jurua F. and the Cocos and Nazca ridges. Their Figure 4B illustrates a major zone of diverging fractures east of the Caribbean (Vema Wedge of James *et al*., 1998a, b, c). These are interesting parallels between the Caribbean and the Amazon Basin.

Finally, the Vema Wedge – Caribbean region is a mirror-image of Figure 7 of Rocchi *et al*. (2005). Mid ocean ridge sinistral offset of 1,500 km occurs across the zone. Most of the offset occurred in the Late Jurassic – early Cretaceous (the width of Jurassic – Cretaceous ocean crust east of N America compared with S America shows this). The NE extensional trends emphasised earlier and shown in Figure. 4 fit perfectly with sinistral offset along fractures within the zone.

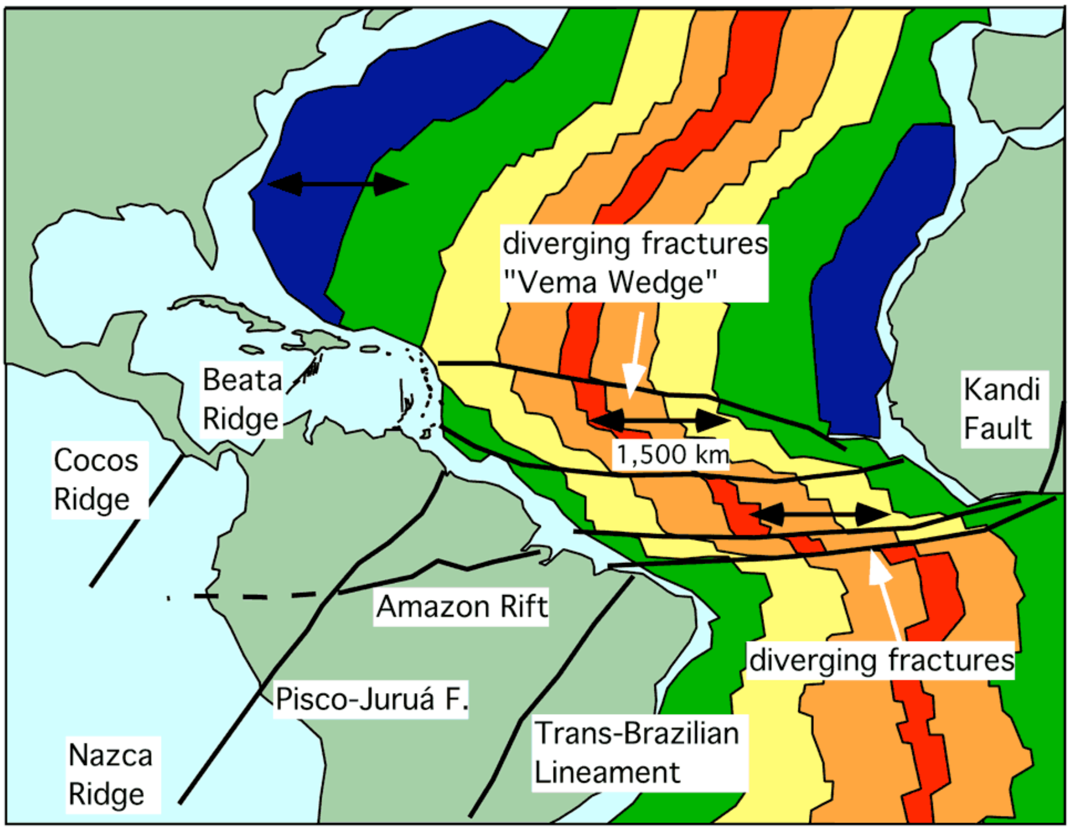

Fig. 8. The Caribbean and the Amazon Basin both lie west of diverging fractures and major (*ca*. 1,500 km) offset of the spreading ridge in the Atlantic. Both are crossed by major NE lineaments that extend into the Pacific as major ridges. Both experienced Jurassic igneous activity (spreading/intrusion).

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