**In situ** origin of the Caribbean: discussion of data

KEITH H. JAMES

Institute of Geography and Earth Sciences, Aberystwyth, Wales, UK and
Consultant Geologist, Plaza de la Cebada, 3, 09346 Covarrubias, Burgos, Spain
(e-mail: khj@aber.ac.uk)

Abstract: Compiled and synthesized geological data suggest that the Caribbean Plate consists of dispersed continental basement blocks, wedges of ?Triassic–Jurassic clastic rocks, Jurassic–Late Cretaceous carbonate rocks, volcanic arc rocks, widespread, probably subaerial basalts and serpentinized upper mantle. This points to an *in situ* origin of the Caribbean Plate as part of Middle America, continuing the geology of the eastern North America margin in a more extensional tectonic setting. Extension increases from the Gulf of Mexico through the Yucatán Basin to the Caribbean.

The Caribbean Plate was formerly seen to be an *in situ* part of Middle America. Stainforth (1969), for example, interpreted the area as the product of extension between North and South America, with much dispersed continental material. In 1966, Wilson, who had observed ice rafts from the air, suggested that the Caribbean and Scotia plates resembled tongues of lithosphere intruding between North and South America and South America and Antarctica. There are now numerous models for the area, admirably summarized by Morris *et al.* (1990) and Rueda-Gaxiola (2003). Most support the idea that the Caribbean Plate migrated from the Pacific.

Understanding of Caribbean evolution is complicated by:

1. Dispersal of geology over a large number of geographic elements (Fig. 1), ranging from the well-documented, onshore South and North America (thorough exploration for abundant hydrocarbons, but with new learnings still coming to light) to the less well known Central America and the discontinuous Caribbean islands. Large submarine extensions of Florida–Bahamas, Yucatán, Nicaragua, Panama, the Greater Antilles and northern South America are not known in detail. The Lower Nicaragua Rise and the Aves and Barbados ridges (Barbados island excepted) are poorly sampled. Young volcanic rocks cover large parts of Central America. Geological synthesis requires familiarity with literature ranging from local to regional focus and from academic to industrial (mainly hydrocarbon) interest. As always, the whole is greater than the sum of the parts.

2. Absence (unexplained) of oceanic spreading anomalies and fractures from the whole of Middle America, apart from the centre of the Cayman Trough.

3. Interpretation of data premised on an oceanic, Pacific origin of the Caribbean Plate.

This paper respects the call of Meyerhoff & Meyerhoff (1973) to honour data. It discusses data synthesized from more than 5000 articles. Together they point to an *in situ* origin of the Caribbean Plate by severe extension of continental crust and serpentinization of mantle, between separating North and South America. An accompanying paper (James 2009) presents an interpretation of *in situ* Caribbean Plate evolution and considers implications, predictions, outstanding questions and tests of the model. This volume also includes other interpretations, especially those of Giunta & Oliveri and Pindell & Kennan, which should be compared and contrasted with these papers.

**Regional setting**

The Caribbean Plate (Fig. 1), roughly 3000 km east–west and 800 km north–south (2.64 million km²), forms part of Middle America, between North and South America. Middle America comprises four marine areas, the Gulf of Mexico, the Yucatán Basin, the Cayman Trough and the Caribbean Sea, dispersed between NW sinistrally offset North and South America. The Gulf of Mexico is intracontinental, surrounded by southern North America and the Florida and Campeche platforms. Cuba, with basement and Mesozoic carbonate cover intimately related to the Florida–Bahamas platform, bounds the Yucatán Basin to the north, while the Cayman Ridge separates the basin from the Cayman Trough. South of the Trough lies the Nicaragua Rise, the marine extension of the Chortís Block – the only place where continental

DOI: 10.1144/SP328.3 0305-8719/09/$15.00 © The Geological Society of London 2009.*
crust is currently recognized on the Caribbean Plate. Together they form about a third of the plate. The Chorotega and Chocó blocks link Chortís to South America. The Greater Antillean islands of Hispaniola, Puerto Rico and the northern Virgin Islands lie on the northern Caribbean Plate boundary, diminishing in size from west to east. A series of small islands, Aruba–Blanquilla, Margarita, Los Frailes and Los Testigos, lie offshore from northern South America, along the southern plate boundary. The east-convex volcanic arc of the active Lesser Antilles bounds the Caribbean Plate to the east. Another active volcanic arc runs along the western margin of Central America.

Water depths range up to 9 km. The greatest depths lie in the Puerto Rico and Muertos troughs, supposedly subduction trenches north and south of Puerto Rico, and along the margins of the Cayman Trough. Depths in the Gulf of Mexico range to more than 4000 m, in the Yucatán Basin to more than 5000 m – a trend that points towards increasing extension. Stratigraphy shows that parts of the Caribbean and the Gulf of Mexico have suffered severe subsidence. Basement blocks in the deep Gulf subsided in the Late Cretaceous–Early Cenozoic (Roberts et al. 2005). The Cayman Ridge was a shallow carbonate bank until subsidence began in the Miocene (Perfit & Heezen 1978). The Nicaraguan plateau sank to its present depth by the Pliocene. Late Cretaceous–Paleocene granodiorites that may have been exposed in the Late Paleocene–Early Eocene are now at 4000 m on the Cayman Ridge and Eocene and Oligocene shallow water carbonates occur at 3000 m of both sides of the Cayman Trench. The Aves and Beata Ridges have similar subsidence histories (Perfit & Heezen 1978). Cretaceous–Cenozoic intertidal–subtidal limestones lie as deep as 6500 m on the south wall of the Puerto Rico Trench (Schneidermann et al. 1972). Turonian basalts of Caribbean seismic Horizon B" that probably formed subaerially now lie below thousands of metres of water.

The Caribbean Plate interacts with the western Atlantic Plate, which carries North and South America, to the north, south and east and with the
Nazca and Cocos plates to the west. Atlantic elements are moving westward relative to the Caribbean Plate. Broad zones (> 250 km wide) of east–west sinistral and dextral strike–slip on the northern and southern Caribbean Plate boundaries and subduction below the Lesser Antilles volcanic arc accommodate these movements. The Pacific Cocos Plate converges NE relative to Central America, where subduction and volcanism also occur. The east–west Nazca/Caribbean boundary is strike–slip and little volcanic activity occurs in Panamá. However, spreading along the east–west Carnegie Ridge provides a northerly component of convergence that drives NW South America and the Panamá block northward. Ahead of these lie the north-verging Southern Caribbean Deformed Belt and the Panamá Fold Belt, respectively. The Beata Ridge separates the Colombian Basin and Venezuelan Basins (contiguous south of the Ridge) while the Aves Ridge separates the Venezuelan and Grenada basins.

Prevailing understanding

Consensus is that ocean spreading in Middle America first occurred in the Jurassic (Gulf of Mexico–Callovian age, peripheral data from the NE Gulf of Mexico; Marton & Buffler 1999, or Toarcian–Aalenian, palaeogeographic reconstruction; Rueda-Gaxiola 2003). This produced ‘Proto-Caribbean’ oceanic crust. Spreading occurred again in the Palaeogene when the Yucatán and Grenada basins and the Cayman Trough formed (heat-flow and depth-to-basement estimates; Bouysse 1988; Rosencrantz et al. 1988).

The Caribbean Plate formed in the Pacific during the Jurassic and thickened in the Cretaceous above a mantle plume/hotspot or above a ‘slab gap’ in subducting ‘Proto-Caribbean’ crust. While migrating eastwards the resulting plateau collided with a linear volcanic arc at the eastern, east-facing subduction margin of the plate, blocking and reversing subduction polarity. On entering between North and South America, the leading edge arc collided with Yucatán and Colombia, subducting pieces of continent to great depths (70–80 km), where they suffered HP/LT metamorphism. Volcanic activity ceased during Eocene to Oligocene oblique and diachronous arc collision with the Florida–Bahamas platform and northern South America. Slab rollback, in two different directions, opened the Yucatán Basin south of the Cuban segment of the arc. The subducted and metamorphosed fragments of Yucatán and Colombia resurfaced in Cuba and along northern Venezuela. Cuba and the Yucatán Basin detached from the Caribbean Plate and joined North America as the Caribbean Plate boundary jumped south to the Cayman Trough. Spreading in the trough accompanied some 1100 km of Caribbean Plate eastward movement. The remaining plate continued eastwards, generating northern uplifts/foreland basins along northern South America and fragmenting and dispersing the Greater Antilles. Cenozoic Grenada Basin inter- or back-arc spreading separated the Aves Ridge from the Lesser Antilles, the active remains of the arc (Bouysse 1988).

This history invokes rotation of the large continental blocks of Yucatán (up to 135° counter clockwise or 100° clockwise) from the Gulf of Mexico, and Chortís (up to 180 counter clockwise or 80° clockwise; e.g. Freeland & Dietz 1972; Pindell et al. 2001; Rogers et al. 2007a). The latter followed the Caribbean Plate into place and accreted to its north-western corner.

According to these models the Caribbean Plate comprises oceanic crust surrounded by volcanic arc rocks, with just one continental component, Chortís. Other models also see the Caribbean Plate as largely oceanic, but formed between the Americas (Meschede 1998; Giunta & Oliveri 2009). Iturralde-Vinent & García-Casco (2007) recognize the element ‘Caribeana’, ‘a thick sedimentary prism represented by a submarine promontory extended eastward into the Proto-Caribbean realm from the Maya Block, somehow as a southern counterpart of the Bahamas’.

Absence of oceanic magnetic anomalies

Middle America carries no identified ocean fractures or magnetic anomalies apart from the centre of the Cayman Trough, a large pull-apart within the sinistral, northern Caribbean Plate boundary. Here, there are two main sets of magnetic anomalies. Central, slow-spreading anomalies record 300 km of extension since the Early Miocene. More distal anomalies vary greatly in shape and have low amplitudes. They are ‘hardly recognizable’; identification is problematic and based on models (Leroy et al. 2000).

On the Caribbean Plate itself, Donnelly (1973a) identified linear magnetic anomalies over thick crust (the Caribbean ‘oceanic plateau’) in the western Venezuela Basin where Edgar et al. (1973) described a corresponding structural grain of buried scarps and seismic isopachs. Diebold et al. (1981) combined these in the same map. Ghosh et al. (1984) attributed the magnetic anomalies to Early Cretaceous spreading but Donnelly (1989) and Diebold et al. (1999) emphasized that they correspond to structure. Age estimations based upon supposed spreading magnetic anomalies have also been proposed for the Colombian
Basin (Late Cretaceous, Christofferson 1976), the western Yucatán Basin (Maastrichtian–Paleocene or Late Paleocene–Middle Eocene, Rosencrantz 1990) and the Grenada Basin (Early Cenozoic, Bird et al. 1999). Again, these are areas of thick crust and magnetic grain probably reflects structure rather than ocean spreading.

**Tectonic setting**

Several interpretations of magnetic anomalies and fracture patterns in the Atlantic show NW–SE separation of North and South America until the Eocene, followed by 250–700 km of NE–SW or north–south convergence (Pindell & Barrett 1990, Pindell et al. 1998, 2006; Müller et al. 1999). They imply significant and abrupt changes in the drift behaviour of North and/or South America. However, there is no indication of convergence where the plates meet in the Atlantic at 15°N, east of the Lesser Antilles, and post Middle Eocene subsidence, with Middle Eocene carbonates now lying kilometres deep, argues for continued extension.

Ball et al. (1969) pointed out that, since the west-convex spreading ridge off NW Africa is moving away from the continent, it has to be increasing in length. Satellite-derived bathymetry details an east–west zone of north–south extension across the Atlantic between West Africa and the Caribbean (Figs 2 & 3, the Vema Wedge; James et al. 1998; see also Funnell & Smith 1968). The wedge began to form in the Albian when South America commenced westward drift. North America was drifting N60°W at that time, and gradually assumed N10°W movement (James 2003a, fig. 4; James 2003b, figs 3a & b). Fractures within the wedge show that the Central Atlantic Ridge continues to extend over Caribbean latitudes.

---

**Fig. 2.** The Caribbean lies west of a zone of diverging ocean fractures (the Vema Wedge), just as the Amazon Rift lies west of diverging fractures further south. These, and highlighted ocean fractures and intracontinental faults, show continued (Cretaceous–Cenozoic) divergence between North and South Americas, focused on Caribbean latitudes (James 2003a, fig. 4). This figure also highlights regional NE-trending faults crossing continents and extending along ocean ridges. In North America, displacements revealed by offsets (of yellow lines) in the Appalachian–Ouachita Palaeozoic suture as it enters the highly extended Gulf of Mexico–Caribbean region can be used to restore Middle America, the Caribbean included, which this map suggests is extended continental crust. This study after Szatmari (1983), Müller et al. (1997), Fairhead & Wilson (2005), Davison (2005).
Models that derive the Caribbean Plate from the Pacific propose that it overrode ‘Proto-Caribbean’ crust between North and South America. Tectonic data are quoted in support. Tomography indicates an anomaly descending to 600 km below the southern Lesser Antilles (Van der Hilst 1990, who qualified his results as preliminary, tentative and a working hypothesis). Since the Wadati–Benioff zone here descends at 60° (vertical south of Grenada), only around 700 km of crust would have been subducted below some 340 km of eastern Caribbean crust. At the present rate of relative eastward Caribbean movement of 2 cm/annum that corresponds to the 35 Ma Oligocene commencement of Central Cayman Trough opening and the approximate 300 km of subsequent strike-slip along northern and southern plate boundaries. The data support neither tomographic suggestion of >1500 km of subducted crust below the Caribbean nor overriding of more than 2500 km of ‘Proto-Caribbean’ crust by a migrating plate (Pindell et al. 2006, fig. 6).

If spreading symmetry is preserved in Caribbean latitudes, absence of Jurassic crust along West Africa south of the Guinea Fault indicates little if any Jurassic crust below the Caribbean. However, some do see Jurassic crust SE of a boundary that passes NW below St Vincent (Maury et al. 1990).

Magnetic anomaly data in the equatorial Atlantic remain poorly known (a blank area on the magnetic anomaly map of Cande et al. 1989), especially in the area of the Vema Wedge. Riffing transition in the Central Atlantic is poorly constrained (limited/contested magnetic data, lack of drilling...
calibration; Withjack & Schlische 2005). Published flow paths for North and South America are based upon fracture and magnetic data from the central North and Southern Atlantic regions (e.g. Pindell 1991; Pindell et al. 2006). According to Eagles (2007), models of relative motion between South America and Africa fail to recognize large offsets within South America and significantly misrepresent the azimuth of Lower Cretaceous seafloor spreading in the South Atlantic.

An alternative interpretation of fracture orientations and published magnetic anomalies shows continued but declining separation of North and South America (James 2002, 2003b). The separation locus was focused over Caribbean and Vema Wedge latitudes, where considerable but diminishing extension occurred. Volcanism along northern and southern plate boundaries in the Jurassic–Cretaceous and its decline in the Early Cenozoic correlate with this history.

**Regional tectonic fabric**

Middle America manifests a regional tectonic pattern of N60°W, N35°E and N60°E trends (Fig. 3). They occur on Caribbean Plate margins and interior and on its continental neighbours.

N60°W trending lineaments of the western Atlantic and the Middle American Trench (Fig. 3) bracket Middle America. Major faults (‘mega-lineaments’) continue the trend into southern North America where they offset the NE-trending Palaeozoic Appalachian suture of eastern North America (Harry et al. 2003, fig. 1). The trend appears briefly on the Yucatán Peninsula as the Ticul F. Projected NW this perhaps continues as the Río Bravo Fault Zone of SW Texas (Flötte et al. 2008). Thick crustal blocks in the Colombian Basin follow this trend (Bowland 1993). Arches in Venezuela (El Baìl, Arauca, Mérida and Vaupés) and the Marañón Basin of Colombia continue the NW trend into NW South America. They parallel Proterozoic structures of the craton (Krüger et al. 2002, fig. 11).

N60°E trending faults are seen as the Hess Escarpment, basement structure of the eastern Yucatán Basin, the La Trocha Fault, the Swan–Eastern Motagua Fault, the NW Campeche Escarpment and the east central Gulf of Mexico. The eastern side of the Espino Graben, eastern Venezuela and parts of the Takutu Graben, magnetic lineations in the Grenada and Venezuela Basin, also exhibit this trend.

The N35°E structural trends are followed by many elements in Middle America. They appear as normal faults in the northwestern Gulf of Mexico and the Tenoachtitan Shear Zone of Mexico. Magnetic trends and the structural grain of the southeastern Gulf of Mexico link the Catoche Tongue, a Jurassic (?Triassic) graben, of the Campeche Platform to Florida, where drilling encountered extensional rhyolites and basalts of a possible Triassic rift (Gough 1967; Heatherington & Mueller 1991; Marton & Buffler 1999; Phair & Buffler 1983; Shaub 1983). Basement structure of the deep Gulf of Mexico exhibits the trend (Roberts et al. 2005). Structure contours of salt in the Isthmian Salt Basin trend NE towards the NE-oriented Comalcalco and Macuspana Basins of the SW Gulf of Mexico (Contreras & Castiñón 1968).

The Maya Mountains of southern Yucatán, the basement structure of the western Yucatán Basin, fault blocks at the distal ends of the Cayman Trough and faulting across Grand Cayman Island manifest the same trend, as does the western margin of the Beata Ridge (Bateson 1972; Donnelly 1973b; Edgar et al. 1973; Case & Holcombe 1980; Holcombe et al. 1990; Leroy et al. 1996; Bain & Hamilton 1999; Diebold et al. 1999; Andreani et al. 2008). The trend crosses Jamaica, Hispaniola, Puerto Rico, the Aklins and Inagua-Caicos islands of the Bahamas, Barbados and La Désirade and follows the Grenada–Mustique volcanic ridge (Trechmann 1937; Westercamp et al. 1985, fig. 1).

The N35°E and N60°E trends often combine to define features such as the eastern margins of the Maya and Chortís Blocks (best illustrated by the Exxon World Geological Map) and the Espino and Takuto grabens in northern South America.

The regional integrity of these structures in Middle America indicates a tectonic fabric and history shared with its continental neighbours. It does not support rotation of major blocks such as Maya and Chortís (see below).

**Structural periodicity along northern and southern margins of the Caribbean Plate**

Along northern South America there is a large-scale (c. 350 km), periodic repetition of extensional basins (see numbers on Fig. 1): (1) Lower Magdalena Valley–Río Magdalena mouth; (2) Maracaibo Basin–Gulf of Venezuela; (3) Guaramenen Basin (overthrust and hidden but revealed by seismic and drilling)—Golfo Triste; (4) El Hatillo–Cariaco; and (5) Gulf of Paria–Carupano. The periodicity is repeated at the same scale along the Greater Antilles from west to east: (6) Windward Passage–Gonave Basin; (7) Asua Basin; (8) Puerto Rico–Hispaniola Mona Passage; (9) Anegada Passage. It appears also in Cuba, from west to east: (10) Pinar fault–Los Palacios Basin; (11) Llabre Lineament; (12) La Trocha Fault–Central Basin; (13) Camagüey Lineament–Vertientes.
Origin of tectonic fabric

Rifting progressed southward in North America and Europe/North Africa in the Early Triassic and affected Middle America by the Late Triassic (Ager 1986; Davison 2005). At 200 ± 4 Ma the Central Atlantic Magmatic Province (CAMP) formed, heralding Pliensbachian–Toarcian (190–180 Ma) Pangaean break-up (Marzoli et al. 1999; McHone 2002, fig. 1 or http://www.mantle-plumes.org/CAMP.html, fig. 2). Large volumes of tholeiitic magma intruded Triassic rocks as sills and later extruded as continental flood basalt lavas (Marzoli et al. 1999; McHone 2008). The CAMP event extended along eastern North America/western Africa and as far south as northern Brazil (Mohriak et al. 2008), but its focus on Middle American latitudes indicates greatest extension there. That this remained the case until the Early Cenozoic.

Rifting followed Caledonian/Hercynian tectonic fabric in North America and West Africa (Davison 2005; Tommasi & Vauchez 2001, fig. 1). Late Triassic–Early Jurassic rifts accommodated 2000 m or more of non-marine beds in NE-trending basins between continental and thick transitional crust in the Gulf of Mexico and along the Eastern Continental Margin of Mexico (Antoine & Bryant 1969; Horbury et al. 2003).

The Central Atlantic began to open in the Jurassic, as North America drifted NW from Gondwana. Rift/drift transition commenced in the south in the Late Triassic and progressed northwards to the NE by the Early Jurassic (Withjack & Schlische 2005). Opening of the South Atlantic began with Early Cretaceous rifting in the south, propagating northwards so that westward drift of South America at Caribbean latitudes occurred around 100 Ma (Albian; Eagles 2007). Consequently, Jurassic crust is present in the Central Atlantic, but not in the Equatorial Atlantic, and Central Atlantic Cretaceous crust is wider (Fig. 2). This map (Fig. 2) is simplified: ridge jumps occurred in the Jurassic along eastern North America, stranding the earliest crust instead of sharing it with Africa (Davison 2005; Bird et al. 2008).

Fractures in the western Atlantic show that the drift path of North America from South America at this time was N60°W (Figs 2–4). Regional N60°E trends fit extensional strain in this sinistral offset. East–west trends, such as the northern Caribbean Plate boundary, are synthetic to the system (James 2009, fig. 2). The N35°E grain reflects Palaeozoic sutures reactivated during

![Fig. 4. Continent margin–Mid Atlantic Ridge distance is c. 1800 km greater in the Central Atlantic than in the Equatorial Atlantic (broken white line reproduces the solid white line; red line indicates additional distance). The difference relates to Jurassic crust, not present in the Equatorial Atlantic, and wider Early Cretaceous crust. The distance (a) equates to the vector sum of offsets between Maya and Chortis (b, early Cayman offset), and Chortis (Hess Escarpment)–South America (c). The stress–strain ellipse indicates that N35°E and N60°E faults were dextral antithetic faults and extensional strain generated by sinistral slip along N60°W fractures.](http://www.mantle-plumes.org/CAMP.html)
Triassic–Jurassic rifting and Jurassic–Cretaceous drifting as dextral and then, normal faults. Cenozoic convergence of the Cocos Plate with the western Caribbean reactivated the trend as sinistral faults (James 2007a).

Rotation of Maya and Chortíś, origin of the ‘Motagua Orocline’

Most plate reconstructions of Middle America rotate Maya and Chortíś by as 80° or more anticlockwise from the Gulf of Mexico and SW Mexico respectively (e.g. Ross & Scotese 1988; Pindell et al. 2005). Others rotate both blocks from the Gulf (Freeland & Dietz 1972).

Restoration of Chortíś against SW Mexico is denied by geology. Two features of the Xolapa Complex of southern Mexico – southward thickening Jurassic–Cretaceous sedimentary rocks and southward increase in Early Cretaceous (c. 132 Ma) HT/LP metamorphism – are not seen in Chortíś (Ortega-Gutiérrez & Elias-Herrera 2003; Keppie & Morán-Zenteno 2005). Instead the non-metamorphosed El Plan Fm and Valle de Angeles Gp, record the Cretaceous (Horne et al. 1990). None of the north–south terrane boundaries of southern Mexico, truncated at the coast, is seen in the Chortíś Block.

Jurassic sections on Maya and Chortíś develop eastwards from continental to marginal to marine facies and the crust thins across the Río Hondo and Guayape faults (Mills et al. 1967; López-Ramos 1975; Mascle et al. 1990; Rogers & Mann 2007). These N35°E trending Jurassic faults remain parallel to the regional trend of Triassic–Jurassic rifts and show that the blocks have not rotated relative to their large continental neighbours. The N60°W Tícut Fault of Maya, parallel to bounding fractures in Middle America, provides a second, fixing coordinate for this block. An unnamed N60°E fault crossing Maya (Mascle et al. 1990, map) and the parallel NW Campeche Escarpment provide a third. When the Caribbean faulted margins of Maya (Yucatán Basin margin; Baie 1970) and Chortíś (Providencia–San Andrés trough; Holcombe et al. 1990) are aligned, the Río Hondo and Guayape faults also line up, suggesting a formerly continuous, major Jurassic graben (James 2007a). This restoration indicates c. 900 km of sinistral offset along the Motagua Fault Zone (MFZ).

Maya and Chortíś meet along the MFZ, bounded north and south by the Polochic and Jocotán faults. Ortega-Gutiérrez et al. (2007) emphasize that this is an important zone of fault-bounded, often rootless, crystalline Jurassic–Early Cretaceous terranes and Palaeozoic rocks. The Jurassic cover common on Chortíś and Maya is absent. The Maastrichtian El Tambor Gp of the Motagua Valley contains rocks similar to those dredged from walls of the Cayman Trough (and denies Cenozoic trough opening). There are large masses (up to 80 km long) of serpentinites, wacke, phyllites and schists, and Valanginian–Aptian and Cenomanian fossils occur in basalt interbeds (Donnelly et al. 1990). Serpentinites mica dates (Ar–Ar) are 77–65 Ma (Campanian–Maastrichtian) to the north and 125–113 Ma (Barremian–Aptian) to the south of the Motagua F (Harlow et al. 2004).

The MFZ curves eastwards from NW to NE. Mountains of southern Maya also follow this trend, forming a ‘Motagua orocline’. Major sinistral movement along NE trending faults such as the Guayape, Río Hondo and eastern boundary faults of Maya began in the Palaeogene, causing inversion and oroclinal bending of NW trending Jurassic and Cretaceous depocentres (Rogers et al. 2007a; James 2007a). Sinistral movement transforms into contraction, curving west in the south and east in the north (James 2007a, figs 11 & 12). The strike–slip/orocline systems are ‘closed’ – deformation does not affect areas further north or south. Northward convex western Cuba mirrors the southward convex Motagua zone. Both restore to linear features when some 350 km of sinistral movement is removed. The oroclines and faults affect Middle Eocene rocks. Movement began in the Late Eocene, coeval with the beginning of transpressional uplift along the Eastern Cordillera–Mérida Andes of NW South America, where similar strike–slip transformation to compression is common (James 2000, figs 4 & 7). Movement along these systems continues today.

Displacement along northern and southern plate boundaries; two-phase opening of the Cayman Trough

Faster westward movement of the Atlantic Plate relative to the Caribbean results today in sinistral and dextral strike–slip along the northern and southern plate boundaries at around 2 cm/year (GPS data, DeMets et al. 2000; Weber et al. 2001). Estimates of maximum offset along the major faults of northern South America sum to 565 km (James 2000). Measured offset along faults of the Motagua fault zone (Motagua, Polochic, Jocotán–Chamelecon) sum to a maximum of 655 km (Gordon & Ave Lallemant 1995). There is no measured fault record of the >2500 km translation required by Pacific models of a migrating Caribbean Plate.

Northern plate boundary offset is generally assumed to be calibrated by the 1200 km long Cayman Trough. This is pivotal to Pacific models of Caribbean Plate history: ‘If smaller estimates of
offset are assumed, an inter-American formation of the Caribbean Plate is required’ (Pindell & Barrett 1990).

The Cayman Trough is a pull-apart within the sinistral, northern Caribbean Plate boundary. The only recorded Middle American spreading centre, with Early Miocene to Recent, north–south ridges and magnetic anomalies, lies in its central 300 km (Leroy et al. 2000). Gradual increase in apparent crustal thickness and shallowing of basement indicate that the (undated) distal parts of Cayman Trough are underlain serpentinized upper mantle/highly attenuated crust (Ten Brink et al. 2003). ‘Ocean’/continent transition is seen on seismic data from the distal eastern part of the trough (Leroy et al. 1996), where NE structural trends indicate Jurassic or reworked Jurassic structures.

North–south trending extension parallels grabens in Chortís and offsets in the Hess Escarpment. It fits the extensional strain expected of major movement along N35°E trending faults, sinistrally active since the Late Eocene, that dominate the western Caribbean (James 2007a). Coeval pull-apart extension dispersing the Greater Antilles and the Aruba-Blanquilla islands along the northern and southern strike–slip plate boundaries also sums to around 300 km. The N60°E trend of the eastern part of the Motagua Fault and Swan Fault as far as Swan Island (Fig. 3; Pinet 1971, fig. 2) parallels the extensional strain expected in regional N60°W sinistral slip (James 2009, fig. 2).

Literature commonly quotes a 45 Ma commencement of Cayman opening (depth-to-basement and heat flow studies, Rosencrantz et al. 1988). However, the continent margin–Mid Atlantic Ridge distance is c. 1800 km greater in the Central Atlantic than in the Equatorial Atlantic. The difference relates to presence of Jurassic crust, absent from the Equatorial Atlantic, and wider Cretaceous crust in the Central Atlantic, north of the Caribbean northern boundary (Fig. 2). The difference is matched by the vector sum of offsets between the Maya and Chortís Blocks and of the Hess Escarpment from the Mérida Andes trend (Fig. 4). These offsets respectfully fit the combined extension/synthetic and extension within N60°W sinistral offset of North from South America.

These data indicate that c. 900 km of Cayman Trough offset occurred during Late Jurassic–Early Cretaceous (James 2006). Lack of disturbance in Upper Cretaceous–Recent sediments in the Gulf of Tehuantepec, west of the Motagua zone (Sanchez-Barreda 1981) supports this early offset, which relates only to the northern plate boundary. The Miocene–Recent 300 km central Cayman spreading and strike–slip along the northern and southern Caribbean boundaries carries total Cayman offset to 1200 km. East–west sinistral faulting and folding and thrusting in southern Maya offset absorb the later offset (Guzman-Speziale & Meneses-Rocha 2000; Guzman-Speziale 2008).

The Cayman Trough boundary continues onshore in Guatemala as the Motagua Fault Zone, regarded as a Late Cretaceous suture between Maya and Chortís (Burke et al. 1984; Donnelly et al. 1990, Draper 1993). Here, two major fault zones are separated by a horst of Palaeozoic and older metamorphic and granitic rocks. The northern zone, Polochic, contains areas of cataclastic rocks overlain by undeformed Permian and Mesozoic sediments. Thus the structural trend was active in pre-Permian time (Bonis 1969). The Sierra de Santa Cruz of eastern Guatemala consists of serpentinized peridotite, gabbro, sheeted dolerite, pillow basalt and minor pelagic sediment and abundant metamorphosed hemipelagic sediment with overlying volcanic wackes (Donnelly 1985). It was emplaced northwards during Late Cretaceous ‘suturing’ of Chortís and Maya. However, a well on Turnefde Cay, offshore Belize, drilled maﬁc volcanic rock overlain by ﬂysch, with the same lithological section as the Sierra de Santa Cruz. Since the two sections lie on opposite sides of the Late Palaeozoic Maya Mountains an alternative to the suture explanation is needed.

Global analogues

Since the Caribbean Plate lacks oceanic fractures and spreading magnetic anomalies, I turn to the Scotia and Banda plates for highly relevant information (James 2005a, fig. 10). Both carry spreading ridges and dated magnetic anomalies and are known to have formed in place by eastward-migrating back-arc spreading (Honthaas et al. 1998; Barker 2001).

The plates lie between sinistrally offset, major continental blocks to the north and south. Each is around 3000 km long and 700–800 km wide. Each has a curved volcanic arc in the east. North-west trending volcanic arcs follow continental Sumatra/Java of Banda and Chortís of the Caribbean in the west. The Scotia Plate is bounded in the west by the shallow (700 m), NW-trending Shackleton Fracture Zone, built of continental slivers (Livermore et al. 2004) and there are active volcanoes in the Drake Passage (Dalziel 1972). Fractures in the ocean east and west of the plates show divergent spreading directions – the plates are located in zones of extension.

Syn-subduction, backarc crust lies behind east-facing western Paciﬁc arcs, while much older crust occurs in the lower plates (Gazanti et al. 2007). Jurassic or Cretaceous oceanic crust is being subducted below the Paciﬁc arcs, the Lesser Antilles and the Scotia Arc. Palaeozoic–Mesozoic continental crust subducts below the Banda Arc (Charlton 2004).
The Scotia Plate formed by backarc extension that distributed continental blocks originally a continuous continental connection between South America and Antarctica (Barker 2001, fig. 3). Magnetic anomalies indicate that spreading was faster than the motion of the South American and Antarctic plates and occurred in different directions, beginning in the south in the Protector and Dove basins (Eagles et al. 2005; Ghiglione et al. 2008). It then expanded the plate eastward above Atlantic crust roll-back.

Similarities between the Caribbean and Scotia plates are remarkable, not only in the general tectonic framework but also in Mesozoic volcanism, orogenic deformation and batholith emplacement (Dalziel 1972). East–west strike–slip zones, dextral in the north and sinistral in the south bound Scotia and the Caribbean. The West and East Scotia ridges coincide with the Caribbean Beata and Aves ridges. Gravity lows along the northern margins connect with lows along the trenches east of the South Sandwich and Lesser Antilles volcanic arcs. The North Scotia Ridge has transgressed northwards over oceanic crust; the Puerto Rico–Virgin Islands segment of the Greater Antilles thrusts northwards over Atlantic oceanic crust. In both the South Sandwich and the Lesser Antilles arcs older oceanic crust is being subducted in the north and suffers an east–west tear.

The North and South Scotia ridges carry continental rocks that correlate with South America and Antarctica. Parts of the Scotia Sea more elevated than normal ocean floor may be continental crust thinned by extension (Barker 2001). The Arctic Peninsula contains Palaeozoic basement and evidence of subduction since the Early Mesozoic or earlier, similar to NW South America (Colombia–Ecuador).

The Neogene Banda Sea also opened in an extensional setting (Hall 1997). Dredged sedimentary and metamorphic rocks show that internal ridges are continental slivers from New Guinea. Oceanic crust forms only a small part of the Flores Sea.

Implications of these plate similarities are:

1. The Caribbean Plate formed in place by north–south extension in the centre, NW–SE extension in the west (Beata Ridge = West Scotia Ridge?) and then east–west back-arc spreading in the east (Aves Ridge = East Scotia Ridge?).
2. The eastern Greater Antilles have migrated northwards over Atlantic oceanic crust.
3. The Lesser Antilles are migrating eastwards over Atlantic crust.
4. The Caribbean Plate is rimmed by continental fragments and carries internal, extended continental crust.

**Continental crust in the Caribbean**

Is there continental crust on the Caribbean Plate? Several, independent lines of data suggest there is.

**Crustal thicknesses**

Crustal thicknesses (Fig. 5) decline progressively from continental (45–50 km) on cratonal North and South America to anomalously thin (c. 3 km) in the SE Venezuela Basin, the centre of the Cayman Trough and the deep Gulf of Mexico. Thicknesses of around 20–30 km characterize areas of known extended continental crust such as the Yucatán Peninsula, Cuba, the Chortís Block and the proximal Bahamas Plateau. Similar thicknesses are common on Caribbean Plate margins. Relatively thick crust (8–20 km) occurs in the Colombian, Venezuelan and Yucatán and the Tobago Trough. The data suggest increasing extension towards the deep Gulf of Mexico and the Caribbean area.

**Gravity data**

The gravity map of Westbrook (1990) shows steep gradient positive anomalies over the active Caribbean Plate margins of the Greater, Lesser and Leeward Antilles–Paraguauná–Guajira–Santa Marta, along the eastern margin of the Maya Block, the SW and NE margins of the Cayman Ridge, over northern Panamá and part of western Central America. On the Caribbean Plate interior positive anomalies occur over the Aves Ridge, the western/southern parts of the Beata Ridge and the Lower Nicaragua Rise. Positive anomalies also occur over the central part of the Cayman Trough. These anomalies correspond to uplifted ‘oceanic’ and volcanic arc rocks, major fault margins and areas of high extension.

Steep gradient negative anomalies characterize the trenches of the Lesser Antilles, the Puerto Rico and Muertos troughs north and south of Puerto Rico, Central America and foreland basins and inverted rifts of northern South America. Elsewhere, rather featureless, neutral gravity anomalies characterize continental South America, the Maya and Chortís Blocks, the Upper Nicaragua Rise and the interiors of the Colombian, Grenada, Venezuelan and Yucatán basins.

Gravity data witness the dynamic nature of Caribbean Plate boundaries (data in Bowin 1976). The world’s largest negative sea-level Bouguer anomaly (−200 mgal) corresponds to the Eastern Venezuela Maturín Basin, which lies south of the southward-moving Interior Ranges (a root whose mountain is on the way). A large negative anomaly (−150 mgal) in the southeastern Maracaibo Basin...
is half overthrust by the Mérida Andes (a root receiving its mountain). A large positive anomaly (+210 mgal) characterizes the 5800 m high Sierra Nevada de Santa Marta, NW Colombia (a mountain without a root). Positive anomalies (up to +222 mgal in the Blue Mountains and over the Cretaceous central inlier) show that most of Jamaica is under-compensated. Cayman Trough gravity lows lie on the northern margin in the east (extension of the Puerto Rico Trough) and on the southern margin in the west, close to the active Oriente and Swan strike-slip faults.

There is little indication of vigorous igneous/tectonic activity in the basins of Middle America, no indication of large igneous provinces and no indication of shallow Moho. Maximum Bouguer anomaly values are lower over the Caribbean than over the neighbouring Atlantic. The Caribbean Sea is not as deep and the combined mass of the crust and the uppermost mantle is less, indicating greater depths to mantle and/or lower densities (Bowin 1976). These data are consistent with the possibility that the area is built of extended continental crust.

**Northern Central America—Chortís**

Chortís is the only recognized continental part of the Caribbean Plate (Schuchert 1935; Dengo 1975). Grenvillian and Palaeozoic crust along with thin Jurassic red beds and Cretaceous carbonates and clastic rocks crop out in the north (Manton 1996). Jurassic–Upper Cretaceous rocks occur in the east. Jurassic red beds thicken from tens of metres to more than 2000 m and crustal thicknesses decrease SE of N35°E-trending faults on Chortís (Maya also), recording continental margin extension.

Chortís has been derived from various locations in the Gulf of Mexico or alongside Colombia or SW Mexico. The most popular model relates Chortís to SW Mexico but, despite attempts to seek geological continuity between the two areas (e.g. Pindell 1993; Rogers *et al.* 2007b), it does not exist (Keppie & Morán-Zenteno 2005). Moreover, this understanding moves Chortís south-eastward to join the rear of the NE-moving Caribbean Plate in the Eocene by an unexplained process (e.g. Mann 2007).

The restoration of Chortís suggested by this paper brings the older crustal rocks into contact with the southern Mexico Oaxaca, Acatlán and Xolapa complexes. All have Grenvillian or inherited Grenvillian components (U–Pb, Sm–Nd data, Nelson *et al.* 1997). The Precambrian granulite–facies Oaxacan Complex of southern Mexico are reported from Chortís as c. 1 Ga amphibolite gneisses and a Permo-Carboniferous tectonomagmatic event seen in northern Honduras may correlate with
a similar event in the Acatlán Complex of southern Mexico (Manton 1996; Keppie et al. 2003).

The 20–25 km thick Siuna complex of eastern Chortís is a mélange of blocks of gabbros, peridotites, greenstones, greenschists, metamafics, schists, metacherts, detrital quartzites, radiolarian cherts, black shales and radiolarites bearing Middle and Late Jurassic radiolaria in a serpentinite matrix (Flores et al. 2006). Conglomerates with abundant quartz and fragments of schists and quartzite indicate a nearby continental source (Venable 1993). The mélange is followed unconformably by thin-bedded calcareous hemipelagites containing Aptian/Albian planktonic foraminifera (Flores et al. 2006). This continues up section into thick-bedded, shallow-water limestones that correlate with the Aptian/Albian Atima Formation of Chortís. These data are incompatible with formation of the complex in ?Jurassic—Early Cretaceous time in a Pacific location and accretion in the Late Cretaceous at the leading edge of a migrating plate (e.g. Rogers et al. 2007a, fig. 9A). The Siuna complex is related to Chortís as its eastern rift/ drift margin.

**Southern Central America—Chorotega and Chocó**

Southern Central America exposes only troughs of marine Cenozoic deposits with volcanic and plutonic igneous rocks above Mesozoic oceanic rocks and is thought to have intra-oceanic origins (Dengo 1985; Escalante 1990).

Crust thickens from 30–31 km below Nicaragua, on the Chortís Block, to 40–45 km below Costa Rica (Chorotega Block) where gravity data indicate continental crust (Case 1974; Case et al. 1990; Auger et al. 2004). Seismic velocities over the Cocos Plate and Costa Rica show transition from oceanic to continental crust, with continental Moho at around 40 km depth (Sallares et al. 2001).

The Costa Rican volcano Arenal produces granulite xenoliths and micaschists and amphibolites occur in the Talamanca Range and on the Osa and Azuero peninsulas (Tournon et al. 1989; Krawinkel & Seyfried 1994; Sachs & Alvaredo 1996). Geochemistry of high silica ignimbite and granitoid rocks of Costa Rica is very similar to continental rocks and to ignimbrites in Guatemala where Palaeozoic crust occurs (Deering et al. 2004; Vogel et al. 2004, 2007).

Albian (Iturralde-Vinent 2004) and Miocene (Escalante 1990) quartz sands are present in Costa Rica and the ?Albian–Santonian volcanic arc section of Santa Elena probably contains continentally derived sediments (Iturralde-Vinent 2004). The southern extension of southern Central America (Choco Block) is accreted to western Colombia as the Serranía de Baudo. Westward-coarsening quartz sands in Late Cretaceous turbidites of the inboard Colombian Cordillera Occidental indicate continental basement for the Serranía (Bourgeois et al. 1987).

The data indicate that the area is underlain by continental crust.

**Nicaragua Rise, Cayman Ridge**

The submarine Nicaragua Rise extends Chortís eastwards to Jamaica. The crustal thickness of Jamaica is around 20 km. Palaeozoic rocks are unknown but drilled platform carbonate rocks suggest continental foundations. Arden (1975) suggested that the Rise rifted away from the Beata Ridge. Parallel to the Rise, on the opposite side of the Cayman Trough, the Cayman Ridge extends to southeast Cuba.

For many authors the Rise and Ridge are built of volcanic arc rocks (e.g. Holcombe et al. 1990). Others note that Northern Nicaragua Rise crust is up to 25 km thick and think it is continental, possibly with Palaeozoic basement (Holcombe et al. 1990; Muñoz et al. 1997). Late Precambrian to Early Palaeozoic metagneous rocks (equivalent to the Grenville or younger gneisses of the Oaxaca or Acatlán complex of southern Mexico) form a ridge along the southern margin of the western Cayman Trough (Donnelly et al. 1990).

Exploration wells on the Nicaragua Rise encountered andesite, granodiorite and metasedimentary rocks as far east as Rosalind Bank (Dengo 1975). However, Upper Cretaceous–Paleocene granitoid rocks of the northern Rise, chemically similar to granitoids from Jamaica, Haiti and the Sierra Maestra, southern Cuba, show affinity with mature oceanic arc rocks uncontaminated by continental material (Lewis et al. 2008).

According to Pacific models Chortís and the Upper Nicaragua Rise were obducted southeastwards from SW Mexico onto the trailing edge of the Caribbean Plate as it entered between the Americas. However, seismic data show northwest vergence of folds and thrusts on Chortís and the adjacent Rise, where continental Jurassic–Cretaceous geology of the N35°E Colón Mountains, Honduras, continues into the offshore, but trending N60°E (Rogers et al. 2007b, fig. 2).

The Miskito Basin, on the Nicaragua Rise east of Nicaragua, is bounded to the north and south by the parallel, N60°E Pedro Fracture and Hess Escarpment. It comprises intermediate, stretched crust and southward decreasing thermal gradient indicates transition to oceanic crust (Muñoz et al. 1997). This, Lower Nicaragua Rise, is shown as a distinct and unexplained element lying north of the Caribbean Plateau in some models, suturing to
the Upper Rise (along the Pedro F.) in the Campanian (e.g. Mann 2007, fig. 4; Pindell & Kennan 2009, fig. 10). Undisturbed, upper Cretaceous sediments lie next to the Hess Escarpment, which therefore is older (Edgar et al. 1973). Both faults represent extensional strain of N60°W sinistral movement of North America (James 2009, fig. 2).

The Cayman Ridge extends to southeast Cuba. Built of tilted fault blocks, it has near-continental crustal thickness and low magnetic susceptibility in the west, similar to rift blocks of the margin of British Honduras (Dillon & Vedder 1973; Rosen- 
northern South America. Together, these areas 
volcanic arc rocks emplaced upon continental base-
ment of the Florida Platform extends through the eastern Bahamas and northern Cuba (Meyerhoff & Hatten 1974; Pardo 1975). DSDP sites 537 and 538, off northwestern Cuba, penetrated Cambrian–Ordovician phyllites, gneisses, amphibolites, intruded by Early–Middle Jurassic diabase dykes, correlative with rift volcanism in the North Atlantic, covered by lower Cretaceous sediments (Schlager et al. 1984). Northwest–southeast gravity and magnetic trends of western and south-
west Florida continue uninterrupted across the Bahamas to Cuba (Meyerhoff & Hatten 1974) and to Yucatán.

Rigassi-Studer (1961) and Hatten (1967), quoting radiogenic ages determined by the Cuban Academy of Sciences, considered that metamorphic and igneous rocks on Cuba are Variscan metamor-
phosed Palaeozoic rocks, though Khudoley (1967) claimed they are Jurassic. Details of these older rocks appear in Stanek et al. (2009).

While no Triassic rocks are known, Triassic gneiss and granite pebbles in a Palaeogene conglomerate in the west indicate Triassic magmatism (zircon dates, Somin et al. 2006). Early Jurassic–Cretaceous sediments occur in western Cuba (Guaniaguano). They indicate quartzose continental basement of Precambrian–Palaeozoic age (zircons, Rojas-Agramonte et al. 2006), suggesting Grenvillian rocks related to SW Mexico and Chortís. Similar rocks occur as exotics on diapirs of Jurassic salt in north-central Cuba. Thick marbles overlain by pelitic and quartzo-pelitic schist occur in the Sierra de Trinidad and rocks on the Isla de Pinos and in eastern Oriente show stratigraphic and lithological similarities (Pszczolkowski 1999). Thicknesses are probably more than 3000 m (Hatten 1967).

Pre-Tithonian arkosic palaeosols overlie base-
ment in west-central Cuba while Early–Middle Tithonian extrusive tholeiites occur in east-central Cuba (Iturralde-Vinent 1994). In western Cuba the northwestern, coastal-shallow-water/neritic, Early– 
Middle Jurassic San Cayetano (Pszczolkowski 1999), Jagua and Francisco Fms change to the deep marine Sábalo Fm in the southeast (Pszczolkowski 1999). The Oxfordian–Early Kimmeridgian El Sabalo Fm and part of the Encrucijada Fm (Aptian–Albian) have been interpreted as oceanic crust contaminated with continental crust. Allibon et al. (2008) relate dolerite dykes of the El Sabalo to continental margin rift basalts.

Tithonian and Berriasian ammonite assemblages of north-central (Bahama platform) and western Cuba show biogeographic/palaeogeographic coupling (Pszczolkowski & Myczynski 2003). Radiolarians in cherts of central and western Cuba in both deep-water continental-margin rocks and ophiolites suggest common palaeogeography (Aiello et al. 2004). Arc rocks of the Mabujina Unit of central Cuba, dated by spores and pollen as Upper Jurassic–Lower Cretaceous, show sedimentary contami-
nation (Stanek et al. 2006).

In the Albian–Conomanian carbonate platforms and banks, hundreds to thousands of metres thick, surrounded much of the Gulf of Mexico (Sheridan et al. 1981; Salvador 1991; Carrasco-V 2003). At least 11 km of horizontal carbonate rocks overlie magnetic basement on the southern margin of the Bahama Platform (Lewis 1990, summarizing Mossakovsky & Albear 1978; Pszczolkowski 1976; see also Iturralde-Vinent 1994). In northern Cuba (Cayo Coco) the section is at least 5 km thick and ranges from Upper Jurassic dolomites and anhy-
drites through Neocomian–Aptian shallow water limestones, Albian–Conianian pelagic limestones and marls, Maastrichtian limestones and Paleocene to Middle Eocene marls and limestones (Pardo 1975). The deep-water equivalent, one-fifth as thick, is seen further south through windows in allochthonous ophiolites. Tithonian to Maastrichtian rocks include pelagic limestones, calcareous turbidites, radiolarian cherts, sandstones and marls. Tuffs and radiolarian cherts record nearby volcanism (Cabaigan Belt of Pardo 1975).

According to Pacific models, sedimentary Juras-
sic continental rocks in western Cuba (Guaniaguano) and their metamorphosed equivalents in
south Central Cuba (Isle of Pines, Escambray) were picked up from southern Yucatán and underplated to the forearc of a migrating volcanic arc in the Campanian (Pszczolkowski 1999; Draper & Pindell 2004). However, palaeomagnetic studies indicate no significant latitudinal differences between Jurassic–Cretaceous rocks of western Cuba relative to North America (Alva-Valdivia et al. 2001). Rocks in this area are different from and do not suggest affinity with Chortis and Mexico (Pszczolkowski & Myczynski 2003).

Cuban continental basement clearly is the autochthonous continuation of the Florida–Bahamas Platform/Caribbean Block, with eastward-increasing extension. The next section shows that it continues below the island blocks further east.

**The Greater Antilles–northern Lesser Antilles, southern Lesser Antilles**

The Greater Antilles extend some 2500 km from western Cuba to the Virgin Islands and, for this paper, through the northern Lesser Antilles (Limestone Caribbean) to their abrupt termination at Marie Galante (Lewis & Draper 1990, saw them continuing as far as Guadeloupe). Their limited subaerial appearance is deceptive. They are massive areas, 200 km wide but two-thirds below sea level, contiguous but for Oligocene/Miocene strata Caribbees) to their abrupt termination at Marie Galante (Lewis & Draper 1990, saw them continuing as far as Guadeloupe). Their limited subaerial appearance is deceptive. They are massive areas, 200 km wide but two-thirds below sea level, contiguous but for Oligocene-younger pull-apart lows of the narrow Windward, Mona and Anegada Passages (Fig. 1).

The Greater Antilles are generally attributed to an extinct Cretaceous volcanic arc (Mattson 1966; Mattson & Schwartz 1971; Donnelly 1989). This began life as the ‘Caribbean Great Arc’ in the Pacific and entered the Caribbean at the leading edge of the migrating Caribbean Plate (Burke 1988). Diachronous collision with the Bahamas and northern South America supposedly caused arc volcanism to cease progressively from west to east (Pindell et al. 2006, fig. 7b; Levander et al. 2004). However, arc activity ceased synchronously from Cuba to Puerto Rico/Virgin Islands, a distance of some 2000 km, in the Middle Eocene (Iturralde-Vinent 1995; Lidiat 2008).

There are several indications that continental crust underpins the Greater Antilles east of Cuba. The idea is not new – Stainforth (1969), Nagle et al. (1982), Joyce & Aronson (1983), Alonso et al. (1987) and Lidz (1988) all observed relevant data.

Schists and marbles on the Samaná Peninsula of Hispaniola and on Tortuga Island north of Hispangola (Nagle 1970; Khudoley & Meyerhoff 1971; Fox & Heezen 1975; Nagle et al. 1982; Lewis et al. 1990; Goncalves et al. 2002; Draper et al. 2008) continue the trend of continental rocks on Cuba (Guaniquanico–Isle of Pines–Escambray). Samaná rocks are ‘strikingly similar’ (Nagle 1974) to the eclogite, eclogite-amphibolite and garnet amphibolite tabular masses, boudins and blocks in graphitic schist and marbles of the Jurassic–Cretaceous (pre-Albian), continental margin Las Mercedes Fm of northern Venezuela.

Marble occurs in continuous outcrop from 2600 to 3600 m off the Samaná Peninsula (Heezen et al. 1976, quoted by Nagle et al. 1978). Two dredges from the south wall of the Puerto Rico Trench north of the Mona Passage retrieved black marble (Fox & Heezen 1975). Two others, east of Cape Samaná, Hispaniola, recovered siltstone and recrystallized carbonate with deformed bands of white mica. Dredges from between 6000 and 3500 m on the south wall of the Trench north of Puerto Rico and the Virgin Islands indicate a stratigraphy of upper Cretaceous to lower Miocene, shallow marine carbonate (Fox & Heezen 1975). Albian to at least Early Miocene inter-tidal to sub-tidal deposits on the Silver–Navidad Banks show palaeogeographic continuity of these areas (Schneidermann et al. 1972). These are not the foundations of an intra-oceanic volcanic arc.

Amphibolitic gneiss crops out at the western end of the Sierra Bermeja of Hispaniola (Mattson 1960; Renz & Verspyk 1962, quoted by Donnelly 1964). Garnet peridotite, normally associated with subducted continental rock, occurs in the Cuaba amphibolite of the Dominican Republic (Draper et al. 2002).

Geophysical data indicate continental crustal thickness of about 30 km in the centre of Puerto Rico and 29 km below the Anegada Platform (Shurbet et al. 1956; Lidz 1988). Rocks known from outcrop on Puerto Rico account for only 6 km of the total thickness – some 24 km of section are unknown (Mattson 1966). The Moho lies at around 29 km below St Thomas and St Croix and 22 km below the Anegada trough (Shurbet et al. 1956).

These data indicate that Hispaniola–North Virgin Islands continue the Cuban geology of basalt and volcanic arc rocks thrust over thick Mesozoic limestones lying on Triassic–Jurassic rift section in Palaeozoic basement.

The Grenada Basin and Aves Ridge terminate against the shallow marine platform of Saba Bank in the north. Drilling on the Bank encountered 2858 m of Cenozoic sedimentary cover and terminated after penetrating 119 m of porphyritic andesite. Seismic data indicate an extensive sedimentary section (upper Cretaceous?) below the andesite to as deep as 4100 mbsl (Bouysse 1984).

**Northern South America**

As in North America, Pangaean rifting began in the Triassic in northern South America. The upper Triassic to lower Jurassic section consists of rift red beds and volcanic rocks in the Sierra de Perijá,
Mérida Andes, on the Guajira Peninsula and in the subsurface San Fernando-Matecal, Espino, Aníbal and Takutu grabens (Bellizzi 1972; Feo-Codecido et al. 1984; Maze 1984; Crawford et al. 1985; Gonzalez & Lander 1990). Similar rocks occur in the Araquita-1 well and Guafita areas of Venezuela’s Llanos Basin (McCullough & Carver 1992). Triassic-Jurassic volcanic rocks occur on Venezuela’s El Baul Uplift (Kiser 1987). The Timaco–Tinaquillo belt of northern Venezuela is a 3 km thick, Jurassic peridotite complex (Ostos 2002; Ostos & Sisson 2002). It formed in NE–SW rifted Cambro–Ordovician basement in the Cordillera de la Costa and could be related to Appalachian–Caledonian events and the Acatlán complex, also affected by Jurassic rifting, of southern Mexico (Ostos & Sisson 2002, fig. 9; Nance et al. 2006).

Upper Triassic continental sediments, sills and flows in the Guajira Peninsula region are followed by several thousands of metres of shallow marine, Jurassic to Late Cretaceous limestones (Middle Jurassic molluscs, Late Jurassic ammonites, Cretaceous molluscs, ammonites, foraminifera; Rollins 1965; Lockwood 1971). Upper Jurassic shales occur on the Paraguaná Peninsula (ammonites; Bartok et al. 1985). While this section is metamorphosed along most of northern South America, these areas carry sedimentary rocks. They escaped metamorphism because they lay at least 300 km SW of the plate boundary until the Eocene.

Thick sections of Jurassic metasediments occur in the Coastal and Northern Ranges of Venezuela and Trinidad (Late Jurassic pelacypods, tuntinnids; Kugler 1953; Feo-Codecido 1962; Bellizzi 1972; Bellizzi & Dengo 1990) and similar rocks crop out on Margarita Island (Gonzalez de Juana et al. 1980). Protoliths were shallow (?Callovian gypsum; Kugler, 1953) to deep marine, passive margin sandstones, organic shales and limestones (Stainforth, 1969; Gonzalez de Juana et al. 1980). In the Coastal Range of Venezuela the section rests upon Precambrian–Palaeozoic basement (Urbani 2004). Northward increasing silica content and lenses of volcanic ash in the Jurassic–Cretaceous (pre-Albian) Las Mercedes Fm record nearby volcanic activity. Metasediments on the Araya Paria and Trinidad’s Northern Range record a vast thickness of ?Triassic–Jurassic–Lower Cretaceous marine beds above the Late Permian–Early Triassic Dragon Gneiss of Paria and Sebastopol Gneiss of central Venezuela (Stainforth 1969; Kugler 1972).

Most of Venezuela’s eastern offshore platform is underlain by metamorphic gneisses and passive margin metasedimentary rocks, meta-ophiolites and MORB volcanic rocks of Jurassic–Early Cretaceous age (Ysacís 1997). Exposed geology of Margarita shows basement of metamorphosed (100–90 Ma) MORB rocks and schists and gneisses (Jurassic–Cretaceous protoliths, Pennsylvanian zircons; Stockhert et al. 1995). East of Margarita, wells have penetrated section ranging from ?Jurassic to Early Cretaceous (shallow water Bocas metabasalts and low grade metasediments), Early to Late Cretaceous deep marine, euxinic shales, limestones, cherts, volcanoclastic rocks and lavas (Mejillones Gp.) and Late Eocene–Lower Early Oligocene arc volcanic (Los Testigos) igneous–metamorphic complexes (Castro & Mederos 1985). The Upper Jurassic–Lower Cretaceous (ammonites, foraminifera) North Coast Schist (greenschist) of Tobago contains metatuffs, graphitic siliceous schist, graphitic quartzose phyllite. The chemically related Aiptan–Albian Tobago Volcanic Group includes volcanoclastic breccias and lavas. The volcanic–intrusive complex continues south of the island to the Jurassic (Tithonian ammonites, aptychi) metasediments black shales and Albian Sans Souci tuffs, tuff breccias, conglomerates and andesitic lava flows of Trinidad’s Northern Range (Ramroop 1985).

For Stockhert et al. (1995) the geology of Margarita is representative of the 70 000 km² area of (eastern) coastal Venezuela, Trinidad and Tobago. They derive it from NW South America by arc–continent collision and subduction, followed by resurrection along the transcurrent boundary following passage of the arc complex, in a manner similar to the proposed history of the Greater Antilles. Kerr et al. (2003) attribute the Sans Souci of Trinidad and parts of the North Coast Schist of Tobago to the Cretaceous Caribbean Plateau. However, they manifest Albian continental input and lie SE (outboard) of the volcanic arc (Lesser Antilles) the plateau is supposed to have followed into place. According to Wadge & Macdonald (1985), Sans Souci theoliteis erupted onto the passive margin of South America in the Aptian–Santonian.

The above units mirror those of southern North America–Cuba. Together with rocks on Maya and Chortís they show a regionally coherent Jurassic–Cretaceous palaeogeography of intra-continental rifts to deep passive margin flanked by volcanic activity along northern South America, southern North America and along the eastern margins of continental fragments in the west.

Igneous rocks

Abundant high-silica rocks indicate the widespread presence of continental crust on Caribbean margins. Tonalites, a chemical signal of continental crust, are common. Many date radiometrically in the region of 86–80 Ma, close to a major pulse of Caribbean Plate thickening at 90–88 Ma (Donnelly 1989; Kerr et al. 2003). Four tonalites on Hispaniola
are Albian in age (U–Pb, Ar/Ar 109–106 Ma, Escuder Viruete et al. 2006), a tonalite–gabbro batholith in the Netherlands Antilles is dated Middle Albian to Coniacian (Beets et al. 1984) and cooling of a Mid-Cretaceous diorite and tonalite on Tobago occurred at 103 Ma (zircon fission track; Cerveny & Snoke 1993). Tonalites have been dredged from the Cayman Trough (Perfit & Heezen 1978). The geochemistry of six of these is typical of continental arc granitoids (Lewis et al. 2005). Their radiometric age, 62–64 Ma, is similar to that of granodiorite intrusions in Jamaica (K–Ar, Ru–Sr, 65 ± 5 Ma, Chubb & Burke 1963).

The silica content of plutonic rocks in the northeast Caribbean (Puerto Rico–northern Lesser Antilles) ranges from 45 to 78% weight (Smith et al. 1998). The Virgin Gorda batholith on the Virgin Islands Tortola and Virgin Gorda consists of diorites, tonalites and granodioritoids. Basement of La Désirade consists of Tithonian trondhjemite and rhyolite and coarse-grained, quartz-rich granite (Fink 1970; Bouysse et al. 1983; Westercamp 1988).

Lesser Antilles basalts are directly comparable in chemical composition and mineralogy with basalts from calc-alkaline suites of circum-oceanic islands and continental margin orogenic belts (Lewis 1971). Lewis & Gunn (1972) regarded basalt–andesites of the Lesser Antilles as products of mantle fusion and differentiation at shallow depths; Benioff zone fusion did not appear to be involved. Siliceous metasedimentary xenoliths occur in basalts and rounded quartz grains in andesites (Nicholls et al. 1971).

Silicic magmas in Costa Rica are chemically similar to those in Guatemala where Palaeozoic crust occurs (Vogel et al. 2007). Crustal thickness (refraction data) and gravity values for Costa Rica are continental, Albian and Miocene quartz sands are present and the Arenal volcano produces granulite xenoliths (Case 1974; Sachs & Alvarado 1996; Iturralde-Vinent 2004; Auger et al. 2004).

The Aves Ridge has a relief of 2–3 km and locally reaches sea level. Dredges from steep pediments recovered glassy and brecciated basaltic rocks, suggesting volcanic origin. Seismic indicates 5 km capping of sediments and/or volcanics above a crustal layer with velocity of 6.2–6.3 km s\(^{-1}\) (Fox et al. 1971). Similar layering is seen in the Grenada and Venezuela basins. Dredging on Aves Ridge also recovered granodiorites, close to Venezuela. Three gave K–Ar ages of 78–89, 65–67 and 57–58 Ma (Lower and Upper Senonian, Upper Paleocene) (Fox & Heezen 1975). The in situ confining pressure of the 6.0 km s\(^{-1}\) under the Aves Ridge is 1–2 kbar. Calculated velocity of the granitic samples at this pressure is 5.8–6.1 km s\(^{-1}\), similar to velocities of continental granodiorites.

Andesites, dacites, diorites and granodiorites (ages not known to the author), also continental signals, occur in Panamá, on the Nicaragua Rise, Jamaica, north Yucatán, Cuba, Hispaniola, the Saba and Mariner Banks, the Virgin Islands and the Lesser Antilles (Butterlin 1956; Donnelly 1966; Lidik 1970; Case 1974; Arden 1975; Banks 1975; Tomblin 1975; Bouysse et al. 1985; Despretz et al. 1985; Jackson et al. 1987; Lewis 1990; Lewis & Draper 1990; Blein et al. 2003). The Testigos-I and -2 wells offshore NE Venezuela bottomed in andesitic basalts of calc-alkaline type, dated 40–35 Ma (Ysaccis 1997).

The Caribbean 'oceanic plateau': continental foundations?


Thick crust in the Venezuela Basin was the 'original' Caribbean Plateau of Donnelly et al. (1973). Later works have implicated accreted oceanic rocks in Cuba, western Colombia, Curaçao, Aruba, Venezuela, Trinidad, Jamaica, Hispaniola and Central America and even Ecuador. Kerr et al. (1997) described the combined Caribbean–Colombian large igneous province as one of the world's best-exposed example of a plume-derived oceanic plateau. However, 'plateau' rocks on Cuba lie on the North American plate and those of western Colombia and Ecuador lie on the South American Plate. The rocks on Costa Rica lie west of the arc that bounds the Caribbean Plate/plateau and those on Tobago lie outboard of the volcanic arcs they are supposed to have followed during plate migration. Thick parts of the Caribbean Plate are bounded by older or coeval thin (3 km) crust in the Colombia and Venezuela basins. Such crust in the SE Venezuela Basin would not be capable of driving the Aves/Lesser Antilles volcanic arc over Atlantic crust of normal thickness.

Kerr et al. (2003, table 2) summarized occurrences and ages of plateau rocks in the Pacific and the Caribbean. Ages cluster at 124–112 Ma (Barremian–Aptian), 91–88 Ma (Turonian) and 78–59 Ma (Campanian–Danian). Activity also occurred at 124–112 Ma on Ontong–Java and Manihiki and at 90 Ma on Ontong–Java (Larson 1997; Birkhold et al. 1999; Larson et al. 2002). Oceanic rocks accreted to Ecuador also fall into ages c. 120 and c. 90 Ma (Jaillard et al. 2009).

The data suggest widespread pulses of igneous activity at these times rather than spatial relation of the localities.
The data compiled by Kerr et al. (2003) include rocks with a wide range of age and chemistry. The Duarte complex of Hispaniola ranges in Ar/Ar age from 86 to 69 Ma but Jurassic radiolaria occur locally. The Curacao Lava Fm yields Ar/Ar dates of 88–90 Ma but Middle Albion ammonites are present (Wiedmann 1978). Basalts at Site 1001 on the Lower Nicaragua Rise/Hess Escarpment are overlain by Campanian limestones (nannofossils with minimum age 77 Ma, Sigurdsson et al. 1996) and give a mean Ar/Ar age of 80.9 ± 0.9 Ma (Sinton et al. 2000). It is important to note that drilling, dredging and submersible sampling of the Venezuela Plateau have tested only the uppermost components of the ‘plateau’ and its faulted (rifted–intruded?) margins. The bulk of the plateau remains uncalibrated and should not be assumed to consist of a huge volcanic pile. Rocks accreted to the plate margins are assumed, not known, to represent the plateau of the plate interior. Older rocks accreted to Ecuador in the Campanian, younger rocks in the Late Maastrichtian and Late Paleocene (Jaillard et al. 2009). This suggests separate origins.

Kerr et al. (2003, see also Kerr et al. 2000) discuss means of identifying oceanic plateaus. Indicators are 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’. However, Kerr et al. (2003) also note that basalts of marginal basins of island and continental arcs are potentially the most difficult to distinguish from oceanic plateaus.

The Caribbean ‘oceanic plateau’ is thought by many to have been generated by a mantle plume (e.g. Kerr et al. 2009). On the other hand, since Caribbean ‘plateau’ magmas formed at three different times show similar petrological and chemical compositions, Révillon et al. (2000) questioned mantle plume genesis, noting instead that lithospheric thinning could produce the same melting conditions. There is no indication anywhere in the Caribbean region of the radial strain expected over mantle plume (Glen & Ponce 2002). Instead, the whole of Middle America manifests NE structural grain that parallels Triassic–Jurassic rifts in neighbouring continental masses (Fig. 4).

Oceanic plateaus are defined as anomalous rises above the seafloor that are not parts of known continents, volcanic arcs or spreading ridges (Nur & Ben-Avraham 1983). Neither the Colombia Basin nor the Venezuela basin ‘plateau’ is elevated today. They mostly lie below more than 3000 m of water (the Beata Ridge, which limits the Venezuela basin ‘plateau’ to the west, rises locally to 1000 m). It is correct to note, however, that Cretaceous basalts of smooth Horizon B’ could have formed under shallow marine/subaerial conditions (below). Reflection data show a basal onlapping stratigraphic section over acoustic basement in the Venezuelan Basin (Driscoll et al. 1995). Correlation from DSDP holes shows this to be older than Middle Eocene (50 ma) and younger than Senonian (88 ma).

The section is absent from the Caribbean ‘plateau’. Together with the presence of Middle Eocene shallow marine carbonates sampled from the Beata Ridge, this shows that the plateau subsided to its present depths since the Middle Eocene.

The term ‘plateau’ in the Caribbean today therefore refers more to its crustal thickness than its elevation. It is not known whether it is part of a continent or spreading ridge. It is presumed to be oceanic because the Caribbean Plate came from the Pacific.

Many oceanic plateaus have crustal thicknesses of 20–40 km and an upper crustal velocity of 6.0–6.3 km s⁻¹, typical of granitic rocks in continental crust. The Caribbean ‘plateau’ is up to 20 km thick. Parts of the Caribbean are floored by thick crust with velocity 6.1–6.5 km s⁻¹.

Rosendahl et al. (1992) suggested that continental crust might occur up to hundreds of kilometres from continental margins. The Kerguelen, Ontong Java Iceland and Rockall plateaus are known from dredge samples or ancient zircons to carry continental rocks (Roberts 1975; Doucet et al. 2002; Frey et al. 2002; Klingelhofer et al. 2005; Paquette et al. 2006; Ishikawa et al. 2007). Granitic basement is exposed on the Seychelles, the Parcel Islands, Kerguelen and Agulhas and possibly underlies the Iceland Plateau (Foulier et al. 2005).

Diebold et al. (1999) noted: ‘The concept that the Colombia and Venezuela basins are capped uniformly by a Cretaceous igneous body persists’ (see illustrations in Mann 2007; Rogers et al. 2007a, b). In reality, crustal thickness of the Caribbean Plate varies from normal, 6–8 km, in the Haiti Basin, west of the Beata Ridge, to thickened, up to 20 km, between the Venezuela Basin Fault Zone, and the western Beata Ridge boundary, to abnormally thin, 3–5 km, in the southeastern Venezuela Basin (Diebold et al. 1999). Crust is also thick in the Yucatan (8–9 km, Hall 1995), Colombian and Grenada Basins (10–22 km; 18 km; Case et al. 1990). These thick areas all display the NE tectonic fabric of continental neighbours (James 2006).

Seismic data shown by Diebold et al. (1999) and Diebold (2009) over the Caribbean ‘plateau’ in the Venezuela Basin show large (35 km wide) NE-trending highs flanked by dipping wedges of reflections and structures that pierce the sea floor. Similar data are seen in the Colombia Basin where thick crust continues uninterrupted to Panama and Costa Rica (Bowlan & Rosencrantz 1988). Diebold
interpret the architecture as blocks of vertical dykes flanked by wedges of igneous flows and seamounts. These authors outline a history of oceanic crust formation by spreading, followed by extension and thinning with widespread eruption of basaltic flows. The top of these forms smooth seismic Horizon B′″ sampled by DSDP and ODP drilling.

Smooth Horizon B′″ is reminiscent of a continental flood basalt and reduced velocities in the upper sub-B′″ sequence could indicate vesicles, brecciation, weathering or interbedded sediments (Diebold et al. 1999). This would explain the great lateral extent of smooth B″. Vesicularity of the uppermost basalts and shallow water fauna in overlying sediments drilled by the DSDP supports this subaerial/shallow origin (Sigurdsson et al. 1996). Other sites of presumed plateau rocks also indicate shallow/subaerial conditions. Aruba and Curacao became emergent in the Late Cretaceous (Beets 1972; Wright 2004). The Curacao Fm has a presumed palaeosol at its top and a palaeosol occurs above weathered basalt on the correlative Aruba Lava Fm (Beets 1977; Snoke 1990). Spheroidal weathering of gabbros and dolerites from the Beata Ridge indicates subaerial weathering (Révillon et al. 2000).

Diebold et al. (1999) recognized upper and lower volcanic sequences on the plateau. Diebold (2009) suggests that the 5 km thick Albion–Cenomanian Curacao Lava Fm (Klaver 1987) is analogous to the upper 5 km of the upper volcanic sequence of the Caribbean Plateau. If they are age equivalent, then the lower part of Diebold’s upper volcanic sequence must be pre-Albian. The lower sequence and its structure must be older still, at least Early Cretaceous, possibly Triassic–Jurassic. This was the time of rift/drift, when the regional inter-American N35°E structural grain developed (below).

Seaward dipping wedges (SDRs) are typical of extended continental crust at the continent–ocean transition (Hinz 1983; Rosendahl et al. 1992). They are common in the North and South Atlantic (Jackson et al. 2000). Characteristic features are oceanward-directed, upwardly convex and diverging dips and seismic velocities increasing from 2.6–4 to 6.4 km s⁻¹ (Mutter et al. 1982; Hinz 1983). They could consist of shallow marine to subaerial volcanic layers (Hinz 1983), volcanic layers on ocean crust (Mutter et al. 1982) or sediments in half grabens with continentward-dipping listric faults (Bally, pers. comm. 2008).

Rifting between North America and Europe/North Africa followed the Newfoundland–Honduras Palaeozoic tectonic belt in the Early Triassic–Hettangian and affected Middle America by the Late Triassic (Ager 1986; Helwig 1975; Manspeizer 1988; Davison et al. 2003; Withjack & Schlische 2005). Basins formed along low angle detachments and sinistral faults, reactivating Palaeozoic thrusts or dextral faults, and filled with red beds and volcanic rocks. Tectonism along eastern North America then abandoned inboard rifts and moved to the Atlantic, where seafloor spreading followed. There, basin fill comprises a syn-rift section separated by a break-up unconformity from post-rift/drift section. Seismic data indicate up to 5 km of Triassic (?) syn-rift deposits in the Baltimore Canyon, Carolina Trough and Blake Plateau basins (Manspeizer 1988). Postrift, wedge strata, 8–13 km thick, are cut by salt diapirs. COST well G-2, on Georges Bank, bottomed in upper Triassic salt (Manspeizer 1988). Figure 6 illustrates a section over these basins.

Attenuated continental crust and SDRs are present below the Gulf of Mexico, where there may be only little true oceanic crust (Johnson et al. 2005; Post 2005). Violet siltstone, with Carboniferous K–Age, dredged from a Sigsbee salt diapir records Palaeozoic basement (Pequegnat et al. 1971) below the deep Gulf of Mexico. Seismic data and DSDP/ODP data reveal large continental horsts flanked by deep wedges of dipping reflections (Jurassic sediments, flows, volcanioclastics, and possibly salt) in the SE Gulf of Mexico (Phair & Buffler 1983), where NE tectonic grain links the Yucatan Peninsula to Florida. Continental signal in oceanic basalts of the Oxfordian–Early Kimmeridgian El Sabalo and Encrucijada Fms (Aptian–Albian) of nearby western Cuba suggests eruption through continental crust like North Atlantic seaward-dipping sequences (Kerr et al. 1999, 2003). Eastern North America geology continues into the Gulf of Mexico.

This paper proposes that Caribbean ‘plateau’ architecture continues the same geology into a more extensional location. In this scenario seismic line 1293 (Diebold et al. 1999) shows blocks of extended continental crust flanked by wedges of dipping Jurassic sediments and flows below the smooth basalt flows of the western Venezuela Basin (fig. 7, James 2007b). The unexplained ‘ski-jump’ (Diebold et al. 1999) at the edge of the plateau may be a marginal reef/carbonate mound. Rough Horizon B″ is the equivalent ‘oceanic’, serpentinitized mantle crust formed during extreme crustal attenuation. ‘Oceanic’ crust derived in this manner does not have organized magnetic anomalies. Downlap of Turonian smooth B′″ onto rough B″ by 20–30 km beyond the plateau boundary (Diebold 2009) for this paper indicates a similar age. Similar geometry appears in the Colombian Basin (Bowland & Rosencrantz 1988).

If all this is true, then (a) the Caribbean plateau formed over a long interval of time, not by a Late Cretaceous ‘large igneous plateau’ event, (b) it is
underlain by extended continental crust, (c) there is little ‘oceanic’ crust in Middle America and (d) it formed by serpentinization of upper mantle during extreme extension of continental crust and thus shows no spreading signature. Thick crust in the Yucatán, northern Grenada (both with NE tectonic grain) and Colombia basins are likely to have similar origins. Seismic over the Colombian Basin shows the character and the same architecture of horsts flanked by wedges of dipping reflections (Bowland & Rosencrantz 1988, figs 7 & 9).

If the ‘plateau’ formerly were shallow, Middle Eocene emplacement (see below) of its upper rocks onto neighbouring continent would be more easily explained than uplift from oceanic depths. Seaways in the area would have been restricted, offering an explanation for the prolific upper Cretaceous hydrocarbon source rocks of northern South America. Reduced velocities in the upper sub-B00 sequence could indicate presence of source rocks on the plateau.

**Salt diapirs**

The ‘seamount’ shown on line 1293 near CDP 2000 (Fig. 7; Diebold et al. 1999, fig. 2) looks like a piercing diapir and so could consist of serpentinite or salt. The diapir rises at least 700 m above the sea floor and resembles Sigsbee Knoll diapirs that rise 200–400 m above the 3600 m deep seafloor of the Gulf of Mexico (Fig. 8). Seafloor sediment push-up indicates that the feature on Line 1293 is active, but there is no reported volcanism in the area. Onlap (arrow of flat onto upturned reflections adjacent to the diapir on its northern side indicates pre-B00 growth. It does not push up Horizon B00, despite being some 14 km wide at this level, which suggests considerable normal fault extension, consistent with the c. 150 m seafloor drop south to north across the feature and an apparently very thick (at least 1.7 secs twt; 4 km?) pre-B00 section on the down thrown side. Dip of Horizon B00 and deeper reflections towards both sides of a similar feature near CDP 6000 suggests a withdrawal rim syncline. Both diapirs appear to root deep in the pre-B00 section. If they are built of salt, this is older Mesozoic in age. Analogy with eastern North America and the Gulf of Mexico suggests Triassic and/or Jurassic age. N35°E projection from the diapir leads to the SE coast of Puerto Rico (Fig. 8). The coastal village of Salinas shows 5 salt knolls (apparently not dated) on its flag.

Diebold et al. (1999) note that positive magnetic anomalies correspond to their seamounts. However, diapirism is often triggered by faults. If the NE trends of the Caribbean are reactivated older structures, they could have been the locus of older intrusions.

**Beata Ridge and Salt Mountain, Hispaniola**

The Beata Ridge is about 23 km thick and its crustal velocity structure is similar to the Nicargua Rise (Edgar et al. 1971). Gravity anomalies indicate that the ridge is not oceanic crust uplifted 3 km (anomalies would be larger) but that topography is compensated at depth by downflexing of lithosphere (Bowin 1976).
The ridge has been seen as a trench–trench transform hinge fault, a ridge–trench transform, as thrusting of the Colombian Plate over the Venezuelan Plate and as part of the Nicaragua Rise (Malfait & Dinkleman 1972; Arden 1975; Anderson & Schmidt 1983; Mauffret & Leroy 1997).

Submarine sampling indicates that the ridge includes hypabyssal intrusive rocks (gabbros and dolerites) alternating with sedimentary rocks, probably in tectonic contacts (Révillon et al. 2000). There are also rare pillow basalts. Diebold (2009) relates the ridge to thick volcanic flows and presents seismic evidence of compressional structure.

Constant seismic interval \( B' - A' \) thickness in the south indicates uplift after the Middle Eocene (Moore & Flaquist 1976). Coring recovered shallow-water Mid-Eocene carbonates from the crest of the ridge (Fox & Heezen 1975) and DSDP Site 151 recorded an Early Oligocene–Middle Eocene hiatus. Deformation increases northwards towards Hispaniola where reverse faults cut upper Miocene strata onshore (Biju-Duval et al. 1982). The ridge is thus seen to have formed since the Miocene by strong transpression, with reverse faults, pop-up structures and strike–slip faults observed in the east (Mauffret & Leroy 1997).

The Beata ridge carries scattered ‘volcanic seamounts’ that rise several hundred metres above the sea floor immediately south of the Bahoruco Peninsula, Hispaniola (Biju-Duval et al. 1982). The western margin of the Ridge, the Beata Fault, follows the regional N35°E tectonic trend and runs east of the Bahoruco Peninsula of Hispaniola to meet the coast in the Azua area (Ramirez et al. 1995). ‘Basement highs’ on seismic offshore Azua are strikingly similar to salt diapirs on the Sigsbee Scarp (Ladd et al. 1981, fig. 1; Buffler, 1983, fig. 4).

Offshore Azua geology is exposed onshore to the west on the Bahoruco Peninsula. Here, the upper part of the Cretaceous geology is exposed onshore to the west on the Bahoruco Peninsula. The upper part of the Cretaceous section in the central Massif de la Selle includes chaotic blocks of upper Albian to upper Coniacian–Santonian radiolarian cherts,
siliceous limestones and dolerites in a volcanic sedimentary matrix of Campanian–Late Maastrichtian age, overlain by Coniacian cherts (Lewis et al. 1990). These deposits can be seen as uplifted samples of the Muertos Trough accretionary prism further east. Cerro del Sal (Salt Mountain), on the north flank of the Bahoruco Range is a 21 km², vertically dipping outcrop of salt and gypsum, one of the world’s largest salt deposits. It seems to be part of the accreted Massif de la Selle geology, structured in the Miocene. Horizontal salt deposits in the Enriquillo Trough, to the north, between Middle and Late Miocene beds (Largo-1 well) are likely to be redeposited. Features on seismic over the Beata Ridge further south (Holcombe et al. 1990, plate 8, fig. U) are very similar to the diapir of Figure 8. They also root below Upper Cretaceous seismic Horizon B⁰.

Other knolls, diapirs, volcanoes

Probable salt piercement structures appear on seismic east of Honduras (Pinet 1972). When Maya–Chortís offset is removed, they lie next to the Chiapas salt basin of southern Maya. ‘Volcanoes’ (or diapirs?) occur throughout the area of the Lower Nicaragua Rise, with some showing Neogene–Recent activity (Holcombe et al. 1990). A series of regularly spaced knolls, 800 m high, occur adjacent to the Muertos Trough and one occurs near the Aruba Gap (Holcombe et al. 1990). A ‘seamount’ domain near the centre of the Yucatán Basin trends NE (Rosencrantz 1990). To the NE, salt diapirs crop out on the north coast of Cuba, along the trend of the major N60°E trending La Trocha Fault that crosses the basin (Fig. 3). A pre-Jurassic ridge in central Cuba, extending to the longitude of the eastern Bahamas, played a major role in localizing salt deposits of the Early and Middle Jurassic Punta Alegre Fm (Kirkland & Gerhard 1971; Meyerhoff & Hatten 1974). Recent exploration has encountered salt diapirs in the Florida Straits further north (Cobiella, pers. comm. 2008).

The Yucatán Basin

This roughly triangular basin between Cuba and the Cayman Ridge has not been drilled and basement is not dated. It is attributed to spreading behind the Cuban volcanic arc (Holcombe et al. 1990) or part of the Caribbean abandoned during a plate boundary jump from north of Cuba to the Cayman Trough (e.g. Pindell et al. 2006).

A characteristic seismic reflection resembles Horizon B⁰ of the Caribbean Basin (Rosencrantz 1990) and the basin exhibits structural grain of N35°E west of the La Trocha Fault and N60°E to the east. Tilted fault blocks occur in the west (Holcombe et al. 1990). A rise south of the Cuban Isle of Pines could be an extension of continental crust (Rosencrantz 1990). Anomalously thick crust (10–15 km) occurs in the southeast adjacent to the Cayman Ridge (Holcombe et al. 1990; Leroy et al. 1996). Rosencrantz (1990) noted that this could be Aptian–Albian or possibly Late Jurassic in age. Its thickness suggests that extended continental crust is present (James 2007a).

Continental rocks on the Cayman Ridge show that Cretaceous volcanic arc rocks accreted to Cuba cannot have come from the Pacific. Since Jurassic ‘oceanic’ rocks have been thrust onto Cuba from the south (Cobiella-Reguera 2009), the Yucatán Basin has to be at least in part Jurassic in age, not Paleocene as proposed by Pacific models.

Thin Caribbean ‘oceanic’ crust, serpentinite

Thin Caribbean crust, seen on seismic SE of thick crust in the Colombia and Venezuela basins, has
not been sampled in place. Ousted Jurassic rocks on Cuba, Hispaniola, Puerto Rico, La Désirade, Costa Rica and northern Venezuela suggest that oldest Mesozoic Caribbean crust is of that age. However, some thin crust could have formed much later (James 2007b).

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 across northern Venezuela from Margarita through Orinoco and El Roque to Cabo Vela on Guajira and southward into the serpentine belt of the Cordillera Central of Colombia. The most spectacular and widespread occurrences are on Cuba, where more than 6500 sq. km of serpentinite are exposed (Khudoley & Meyerhoff 1971). Yet more lies beneath Late Eocene and younger strata, so the total area is at least 15 000 sq. km (Kozary 1968). According to Donnelly et al. (1990) some (onshore) ‘plateau’ occurrences are dominantly serpentine, others basalt. Many consist of highly deformed and scattered mafic lithologies in a serpentinite matrix. Gabbros and peridotite with cumulate texture occur in a serpentinite matrix on NE Nicaragua (Flores et al. 2006). Dredging recovered serpentinite from the centre of the Cayman Trough (Eggler et al. 1973).

Hess (1966) suggested that serpentinized peridotite in the Caribbean region was hydrated upper mantle. The idea is supported by studies of the Galicia Bank and Iberian margins that indicate exhumation and serpentinization of upper mantle near the base of extremely thinned continental crust to form a layer with crust-like seismic velocities (Hopper et al. 2004). Diebold et al. (1999) noted low velocities in the mantle beneath thin crust southeast of the Caribbean plateau. Possible listric faults extend from the seafloor to the Moho. Serpentinite in the Cuban Jarahueca oilfield passing abruptly to almost unaltered peridotite (Rigassi-Studer 1961) supports this origin. Hydration results in density decrease and many serpentinites are diapiric or intruded along fault planes. Hence the typical sheared texture. Intrusion of the circum-Caribbean belt probably occurred around end Middle Eocene, with serpentinite occurring in and perhaps lubricating zones of greatest deformation (Hess 1938).

Volcanic arc rocks

Active, andesitic volcanic arcs on the southwestern and eastern Caribbean Plate margins in Central America and the Lesser Antilles relate to subduction of the Cocos and Atlantic plates, respectively, marked by the Middle America Trench, the Barbados Accretionary Prism in the south and a trench further north.

Volcanism in the Lesser Antilles terminates in the north near Saba, at the southern margin of the Greater Antilles, and in the south at Grenada, near the northern limit of the South American shelf. Tectonic faults in Atlantic crust in the north and south are envisaged to accommodate eastward movement of the Caribbean relative to the Americas. Central American volcanism terminates abruptly at the limits of convergence between the Cocos and Caribbean plates, at the Mexico–Guatemala border in the north (northern Caribbean Plate boundary) and at the Cocos Ridge in the south.

Ages of arc rocks are important for Caribbean understanding. Donnelly (1989) pointed out that if the Caribbean Plate migrated from the Pacific there should be no subduction zone on its western margin until eastward migration became impeded by Palaeogene collision at its leading edge. Thus it is important to note that Jurassic–Lower Dogger volcaniclastic rocks occur in Costa Rica (De Wever et al. 1985) and there is a Middle–Upper Jurassic subduction mélangé in NE Nicaragua (Flores et al. 2006).

Upper Jurassic volcanic rocks also occur on Cuba, Hispaniola and Puerto Rico, La Désirade and perhaps Tobago (Fink 1972; Bouysse et al. 1983; Snoke et al. 2001) and volcaniclastic rocks at least as old as Albian are known from the north-eastern Lesser Antilles (Donnelly et al. 1990). They suggest that volcanism around the Caribbean area began during Jurassic extension.

Stratigraphic and magmatic similarity of the upper parts of Cuban proximal and distal Jurassic sections shows that this volcanic-arc sequence was related to the continental margin (Cobiella-Reguera 2000) and ancient zircons in Cretaceous arc rocks (Rojas-Agramonte et al. 2006) confirm this. Basalts of the Oxfordian–Early Kimmeridgian El Sabalo Fm and part of the Encrucijada Fm (Aptian–Albian) appear to be oceanic crust contaminated by/erupted through continental crust (Kerr et al. 2003). Tobago arc rocks show continental input from the Albian and suffered tonalitic intrusion at that time (Snoke 1990; Snoke et al. 1990).

Cretaceous volcanic rocks and associated sediments are present on Cuba, Hispaniola, Puerto Rico, Aruba, Curaçao, Venezuela, Trinidad and Tobago. Together with the Aves Ridge, assumed to be an abandoned volcanic arc, and the active Lesser Antilles, assumed to be a Cenozoic volcanic arc, these are regarded as a ‘Great Caribbean Arc’ (Burke 1988), formed in the Pacific and driven between the Americas ahead of a migrating Caribbean Plate. The total length of this arc, consisting of the Greater Antilles, Lesser Antilles, Netherlands–Venezuelan Antilles is around 4000 km (300 km of
Oligocene–Recent, pull-apart extension removed). Pacific models illustrate the 4000 km Great Arc as originally nearly straight, trending NW or SE, then entering a gap of around 700 km wide and becoming highly curved, extinct and accreted to northern and southern plate margins and extant along the Lesser Antilles. This is, at best, difficult to imagine. Cretaceous–Eocene Caribbean and Cuban arc rocks were seen to subdivide into Late Jurassic–Early Cretaceous primitive island arc (PIA) and Late Cretaceous–Oligocene calc-alkaline (CA) suites (Donnelly et al. 1990). The chemical change occurred abruptly in the Albian (rocks on Hispaniola, Puerto Rico and Tobago, Lebron & Perfit 1993; Frost & Snoke 1989). However, calc-alkaline arc-like rocks occur in Jurassic meta-sedimentary rocks in the Escambray Massif of Cuba and PIA rocks range up to the Turonian in Cuba and the northern Virgin Islands (Kerr et al. 2003; Lardeaux et al. 2004; Proenza et al. 2006; Jolly et al. 2006).

The change from PIA to CA chemistry has been attributed to a reversal of subduction direction (Mattson 1984, 110 Ma; Pindell & Barrett 1990, 84 Ma; Lewis & Draper 1990, 95–90 Ma; Lebron & Perfit 1993, Albian). Frost & Snoke (1989) noted the influence of continent-derived sediments in the (oceanic arc) North Coast Schist of Tobago by the Albian. PIA Albian–Lower Cenomanian (planktonic foraminifera; K–Ar 91–102 Ma, Castro & Mederos 1985) volcanic rocks penetrated by the well Patao-1 offshore eastern Venezuela formed above metamorphosed continental crust. If the change of chemistry implies continental input, as suggested by Lebron & Perfit (1993), the arc could not have been in the Pacific when it occurred.

Reversal seems equivocal, with Maresch & Gerya (2005) even questioning its possibility. Kerr et al. (2003) conclude that there was no sudden change of chemistry and no Albian subduction polarity reversal. Samples of arc-related basalts of the same stratigraphic unit and age and just a few metres apart on Cuba have different geochemical signatures, reflecting different parental magmas (Kerr et al. 1999). Both island arc–tholeiite and calc-alkaline rocks occur in the Colombia basin of east-central Cuba. Kerr et al. (2003) and Jolly et al. (2006) suggest that chemical change resulted from increasing sediment input. The latest ideas are that chemistry changed diachronously eastwards and that it resulted from variation in subducted material (Lidiak 2008; Mitchell 2008).

Somoza (2008) suggests that early evolution of the Caribbean area was likely associated with opening of the central Atlantic, with NW–SE extension accommodated in corridors of thinned continental and oceanic lithosphere, separated by strike–slip/transform faults. Tholeiitic lavas emanated along NE trending faults. These faults changed to oblique sinistral transpression and even subduction when motion between the Americas changed to left lateral around 125 Ma. The NE faults became the locus of calc-alkaline activity and HP/LT metamorphism, producing a record similar to a subduction zone.

Volcanic arc activity ceased along 1000 km in Cuba in the Campanian and a new arc, with different orientation, formed in southeastern Cuba, Hispaniola and Puerto Rico in the Palaeogene (Iturralde-Vinent 1995; Mattietti-Kysar 1999; Rojas-Agramonte et al. 2006). It formed at 45° to the Cretaceous arc after a 15 Ma gap and faced south or SE, contrary to Pacific models (Iturralde-Vinent 1995). Blein et al. (2003) also concluded that two different island arcs were tectonically juxtaposed in central Cuba: the classical Lower and Upper Cretaceous suites of the Greater Antilles and a Jurassic to Lower Cretaceous island-arc suite with a Pacific provenance. Contrast in structural grain and lithology between southern Haiti and the rest of Hispaniola suggests that two island arcs existed in the Late Cretaceous, one in southern Haiti, Jamaica and the Nicaragua Rise and the other in northern Hispaniola, Puerto Rico and Cuba (Maurasse 1981).

Activity in the younger Cuban arc died in the Middle Eocene. Volcanism also largely ceased in Greater Antilles (36 Ma in the Virgin Islands) and along northern South America in the Middle Eocene. Volcanism switched off synchronously from Cuba to Puerto Rico, a distance of around 2000 km.

These multiple arcs, ages and chemistries do not reconcile with a single, Pacific-derived, Great Arc (Burke 1988) that collided diachronously with Cuba–Hispaniola–Puerto Rico.

The relation between subduction and volcanism seems problematic. Most of the Grenadines archipelago has not experienced calc-alkaline activity since the end of the Early Pliocene (c. 3.5 Ma), during which time a slab of 90 × 70 km has been subducted without producing surface volcanic activity (Westercamp 1988). Lesser Antilles basalt–andesites are products of mantle fusion and differentiation at shallow depths; fusion down a Benioff zone does not appear to be involved (Lewis & Gunn 1972). While Caribbean crust supposedly dips to around 300 km below the Maracaibo Basin (tomography, Hilst & Mann 1994), there is no volcanism and little seismicity in the area. No volcanism occurs in NW Colombia above a supposed Jurassic arc and Upper Cretaceous suites of the Greater Antilles that two different island arcs were tectonically juxtaposed in central Cuba: the classical Lower and Upper Cretaceous suites of the Greater Antilles and a Jurassic to Lower Cretaceous island-arc suite with a Pacific provenance. Contrast in structural grain and lithology between southern Haiti and the rest of Hispaniola suggests that two island arcs existed in the Late Cretaceous, one in southern Haiti, Jamaica and the Nicaragua Rise and the other in northern Hispaniola, Puerto Rico and Cuba (Maurasse 1981).

Activity in the younger Cuban arc died in the Middle Eocene. Volcanism also largely ceased in Greater Antilles (36 Ma in the Virgin Islands) and along northern South America in the Middle Eocene. Volcanism switched off synchronously from Cuba to Puerto Rico, a distance of around 2000 km.

These multiple arcs, ages and chemistries do not reconcile with a single, Pacific-derived, Great Arc (Burke 1988) that collided diachronously with Cuba–Hispaniola–Puerto Rico.

The relation between subduction and volcanism seems problematic. Most of the Grenadines archipelago has not experienced calc-alkaline activity since the end of the Early Pliocene (c. 3.5 Ma), during which time a slab of 90 × 70 km has been subducted without producing surface volcanic activity (Westercamp 1988). Lesser Antilles basalt–andesites are products of mantle fusion and differentiation at shallow depths; fusion down a Benioff zone does not appear to be involved (Lewis & Gunn 1972). While Caribbean crust supposedly dips to around 300 km below the Maracaibo Basin (tomography, Hilst & Mann 1994), there is no volcanism and little seismicity in the area. No volcanism occurs in NW Colombia above a supposed Jurassic arc and Upper Cretaceous suites of the Greater Antilles that two different island arcs were tectonically juxtaposed in central Cuba: the classical Lower and Upper Cretaceous suites of the Greater Antilles and a Jurassic to Lower Cretaceous island-arc suite with a Pacific provenance. Contrast in structural grain and lithology between southern Haiti and the rest of Hispaniola suggests that two island arcs existed in the Late Cretaceous, one in southern Haiti, Jamaica and the Nicaragua Rise and the other in northern Hispaniola, Puerto Rico and Cuba (Maurasse 1981).
Ancient zircons in arc rocks

Precambrian and Paleozoic zircons occur in Cretaceous calc-alkaline volcanic arc rocks in central and eastern Cuba and earliest Triassic or older zircons occur in gneiss in western Cuba (Rojas-Agramonte et al. 2006). Zircons of the same age occur in metasediments of the continental Escambray Massif. Detrital zircons in Cretaceous metavolcano-sedimentary rocks accreted to NW South America show proximity to continental margin (Cardona et al. 2008).

Upper Cretaceous turbidites on Curacao contain Mesozoic, Paleozoic and Precambrian zircons along with Barremian–Albian and Santonian–Campanian arc-derived grains (Wright 2004). Orthogneiss on the Macanáo Peninsula, Margarita Island, contains zircons with Carboniferous crystallization ages (U–Pb 315 +35/−24 Ma, Stockhert et al. 1995).

Pacific models maintain that the zircons were picked up by a migrating volcanic arc. The alternative is that they reflect autochthonous basement.

Metamorphic rocks

Metamorphic rocks, commonly HP/LT and attributed to subduction, are widespread on Caribbean Plate margins. Pacific models explain HP/LT rocks by capture of continental crust from Yucatán and Colombia by the entering Caribbean Plate in the Late Cretaceous. After burial to great depths (40–80 km) but at low temperatures, HP/LT metamorphic rocks surfaced ‘by arc-parallel stretching resulting from displacement partitioning along an oblique plate margin’ (Sisson & Lallemant 2002).

Along both the northern and southern plate boundaries uplift/elevation, size of islands/width of mountains, age of exposed basement, metamorphic grade and age of metamorphism decline from west to east, reflecting eastward-migrating transpression.

Greater Antilles island size diminishes from Cuba through Hispaniola and Puerto Rico to the Virgin Islands. Lower Cretaceous arc rocks are metamorphosed to blueschists in formerly contiguous SE Cuba–NW Hispaniola (Draper 1988) and in Jamaica (Abbott et al. 2003), greenschists–amphibolites occur on Puerto Rico while unmetamorphosed, Late Aptian–Early Albian Water Island volcanic rocks occur on the Virgin Islands (Jolly & Lidiak 2005). Jurassic metambasalts occur on La Desirade (Westercamp 1988). Jamaican blueschist formed at 5.1–6.2 kbar (Abbott et al. 2003). Eclogite and garnet glaucophanite from the Samaná complex of Hispaniola formed at 22–24 kbar and part of the Cuban Escambray Massif at 16–25 kbar (Stanek & Maresch 2006; c. 80 km lithostatic depth).

Along northern S America uplift diminishes from the Sierra Nevada de Santa Marta (>5000 m) through the Coastal Range of Venezuela (2400 m) to the Northern Range of Trinidad (1000 m), finally disappearing below sea level further east. Blueschists and eclogites derived from Late Jurassic–Cretaceous continental slope deposits occur between Puerto Cabello and Choroni in western Venezuela and in the Villa de Cura rocks of north central Venezuela (Menéndez 1966; Sisson & Ave Lallemant 1992). On the Paria Peninsula metamorphism is of extremely low grade (greenschist–chlorite); regional metamorphism grades from quartz–chlorite and quartz–mica schist to phyllites and slates and then sediments (Rodriguez 1968). Volcanic rocks of the islands Frailes and Testigos show, at most, low level metamorphism (Pereira 1985). Metamorphism of Palaeozoic rocks on the Paria Peninsula, Venezuela and in the Northern Range, Trinidad, occurred at 20–30 Ma (Speed et al. 1991). However, arc rocks on Tobago were metamorphosed to lower greenschists in the Alban (Snoke et al. 2001).

Greenschist to blueschists facies occur in the Purial area of eastern Cuba but in some sections the rocks are only slightly recrystallized (Boiteau et al. 1972). Interlayering of carbonate, pelitic and mafic metamorphic rocks is common on the Samaná Peninsula of NE Hispaniola (Joyce 1991). Cretaceous pelagic mudstones and limestone interlayered with basalt sills and flows occur on the Atlantic seafloor north of the Puerto Rico Trench and are exposed on the Presqu’île de Sud of Haiti. The Samaná rocks may be metamorphosed equivalents (Joyce 1991).

Metamorphic grade in the Caracas Group of northern Venezuela increases northward towards major transcurrent faults of the plate boundary but metamorphism remains locally low (Oxburgh 1966; Wehrmann 1972). HP metamorphic rocks of the western Coastal Range of Venezuela had Jurassic–Cretaceous continental margin protoliths and include reworked Palaeozoic rocks (Sisson et al. 2005). Further east greenschists of the Caribbean Series on the north of the Araya–Paria Peninsula are separated by the El Pilar Fault from Late Jurassic–Mid-Cretaceous sedimentary equivalents (Christensen 1961; Cruz et al. 2004).

According to Pacific models sedimentary Jurassic continental rocks in western Cuba (Guianagua-nico) and their metamorphosed equivalents in south Central Cuba (Isle of Pines, Escambray) were picked up from southern Yucatán and underplated to the forearc of a migrating volcanic arc in the Campanian (Pszczolowski 1999; Draper & Pindell 2004). However, similar rocks continue
through northern Hispaniola to the walls of the Puerto Rico Trough and as far as the Lesser Antilles (e.g. Boiteau et al. 1972), a distance of some 2500 km. It is unlikely that they all came from Yucatán. It is also unlikely that some of rocks were buried as much as 80 km to become metamorphosed while others remained unmetamorphosed. Similarly, metamorphic rocks along northern South America occur along with sedimentary rocks, a complication highlighted by Giunta & Oliveri (2009).

Metamorphic rocks systematically occur close to strike-slip faults along Caribbean margins (Goncalves et al. 2002). El Tambor HP/LT rocks of Guatemala occur in fault slices associated with the Motagua Fault Zone and preserve primary lithological features (Chiari et al. 2004; Harlow et al. 2004). Generally slight metamorphism in the Organos Belt of Cuba becomes extreme along the Pinar Fault (Pardo 1975). Pardo (1975) emphasized that Jurassic or older metasediments, marbles, dolomites, schists, graphitic schists, quartzite, gneiss and serpentinite of his Trinidad Belt are surrounded to the west, north and east by rocks of the Cabaigan belt (volcanic sediments, basalts, oolitic limestones tuffs, sandstones). Completely unaltered and unmetamorphosed Upper Jurassic oolitic limestones and Neocomian limestones occur along faults between the belts.

The oldest rock fabrics in eclogite- and blueschist-facies rocks of the Upper Jurassic–Lower Cretaceous Gavilanes unit of south-central Cuba indicate arc-parallel extension and the NW-trending mineral lineations and sheath folds parallel present-day structure (Stanek et al. 2006). Fabric in eclogite and blueschist of western Venezuela manifests dextral shear (Avé Lallemant & Sisson 1992), parallel to major faults. Arc-parallel shear affected the North Coast Schist of Tobago during Albian, producing low-grade regional metamorphism (Snoke 2003). Strain must have occurred in the present location/orientation and not along a north–south trending arc.

Paired metamorphic belts are observed on northern Jamaica and Hispaniola (Abbott et al. 2003; Nagle 1974) alone and both indicate continent to the south during the Cretaceous. On Cuba thrusting of Bathonian (170 Ma, zircon data) eclogite and metasediments metamorphosed in the Middle to Late Cretaceous (U–Pb, Rb–Sr, Ar/Ar dates) occurred to the north (Stanek et al. 2005).

For this paper, it is not reasonable to attribute Mesozoic HP/LT metamorphism in the Caribbean area to ancient subduction zones when no such rocks are seen along active zones. There is no evidence of return-path (HP/LT) material in the Lesser Antilles or Central America, where volcanic arc activity has been underway since at least the Albian and probably since the Jurassic. Some blueschists obducted in the Caribbean show no evidence of coeval volcanism (Maresch & Gerya 2006). Andesites are common in subduction volcanic arcs (Leat & Larter 2002), but there is little mention of andesites along northern South America (Eocene andesite on Los Testigos). This at odds with Mid-Cretaceous subduction invoked to explain eclogites and blueschists from Late Jurassic–Cretaceous continental slope protoliths (e.g. Avé Lallemant & Guth 1990; Avé Lallemant & Sisson 1992; Sisson et al. 2005). Bellizia (1972) also noted the absence of paired metamorphism along this area.

The above data suggest development of metamorphism close to plate boundary faults where great burial depths occur in foredeeps associated with strike-slip. Since transpression is migrating eastward along northern and southern plate boundaries, we can look to the east for a modern scenario where HP/LT metamorphism might occur.

The Columbus Basin south of Trinidad today contains up to 25 km of Cenozoic sediments above Mesozoic section perhaps equally thick (e.g. Heppard et al. 1998, fig. 5). Heat flow in the contiguous Maturín Basin is low to moderate (1.3 ± 100/100, 1–1.5 hfu, 35–40 mW/m², George & Socas 1994; Summa et al. 2003), as is common in foreland basins. These are conditions capable of generating blueschists.

Maturation of organic matter, clay diagenesis, mineral transformation, osmosis and fluid volume increase with rising temperature can all add to lithostatic pressure. Such mechanisms, coupled with clay seals of zero permeability, are responsible for pressures up to twice lithostatic in the Columbus Basin where Late Cenozoic subsidence (up to 9 km Pli–Pliocene sediments) has been dramatic (Heppard et al. 1998).

Transpression west of Trinidad led to thrusting and exhumation of deeply buried rocks. The horizontal stress required to form mountains is estimated to be as high as 6.0 kbar (Price 2001). Transpression that emplaced nappes of oceanic crust several kilometres thick and hundreds of kilometres long onto Caribbean continental margins and rapidly lifted metamorphosed Mesozoic section to form mountain ranges must play an important role.

**Palaeontology**

**Central American land bridge/barrier**

Just as Central America forms a land bridge between North and South America today, so it did at times in the past. Faunal studies indicate times of connection and thus separation of Pacific from the Caribbean.
Morris et al. (1990) summarized palaeontological evidence of connection between North and South America from the Early Carboniferous, through the Triassic, all of the Jurassic and parts of the Cretaceous (Kauffman 1973; Abouin et al. 1982; Rémane 1980). Widespread Jurassic calpionellids in the Caribbean, absent from coeval strata in the Pacific (Rémane 1980), record a barrier between the areas. Dinosaur and marsupial fossils show that North and South America were connected in the Cretaceous (Keast 1972; Estes & Báez (1985). Mammalian faunas show North–South America connection in the Late Cretaceous but little evidence of interchange in the Paleocene and Eocene (Gingerich 1985). Disappearance of hermatypic corals from the Caribbean in the Late Oligocene resulted from isolation from the Pacific by Central America (Frost 1972). An Oligo–Miocene turtle from Costa Rica and Middle–Late Miocene terrestrial mammalian fossils from Panama, Honduras and El Salvador show North American affinities (Lucas et al. 2006). The Middle Miocene–Upper Pliocene saw the steady disappearance of genera still living in the Indo-Pacific. Early–Middle Miocene formations in Panama show sub-aerial environments (Morón & Jaramillo 2008).

In summary, there is evidence of a long-lived Central America land bridge.

Radiolaria

In the Caribbean region ribbon-bedded radiolarites occur on the Nicoya Complex (NW Costa Rica), the Siuna Oceanic Complex (NE Nicaragua), Duarte Complex (Hispaniola), Mariquita Chert (SW Puerto Rico) and in the Phare Unit (La Deísirade) (Baumgartner et al. 2005). The only clear occurrence as cover to MORB-type ocean floor seems to be in the Duarte Complex, Hispaniola. On La Déísirade they are interbedded with back-arc pillow basalts (Gauchat 2004).

Since no DSDP/ODP site in the Atlantic has penetrated red radiolarian chert, Caribbean bedded cherts are seen to indicate a Pacific origin (e.g. Montgomery & Kerr 2009). However, Jurassic radiolaria occur in sediments just above basalt at Site 534, on the Blake Plateau, close by the Caribbean islands (Bartolini & Larson 2001) and it has to be possible that Atlantic red cherts exist but remain unsampled. Jurassic red cherts are present throughout the Mediterranean and Middle East.

Late Tithonian radiolaria occur in the volcano-sedimentary component of the Northern Ophiolite Belt of Cuba (Cobiella-Reguera 2009). The rocks were obducted from the south. Since continental rocks occur in the walls of the Cayman Trough these oceanic rocks must have come from the Yucatán Basin. Jurassic ribbon-bedded radiolarites in the lower Cretaceous Siuna mélangé must also have formed in a Caribbean location.

Some bedded cherts are not associated with ophiolites and mélanges and some formed in deep, elongate basins like the Gulf of California or Red Sea (Blatt et al. 2006). The continental margin rift origin for the Caribbean discussed in this paper fits this scenario and might explain some of the radiolarites in the area.

Rudists

Rojas (2004) noted rudistid correlations between the Caribbean margin and Cretaceous volcanic arc rocks. Early Aptian rudistids (Amphitritiscoelus waringi association) extended from Mexico and Trinidad to France and were linked to the Tethyan continental margin. Albion, Santonian and Campian Tepeyacia corrugata, Durania curasavica and Barrettsia monilifera associations (Antillean region and Mexico) appear to have characterized the Cretaceous volcanic island arc while the Maastrichtian Tepeyacia giganteus association characterized carbonate platforms of the largest Antilles, the Bahamas (Cuba), Central America and Mexico (Chiaapas).

Cretaceous rudists from Cuba, Hispaniola and the continental margins and Aptian–Cenomanian gastropods of Mexico, the Gulf of Mexico and the Caribbean show strong affinity with Tethyan faunas (Buitrón-Sánchez & Gómez-Espinosa 2003; Rojas 2004; Mycxynski & Iturralde-Vinent 2005).

Organic material

Upper Cretaceous organic-rich sediments occur at several widely separated sites in the Caribbean and Atlantic. Absence of carbonaceous material in Pacific cores of the same age shows that a barrier separated bottom waters of the Pacific and Caribbean (Saunders et al. 1973).

Oil offshore Belize is typed to Jurassic source rocks with chemistry similar to the Smackover of the Gulf of Mexico. If the volcanic arc of Pacific models had passed by, removing continental basement, Jurassic source rocks would not be preserved at this location. Similar oil on Jamaica shows that the island did not come from the Pacific.

Lower Cretaceous rocks on Hispaniola resemble the La Luna of Venezuela (black, chert nodules, Bowin 1975). They indicate similar palaeogeography of restriction close to continent, not open ocean conditions.
**Palaeomagnetic data**

Palaeomagnetic data show that ophiolite complexes of the Pacific coast of Costa Rica and western Panama formed in an equatorial position and moved approximately 10° since, conforming with the movement of South America (Frisch et al. 1992, Calvo & Bolz 1994). Data show that Chorotega has not rotated relative to South America (Di Marco et al. 1995). Palaeomagnetism of rocks of the Guaniguangoan Terrane, western Cuba indicates a palaeopole not significantly different from North American Jurassic–Cretaceous poles (Alva-Valdivia et al. 2001).

Drilling at DSDP Sites 146, 150, 151, 152, 153 penetrated diabase sills below upper Cretaceous sediments. Palaeomagnetic measurements on 23 igneous specimens and a further 11 from adjacent sediments at Sites 146 and 152 conform to those from the surrounding area including Jamaica, Puerto Rico, northern Colombia and Venezuela (Lowrie & Opdyke 1975). Two holes at Site 1001 penetrated Mid-Campanian volcanic rocks. Magnetic directions recorded by the flows indicate that the plateau was near the palaeoequator in the Mid-Campanian (Sigurdsson et al. 1996).

In contrast to these ‘in situ’ indications, other studies claim to document rotation of elements during plate or block migrations. Cretaceous and Cenozoic intrusive rocks of the Villa de Cura and Tinaco belts of Venezuela are seen to have rotated clockwise by 90° during accretion onto the northern margin of South America as a north–south trending arc collided with the continent (Skerlec & Hargraves 1980). Similar data from the northern plate boundary, where anticlockwise rotation mirror imaging of this model would be expected, are lacking. While data from the Chiapas Massif, southern Mexico, are consistent with a pre-rift location of the Maya Block rotated to the coast of Texas and Louisiana (Molina-Garza et al. 1992), rotation of the block is denied by parallelism of its structural trends with regional tectonic fabric. These magnetic data are all from locations of oroclinal bending and strike–slip.

Gose & Swartz (1977) show Honduras migrating since the Aptian–Albian from 10°N to 30°N, back to 20°N then to 15°N to 20°N and finally to its present position at 15°N. These unlikely wanderings are the result of poorly controlled stratigraphy (Wilson & Meyerhoff 1978). Steiner (2005) shows a similarly unlikely history for the Maya Block (Yucatán), migrating from a Permain position off NW South America to SW Mexico in the Triassic, then into the northern Gulf of Mexico (Middle–Late Jurassic) and finally south to its present position in the Late Jurassic.

**Stratigraphy**

**Cretaceous**

There is geographic continuity from Mesozoic sedimentary to metamorphic rocks and indications of nearby volcanoes along northern South America. The Cenomanian–Turonian La Luna Fm, source of the rich resources of the Mara__caibo Basin, contains tuffs and shows silica content increasing to the north. Here, graphitic schists of Las Mercedes Fm also show northward-increasing silica content and lenses of volcanic ash occur in the northernmost outcrops (Wehrmann 1972). Some units are only lightly metamorphosed and contain concretions identical to those in the La Luna Fm (Wehrmann 1972). Further north the Las Mercedes interdigitates with the metamorphic Tacagua Fm, originally tuff or volcanic ash (Dengo 1953; Feo Codicido 1962). The northern sections thicken to several thousand metres and possibly extend down to the Jurassic.

The eastern Venezuela equivalent of the La Luna, the Querecul Fm, also exhibits northward-increasing chert content. Lower Cretaceous (?) serpentinites and low grade metagabbro, metatuffs and metapillow lavas on the Araya Peninsula and Margarita are possible stratigraphic equivalents to the Querecul (Chevalier 1987). Offshore the low-grade metamorphic rocks of the deep-marine, Lower–Upper Mejillones Complex include lavas, volcaniclastics, radiolarites, basalts, massive limestones and organic brown cherts. The well Patao-1 found tholeiitic basalts (radiometric ages 91–102 Ma, Albian–Cenomanian planktonic forams) associated with metamorphosed continental crust (Pereira 1985).

Yet further east the bituminous, cherty argillites of the Albian–Campanian Naparima Hill and Gautier limestone Fms source hydrocarbons in Trinidad. In the Northern Range tuffs occur in the Barremian Toco Fm. The overlying Sans Souci Volcanic Fm is a series of volcanic tuffs, tuff breccias, agglomerates and andesitic lavas erupted onto the passive margin of South America during the Aptian–Santonian (Kugler 1953). Associated sediments are limestones, black, carbonate shale and quartz sandstones and conglomerates with continental provenance (Wadge & Macdonald 1985). Albian tuff on Tobago shows continental chemical signal (Sharp 1988; Frost & Snoke 1989).

On the northern Caribbean margin the clay content of the Florida Cretaceous shows montmorillonite in Upper Cretaceous and illite in Lower Cretaceous rocks increasing from north to south (Weaver & Stevenson, 1971, quoted by Meyerhoff & Hatten 1974). Illite comes from a mica–schist terrane such as south Cuba; the montmorillonite
comes from a volcanic terrane, such as Cuba. Tuffs and radiolarian cherts in autochthonous deep water Tithonian to Maastrichtian rocks on Cuba (Lewis 1990) record nearby volcanism.

**Late Cretaceous–Paleocene**

At Site 146/149 aphanitic limestones and clays-
tones of Campanian age are followed by siliceous limestones and black cherts with Maastrichtian claystones and Paleocene laminated claystones interbedded with siliceous limestones (Saunders et al. 1973). The same sequence occurs in the Río Chávez Fm and in the Mucaria Fm of the Piemont- tine Nappe in northern Venezuela (Vivas & Macsotay 2002). The abyssal sediments remained in their original position, while the Mucaria and Río Chávez formations were imbricated and thrust above the South American passive margin during a Middle Eocene event.

**Eocene**

*Middle Eocene seismic horizons and cherts show Caribbean–Atlantic affinities.** Regional Caribbean seismic Horizon A’’ is identified at ODP sites 146/149 and 153 as the onset of lithification at the Early–Middle Eocene level (Saunders et al. 1973). Chert (crystalobalite) and interbedded compact chalks and limestones underlie radiolarian–foraminiferal ooze and chalks. Chert formation involves redistribution of silica from radiolarian tests and no additional silica is involved according to Saunders et al. (1973). However, dispersed volcanic ash forms 10–20% of the deeper sedimentary column at Site 1001 and ash alteration may have provided silica for the chert (Sigurdsson et al. 1996). Coincidence of Horizon A’’ with cessation of volcanism along the northern and southern margins of the Caribbean Plate supports this idea. Cristobalite occurs in ash from the Soufriere Hills Volcano of Montserrat (Baxter et al. 1999).

Eocene chert occurs also in cores from the Straits of Florida where rapid deepening (below the CCD?) occurred from the Late Cretaceous through Early Cenozoic (Schlager & Buffle 1984; Roberts et al. 2005). Radiolaria-rich sediments overlying earliest Middle Eocene siliceous limestones and cherts correlated with horizon A’’ are also found in the Middle Eocene at Sites 27 and 28 east of the Lesser Antilles and north of the Greater Antilles (Edgar et al. 1973). Similar radiolarian rich sediments appeared suddenly in the Middle Eocene of Barbados, in the Atlantic. Paleoe- cene and Eocene green cherty tuffs and pelagic sedi-

Early Middle Eocene Atlantic Layer Ac (Mountain & Tucholke 1985), calibrated by Joides 6 and 7, also comprises cherty turbidites, lutites and siliceous mudstones, rich in radiolaria, diatoms and sponge spicules, overlain by red clays.

There is no record of Middle Eocene cherts in the Pacific.

**The Scotland Group of Barbados; the Barbados Ridge and thick sediments in the SW Caribbean.** The Barbados accretionary prism includes the Middle Eocene Scotland Group of Barbados, an almost pure quartzite with blue quartz derived from the Guayana Shield. It resembles the Lower–Middle Eocene Mirador and Misoa Fms of Colombia and Venezuela (Senn 1940; Meyerhoff & Meyerhoff 1972; Dickey 1980). The Scotland sandstones are interbedded with hemipelagic units containing Middle and Late Eocene radiolaria (Cuevas & Mau rasse 1995).

Models of Caribbean Plate migration along northern South America suggest that Scotland sediments were shunted from a location north of the Maracaibo Basin (Dickey 1980; Burke et al. 1984; Pindell 1993). However, zircon fission track ages for this area range from 50 to 126 Ma. Zircons from Scotland sandstones give fission track ages of 20–80, 200–350 and >500 Ma (Baldwin et al. 1986). Other models have shown the sands arriving north of the Araya Peninsula in the Middle Eocene (Kasper & Larue 1986) or Oligocene (Pindell et al. 1998). The latest model suggests that the ridge comprises two prisms merged in the Miocene (Pindell & Kennan 2009).

As long ago as 1908 Suess noted that older formations of Barbados are genetically related to correlative units on Trinidad. The sandstones lie outboard of the Lesser Antilles are but contain no volcanic quartz. Instead, polycrystalline quartz, feldspars and heavy minerals reflect orogenic and cratonic metamorphic/plutonic crystalline sources (Kasper & Larue 1986). Exotic rocks like the Napa-ima Hill and blocks of Albian limestone bearing fauna identical to rocks of Trinidad and eastern Venezuela show northeastern South America provenance (Vaughan & Wells 1945; Kugler 1953; Douglass 1961; Tomblin 1970; Meyerhoff & Meyerhoff 1972). Poor sorting and angular to sub-rounded grains (Senn 1944) indicate abrupt or short distance rather than prolonged transport though Trechmann (1925) described rounded quartz pebbles and sand grains.

Basement ridges on the Atlantic floor cause ponding of modern Orinoco fan sediments (Peter & Westbrook 1976). The Barbados Ridge dies out at the Tiburón Rise (Dolan et al. 1990) where
Panama arc collided with the SW Caribbean in the 2003; García-Senz & Pérez-Estaún 2008). The 1987; Mauffret & Leroy 1997; Jacques & Otto 2002 transport of Barbados Ridge sediments was stopped by the Tiburón Rise, which lies on the Atlantic Plate and is moving west.

Scotia deposition is thought to most be a deepwater deposit (e.g. Pudsey & Reading 1982), though earlier investigators recognized shallow indicators (Hess 1938 – shallow water, perhaps terrestrial; Baadsgaard 1960 – polygonal mudcracks; Barker & McFarlane 1980 – supratidal flat). Fresh and unbroken fresh-water genera (Unio, Cyprea, Ampullaria) occur in ‘beds full of large fresh-water mollusca’ and show affinity with Soldado Rock, Trinidad (Trechmann 1925). Wide-spread Middle Eocene shallow water carbonates in the Caribbean region support a shallow origin for the Middle Eocene Scotland.

Barbados Ridge basement is not calibrated by the drill. Seismic data show what appears to be rifted basement to the west and east of the Barbados Accretionary Prism. It could be transitional crust, extended in the Jurassic. This would explain the NE trend of structures on Barbados (Trechmann 1937; Meyerhoff & Meyerhoff 1972), which conform to the regional tectonic grain of Middle America.

The eastern Caribbean was the site of a thick Eocene deposition at sites west of the Aves Ridge, in the Grenada Basin and in front of the Lesser Antilles. A fan of probably Cretaceous–Eocene turbidites lies in the southern part of the Venezuela Basin and the Grenada Basin contains up to 9 km of sediments (Driscoll et al. 1995). They do not support opening of the Grenada Basin by Oligocene back-arc spreading (e.g. Pindell et al. 2005, fig. 5G) and such a thickness does not support Pacific origins of the Caribbean Plate.

**Major Caribbean ‘events’**

Mattson (1984) noted unconformities and hiatuses around the Caribbean in the Aptian–Albian, Santonian, Paleocene, Middle–Late Eocene and Oligocene. To these we can add Campanian and Miocene unconformities. The latter is seen along northern South America, in Panamá, the Dominican Republic and on the Caribbean Plate interior (Biju-Duval et al. 1982; Okaya & Ben-Avraham 1987; Mauffret & Leroy 1997; Jacques & Otto 2003; García-Senz & Pérez-Estaún 2008). The Panamá arc collided with the SW Caribbean in the Middle Miocene and a structural event is observed in the Serranía del Interior of eastern Venezuela (Benkovics et al. 2006). The Campanian event is recognized in western Venezuela (Cooney & Lorente 2009).

Data relevant to three circum-Caribbean unconformities are discussed here because they underscore regional, contiguous geology and they raise questions about responsible processes.

**Aptian–Albian**

Albian shallow marine limestones, commonly associated with unconformities and often karstified, are regionally distributed around margins of Middle America. Albian plate margin collision, intrusion and change of arc chemistry characterize Caribbean margins (James 2006, fig. 5).

Donnelly (1989) observed that shallow-water, Albian limestones overlie an unconformity around the Caribbean. Shallow marine Albian Atima limestones overlie metasedimentary basement in Honduras (Rogers & Mann 2007). In Nicaragua, thick-bedded limestones that correlate with the Atima Fm contain well-rounded/sorted and imbricated volcanic pebble conglomerates recording a high energy/beach environment (Flores et al. 2006). Albian–Campanian platform limestones occur above thin continental Jurassic or Palaeozoic basement rocks on Maya (Cobán/Ixcoy, Campur Fms; Donnelly 1989). Oceanic and continental basement of western Mexico (Guerrero) is capped by Albian limestones (Tardy et al. 1994).

On Cuba, Aptian–Albian limestones occur both in the North American passive margin section of the north (Palenque and Guajaibon Fms) and in the volcanic arc terrane of the south (Guaos Fm, Cobbella-Reguera 2001, pers. comm.). On Hispaniola and Puerto Rico the limestones are the Hatillo Fm and the Barrancas and Río Matón limestones (Lewis 2002; Myczynski & Iturralde-Vinent 2005). The Andros-I well (Bahamas) bottomed in Albian back-reef carbonates (Meyerhoff & Hatten 1974). Albian intertidal–supratidal carbonates form the eastern-most Bahamas Platform (Silver and Navidad Banks) and on the southern wall of the Puerto Rico Trench (Schneidermann et al. 1972). A shallow-water carbonate platform-complex extended from the West Florida Shelf across what is now the Straits of Florida and northern Cuba to the Bahamas (Iturralde-Vinent 1996).

Albian limestones occur across northern South America (e.g. James 2000). The Late Aptian Machiques Member of the Maracaibo Basin consists of bituminous shales and limestones. Limestones of the overlying Lisure and Maraca Formations range to Late Alban and record open marine conditions. In Eastern Venezuela Albian bituminous limestones and shales occur in the Cutacual Formation of the
Serranía del Interior. They interinger with open marine El Cantil Formation limestones.

Lewis (2002) listed Albian unconformities on Hispaniola, Cuba, Puerto Rico, Jamaica and the Virgin Islands. Aptian–Albian (110 Ma) metamorphism, deformation and intrusion occurred north-eastern Nicaragua, Cuba, Hispaniola and Puerto Rico and a coeval break is present along the southern plate boundary in the Caribbean Mountains, Santa Marta Massif and on the Colombia–Caribbean coast (Mattson 1984). Obduction of peridotites onto Hispaniola occurred in the Aptian–Albian (Draper et al. 1996). Metamorphism of the Venezuelan Caracas Group occurred in the Early Albian. There is a probable karstification surface within Aptian carbonates in the Maracaibo Basin (Castillo & Mann 2006) and cavernous limestones at the Lower–Upper Cretaceous boundary indicate subaerial exposure on the Bahamas Platform (Cay Sal well, Paulus 1972). The Late Albian–Early Cenomanian El Abra Fm of Mexico is karstified and there is a karsted unconformity at the top of the Albian Edwards and Orizaba limestones of the San Marcos and Cordoba platforms of Texas and Mexico (Carrasco 2003).

Volcanic arc rock chemistry changed from primitive to calc-alkaline in many areas, reflecting continental input. Aptian U–Pb ages of zircons and equivalent trace-element geochemistry link volcanic rocks and tonalites on Hispaniola, while Albian Ar/Ar ages of tonalite hornblende record final cooling after emplacement (Escuder Viruete et al. 2006). Zircon fission track cooling of diorite and tonalite occurred at 103 Ma on Tobago (Cerveny et al. 1990; Sigurdsson et al. 1996), calibrated by DSDP Leg 15, formed at 90–88 Ma.

Foundering of carbonate platforms occurred during the Mid-Cretaceous. DSDP sites along the top of the Campeche Escarpment found Albian shallow-water sediments at depths of 1500–1800 m water depth unconformably overlain by Late Cretaceous–Paleocene deep-water deposits (Worzel et al. 1973; Antoine et al. 1974). Drowning and breakup of the west Florida–Cuba–Bahamas platform began during the Late Albian (?) to Middle Cenomanian when the southern Straits of Florida became a deep water trough (Iturralde-Vinent 1996).

These data point to regional convergence, uplift, shallow-water carbonate deposition, exposure and karstification and accretion. Perhaps they are related to the Albian separation of South America from Africa (Ladd 1976).

Cenomanian

An angular unconformity developed on Chortís between the marine shales of the Late Albian to Early Cenomanian Krausirpe Fm and the overlying Late Cretaceous Valle de Angeles Fm clastics and there is a palaeokarst on top of the Albian–Cenomanian Atima limestone (Rogers & Mann 2007). An angular unconformity separates Cenomanian or Turonian and the overlying Campanian or Maastrichtian throughout the Greater Antilles (Khudoley & Meyerhoff, 1971). Late Senonian reef/-platform carbonates lie above a Cenomanian unconformity on the Nicoya Peninsula, Costa Rica (Calvo & Bolz 2003, pers. comm.). Shallow-water limestones formed in Cuba (Pardo 1975) Puerto Rico (Santos 2002; Laó-Dávila et al. 2004) and Jamaica (Mitchell 2005).

A Cenomanian hiatus is recorded on the Guajira Peninsula and Aruba and Curacao became emergent in the Late Cretaceous (Alvarez 1968; Beets 1972; Wright 2004). Aruba suffered tonalite intrusion at 89 Ma.

Metamorphism affected Guatemala, the Isthmus of Tehuantepec (Dengo 1985) and Aruba (Wright 2004). Cretaceous volcanism ceased along 1000 km of the Cuban arc (Iturralde-Vinent 1995; Cobilla-Reguera 2009), in Jamaica (Draper 1986), the Netherlands Antilles (Beets et al. 1984) and Costa Rica (Calvo 2003).

Regional Caribbean seismic Horizon B” (Case 1974; Donnelly et al. 1990; Sigurdsson et al. 1996), calibrated by DSDP Leg 15, formed at 90–88 Ma.

Middle Eocene

Kugler (1953) introduced the term wildflysch to South America to describe slump masses of Barremian, Aptian, Albian and Turonian rocks in Paleocene shales in Trinidad and eastern Venezuela. The concept was rapidly applied to units containing large (several to many kilometres, formerly mapped as distinct formations) olistoliths/olistostromes in western Venezuela. The American Geological Institute defines wildflysch as a mappable stratigraphic unit of flysch containing large and irregularly sorted blocks and boulders resulting from tectonic fragmentation, and twisted, contorted and confused beds resulting from slumping or sliding under the influence of gravity (Jackson 1997). In many cases the wildflysch lies beneath nappes that supplied the detritus. The deposits in this sense record approach and emplacement of displaced rocks that supplied and came to overlay the wildflysch. In many Caribbean cases the wildflysch formed and the nappes, some of very great thickness and area, were emplaced rapidly in the Middle Eocene, seemingly recording a regional, abrupt and violent event (Stainforth 1969; James 1997, 2005a, 2006, fig. 6).

Flysch and wildflysch deposits occur in Central America (Rivas, Las Palmas and Brito Fms),
Paleocene flysch. The western continuation of the Villa de Cura allochthons today lies offset to the north and dispersed along the Aruba–Blanquilla islands (James 2005a).

This was a violent and unexplained event, clearly distinct from Oligocene–Recent, diachronous transpression along the northern and southern Caribbean Plate boundaries. Its energy is recorded by the size of emplaced bodies. Cuban ophiolites extend for some 1000 km, are up to 5 km thick and suffered up to 140 km of transport (Cobiella-Reguera 2008, 2009). In Venezuela the Villa de Cura nappe is 250 km long and 5 km thick. Up to 18 thrust slices in Mexico’s Veracruz Basin stack 6 km high and moved at least 30 km (Mossman & Viniegra 1976, fig. 2).

The deposits record regional, shared, coeval history between the Caribbean Plate and its continental neighbours. They do not support diachronous passage of a migrating plate or localized ‘Proto-Caribbean’ subduction along northern South America (Pindell & Barrett 1990, Pindell et al. 2006; Pindell & Kennan 2009).

Middle Eocene unconformity overlain by shallow marine limestones

The Middle Eocene event resulted in uplift to wave-base where a regional unconformity formed. Overlying shallow marine, Middle Eocene limestones developed in the photic zone (James 2005a).

Several authors refer to this 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. Gudez (1985) noted late Middle Eocene uplift of the Monay–Carora area. Uplift of the Mérida Andes and the Sierra de Perija began in the Eocene (Chigne & Hernandez 1990; Audemard 1991). Fission-track data indicate Middle Eocene uplift of the Cordillera de la Costa, Serrania del Interior and the Maracaibo Basin (Perez de Armas 1999; Sisson et al. 2005) and apatite annealing at 45 Ma shows uplift was occurring on Tobago (Cerveny & Snoke 1993). Maresch et al. (1993) and Kluge et al. (1995) reported (K–Ar) radiometric data indicating uplift of Margarita Island at 50–55 Ma. A regional unconformity (‘Post-Eocene Unconformity’) truncates the Eocene section in the Maracaibo Basin. The greatest erosional vacuity (3000 m) is in the north of the basin but yet further north an estimated 4000 m of Eocene were removed from the Guajira area. An Eocene unconformity separates the primary reservoirs above from the secondary reservoir and source rocks below in Colombia’s Middle Magdalena Valley (Mora et al. 1996).
In the Golfo Triste, western Venezuela, sedimentary upper Eocene lies above lightly metamorphosed Eocene-Paleocene (Ysaccis 1997). The Middle Eocene section of the northern Tuy–Cariaco Basin, east-central Venezuela, comprises lower, deep-water shales and upper, shallow, algal, platform limestones.

In the Greater Antilles tectonic unconformities are observed on land and at sea in the Upper Eocene of Cuba and Hispaniola (Calais & Mercier de Lepinay 1995). In western and central Cuba the Upper Eocene overlies the Lower and Middle Eocene with prominent angular unconformity (Kholodley & Meyerhoff 1971). Arc volcanism in Cuba that had resumed in the Mid or Late Danian along the east–west trending, south-facing Turquino–Cayman Ridge–Hispaniola(?) Arc died in the Middle Eocene (Iturralde-Vinent 1995; Cobiella-Reguera 2009). Arc volcanism also died along 2000 km of the Greater Antilles at this time (Gestel et al. 1999). Isotopic data indicate exhumation of metamorphic rocks on Roatan Island, Honduras, in the Late Eocene–Early Oligocene (Avé Lalleman & Gordon 1999).

A regional unconformity separates the upper Middle Eocene through the lower Oligocene in northern Puerto Rico and Late Eocene–Oligocene uplift from basal to shallow marine conditions occurred in the south (collision), with erosion of 1–2 km of section (Montgomery 1998; Larue et al. 1998). Middle Eocene emergence of the Greater Antilles allowed terrestrial flora and fauna to colonize the area (Graham 2003). A prominent Middle to Late Eocene unconformity in the deep western approaches to the Straits of Florida, calibrated by DSDP site 540 and by seismic data, reflects slope instability and mass wasting (Angstadt et al. 1983).

In Central America a Middle Eocene tectonic uplift and erosion terminated activity of the Santa Elena subduction zone (Lew 1985). A hiatus covers most of the Late Eocene–Early Oligocene interval in eastern Panamá, with deep-water sedimentation occurring again in the Middle Oligocene (Bandy & Casey 1973). Continental areas formed in the arc in the Middle–Late Eocene in Costa Rica (Barbosa et al. 1997).

Hunter (1995) described a line of late Middle Eocene algal/foraminiferal limestones from the Central American Isthmus, Colombia (Ciéncias de Oro or Tolu) to Venezuela (Tinajitas), capping highly deformed flysch and other deep-water sediments. They are best developed on the frontal thrusts. They occur on Aruba (Helmers & Beets 1977) and Curaçao (Beets 1977). On Bonaire a ?Paleocene/Eocene fluvial conglomerate (Soebi Blanco Fm) is followed by upper Eocene limestones (Lagaay 1969). Middle Eocene limestones occur on Jamaica (Fonthill limestone, White Limestone, Chapleton Fm), Cuba, Haiti (Plaisance or Hidalgo limestones), St Barts (St Bartholomew Fm), Tortolla and Virgin Gorda (Tortola, Neckler Fms; Christman 1953; Butterlin 1956; Burke and Robinson 1965; Robinson 1967; Tomblin 1975; Lewis & Draper 1990; Iturralde-Vinent 1994; Pubellier et al. 2000; James & Mitchell 2005). They are known also from the southern wall of the Puerto Rico Trench and from the Mona Canyon (Fox & Heezen 1975; Perfit et al. 1980). Jordan Knoll may have been uplifted in Middle Eocene time (erosion; Bryant et al. 1969).

Shallow marine limestones occur in Costa Rica at Parritilla (southern Valle Central), Damas (Parrita), Punta Catedral (Quepos promontory), Penón de Arío (Nicoya Peninsula), and Quebrada Piedra Azul (Burica Peninsula) (Bolz & Calvo 2002). Carbonate platforms developed on late Middle Eocene folds and thrusts in the South Limón Basin (Fernández et al. 1994). A widespread limestone at the top of the turbiditic Brito Fm in the Nicoya Complex continues through the Nicoya Peninsula (Junquillal and Punta Cuevas Limestones), the Central Pacific provinces (Damas Limestone) and the Térraba Basin (El Cajón and Fila de Cal limestones) to the Chiriquí (David Limestone) and Tuira-Chucunaque (Corcona Limestone) basins of Panamá (Escalante 1990). Middle Eocene reef limestone (Río Tonosi Fm) overlies upper Cretaceous basalt in SW Panamá (Kolarsky et al. 1995).

In the Lesser Antilles the northeastern branch of low-lying Lesser Antillean islands is called the Limestone Caribees because of extensive Middle Eocene–Pleistocene calcareous cover (Maury et al. 1990). Siliceous limestones with Middle–Early Eocene foraminifera occur on Mayreau and of Upper Eocene, reefal limestones on Carriacou (Tomblin 1970).

Middle Eocene limestone also occurs within the Caribbean Plate on the Aves Ridge, Saba Bank and the Beata Ridge (Fox et al. 1970, 1971; Nagle 1972; Pinet et al. 1985; Bouysse et al. 1990). The Middle Eocene Punta Gorda limestone occurs above deformed Late Cretaceous Valle de Angeles beds on the Nicaragua Rise (Alivia et al. 1984). A Middle to Late Eocene hiatus is recorded in DSDP Site 540 (44–38.5 Ma).

Conclusions

Many aspects of geology between North and South America (Middle America) show regional harmony and a shared history among the many geographic components. Crustal thicknesses, gravity
data and high silica content of igneous rocks indicate presence of continental fragments dispersed around and within the Caribbean Plate. They underlie the whole of Central America and the Greater and Lesser Antilles at least the northern and southern Lesser Antilles. They underpin the thick ‘plateau’ areas of the Venezuelan Basin and probably of the Colombion, Yucatán and Grenada basins as well.

Following Triassic/Jurassic extrusion of the Central Atlantic Magmatic Province North America separated from South America/Africa. Triassic–Jurassic rifting reactivated N35°E trending basement lineaments along eastern North America south to the Gulf of Mexico and on into northern South America. Jurassic–Cretaceous N60°W drift and sinistral offset of North from South America added N60°E extensional strain, strikingly illustrated by the Hess Escarpment, and synthetic, east–west, sinistral offset along the northern Caribbean boundary. The N670°W, N35°E and N60°E structural trends are regionally preserved today in Middle America. They occur on the Caribbean Plate interior and on Maya and Chortís. They prove that the latter blocks have not rotated.

Subsidence of proximal areas (Bahamas and Yucatán–Campeche platforms, Nicaragua Rise) accommodated kilometres-thick carbonate sections. Horsts of continental crust flanked by wedges of Jurassic–Cretaceous sediments, flows and salt formed in more distal areas along the eastern margin of North America and within Middle America (Yucatán, Colombian and Venezuelan Basins). Shallow/subaerial flows of smooth seismic Horizon B” capped the Caribbean areas in the Late Cretaceous. Areas of extreme extension suffered serpentinization of upper mantle, forming rough Horizon B”. Areas of both occur in the Venezuela, Colombia and Yucatán basins.

While the Gulf of Mexico remained largely intra-continental, the Caribbean area, west of diverging fractures in the Central Atlantic and a lengthening Mid Atlantic Ridge, suffered greater extension and volcanism. Convergence in the Middle and Late Cretaceous and Middle Eocene led to pause or cessation of activity, uplift to wavebase or subaerial erosion and development of unconformities and shallow marine carbonates. Change of chemical composition from primitive to calc-alkaline recorded continental input. The Middle and Late Cretaceous events in the Colombia and Venezuela basins are recorded by abundant extrusion (subaerial flood basalts) and organic-rich sediments of restricted marine conditions. The Middle Eocene regional, convergent event terminated most volcanic activity along the northern and southern Caribbean Plate boundaries, where Oligocene–Recent strike–slip followed. The only oceanic spreading in Middle America, with recognizable spreading ridges and magnetic anomalies, occurred in the central 300 km of the Cayman Trough during this latest tectonic phase. The Caribbean Plate has extended eastwards over Atlantic crust. Analogy with the Scotia Plate, which occupies a similar tectonic setting, suggests that this occurred by back-arc spreading along the Aves Ridge.

I thank B. Bally for many detailed, perceptive comments on this paper and M. A. Lorente, Y. Chevalier, G. Giunta and C. Rangin for several general suggestions. H. Krause and A. Aleman provide continuing encouragement in my efforts to change the ‘Pacific Paradigm’. Thanks to M. A. Lorente, C. Repzka de Lombras, Lorenzo and N. Villalobos for their great enthusiasm and energy in the organization of the Sigüenza 2006 conference, which led to this publication. Thanks to those who attended, including chairpersons B. Bally, T. Lorente and D. Roberts, and made that meeting an enjoyable success. Thanks to all who contributed to this volume.

References


ANDERSON, T. H. & SCHMIDT, V. A. 1983. The evolution of Middle America and the Gulf of Mexico-Caribbean


DENG, G. 1968. Estructura geológica, historia tectónica y morfología de América Central. Guatemala Instituto Centroamericano de Investigación y Tecnología Industrial, Centro Regional de Ayuda Técnica, Agencia para el Desarrollo Internacional.


DONNELLY, T. W. 1973b. Late Cretaceous basaltas from the Caribbean, a possible flood-basalt province of vast size. EOS American Geophysical Union Transactions, 54, 1004.


KERR, A. C., PEARSON, D. G. & NOWELL, G. M. 2009. Magma source evolution beneath the Caribbean


MATTSON, P. H. & SCHWARTZ, D. P. 1971. Control of
MAURASSE, F. 1981. Relations between the geologic
MENEZ, A. 1966. Tectonica de la parte central de las
MAURY, R. C., WESTBROOK, G. K., BAKER, P. E.,
MCHONE, J. G. 2002. Volatile emissions from Central
MATTSON, P. H. 1966. Geological characteristics of
MAURY, R. A. & MEYERHOFF, H. A. 1990. Tectonic evolution of
MILLS, R. A., HUGH, K. E., FERAY, F. E. & SWOLFS,
MITCHELL, S. 2005. Cretaceous and Cainozoic evolution of


