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Notes

In situ origin of the Caribbean: discussion of data

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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, Panamá, 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 km^2), 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

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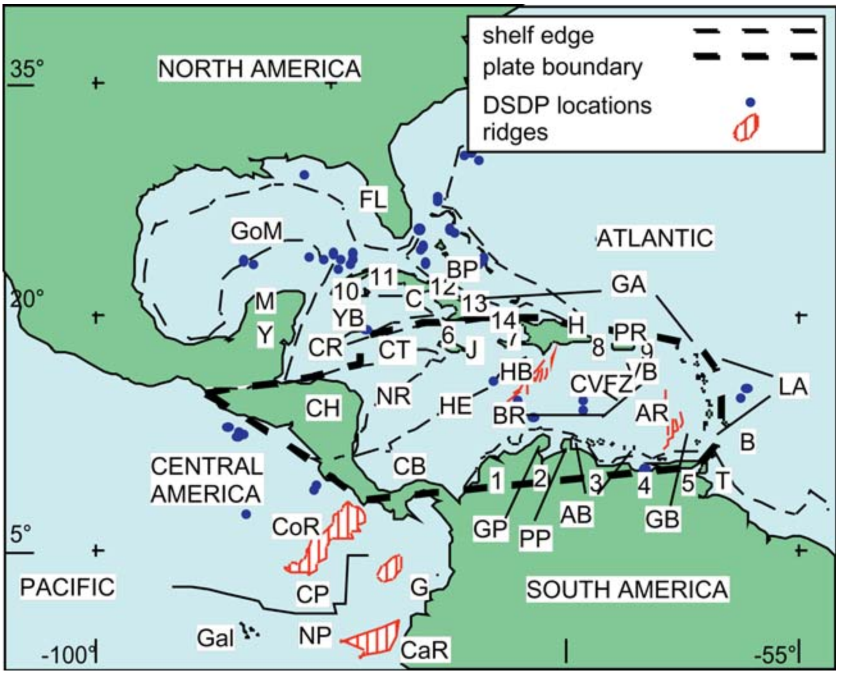

Fig. 1. Middle America, Caribbean Plate outlined by heavy dashed line. AB, Aruba–Blanquilla; AR, Aves Ridge; B, Barbados; BP, Bahamas Platform; BR, Beata Ridge; C, Cuba; CaR, Carnegie Ridge; CB, Colombia Basin; CH, Chortís; CoR, Cocos Ridge; CP, Cocos Plate; CR, Cayman Ridge; CT, Cayman Trough; CVFZ, Central Venezuela fault zone; FL, Florida; G, Gorgona; GA, Greater Antilles; Gal, Galapagos Islands; GB, Grenada Basin; GoM, Gulf of Mexico; GP, Guajira Peninsula; H, Hispaniola; HB, Haiti Basin; J, Jamaica; HE, Hess Escarpment; LA, Lesser Antilles; M, Maya; SCDB, South Caribbean Deformed Belt; NP, Nazca Plate; PFB, Panamá Fold Belt; NR, Nicaragua Rise; PP, Paraguaná Peninsula; T, Trinidad; VB, Venezuela Basin; Y, Yucatán; YB, Yucatán Basin. Numbers refer to basins named in text.

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 3000 m, in the Yucatán Basin to more than 4000 m and in the Caribbean 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.* 2007*a*). 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 (1973*a*) 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 2003*a*, fig. 4; James 2003*b*, figs 3a & b). Fractures within the wedge show that the Central Atlantic Ridge continues to extend over Caribbean latitudes.

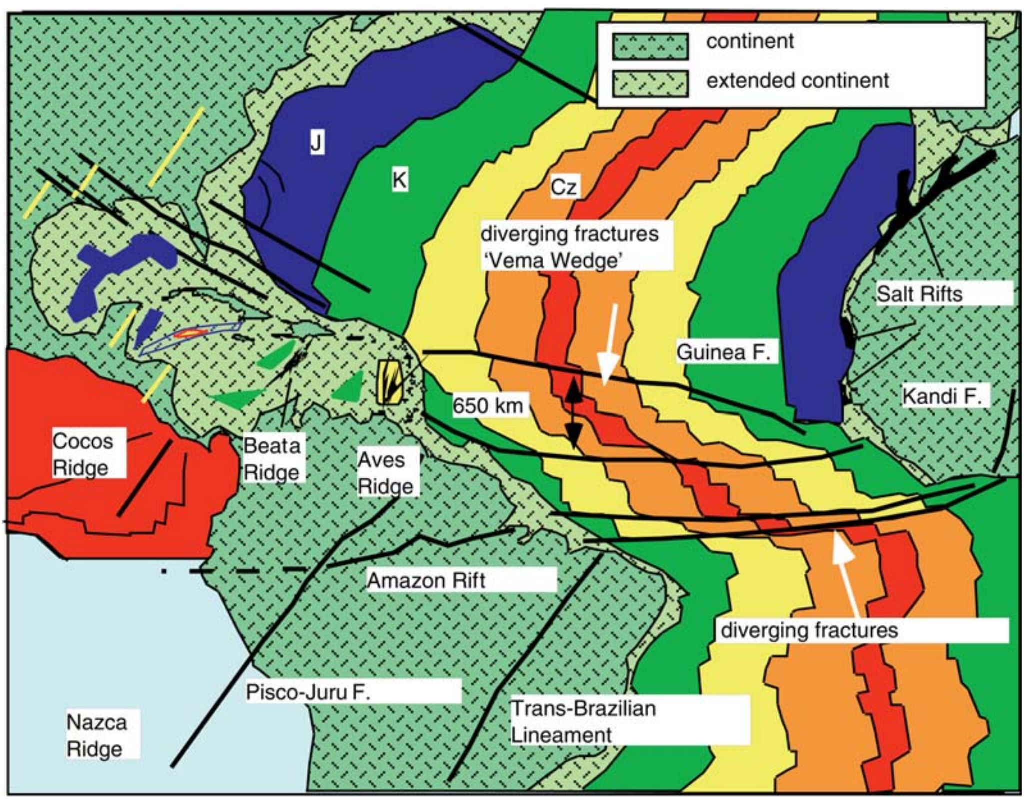

Fig. 2. The Caribbean lies west of a zone of diverging ocean fractures (the Vema Wedge), just as the Amazon Rift lies west of diverging fractures further south. These, and highlighted ocean fractures and intracontinental faults, show continued (Cretaceous–Cenozoic) divergence between North and South Americas, focused on Caribbean latitudes (James 2003*a*, 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).

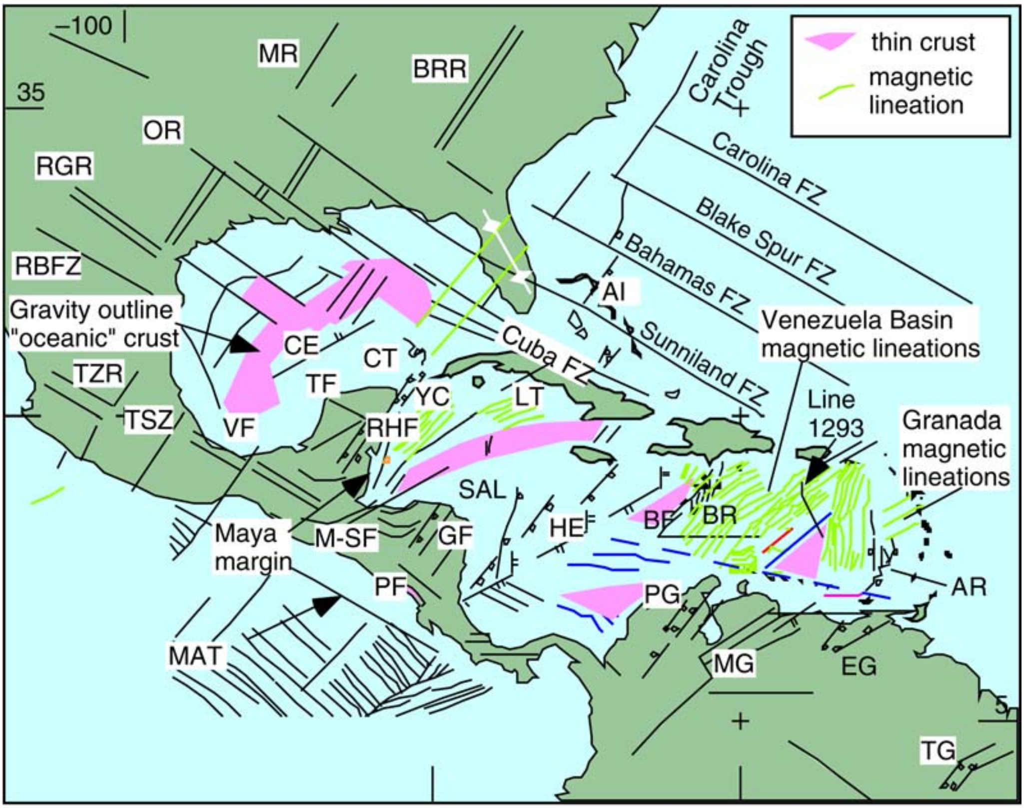

Fig. 3. Tectonic fabric of Middle America. AI, Aklins–Inagua–Caicos; BF, Beata F; BR, Beata Ridge; BRR, Blue Ridge Rift; CE, Campeche Escarpment; CT, Catoche Tongue; EG, Espino Graben; GF, Guayape FM; HE, Hess Escarpment; LT, La Trocha FM; MG, Mérida Graben; MiG, Mississippi Graben; M-SF, Motagua–Swan FM; OR, Oachita Rift; PF, Patuca FM; PG, Perijá Graben–Urdaneta; RBFZ, Río Bravo fault zone; RGR, Río Grande Rift; RHF, Río Hondo FM; SAL, San Andrés Lineament; TF, Ticul FM; TG, Takutu Graben; TT, Texas Transform; TSZ, Tenochtitlan Shear Zone; TZR, Tepic–Zacoalco Rift; VF, Veracruz FM; YC, Yucatán Channel. Red line, SE limit of Caribbean Plateau, the Central Venezuela FZ. Green lines, magnetic anomalies (Gough 1967; Hall & Yeung 1980; Ghosh *et al.* 1984). Compiled from many sources including the Exxon world geological map, IFP map of Caribbean Geology (Mascle *et al.* 1990) and GSA Geological Map of North America (Reed *et al.* 2005).

Models that derive the Caribbean Plate from the Pacific propose that it overrode ‘Proto-Caribbean’ crust between North and South America. Tomographic 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. Rift/drift 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, 2003*b*). 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 ('megalineaments') 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 (Flotté *et al.* 2008). Thick crustal blocks in the Colombian Basin follow this trend (Bowland 1993). Arches in Venezuela (El Baúl, Arauca, Mérida and Vaupes) and the Marañon 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 Tenochtitlan 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 & Castillón 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 1973*b*; 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) Guarumen 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

Basin; (14) Oriente Fault–San Luis–Guantánamo Basin. The periodicity suggests a shared geology of a common, reworked basement pattern (Stainforth 1969; Mora *et al.* 1993; James 2000).

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 $\pm$ 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.mantleplumes.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

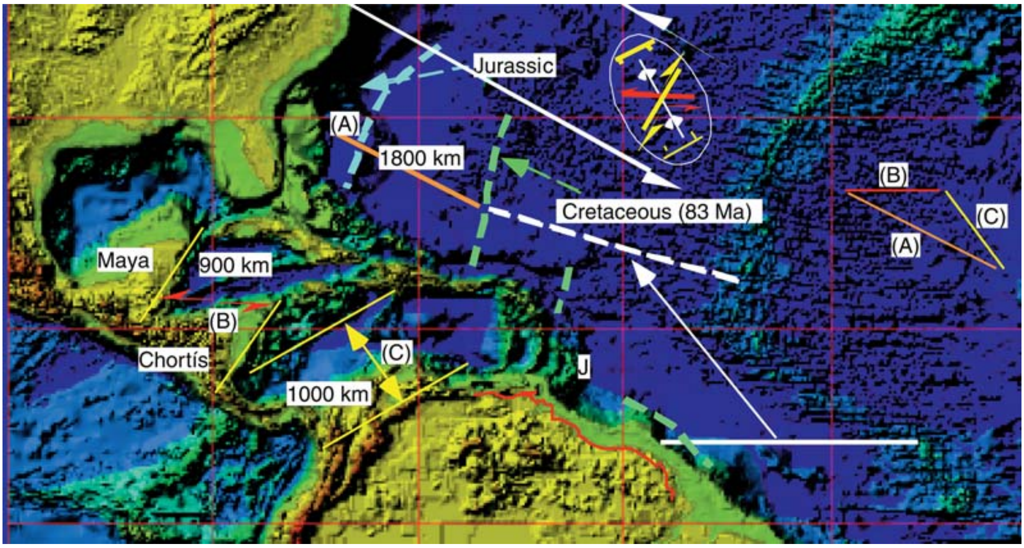

Fig. 4. Continent margin–Mid Atlantic Ridge distance is *c.* 1800 km greater in the Central Atlantic than in the Equatorial Atlantic (broken white line reproduces the solid white line; red line indicates additional distance). The difference relates to Jurassic crust, not present in the Equatorial Atlantic, and wider Early Cretaceous crust. The distance (**a**) equates to the vector sum of offsets between Maya and Chortís (**b**, early Cayman offset), and Chortís (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.

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 2007*a*).

Rotation of Maya and Chortís, origin of the 'Motagua Orocline'

Most plate reconstructions of Middle America rotate Maya and Chortís 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 Chortís 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 Chortís (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 Chortís Block.

Jurassic sections on Maya and Chortis 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 Ticul 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 Chortís (Providencia–San Andres trough; Holcombe *et al.* 1990) are aligned, the Río Hondo and Guayape faults also line up, suggesting a formerly continuous, major Jurassic graben (James 2007*a*). This restoration indicates *c.* 900 km of sinistral offset along the Motagua Fault Zone (MFZ).

Maya and Chortís meet along the MFZ, bounded north and south by the Polochic and Jocotán faults. Ortega-Guttiérez *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 Chortís 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 tend, 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.* 2007*a*; James 2007*a*). Sinistral movement transforms into contraction, curving west in the south and east in the north (James 2007*a*, 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 2007*a*). 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 Turneffe 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 2005*a*, fig. 10). Both carry spreading ridges and dated magnetic anomalies and are known to have formed in place by eastward-migrating backarc 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. Northwest 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 (Garzanti *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 ocean 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–Paraguaná–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

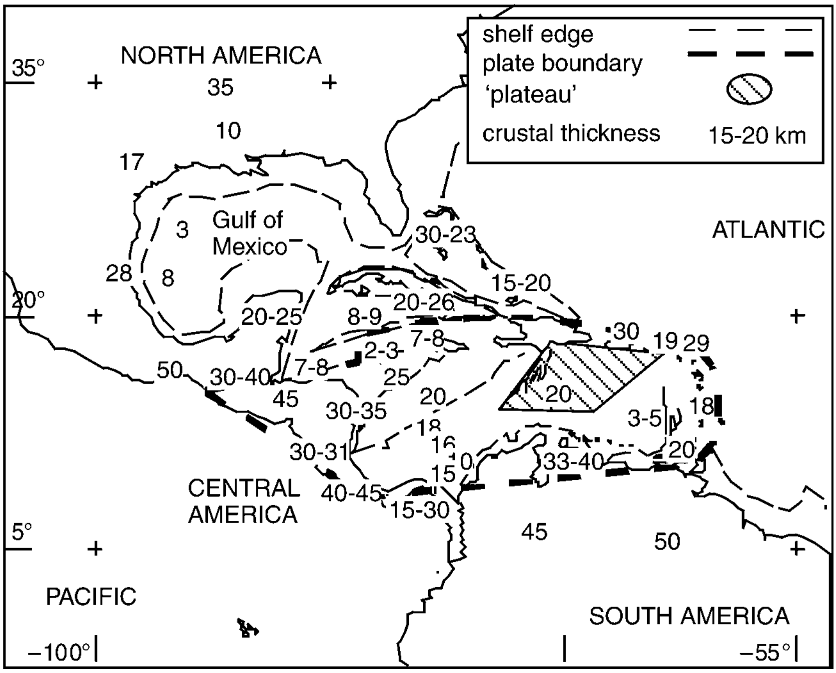

Fig. 5. Crustal thicknesses in Middle America. Compiled from many sources.

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 undercompensated. 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.* 2007*b*), it does not exist (Keppie & Morán-Zenteno 2005). Moreover, this understanding moves Chortís southeastward 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.* 2007*a*, 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 ignimbrite 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 (Bourgois *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 metaigneous 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.* 2007*b*, 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; Rosencrantz 1990). Acoustic basement is interpreted to be continental (Malin & Dillon 1973; Dillon & Vedder 1973). Paleocene continental granitoids (U–Pb and Ar/Ar 62–64 Ma) occur on the walls of the Cayman Trough (Lewis *et al.* 2005) along with red beds, greywackes and arkose (Perfit & Heezen 1978).

Cuba

The well-exposed Cuban geology of oceanic and volcanic arc rocks emplaced upon continental basement by northward thrusting mirrors geology of northern South America. Together, these areas are key to understanding the segmented northern Caribbean boundary east of Cuba.

Late Proterozoic–Early Palaeozoic continental basement 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 southwest 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 metamorphosed 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–?Callovian/Early Oxfordian clastic, syn-rift sediments occur in western Cuba (Guaniguanico). 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 overly basement 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). Radiolaria 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 contamination (Stanek *et al.* 2006).

In the Albian–Cenomanian 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 anhydrites through Neocomian–Aptian shallow water limestones, Albian–Coniacian 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 Jurassic continental rocks in western Cuba (Guaniguanico) 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 Chortís and Mexico (Pszczolkowski & Myczynski 2003).

Cuban continental basement clearly is the autochthonous continuation of the Florida–Bahamas Platform/Maya 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 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; Lidiak 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 Hispaniola (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 (Guaniguanico–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 platform carbonates (Fox & Heezen 1975). Albian to at least Early Miocene inter-tidal to subtidal 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, Anibal and Takutu grabens (Bellizia 1972; Feo-Codecido *et al.* 1984; Maze 1984; Crawford *et al.* 1985; Gonzalez & Lander 1990). Similar rocks occur in the Arauquita-1 well and Guafita areas of Venezuela's Llanos Basin (McCollough & Carver 1992). Triassic-Jurassic volcanic rocks occur on Venezuela's El Baul Uplift (Kiser 1987). The Tinaco–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 pelecypods, tintinnids; Kugler 1953; Feo-Codecido 1962; Bellizia 1972; Bellizia & 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 (Ysaccis 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, volcaniclastic 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 Aptian–Albian Tobago Volcanic Group includes volcaniclastic 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 km^2 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 tholeiites 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 $\pm$ 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 granodiorites. 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 pedestals 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 *et al.* 1971; 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; Lidiak 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-1 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?

Donnelly *et al.* (1990) wrote comprehensive early discussions of the Caribbean ‘oceanic plateau’ while Kerr *et al.* (1999, 2003) provided later data and an update on analytical/dating techniques. A detailed discussion of the Caribbean plateau is given by James (2007*b*).

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 Curaçao Lava Fm yields Ar/Ar dates of 88–90 Ma but Middle Albian 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; Klingelhöfer *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 (Foulger *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.* 2007*a*, *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 Yucatán (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 Panamá and Costa Rica (Bowland & Rosencrantz 1988). Diebold *et al.* (1999, fig. 15) 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 Curaçao became emergent in the Late Cretaceous (Beets 1972; Wright 2004). The Curaçao 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 Albian–Cenomanian Curaçao 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; Manspiezer 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 (Manspiezer 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–Ar 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, volcaniclastics, and possibly salt) in the SE Gulf of Mexico (Phair & Buffler 1983), where NE tectonic grain links the Yucatán 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 2007*b*). The unexplained 'ski-jump' (Diebold *et al.* 1999) at the edge the plateau may be a marginal reef/carbonate mound. Rough Horizon B″ is the equivalent 'oceanic', serpentinized 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

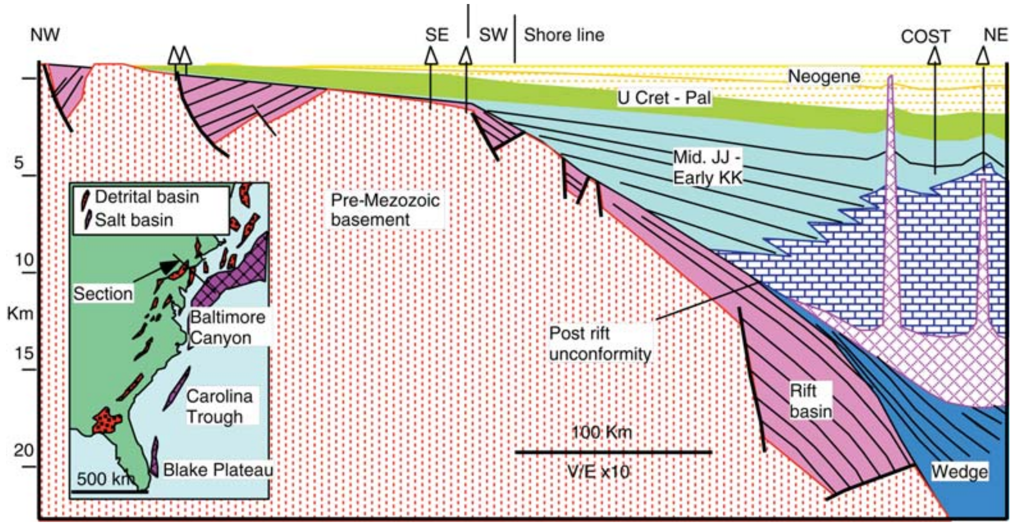

Fig. 6. Cross section, eastern North America continental margin. After Benson & Doyle (1988) and Manspeizer (1988) (inset).

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-B″ 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-B″ growth. It does not push up Horizon B″, 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-B″ section on the down thrown side. Dip of Horizon B″ 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-B″ 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 Nicaragua 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).

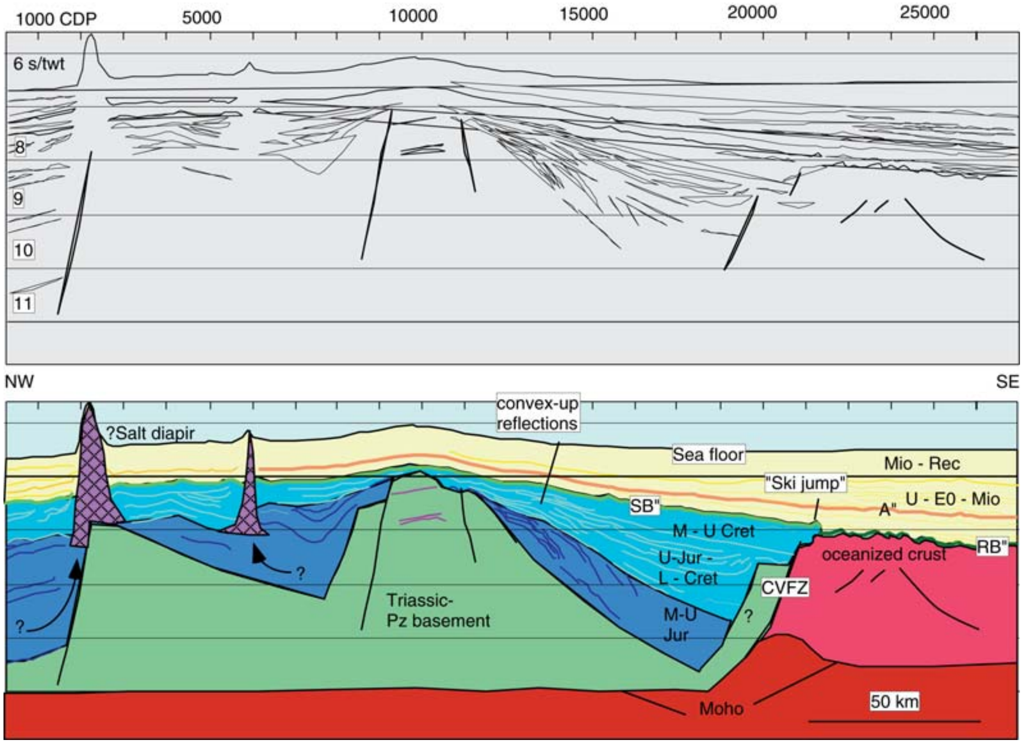

Fig. 7. Line drawing and geology, this study, of seismic line 1293 (located on Fig. 3) from Diebold *et al.* (1999, fig. 2). The figure suggests that Caribbean geology continues that of eastern offshore North America (Fig. 6). Triassic–Jurassic rifting accommodated continental–shallow marine sediments, volcanic flows and salt. Drifting introduced open marine Jurassic–Cretaceous sediments, probably very thick carbonate sections. Late Cretaceous extension resulted in subaerial basalt flows over this architecture, forming smooth Horizon B″ (SB″), and serpentinization of adjacent mantle, forming rough Horizon B″ (RB″). Horizon A″, the Middle Eocene contact between chert and overlying unconsolidated sediment correlates with cessation of volcanism along the north and south plate boundaries. CVFZ, Central Venezuelan Fault Zone.

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 section in the central Massif de la Selle includes chaotic blocks of upper Albian to upper Coniacian–Santonian radiolarian cherts,

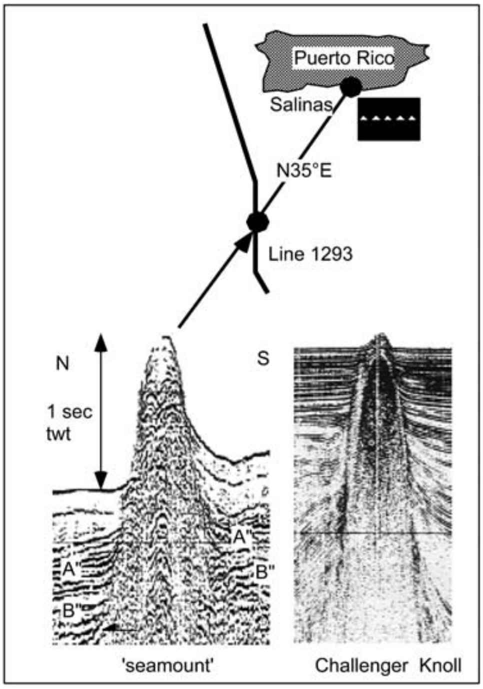

Fig. 8. Similarity of Caribbean 'seamount' (after Diebold *et al.* 1999, seismic line 1293, fig. 2) to a drilled salt dome in the Gulf of Mexico (after Burk *et al.* 1969). Rim syncline adjacent to diapir in deeper reflections indicates withdrawal. Projection from the diapir along regional structural trend N35°E leads to SE Puerto Rico and the coastal village of Salinas, whose flag illustrates five salt knolls. Seismic line is located on Fig. 4. A″, B″, seismic horizons.

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 km^2, 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 B″.

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 B″ 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 2007*a*).

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. Obducted 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 2007*b*).

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 Orchila and El Roque to Cabo Vela on Guajira and southward into the serpentinite 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 serpentinite, 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. Tear 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 Liassic–Lower Dogger volcaniclastic rocks occur in Costa Rica (De Wever *et al.* 1985) and there is a Middle–Upper Jurassic subduction mélange 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 northeastern 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 basalt 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 arc 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 Caribbean oceanic slab at 158 km (seismicity, Pennington 1981). No volcanism occurs in the Greater Antilles where subduction is supposed to be recorded by both the Muertos and Puerto Rico troughs.

Ancient zircons in arc rocks

Precambrian and Palaeozoic 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 Curaçao contain Mesozoic, Paleozoic and Precambrian zircons along with Barremian–Albian and Santonian–Campanian arc-derived grains (Wright 2004). Orthogneiss on the Macanao 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 metabasalts occur on La Désirade (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 Choroní 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 Albian (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’ile 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 (Guaniguanico) 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, 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, sandtones). 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) ecologite 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 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 (1.3F°/100′, 1–1.5 hfu, 35–40 mW/m^2, 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 Plio–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 Panamá 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), El Tambor Group (Montagua Suture Zone, Guatemala), Duarte Complex (Hispaniola), Mariquita Chert (SW Puerto Rico) and in the Phare Unit (La Désirade) (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 Désirade 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 mélange 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 (*Amphitriscoelus waringi* association) extended from Mexico and Trinidad to France and were linked to the Tethyan continental margin. Albian, Santonian and Campanian *Tepeyacia corrugata, Durania curasavica* and *Barrettia 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 (Chiapas).

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 Guaniguanico 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 to 12°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 Permian 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 Maracaibo 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 Codecido 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 Querecual 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 Querecual (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, carbonaceous 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 claystones 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 Piemontine 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 (cristobalite) and interbedded compact chalks and limestones underlie radiolarian–foraminiferal oozes 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 & Buffler 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. Paleocene and Eocene green cherty tuffs and pelagic sediments in Puerto Rico and the Dominican Republic correlate with oceanic horizons Layer A in the Atlantic Ocean and Layer A″ in the Caribbean (Mattson *et al.* 1972).

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 & Maurasse 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 arc but contain no volcanic quartz. Instead, polycrystalline quartz, feldspars and heavy minerals reflect orogenic and cratonal metamorphic/plutonic crystalline sources (Kasper & Larue 1986). Exotic rocks like the Naparima 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

ODP Leg 110 found Middle Eocene–Oligocene (Middle Eocene peak) 'coarse' sand. Mineralogy of these sands also suggests a South American source. Such sediments are absent from Site 543, just 19 km to the north but DSDP Site 672, on the Atlantic Plate to the east, encountered correlative Middle and Upper Eocene sands (Mascle *et al.* 1986). Northward transport of Barbados Ridge sediments was stopped by the Tiburón Rise, which lies on the Atlantic Plate and is moving west.

Scotland deposition is thought by most to 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 – surpratidal flat). Fresh and unbroken fresh-water genera (*Unio, Cyrena, Ampullaria*) occur in 'beds full of large fresh-water mollusca' and show affinity with Soldado Rock, Trinidad (Trechmann 1925). Widespread 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, Cobiella-Reguera 2001, pers. comm.). On Hispaniola and Puerto Rico the limestones are the Hatillo Fm and the Barrancas and Río Matón limestones (Lewis 2002; Mycxynski & Iturralde-Vinent 2005). The Andros-1 well (Bahamas) bottomed in Albian backreef carbonates (Meyerhoff & Hatten 1974). Albian intertidal–supratidal carbonates form the easternmost 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 Albian and record open marine conditions. In Eastern Venezuela Albian bituminous limestones and shales occur in the Cutacual Formation of the

Serranía del Interior. They interfinger 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 northeastern 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 & Snoke 1993), where volcaniclastic rocks of the North Coast Schist show continental input from the Albian (Frost & Snoke 1989).

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 Curaçao 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; Cobiella-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 overlie 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, 2005*a*, 2006, fig. 6).

Flysch and wildflysch deposits occur in Central America (Rivas, Las Palmas and Brito Fms), between the Maya and Chortís Blocks (Sepur Fm), in the Guaniguanico Cordillera (Manacas Fm) and in north central Cuba Vegas and Vega Alta Fms (Cobiella-Reguera 2001, pers. comm.), on Jamaica (Richmond Fm, Wagwater) and Puerto Rico (San German Fm), in NW Colombia (Luruaco Fm; Maco Conglomerate, Aleman 1997, pers. comm.), in western and central Venezuela (Matatere, Río Guache, Guárico, Paracotos Fms, in Trinidad (Pointe-a-Pierre, Chaudiere and Lizard Springs Fms), offshore Venezuela on Bonaire (Rincón Fm) and Margarita (Punta Mosquito/Carnero Fms) and in Golfo Triste wells, on Grenada (Tufton Hall Fm) and on Barbados (Scotland Group) (see James 2005*a*, for comprehensive discussion of these units).

They also occur in SE Mexico (Ocozocuautla Fm, Dengo 1968), in the Parras and Chicontepec basins of NNE Mexico (Tardy *et al.* 1994) and the Veracruz Basin of eastern Mexico (Mossman & Viniegra 1976).

The main phase of arc and ophiolite emplacement in Cuba occurred in the Middle Eocene (Pardo 1975). In Bahía Honda, west Cuba, an apparently overturned sequence includes ultramafic rocks, mafic lavas and gabbros upon the distal margin assemblage mafic tuffs, lavas, slates and laminated limestones (Lewis 1990), recording unroofing of the source area (Pszczolkowski 1999). The Pinar-1 well of western Cuba penetrated thrust sheets with lower Cretaceous, Eocene and Jurassic rocks and bottomed in a thick Jurassic section. Overlying Jurassic sections are thinner upsection, suggesting that the allochthons came from more distal sites. By late Middle or Early Late Eocene time, faulting and subsidence were so intense that great 'chaos breccias' formed in northern Pinar del Río, northern Las Villas Province, and northern Camaguey (Khudoley & Meyerhoff 1971). Blocks of crushed serpentinites are as much as 50–100 km^2 in area.

Metamorphosed mid-oceanic ridge basalt and peridotite were thrusted northward onto early arc rocks of Hispaniola and Jamaica in the Middle Eocene (Draper & Lewis 1991; Draper *et al.* 1996). Jamaican Eocene deposits (the Wagwater Belt) contain flysch derived from the north and NE. Conglomerates contain Cretaceous rudist-bearing limestones, gneiss, schist, quartzite, slate, marble and various igneous rocks indicate a continental provenance with metamorphic basement and Cretaceous carbonate platform (Cuba? Trechmann 1925).

This geology is mirrored in northern Venezuela where metamorphic grade increases upwards (again, unroofing, Stainforth 1966, quoting Menéndez 1975 and Seiders 1965) in the Villa de Cura Group, a 4–5 km thick section of lower Cretaceous gabbros, diorites, volcanic and volcaniclastic rocks, emplaced from the north in the Middle Eocene above 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 2005*a*).

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 2005*a*).

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. Guedez (1985) noted late Middle Eocene uplift of the Monay–Carora area. Uplift of the Mérida Andes and the Sierra de Perijá 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 (Khudoley & 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–Oliogocene uplift from basinal 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 (Ciénega 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), Tortola and Virgin Gorda (Tortola, Necker 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 Tonosí 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 Colombian, 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.

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References

Abbott, R. N. Jr, Bandy, B. R., Jackson, T. A. & Scott, P. W. 2003. Blueschist–Greenschist Transition in the Mt. Hibernia Schist, Union Hill, Parish of St. Thomas, Jamaica. *International Geology Review*, **45**, 1–15.

Abouin, J., Azema, J. *et al.* 1982. The Middle America Trench in the geological framework of Central America. *Initial Reports of the Deep Sea Drilling Project*, **67**, 747–775.

Ager, D. V. 1986. Migrating fossils, moving plates and an expanding Earth. *Modern Geology*, **10**, 377–390.

Aiello, I. W., Chiari, M., Principi, G. & García, D. 2004. Stratigraphy of Cretaceous radiolarian cherts of Cuba (absent). *32nd IGC*, Florence, 2004, IGCP Project 433 Caribbean Plate Tectonics, Abstracts.

Alivia, F., Tappmeyer, D., Aves, H., Gillet, M. & Klenk, C. 1984. Recent studies of basins are encouraging for future exploration of Honduras. *Oil and Gas Journal*, **17**, 139–149.

Allibon, J., Lapierre, H., Bussy, F., Tardy, M., Cruz Gamez, E. M. & Senebier, F. 2008. Late Jurassic continental flood basalt doleritic dykes in northwestern Cuba: remnants of the Gulf of Mexico opening. *Bulletin Societe Géologie Français*, **179**, 445–452.

Alonso, R. M., Krieg, E. A. & Meyerhoff, A. A. 1987. Age and origin of the Puerto Rico Trench. *Transactions, X Caribbean Geological Conference*, Cartagena, 1983, 82–103.

Alvarez, W. 1968. *Geology of the Simarua and Carpintero areas, Guajira Peninsula, Colombia.* PhD thesis, Princeton University.

Alva-Valdivia, L. M., Goguitchaivhvili, A. *et al.* 2001. Palaeomagnetism of the Guaniganico Cordillera, Western Cuba: a pilot study. *Cretaeous Research*, **22**, 705–718.

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

Sea region during Mesozoic time. *Geological Society of America Bulletin*, **94**, 941–966.

ANDREANI, L., RANGIN, C. *ET AL*. 2008. The Neogene Veracruz Fault: evidences for left-lateral slip along the southern Mexico block. *Bulletin de la Société Géologique de France*, **179**, 195–208.

ANGSTADT, D. M., AUSTIN, J. A. JR & BUFFLER, R. T. 1983. Deep-sea erosional unconformity in the southeastern Gulf of Mexico. *Geology*, **11**, 215–218.

ANTOINE, J. W. & BRYANT, W. R. 1969. Distribution of salt and salt structures in Gulf of Mexico. *American Association of Petroleum Geologists Bulletin*, **53**, 2543–255.

ANTOINE, J. W., MARTIN, R. G., PYLE, T. G. & BRYANT, W. R. 1974. Continental margins of the Gulf of Mexico. *In*: BURK, C. A. & DRAKE, C. L. (eds) *The Geology of Continental Margins*. Springer, Berlin, 683–693.

ARDEN, D. D. 1975. The geology of Jamaica and the Nicaragua rise. *In*: NAIRN, A. E. M. & STEHLI, F. G. (eds) *The Ocean Basins and Margins*, **3**, *The Gulf of Mexico and the Caribbean*. Plenum Press, New York, 617–661.

AUDEMARD, F. M. 1991. *Tectonics of Western Venezuela*. PhD thesis, Rice University, Houston, Texas.

AUGER, L. S., ABERS, G. *ET AL*. 2004. Crustal thickness along the Central American Volcanic Arc. *EOS Transactions, American Geophysical Union*, **85**, Fall Meeting Supplement, Abstract.

AVÉ LALLEMENT, H. G. 1997. Transpression, displacement partitioning, and exhumation in the eastern Caribbean/South American plate boundary. *Tectonics*, **16**, 272–289.

AVÉ LALLEMENT, H. G. & GUTH, L. R. 1990. Role of extensional tectonics in exhumation of eclogites and blueschists in an oblique subduction setting: Northeastern Venezuela. *Geology*, **18**, 950–953.

AVÉ LALLEMENT, H. G. & SISSON, V. B. 1992. Burial and ascent of blueschists and eclogites, Venezuela, part 1: structural constraints. *Geological Society of America Annual Meeting*, Abstracts, A149.

AVÉ LALLEMANT, H. G. & GORDON, M. B. 1999. Deformation history of Roatan Island: implications for the origin of the Tela Basin (Honduras). *In*: MANN, P. (ed.) *Caribbean Sedimentary Basins, Sedimentary Basins of the World*. Elsevier, 197–218.

BAADSGAARD, P. H. 1960. Barbados, W. I. Exploration Results 1950–1958. *In*: KALE, A. & METZGER, A. (eds) *Structure of the Earth's Crust and Deformation of Rocks: 21st International Geological Congress*, Copenhagen, 18.

BAIE, L. F. 1970. Possible structural link between Yucatán and Cuba. *American Association of Petroleum Geologists Bulletin*, **54**, 2204–2207.

BAIN, J. E. & HAMILTON, K. J. 1999. Finding new structural features that focus sediment flows. *Offshore*, 78–80.

BALDWIN, S. L., HARRISON, T. M. & BURKE, K. 1986. Fission track evidence for the source of accreted sandstones, Barbados. *Tectonics*, **5**, 457–468.

BALL, M. M., HARRISON, C. G. A. & SUPKO, P. R. 1969. Atlantic opening and the origin of the Caribbean. *Nature*, **223**, 167–168.

BANDY, O. L. & CASEY, R. E. 1973. Reflector Horizons and Paleobathymetric History, Eastern Panama. *Geological Society of America Bulletin*, **84**, 3081–3086.

BANKS, P. O. 1975. Basement rocks bordering the Gulf of Mexico and the Caribbean Sea. *In*: NAIRN, A. E. M. & STEHLI, F. G. (eds) *The Ocean Basins and Margins*, **3**, *The Gulf of Mexico and the Caribbean*. Plenum Press, New York, 181–199.

BARBOSA, G., FERNÁNDEZ, J. A., BARRIENTOS, J. & BOTTAZI, G. 1997. Costa Rica: petroleum geology of the Caribbean margin. *The Leading Edge*, 1787–1794.

BARKER, P. F. 2001. Scotia Sea tectonic evolution: implications for mantle flow and palaeocirculation. *Earth-Science Reviews*, **55**, 1–39.

BARKER, L. & MCFARLANE, N. 1980. Notes on some sedimentological evidence for shallow water origin of parts of the Scotland Formation of Barbados. *Journal of the Geological Society of Jamaica*, **xix**, 46.

BARTOK, P. E., RENZ, O. & WESTERMAN, G. E. G. 1985. The sisquisique ophiolites, Northern Lara State, Venezuela: a discussion on their Middle Jurassic ammonites and tectonic implications. *Geological Society of America Bulletin*, **96**, 1050–1055.

BARTOLINI, A. & LARSON, R. L. 2001. Pacific microplate and the Pangea supercontinent in the Early to Middle Jurassic. *Geology*, **29**, 735–738.

BATESON, J. H. 1972. New interpretation of geology of Maya Mountains, British Honduras. *American Association of Petroleum Geologists Bulletin*, **56**, 956–963.

BAUMGARTNER, P. O., BANDINI, A. N. & DENYER, P. 2005. Remnants of Pacific ocean floor: Jurassic-lower Cretaceous radiolarites in central America and the Caribbean. *17th Caribbean Geological Conference*, Puerto Rico, Abstracts, 5.

BAXTER, P. J., BONADONNA, C. *ET AL*. 1999. Cristobalite in volcanic ash of the Soufriere Hills Volcano, Montserrat, British West Indies. *Science*, **283**, 1142–1145.

BEETS, D. J. 1972. *Lithology and stratigraphy of the Cretaceous and Danian succession of Curaçao*. Uitgaven Natuurweternschappelijke Studierkring voor Suriname en Nederlandse Antillen, Utrecht, **70**, 153.

BEETS, D. J. 1977. Cretaceous and Early Tertiary of Curaçao. *In*: *8th Caribbean Geological Conference Guide to Field Excursions*. Geophysical Union of America, Papers of Geology, Amsterdam, **10**, 18–28.

BEETS, D. J., MARESCH, W. V. *ET AL*. 1984. Magmatic rock series and high-pressure metamorphism as constraints on the tectonic history of the southern Caribbean. *In*: BONINI, W. E. *ET AL*. (eds) *The Caribbean–South American Plate Boundary and Regional Tectonics*, Geological Society of America Memoirs, **162**, 95–130.

BELL, J. S. 1972. Geotectonic evolution of the southern Caribbean area. *In*: *Studies in Earth and Space Sciences*. Geological Society of America Memoirs, **132**, 367–386.

BELLIZIA, A. G. 1972. Sistema Montañoso del Caribe, Borde Sur de la Placa Caribe ¿Es Una Cordillera Aloctona? *VI Conferencia Geológica del Caribe*, Margarita, Venezuela, Memorias, 247–257.

BELLIZIA, A. & DENGO, C. 1990. The Caribbean mountain system, northern South America; a summary. *In*: DENGO, G. & CASE, J. E. (eds) *The Geology of*

North America, Vol. H, The Caribbean Region, Geological Society of America, 167–175.

BENKOVICS, L., FRANCO, A., ETEMADI, M., FINTINA, C. & NOVOA, E. 2006. Analogies and differences between the Eastern Venezuela fold and thrust belt and the Trinidad Nariva fold and thrust belt. *In*: JAMES, K. H. & LORENTE, M. A. (eds) *Geology of the Area between North and South America, with Focus on the Origin of the Caribbean Plate*. An International Research Conference, Sigüenza, Spain, Abstracts.

BENSON, R. N. & DOYLE, R. G. 1988. Early Mesozoic rift basins and the development of the United States middle Atlantic continental margin. *In*: MANZPEIZER, W. (ed.) *Triassic–Jurassic Rifting*, Part A. Elsevier, Amsterdam, 99–127.

BIJU-DUVAL, B. G., BIZON, A., MASCLE & MULLER, C. 1982. Active margin processes: field observations in Southern Hispaniola. *In*: WATKINS, J. S. & DRAKE, C. L. (eds) *Studies in Continental Margin Geology*. American Association of Petroleum Geologists Memoirs, **34**, 325–344.

BIRD, D. E., HALL, S. A. & CASEY, J. F. 1999. *Tectonic Evolution of the Grenada Basin: Caribbean Basins*. Sedimentary Basins of the World Series, **4**. Elsevier, Amsterdam, 389–416.

BIRD, D., HALL, S., BURKE, K., CASEY, J. & SAWYER, D. 2008. *Mesozoic seafloor spreading history of the Central Atlantic Ocean*. World Wide Web Address: http://www.conjugatemargins.com/abstracts/by_session/1

BIRKHOLD, A. B., NEAL, C. R., MAHONEY, J. J. & DUNCAN, R. A. 1999. The Ontong Java Plateau: episodic growth along the SE margin. *American Geophysical Union Fall Meeting*, San Francisco, EOS, **80**, F1103.

BLATT, H., TRACEY, R. J. & OWENS, B. E. 2006. *Petrology, Igneous, Sedimentary and Metamorphic*. Freeman, New York.

BLEIN, O., GUILLOT, S. H. *ET AL.* 2003. Geochemistry of the Mabujina Complex, Central Cuba: Implications on the Cuban Cretaceous Arc Rocks. *Journal of Geology*, 2003, **111**, 89–101.

BOITEAU, A., MICHARD, A. & SALIOT, P. 1972. High pressure metamorphism within the Purial Ophiolite Complex (Oriente, Cuba). *Comptes Rendus Académie de Science (Paris), Series D*, **274**, 2137–2140.

BOLZ, A. & CALVO, C. 2002. Calizas Lutetianas del arco interno Paleógeno de Costa Rica. *Revista Geológica de América Central*, **26**, 7–24.

BONIS, S. B. 1969. *Evidence for a Paleozoic Cayman Trough*. Geological Society of America Special Papers, **121**, Abstracts, 32.

BOURGOIS, J., TOUSSAINT, J.-F. *ET AL.* 1987. Geological history of the Cretaceous ophiolitic complexes of northwestern South America (Colombian Andes). *Tectonophysics*, **143**, 307–327.

BOUYSSE, P. 1984. The Lesser Antilles Island Arc: structure and geodynamic evolution. *Initial Reports, DSDP*, **LXXVIIA**, 83–103.

BOUYSSE, P. 1988. Opening of the Granada back-arc basin and evolution of the Caribbean Plate during the Mesozoic and Early Paleogene. *Tectonophysics*, **149**, 121–143.

BOUYSSE, P., SCHMIDT-EFFING, R. & WESTERCAMP, D. 1983. La Desirade Island (Lesser Antilles) revisited: Lower Cretaceous radiolarian cherts and arguments against an ophiolitic origin for the basal complex. *Geology*, **11**, 244–247.

BOUYSSE, P., ANDREIEFF, P. *ET AL.* 1985. Aves Swell and northern Lesser Antilles Ridge: rock dredging results from Arcante 3 Cruise. *Géodynamique des Caraibes*, Symposium Paris, Editions Technip, **27**, Rue Ginoux, 65–76.

BOUYSSE, P., WESTERCAMP, D. & ANDREIEFF, P. 1990. *The Lesser Antilles Island Arc: Proceedings of the Ocean Drilling Program, Scientific Results*. College Station, TX, **110**, 29–44.

BOWIN, C. 1975. The geology of Hispaniola. *In*: NAIRN, A. E. M. & STEHLI, F. G. (eds) *The Ocean Basins and Margins*, **3**. Plenum Press, New York, 501–552.

BOWIN, C. 1976. Caribbean gravity field and plate tectonics. *Geological Society of America Special Papers*, **169**.

BOWLAND, C. L. 1993. Depositional history of the western Colombian Basin, Caribbean Sea, revealed by seismic stratigraphy. *Geological Society of America Bulletin*, **105**, 1321–1345.

BOWLAND, C. L. & ROSENCRANTZ, E. 1988. Upper crustal study of the western Colombian Basin, Caribbean Sea. *Geological Society of America Bulletin*, **100**, 534–546.

BUITRÓN-SÁNCHEZ, B. E. & GÓMEZ-ESPINOSA, C. 2003. Cretaceous (Aptian-Cenomanian) gastropods of Mexico and their biogeographic implications. *In*: BARTOLINI, C., BUFFLER, R. T. & BLICKWEDE, I. F. (eds) *The Circum-Gulf of Mexico and the Caribbean: Hydrocarbon Habitats, Basin Formation, and Plate Tectonics*. American Association of Petroleum Geologists, Memoir **79**, p. 403–418.

BUFFLER, R. T. 1983. Structure of the Sigsbee Scarp, Gulf of Mexico. *In*: BALLY, A. W. (ed.) *Seismic Expression of Structural Styles*. American Association of Petroleum Geologists Studies in Structural Geology, Series 15, **2**.

BURK, C. A., EWING, M. *ET AL.* 1969. Deep-sea drilling into the Challenger Knoll, central Gulf of Mexico. *American Association of Petroleum Geologists Bulletin*, **53**, 1338–1347.

BURKE, K. 1988. Tectonic evolution of the Caribbean. *Annual Reviews in Earth and Planetary Science*, **16**, 201–230.

BURKE, K. & ROBINSON, E. 1965. Sedimentary structures in the Wagwater Belt, Eastern Jamaica. *The Journal of the Geological Society of Jamaica*, **VII**, 1–10.

BURKE, K., COOPER, C., DEWEY, J. F., MANN, P. & PINDELL, J. L. 1984. Caribbean tectonics and relative plate motions. *In*: BONINI, W. E. *ET AL.* (eds) *The Caribbean-South American Plate Boundary and Regional Tectonics*. Geological Society of America Memoirs, **162**, 31–63.

BUTTERLIN, J. 1956. *La constitucion géologique et la structure des Antilles*. Centre National de la Recherche Scientifique, Paris.

BRYANT, W. R., MEYERHOFF, A. A., BROWN, N. K., FURRER, M. A., PYLE, T. E. & ANTOINE, J. W. 1969. Escarpments, reef trends, and diapiric structures, Eastern Gulf of Mexico. *American Association of Petroleum Geologists Bulletin*, **53**, 2506–2542.

CALAIS, E. & MERCIER DE LEPINAY, B. 1995. Strike–slip tectonic processes in the northern Caribbean between Cuba and Hispaniola (Windward Passage). *Marine Geophysical Research*, **17**, 63–95.

CALVO, C. 2003. Provenance of plutonic detritus in cover sandstones of Nicoya Complex, Costa Rica: Cretaceous unroofing history of a Mesozoic ophiolite sequence. *Geological Society of America Bulletin*, **115**, 832–844.

CALVO, C. & BOLZ, A. 1994. The oldest calcalkaline island arc volcanism in Costa Rica. Marine tephra deposits from the Loma Chumico Formation (Albian to Campanian). *In*: SEYFRIED, H. & HELLMANN, W. (eds) *Geology of an Evolving Island Arc*, **7**. Institute of Geology and Paleontology, University of Stuttgart, 235–264.

CANDE, S. C., LABREQUE, J. L., LARSON, R. L., PITMAN III, W. C., GOLOVCHENKO, X. & HAXBY, W. F. 1989. *Magnetic Lineations of the World's Ocean Basins*. American Association of Petroeleum Geologists Bookstore, Tulsa, OK. Map.

CARDONA, A., VALENCIA, V. ET AL. 2008. Cenozoic exhumation of the Sierra Nevada De Santa Marta, Colombia: implications on the interactions between the Carribean and South American Plate. *2008 Joint Meeting of the Geological Society of America, American Society of Agronomy, Crop Science Society of America, Gulf Coast Association of Geological Societies with the Gulf Coast Section of the Society for Sedimentary Petrology*, Abstracts, paper no. 128-5.

CARRASCO-V, B. 2003. Paleokarst in the marginal Cretaceous rocks, Gulf of Mexico. *In*: BARTOLINI, C. ET AL. (eds) *The Circum-Gulf of Mexico and the Caribbean: Hydrocarbon habitats, basin formation, and plate tectonics*. *American Association of Petroleum Geologists Memoirs*, **79**, 169–183.

CASE, J. E. 1974. Oceanic crust forms basement of Eastern Panamá. *Geological Society of America, Bulletin*, **85**, 645–652.

CASE, J. E. & HOLCOMBE, T. L. (compilers). 1980. Geologic–tectonic map of the Caribbean region. *U.S. Geological Survey Miscellaneous Investigation Series* Map **I-1100**, scale 1 : 2 500 000.

CASE, J. E., MACDONALD, W. D. & FOX, P. J. 1990. Caribbean crustal provinces; Seismic and gravity evidence. *In*: DENGO, G. & CASE, J. E. (eds) *The Geology of North America*, **H**, *The Caribbean Region*. Geological Society of America, 15–36.

CASTRO, M. & MEDEROS, A. 1985. Litoestratigrafia de la Cuenca de Carúpano. *VI Congreso Geologico Venezolano*, Caracas, Memoria, **I**, 201–225.

CASTILLO, M. V. & MANN, P. 2006. Deeply buried, Early Cretaceous paleokarst terrane, southern Maracaibo Basin, Venezuela. *American Association of Petroleum Geologists Bulletins*, **90**, 529–565.

CERVENY, P. F. & SNOKE, A. W. 1993. Thermochronologic data from Tobago, West Indies: constraints on the cooling and accretion history of Mesozoic oceanic-arc rocks in the southern Caribbean. *Tectonics*, **12**, 433–440.

CHARLTON, T. R. 2004. The petroleum potential of inversion anticlines in the Banda Arc. *American Association of Petroleum Geologists Bulletins*, **88**, 565–585.

CHEVALIER, Y. 1987. *Les zones internes de la chaîne sud-caraibe sur la transect: Ile de Margarita–Pénsula d'Araya (Venezuela)*. PhD thesis, Université de Bretagne Occidentale, Brest.

CHIARI, M., DUMITRICA, P., MARRONI, M., PANDOLFI, L. & GIANFRANCO, G. 2004. Paleontological evidences for a Late Jurassic age of the Guatemala ophiolites. *32nd IGC*, Florence, 2004, IGCP Project 433 Caribbean Plate Tectonics, Abstracts.

CHIGNE, N. & HERNANDEZ, L. 1990. Main aspects of petroleum exploration in the Apure area of southwestern Venezuela, 1985–1987. *In*: BROOKS, J. (ed.) *Classic Petroleum Provinces*. Geological Society, London, Special Publications, **50**, 55–75.

CHRISTENSEN, R. M. 1961. *Geology of the Paria-Araya Peninsula, Northeastern Venezuela*. PhD University of Nebraska.

CHRISTMAN, R. A. 1953. Geology of St. Bartholomew, St. Martin, and Anguilla, Lesser Antilles. *Geological Society of America Bulletin*, **64**, 65–96.

CHRISTOFFERSON, E. 1976. Colombian Basin magmatism and Caribbean Plate tectonics. *Geological Society of America Bulletin*, **87**, 1255–1258.

CHUBB, L. J. & BURKE, K. 1963. Age of the Jamaican granodiorite. *Geology Magazine*, **100**, 524–532.

COBIELLA-REGUERA, J. L. 2000. Jurassic and Cretaceous geological history of Cuba. *International Geology Review*, **42**, 594–616.

COBIELLA-REGUERA, J. L. 2008. Reconstrucción palinspástica del paleomargen de América del Norte en Cuba occidental y el sudeste del Golfo de México. Implicaciones para la evolución del SE del Golfo de México. *Revista Mexicana de Ciencias Geológicos*, **25**, 382–401.

COBIELLA-REGUERA, J. L. 2009. Emplacement of the northern ophiolites of Cuba and the Campanian–Eocene geological history of the northwestern Caribbean–SE Gulf of Mexico region. *In*: JAMES, K. H., LORENTE, M. A. & PINDELL, J. L. (eds) *Origin and Evolution of the Caribbean Plate*. Geological Society, London, Special Publications, **328**, 315–338.

CONTRERAS, V. H. & CASTILLÓN, M. B. 1968. Morphology and origin of salt domes of Isthmus of Tehuantepec. *In*: BRAUNSTEIN, J. & O'BRIAN, G. D. (eds) *Diapirism and Diapirs*. American Association of Petroleum Geologists Memoirs, **8**, 244–260.

COONEY, P. M. & LORENTE, M. A. 2009. A structuring event of Campanian age in western Venezuela, interpreted from seismic and palaeontological data. *In*: JAMES, K. H., LORENTE, M. A. & PINDELL, J. L. (eds) *Origin and Evolution of the Caribbean Plate*. Geological Society, London, Special Publications, **328**, 687–703.

CRAWFORD, F. D., SZELEWSKI, C. E. & ALVEY, G. D. 1985. Geology and exploration in the Takutu Graben of Guyana and Brazil. *Journal of Petroleum Geology*, **8**, 5–36.

CRUZ, L., FAYON, A., TESSIER, C. & WEBER, J. 2004. Exhumation and deformation processes in transpressional orogens: the Venezuelan Paria Peninsula, SE Caribbean–South American plate boundary. *In*: TILL, A. B. ET AL. (eds) *Exhumation Associated with*

Continental Strike–Slip Fault Systems. Geological Society of America Special Papers, **434**, 149–165.

Cuevas, E. D. & Maurasse, F. J-M. R. 1995. Radiolarian biostratigraphy of the Conset Bay Series, Barbados, West Indies. *3rd Geological Conference of the Geological Society of Trinidad and Tobago and 14th Caribbean Geological Conference*, Abstracts, 20.

Dalziel, I. W. D. 1972. The tectonic framework of the southern Antilles (Scotia Arc). Its possible bearing on the evolution of the Antilles. *VI Conferencia Geológica del Caribe–Margarita, Venezuela, Memorias*, 300–301.

Davison, I. 2005. Central Atlantic margin basins of North West Africa: Geology and hydrocarbon potential (Morocco to Guinea). *Journal of African Earth Sciences*, **43**, 254–274.

Davison, I., Taylor, M. & Longacre, M. 2003. Central Atlantic Salt Basins Correlation. *AAPG International Meeting*, Barcelona, Extended Abstracts.

Deering, C. D., Vogel, T. A., Patino, L. C. & Alvarado, G. E. 2004. Implications for the petrogenesis of distinct silicic magma types from the Lower Pleistocene Guachipelin Caldera, NW Costa Rica. *EOS Transaction of the American Geophysical Union*, 85, Fall Meeting Supplement, Abstract.

DeMets, C., Jansma, P. E. *et al.* 2000. GPS geodetic constraints on Caribbean–North America plate motion: implications for plate rigidity and oblique plate boundary convergence. *Geophysical Research Letters*, **27**, 437–440.

Dengo, G. 1953. Geology of the Caracas region in Venezuela. *Bulletin of the Geological Society of America*, **64**, 7–40.

Dengo, G. 1968. *Estructura geológico, 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.

Dengo, G. 1975. Paleozoic and Mesozoic tectonic belts in Mexico and Central America. *In*: Nairn, A. E. M. & Stehli, F. G. (eds) *The Ocean Basins and Margins*, **3**. *The Gulf of Mexico and the Caribbean*. Plenum Press, New York, 283–323.

Dengo, G. 1985. Mid America: tectonic setting for the Pacific margin from southern Mexico to northwestern Colombia. *In*: Nairn, A. E. M., Stehli, F. G. & Uyeda, S. (eds) *The Ocean Basins and Margins*, **7A**. *The Gulf of Mexico and the Caribbean*. Plenum Press, New York, 123–180.

Despretz, J. M., Daly, T. E. & Robinson, E. 1985. Geology and petroleum potential of Saba Bank area, northeastern Caribbean. *American Association of Petroleum Geologists Bulletin*, **69**, 249, Abstract.

De Wever, P., Azema, J., Tournon, J. & Desmet, A. 1985. Discovery of Lias–Lower Dogger Ocean material on Santa Elena Peninsula (Costa Rica, Central America). *Pierre & Marie Curie Université, Nancy Université Compte Renduez,* **300**, 759–764.

Dickey, P. A. 1980. Barbados as a fragment of South America ripped off by continental drift. *Transactions Caribbean Geological Conference*, 51–52.

Diebold, J. 2009. Submarine volcanic stratigraphy and the Caribbean LIP's formational environment. *In*: James, K. H., Lorente, M. A. & Pindell, J. L. (eds) *Origin and Evolution of the Caribbean Plate*. Geological Society, London, Special Publications, **328**, 799–808.

Diebold, J., Driscoll, N. & The Ew-9501 Science Team. 1999. New insights on the formation of the Caribbean Basalt Province revealed by multichannel seismic images of volcanic structures in the Venezuela Basin. *In*: Mann, P. (ed.) *Caribbean Sedimentary Basins, Sedimentary Basins of the World*. Elsevier, Amsterdam, 561–589.

Diebold, J. B., Stoffa, P. L., Buhl, P. & Truchan, M. 1981. Venezuela Basin crustal structure. *Journal of Geophysical Research*, **86**, 7901–7923.

Dillon, W. P. & Vedder, J. G. 1973. Structure and development of the continental margin of British Honduras. *Geological Society of America Bulletin*, **84**, 2713–2732.

Di Marco, G., Baumgartner, P. O. & Channell, J. E. T. 1995. Late Cretaceous–Early Tertiary paleomagnetic data and a revised tectonostratigraphic subdivision of Costa Rica and western Panama. *In*: Mann, P. (ed.) *Geologic and Tectonic Development of the Caribbean Plate Boundary in Southern Central America*. Geological Society of America Special Papers, **295**, 1–28.

Dolan, J. F., Beck, C., Ogawa, Y. & Klaus, A. 1990. Eocene–Oligocene sedimentation in the Tiburón Rise/ODP Leg 110 area: an example of significant upslope flow of distal turbidity currents. *Proceedings of the Ocean Drilling Program, Scientific Results*, **110**, 47–63.

Donnelly, T. W. 1964. Evolution of eastern Greater Antilles island arc. *American Association of Petroleum Geologists Bulletin*, **48**, 680–696.

Donnelly, T. W. 1966. Geology of St. Thomas and St. John, Virgin Islands. *In*: Hess, H. H. (ed.) *Caribbean Geological Investigations*. Geological Society of America Memoirs, **98**, 85–176.

Donnelly, T. W. 1973*a*. *Magnetic Anomaly Observations in the Eastern Caribbean Sea*. Initial Reports of the Deep Sea Drilling Project. US Government Printing Office, Washington, DC, **15**, 1023–1025.

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

Donnelly, T. W. 1985. Mesozoic and Cenozoic plate evolution of the Caribbean region. *In*: Stehli, F. G. & Webb, S. D. (eds) *The Great American Biotic Interchange*. Plenum Press, London, 89–121.

Donnelly, T. W. 1989. Geologic history of the Caribbean and Central America. *In*: Bally, A. W. & Palmer, A. R. (eds) *The Geology of North America*, **A**, *An Overview*. Geological Society of America, 299–321.

Donnelly, T. W., Melson, W., Kay, R. & Rogers, J. J. W. 1973. Basalts and dolerites of Late Cretaceous age from the central Caribbean. *Initial Reports of the Deep Sea Drilling Project*, **XV**, 989–1011.

Donnelly, T. W., Beets, D. *et al.* 1990. History and tectonic setting of Caribbean magmatism. *In*: Dengo, G. (ed.) *The Geology of North America*, **H**, *The Caribbean Region*, chapter 13, 339–374.

DOUCET, S., WEIS, D., SCOATES, J. S., NICOLAYSEN, K., FREY, F. A. & GIRET, A. 2002. The depleted mantle component in Kerguelen Archipelago Basalts: petrogenesis of tholeiitic–transitional basalts from the Loranchet Peninsula. *Journal of Petrology*, **43**, 1341–1366.

DOUGLASS, R. C. 1961. Orbitolinas from Caribbean Islands. *Journal of Paleontology*, **35**, 475–479.

DRAPER, G. 1986. Blueschists and associated rocks in eastern Jamaica and their significance for Cretaceous plate-margin development in the northern Caribbean. *Geological Society of America Bulletin*, **97**, 48–60.

DRAPER, G. 1988. Tectonic reconstruction of N. Hispaniola and S. E. Cuba: dissection of a Cretaceous island arc. *Annual Geological Society of America Centennial Celebration Meeting Abstracts*, No. 9991.

DRAPER, G. 1993. Metamorphic map of the Caribbean region, including Central America and Northern South America. *Geological Society of America, Abstracts*, **25**, A-285.

DRAPER, G. & LEWIS, J. F. 1991. Metamorphic belts of central Hispaniola. *In*: MANN, P., DRAPER, G. & LEWIS, J. F. (eds) *Geologic and Tectonic Development of the North America–Caribbean Plate Boundary in Hispaniola*. Geological Society of America Special Papers, **262**, 29–45.

DRAPER, G. & PINDELL, J. L. 2004. Arc-continent collision on the southern margin of North America: Cuba and Hispaniola. *EOS Transactions American Geophysical Union*, **85**, Fall Meeting Supplement, Abstract.

DRAPER, G., GUTIERREZ, G. & LEWIS, J. F. 1996. Thrust emplacement of the Hispaniola peridotite belt: orogenic expression of the Mid-Cretaceous Caribbean arc polarity reversal? *Geology*, **24**, 1143–1146.

DRAPER, G., ABBOTT, R. A. *ET AL*. 2008. Tectonic overview of the Late Cretaceous–Paleogene subduction zone rocks of Hispaniola. *18th Caribbean Geological Conference*, Santo Domingo, Abstracts.

DRISCOLL, N. W., DIEBOLD, J. B. & LAINE, E. P. 1995. New seismic evidence for Late Cretaceous to Eocene turbidite deposition in the Venezuela Basin. *EOS, Transactions, American Geophysical Union*, **76**, supplement, F615.

EAGLES, G. 2007. New angles on South Atlantic opening. *Geophysical Journal International*, **168**, 353–361.

EAGLES, G., LIVERMORE, R. & MORRIS, P. 2005. Small basins in the Scotia Sea: the Eocene Drake Passage gateway. *Earth and Planetary Science Letters*, **242**, 343–353.

EDGAR, N. T., EWING, J. I. & HENNION, J. 1971. Seismic refraction and reflection in Caribbean Sea. *American Association of Petroleum Geologists Bulletin*, **55**, 833–870.

EDGAR, N. T., SAUNDERS, J. B. *ET AL*. 1973. *Initial Reports of the Deep Sea Drilling Project*. US Government Printing Office, Washington, DC, **15**.

EGGLER, D. H., FAHLQUIST, D. A., PEQUEGNAT, W. E. & HERNDON, J. M. 1973. Ultrabasic rocks from the Cayman Trough, Caribbean Sea. *Geological Society of America Bulletin*, **84**, 2133–2138.

ESCALANTE, G. 1990. The geology of southern Central America and western Colombia. *In*: DENGO, G. & CASE, J. E. (eds) *The Caribbean Region, The Geology of North America*. Geological Society of America, **H**, 201–223.

ESCUDER VIRUETE, J., DÍAZ DE NEIRA, A. *ET AL*. 2006. Island-arc tholeiites, boninites and related felsic rocks in Hispaniola: magmatic and age constraints on initiation of intra-oceanic subduction and development of the Caribbean island arc. *Geophysical Research Abstracts*, **8**.

ESTES, R. & BÁEZ, A. 1985. Herpetofaunas of North and South America during the Late Cretaceous and Cenozoic: evidence for interchange? *In*: STEHLI, F. G. & WEBB, S. D. (eds) *The Great American Biotic Interchange*. Plenum Press, London, 139–197.

FAIRHEAD, J. D. & WILSON, M. 2005. Plate tectonic processes in the South Atlantic Ocean: Do we need deep mantle plumes? *In*: FOULGER, G. R., NATLAND, J. H., PRESNALL, D. C. & ANDERSON, D. L. (eds) *Plates, Plumes, and Paradigms*. Geological Society of America Special Papers, **388**, 537–553.

FEO-CODECIDO, G. 1962. Contribution to the geology of north-central Venezuela: Boletín Informativo. *Asociacion Venezolana de Geología, Minería y Petroleo*, **5**, 119–142.

FEO-CODECIDO, G., SMITH, F. D., ABOUD, N. & DI GIACOMO, E. 1984. Basement and Paleozoic rocks of the Venezuelan Llanos basins. *In*: *The Caribbean–South America Plate Boundary and Regional Tectonics*. Geological Society of America Memoirs, **162**, 175–187.

FERNÁNDEZ, J. A., BOTTAZZI, G., BARBOZA, G. & ASTORGA, A. 1994. Tectónica y estratigrafía de la Cuenca Limón Sur. *Revista Geológica de América Central*, volumen especial, Terremoto de Limón, 15–28.

FINK, L. K. 1970. Field guide to the island of La Desirade with notes on the regional history and development of the Lesser Antilles island arc. *International Field Institute Guidebook to the Caribbean Island–Arc system*. American Geological Institute/National Science Foundation.

FINK, L. K. 1972. Bathymetric and geologic studies of the Guadeloupe Region, Lesser Antilles Island Arc. *Marine Geology*, **12**, 267–288.

FLORES, K., BAUMGARTNER, P. O., SKORA, S., BAUMGARTNER, L., BAUMGARTNER-MORA, C. & RODRIGUEZ, D. 2006. Jurassic oceanic remnants. *In*: The Siuna area (NE-Nicaragua)—Tracing the Chortís–Caribbean paleo-plate boundary. *EOS Transactions of the American Geophysical Union*, **87**, Fall Meeting Supplement, Abstract.

FLOTTÉ, N., RANGIN, C., MARTINEZ-REYES, J., LE PICHON, X., HUSSON, L. & TARDY, M. 2008. The Rio Bravo Fault, a major Late Oligocene left-lateral shear zone. *Bulletin de la Société Géologique de France*, **179**, 147–160.

FOULGER, G. R., NATLAND, J. H. & ANDERSON, D. L. 2005. Genesis of the Iceland melt anomaly by plate tectonic processes. *In*: FOULGER, G. R., NATLAND, J. H., PRESNALL, D. C. & ANDERSON, D. L. (eds) *Plates, Plumes, and Paradigms*. Geological Society of America Special Papers, **388**, 595–625.

FOX, P. J. & HEEZEN, B. C. 1975. The geology of the Caribbean Crust. *In*: NAIRN, A. E. M. & STEHLI,

F. G. (eds) *The Ocean Basins and Margins*. Plenum Press, New York, **3**, 421–466.

FOX, P. J., RUDDIMAN, W. F., RYAN, W. B. F. & HEEZEN, B. C. 1970. The geology of the Caribbean crust, I: Beata Ridge. *Tectonophysics*, **10**, 495–513.

FOX, P. J., SCHREIBER, E. & HEEZEN, B. C. 1971. The geology of the Caribbean crust, Tertiary sediments, granitic and basic rocks from the Aves Ridge. *Tectonophysics*, **12**, 89–109.

FREELAND, G. L. & DIETZ, R. S. 1972. Plate tectonic evolution of the Caribbean–Gulf of Mexico region. *6th Caribbean Geological Conference, Venezuela, Transactions*, 259–264.

FREY, F. A., WEIS, D., BORISOVA, A. Yu. & XU, G. 2002. Involvement of continental crust in the formation of the Cretaceous Kerguelen Plateau: new perspectives from ODP Leg 120 Sites. *Journal of Petrology*, **43**, 1207–1239.

FRISCH, W., MESCHEDE, M. & SICK, M. 1992. Origin of the Central American ophiolites: Evidence from paleomagnetic results. *Geological Society of America Bulletin*, **104**, 1301–1314.

FROST, C. D. & SNOKE, A. W. 1989. Tobago, West Indies, a fragment of a Mesozoic oceanic island arc: petrochemical evidence. *Journal of the Geological Society, London*, **146**, 953–964.

FROST, S. H. 1972. Evolution of Cenozoic Caribbean coral faunas. *VI Conferencia Geologica del Caribe–Margarita*, Venezuela, Memorias, 461–464.

FUNNELL, B. M. & SMITH, A. G. 1968. Opening of the Atlantic Ocean. *Nature*, **219**, 1328.

GARCÍA-SENZ, J. & PÉREZ-ESTAÚN, A. 2008. Miocene to Recent tectonic elevation in Eastern Dominican Republic. *18th Caribbean Geological Conference*, Santo Domingo, Abstracts.

GARZANTI, E., DOGLIONI, C., VEZZOLI, G. & ANDO, S. 2007. Orogenic belts and orogenic sediment provenance. *Journal of Geology*, **115**, 315–334.

GAUCHAT, K. 2004. *Geochemistry of Desirade Islands rocks (Guadeloupe, French Antilles)*. Unpublished Diploma, University of Lausanne.

GEORGE, R. P. JR & SOCAS, M. B. 1994. Historia de maduracion termal de rocas madre del Cretacico superior y Mioceno en la subcuenca de Maturin. *V Simposio Bolivariano, Puerto La Cruz, Memoria*, 405–407.

GHIGLIONE, M. C., YAGUPSKY, D., GHIDELLA, M. & RAMOS, V. A. 2008. Continental stretching preceding the opening of the Drake Passage: evidence from Tierra del Fuego. *Geology*, **36**, 643–646.

GHOSH, N., HALL, S. A. & CASEY, J. F. 1984. Sea floor spreading magnetic anomalies in the Venezuelan Basin. *In*: *The Caribbean–South American Plate Boundary*. Geological Society of America Memoirs, **162**, 65–80.

GINGERICH, P. D. 1985. South American mammals in the Palaeocene of North America. *In*: STEHLI, F. G. & WEBB, S. D. (eds) *The Great American Biotic Interchange*. Plenum Press, London, 123–137.

GIUNTA, G. & OLIVERI, E. 2009. Some remarks on the Caribbean Plate kinematics: facts and remaining problems. *In*: JAMES, K. H., LORENTE, M. A. & PINDELL, J. (eds) *Origin and Evolution of the Caribbean Plate*. Geological Society, London, Special Publications, **328**, 57–75.

GLEN, J. M. G. & PONCE, D. A. 2002. Large-scale fractures related to inception of the Yellowstone hotspot. *Geology*, **30**, 647–650.

GONCALVES, P., GUILLOTE, S., LARDEAUX, J.-M., NICOLLETA, C. & MERCIER DE LEPINAY, B. 2002. Thrusting and wrenching in a pre-Eocene HP-LT Caribbean accretionary wedge (Samaná Peninsula, Dominican Republic). *Geodinamica Acta*, **13**, 119–132.

GONZALEZ, A. & LANDER, R. 1990. Regimes tectonicos desde el Triasico hasta el Neogeno en el area occidental de la Cuenca Oriental de Venezuela. *V Congreso Venezolano de Geofisica, Caracas, Memorias*, 134–141.

GONZALEZ DE JUANA, C., ITURRALDE DE AROZENA, J. M. & CADILLAT, X. P. 1980. *Geología de Venezuela y de sus Cuencas Petrolíferas*. Ediciones Foninves, Caracas.

GORDON, M. B. & AVE LALLEMENT, H. G. 1995. Cryptic strike–slip faults of the Chortís block. *GSA Abstracts with Programs*, **27**, 227–228.

GOSE, W. A. & SWARTZ, D. K. 1977. Paleomagnetic results from Cretaceous sediments in Honduras: tectonic implications. *Geology*, **5**, 505–508.

GOUGH, D. I. 1967. Magnetic anomalies and crustal structure in eastern Gulf of Mexico. *American Association of Petroleum Geologists Bulletin*, **51**, 200–211.

GRAHAM, A. 2003. Geohistory models and Cenozoic paleoenvironments of the Caribbean region. *Journal of Systematic Botany*, **28**, 378–386.

GUEDEZ, V. 1985. Revision geologíca y evaluación exploratoria del sector de Monay–Carora. *VI Congreso Geológico Venezolano*, 3103–3143.

GUZMÁN-SPEZIALE, M. 2008. Beyond the Motagua and Polochic faults: active transform faults in the North America–Caribbean Plate boundary zone. *18th Caribbean Geological Conference*, Santo Domingo, Abstracts.

GUZMAN-SPEZIALE, M. & MENESES-ROCHA, J. J. 2000. The North America-Caribbean Plate boundary west of the Motagua–Polochic fault system, a jog in southeastern Mexico. *Journal of South American Earth Sciences*, **13**, 459–468.

HALL, R. 1997. Cenozoic plate tectonic reconstruction of SE Asia. *In*: FRASER, A. J. ET AL. (eds) *Petroleum Geology of Southeast Asia*. Geological Society, London, Special Publications, **126**, 11–23.

HALL, S. A. 1995. Oceanic basement of the Caribbean Basins. *Annual Geological Society of America meeting*, New Orleans, poster, abstract in proceedings, **27**, A-153.

HALL, S. A. & YEUNG, T. 1980. A study of magnetic anomalies in the Yucatán Basin: Transactions, *9th Caribbean Geological Conference*, 519–526.

HARLOW, G. E., HEMMING, S. R., AVÉ LALLEMENT, H. G., SISSON, V. B. & SORENSEN, S. S. 2004. Two high-pressure–low-temperature serpentinite-matrix mélange belts, Motagua fault zone, Guatemala: a record of Aptian and Maastrictian collisions. *Geology*, **32**, 17–20.

HARRY, D. L., LODONO, J. & HUERTA, A. 2003. Early Paleozoic transform-margin structure beneath the Mississippi coastal plain, southeast United States. *Geology*, **31**, 969–972.

HATTEN, C. W. 1967. Principal features of Cuban geology: discussion. *American Association of Petroleum Geologists Bulletin*, **51**, 780–789.

HEATHERINGTON, A. L. & MUELLER, P. A. 1991. Geochemical evidence for Triassic rifting in southwest Florida. *Tectonophysics*, **188**, 291–302.

HELMERS, H. & BEETS, D. J. 1977. Cretaceous of Aruba. *In*: *Guide to Geological Excursions on Curaçao, Bonaire and Aruba. 8th Caribbean Geological Conference*, 29–35.

HELWIG, J. 1975. Tectonic evolution of the Southern Continental margin of North America from a Palaeozoic perspective. *In*: NAIRN, A. E. M. & STEHLI, F. G. (eds) *The Ocean Basins and Margins*, **3**, *The Gulf of Mexico and the Caribbean*, 243–256.

HEPPARD, P. D., CANDER, H. S. & EGGERTSON, E. B. 1998. Abnormal pressure and the occurrence of hydrocarbons in offshore Eastern Trinidad, West Indies. *In*: LAW, B. E., ULMISHEK, G. F. & SLAVIN, V. I. (eds) *Abnormal Pressures in Hydrocarbon Environments*. American Association of Petroleum Geologists Memoirs, **70**, 215–246.

HESS, H. H. 1938. Gravity anomalies and island arc structure with particular reference to the West Indies. *American Philosophical Society Proceedings*, **79**, 71–96.

HESS, H. H. 1966. *Caribbean Geological Investigations*. Geological Society of America Memoirs, **98**.

HINZ, K. 1983. Line BFB (24-fold stack) from the Norwegian continental margin/outer Voring Plateau. *In*: BALLY, A. W. (ed.) *Seismic Expression of Structural Styles – a Picture and Work Atlas*. American Association of Petroleum Geologists Studies in Geology, **15**, 2.2.3–39.

HOLCOMBE, T. L., LADD, J. W., WESTBROOK, G., EDGAR, N. T. & BOWLAND, C. L. 1990. Caribbean marine geology; ridges and basins of the plate interior. *In*: DENGO, G. & CASE, J. E. (eds) *The Caribbean Region. The Geology of North America*, **H**. Geological Society of America, 231–260.

HONTHAAS, C., R'HAULT, J.-P. *ET AL*. 1998. A Neogene back-arc origin for the Banda Sea basins: geochemical and geochronological constraints from the Banda ridges (East Indonesia). *Tectonophysics*, **298**, 297–317.

HOPPER, J. R., FUNCK, T. & TUCHOLKE, B. E. 2004. Continental break up and the onset of ultraslow seafloor spreading off Flemish Cap on the Newfoundland margin. *Geology*, **32**, 93–96.

HORBURY, A. D., HALL, S. *ET AL*. 2003. Tectonic sequence stratigraphy of the western margin of the Gulf of Mexico in the Late Mesozoic and Cenozoic: less passive than previously imagined. *In*: BARTOLINI, C. *ET AL*. (eds) *The Circum-Gulf of Mexico and the Caribbean: Hydrocarbon Habitats, Basin Formation, and Plate Tectonics*. American Association of Petroleum Geologists Memoirs, **79**, 184–245.

HORNE, G. S., FINCH, R. C. & DONNELLY, T. W. 1990. The Chortís Block. *In*: DENGO, G. & CASE, J. E. (eds) *Geology of North America*, **H**. Geological Society of America, 55–76.

HUNTER, V. F. 1995. Limestone buildups as ecotectonic indicators within the Tertiary of the southern Caribbean region. *3rd Geological Conference of the Geological Society of Trinidad and Tobago and 14th Caribbean Geological Conference*, Abstracts, 35.

ISHIKAWA, A., KURITANI, T., MAKISHIMA, A. & NAKAMURA, E. 2007. Recycling of the Rodinia supercontinent in the Cretaceous Ontong Java Plateau? *Earth and Planetary Science Letters*, **259**, 134–148.

ITURRALDE-VINENT, M. A. 1994. Cuban Geology: a new plate-tectonic synthesis. *Journal of Petroleum Geology*, **17**, 39–70.

ITURRALDE-VINENT, M. A. 1995. Late Paleocene to early Middle Eocene Cuban Island Arc. *3rd Geological Conference of the Geological Society of Trinidad and Tobago*, Program and Abstracts, 37.

ITURRALDE-VINENT, M. 1996. *IGCP Project 364. Correlation of Episodes, Caribbean Ophiolites and Volcanic Arcs*. **19**, 1–2.

ITURRALDE-VINENT, M. 2004. IGCP Project 433 Caribbean Plate Tectonics: State of the debate and future developments. *32nd IGC, Florence*, 2004, *IGCP Project 433. Caribbean Plate Tectonics*, Abstracts.

ITURRALDE-VINENT, M. A. & GARCÍA-CASCO, A. 2007. Caribeana, a possible solution to a long standing puzzle: the Caribbean latest Cretaceous tectonic events. *Field-Workshop of Caribbean Geology, 2da Convención Cubana de Ciencias de la Tierra, Havana, Cuba*, UNESCO/IUGS – IGCP Project 546, Abstracts GEO10-02.

JACKSON, J. 1997. *Glossary of Geology*. American Geological Institute.

JACKSON, T. A., SMITH, T. E. & HUANG, C. H. 1987. The geochemistry and geochemical variations of Cretaceous andesites and dacites from Jamaica West Indies. *In*: DUQUE-CARO, H. (ed.) *10th Caribbean Geological Conference*, Cartegena, Colombia, 473–479.

JACKSON, M. P. A., CRAMEZ, C. & FONCK, J. M. 2000. Role of subaerial volcanic rocks and mantle plumes in creation of South Atlantic margins: implications for salt tectonics and source rocks. *Marine and Petroleum Geology*, **17**, 477–498.

JACQUES, J. M. & OTTO, S. 2003. Two major tectonic events expressed in the tectonostratigraphic evolution of the Caribbean, Gulf of Mexico and Sub-Andean Basins: 25 and 12 Ma. *AAPG Bulletin*, **87**, 13 (supplement).

JAILLARD, E., LAPIERRE, H., ORDOÑEZ, M., ÁLAVA, J. T., AMÓRTEGUI, A. & VANMELLE, J. 2009. Accreted oceanic terranes in Ecuador: southern edge of the Caribbean Plate? *In*: JAMES, K. H., LORENTE, M. A. & PINDELL, J. L. (eds) *Origin and Evolution of the Caribbean Plate*. Geological Society, London, Special Publications, **328**, 469–485.

JAMES, E. & MITCHELL, S. F. 2005. Comparison of the stratigraphy of the Tertiary limestone across central Jamaica. *17th Caribbean Geological Conference*, Puerto Rico, Abstracts, 39.

JAMES, K. H. 1997. Distribution and tectonic significance of Cretaceous–Eocene flysch/wildflysch deposits of Venezuela and Trinidad. Sociedad Venezolana de Geologos. *VIII Venezuelan Geological Congress*, Margarita, 415–421.

JAMES, K. H. 2000. The Venezuelan hydrocarbon habitat. Part 1: Tectonics, structure, palaeogeography and source rocks. *Journal of Petroleum Geology*, **23**, 5–53.

JAMES, K. H. 2002. A discussion of arguments for and against the far-field origin of the Caribbean Plate, finding for an *in situ* origin. *16th Caribbean Geological Conference*, Barbados, Abstracts, 89.

JAMES, K. H. 2003*a*. Caribbean Plate origin: discussion of arguments claiming to support a Pacific origin; arguments for an *in situ* Origin. *American Association of Petroleum Geologists Bulletin*, **87**, 13 (supplement).

JAMES, K. H. 2003*b*. A simple synthesis of Caribbean geology. *American Association of Petroleum Bulletin*, **87** (supplement).

JAMES, K. H. 2005*a*. Arguments for and against the Pacific origin of the Caribbean Plate and arguments for an *in situ* origin: transactions, 16th Caribbean Geological Conference, Barbados. *Caribbean Journal of Earth Sciences*, **39**, 47–67.

JAMES, K. H. 2005*b*. A simple synthesis of Caribbean geology: transactions, 16th Caribbean Geological Conference, Barbados. *Caribbean Journal of Earth Sciences*, **39**, 71–84.

JAMES, K. H. 2005*c*. Palaeocene to Middle Eocene flysch–wildflysch deposits of the Caribbean area: a chronologicla compilation of literature reports, implications for tectonic history and recommendations for further investigation: transactions, 16th Caribbean Geological Conference, Barbados. *Caribbean Journal of Earth Sciences*, **39**, 29–46.

JAMES, K. H. 2006. Arguments for and against the Pacific origin of the Caribbean Plate: discussion, finding for an inter-American origin. *In*: ITURRALDE-VINENT, M. A. & LIDIAK, E. G. (eds) *Caribbean Plate Tectonics. Geologica Acta*, **4**, 279–302.

JAMES, K. H. 2007*a*. Structural geology: from local elements to regional synthesis. *In*: BUNDSCHUH, J. & ALVARADO, G. E. (eds) *Central America: Geology, Resources and Hazards*. Balkema, Rotterdam, 277–321.

JAMES, K. H. 2007*b*. The Caribbean Plateau. World Wide Web Address: http://www.mantleplumes.org/Caribbean.html.

JAMES, K. H. 2009. Evolution of Middle America and the *in situ* Caribbean Plate model. *In*: JAMES, K. H., LORENTE, M. A. & PINDELL, J. L. (eds) *Origin and Evolution of the Caribbean Plate*. Geological Society, London, Special Publications, **328**, 127–138.

JAMES, K. H., SOOFI, K. A. & WEINZAPFEL, A. C. 1998. Ocean floor mapped from space. *American Association of Petroleum Geologists Explorer*, 20–23.

JOHNSON, E. A. E., KACEWICZ, M., BLICKWEDE, J. F. & HUSTON, H. H. 2005. An interpretation of the crustal framework and continent–oceanic boundary in U.S. OCS of the Gulf of Mexico, based on gravity and refraction data analysis. *25th Annual Gulf Coast Section SEPM Foundation Bob F. Parker Research Conference*, Abstracts, 48.

JOLLY, W. T. & LIDIAK, E. G. 2005. Role of crustal melting in petrogenesis of the Cretaceous Water Island Formation, Virgin Islands northeast Antilles Island Arc. *17th Caribbean Geological Conference*, Puerto Rico, Abstracts, 41.

JOLLY, W. T., LIDIAK, E. G. & DICKIN, A. P. 2006. Cretaceous to Mid-Eocene pelagic sediment budget in Puerto Rico and the Virgin Islands (northeast Antilles Island arc). *In*: ITURRALDE-VINENT, M. A. & LIDIAK, E. G. (eds) *Caribbean Plate Tectonics. Geologica Acta*, **4**, 35–62.

JOYCE, J. 1991. Blueschist metamorphism and deformation on the Samana Peninsula – a record of subduction and collision in the Greater Antilles. *In*: MANN, P., DRAPER, G. & LEWIS, J. F. (eds) *Geologic and Tectonic Development of the North America–Caribbean Plate Boundary in Hispaniola*. Geological Society of America Special Papers, **262**, 29–46.

JOYCE, J. & ARONSON, J. 1983. K–Ar age dates for blueschist metamorphism on the Samaná Peninsula, Dominican Republic. *10th, Caribbean Geological Conference*, Cartagena.

KASPER, D. C. & LARUE, D. K. 1986. Paleogeographic and tectonic implications of quartzose sandstones of Barbados. *Tectonics*, **5**, 837–854.

KAUFFMAN, E. G. 1973. Cretaceous bivalvia. *In*: HALLAM, A. (ed.) *Atlas of Paleogeography*. Elsevier, New York, 353–383.

KEAST, A. 1972. Continental drift and evolution of biota on southern continents. *In*: KEAST, A. *ET AL*. (eds) *Evolution, Mammals, and Southern Continents*. State University of NY Press, Albany, NY, 23–88.

KEPPIE, J. D. & MORÁN-ZENTENO, D. J. 2005. Tectonic implications of alternative Cenozoic reconstructions for Southern Mexico and the Chortís Block. *International Geology Review*, **47**, 473–491.

KEPPIE, J. D., DOSTAL, J., CAMERON, K. L., SOLARI, L. A., ORTEGA-GUTIÉRREZ, F. & LOPEZ, R. 2003. Geochronology and geochemistry of Grenvillian igneous suites in the northern Oaxacan Complex, southern Mexico: tectonic implications. *Precambrian Research*, **120**, 365–389.

KERR, A. C., TARNEY, J., MARRINER, G. F., NIVIA, A. & SAUNDERS, A. D. 1997. The Caribbean–Colombian Cretaceous Igneous Province: the internal anatomy of an oceanic plateau. *In*: MAHONEY, J. J. & COFFIN, M. F. (eds) *Large Igneous Provinces, Continental, Oceanic, and Planetary Flood Volcanism*. American Geophysical Union Geophysical Monographs, **100**, 123–144.

KERR, A. C., ITURRALDE-VINENT, M. A., SAUNDERS, A. D., BABBS, T. L. & TARNEY, J. 1999. A new plate tectonic model of the Caribbean: implications from a geochemical reconnaissance of Cuban Mesozoic volcanic rocks. *Geological Society of America Bulletin*, **111**, 1581–1599.

KERR, A. C., WHITE, R. V. & SAUNDERS, A. D. 2000. LIP reading: Recognizing oceanic plateaux in the geological record. *Journal of Petrology*, **41**, 1041–1056.

KERR, A. C., WHITE, R. V., THOMPSON, P. M. E., TARNEY, J. & SAUNDERS, A. D. 2003. No Oceanic Plateau – no Caribbean Plate? The seminal role of oceanic plateau(s) in Caribbean Plate evolution. *In*: BARTOLINI, C., BUFFLER, R. T. & BLICKWEDE, J. (eds) *The Gulf of Mexico and Caribbean Region: Hydrocarbon Habitats, Basin Formation and Plate Tectonics*. American Association of Petroleum Geologists Memoirs, **79**, 126–268.

KERR, A. C., PEARSON, D. G. & NOWELL, G. M. 2009. Magma source evolution beneath the Caribbean oceanic plateau: new insights from elemental and Sr–Nd–Pb–Hf isotopic studies of ODP Leg 165 Site 1001 basalts. *In*: JAMES, K. H., LORENTE, M. A. & PINDELL, J. L. (eds) *Origin and Evolution of the Caribbean Plate*. Geological Society, London, Special Publications, **328**, 809–827.

KHUDOLEY, K. M. 1967. Principal features of Cuban geology: discussion. *American Association of Petroleum Geologists Bulletin*, **51**, 789–791.

KHUDOLEY, K. M. & MEYERHOFF, A. 1971. *Paleogeography and Geological History of the Greater Antilles*. Geological Society of America Memoirs, **129**.

KIRKLAND, D. W. & GERHARD, J. E. 1971. Jurassic salt, central Gulf of Mexico, and its temporal relation to circum-Gulf evaporites. *American Association of Petroleum Geologist Bulletin*, **55**, 680–686.

KISER, G. D. 1987. Exploration results, Machete area, Orinoco Oil Belt, Venezuela. *Journal of Petroleum Geology*, **10**, 149–162.

KLAVER, G. Th. 1987. *The Curaçao Lava Formation, an ophiolitic analogue of the anomalous thick layer 2B of the Mid-Cretaceous oceanic plateaus in the western Pacific and central Caribbean*. PhD thesis, Amsterdam.

KLINGELHÖFER, F., EDWARDS, R. A., HOBBS, R. W. & ENGLAND, R. W. 2005. Crustal structure of the NE Rockall Trough from wide-angle seismic data modeling. *Journal of Geophysical Research*, **110**, B11105; doi:10.1029/2005JB003763.

KLUGE, R., BAUMANN, A., TOETZ, A., MARESCH, W. V., STOCKHERT, B. & TROESCH, M. 1995. New geochronological constraints on the crustal history of Margarita Island. *3rd Geological Conference of the Geological Society of Trinidad and Tobago and 14th Caribbean Geological Conference*, Abstracts, 41.

KOLARSKY, R. A., MANN, P. & MONECHI, S. 1995. Stratigraphic development of southwestern Panama as determined from integration of marine seismic data and onshore geology. *In*: MANN, P. (ed.) *Geologic and Tectonic Development of the Caribbean Plate Boundary in Southern Central America*. Geological Society of America Special Papers, **295**, 159–200.

KOZARY, M. T. 1968. Ultramafic rocks in thrust zones of northwestern Oriente Province, Cuba. *American Association of Petroleum Geologists Bulletin*, **52**, 2298–2317.

KRAWINKEL, J. & SEYFRIED, H. 1994. A review of plate-tectonic processes involved in the formation of the southwestern edge of the Caribbean Plate. *Profil*, **7**, 47–61.

KRÜGER, F., SCHERBAUM, F., ROSA, J. W. C., KIND, R., ZETSCHE, F. & HOHNE, J. 2002. Crustal and upper mantle structure in the Amazon region (Brazil) determined with broadband mobile stations. *Journal of Geophysical Research*, **107**, 2265.

KUGLER, H. G. 1953. Jurassic to Recent sedimentary environments in Trinidad. *Bulletin Asociacion Suisse des Géologues et Ingénieurs du Petrole*, **20**, 27–60.

KUGLER, H. G. 1972. The Dragon Gneiss of Paria Peninsula (Eastern Venezuela). *VI Conferencia Geológica del Caribe*, Margarita, Venezuela, Memorias, 113–116.

LADD, J. W. 1976. Relative motion of South America with respect to North America and Caribbean tectonics. *Geological Society of America Bulletin*, **87**, 969–976.

LADD, J. W., SHIH, T-Ch. & TSAI, C. J. 1981. Cenozoic tectonics of Central Hispaniola and adjacent Caribbean Sea. *American Association of Petroleum Geologists Bulletin*, **65**, 466–489.

LAGAAY, R. A. 1969. *Geophysical investigations of the Netherlands Leeward Antilles*. Verhandelingen der Koningkliike Nederlandse Akademie van Wetenschappen, Afd. Natuurkunde, V. **25**, 2.

LAÓ-DÁVILA, C. A., ANDERSON, T. H. & LLERANDI-ROMÁN, P. A. 2004. Olistostromes and allochthonous serpentinite: major tectonostratigraphic elements in southwest Puerto Rico. *32nd IGC*, Florence, 2004, IGCP Project 433 Caribbean Plate Tectonics, Abstracts.

LARDEAUX, J. M., TORRES-ROLDÁN, R. L. & MILLÁN TRUJILLO, G. 2004. Origin and evolution of the Escambray Massif (Central Cuba): an example of HP/LT rocks exhumed during intraoceanic subduction. *Journal of Metamorphic Geology*, **22**, 227.

LARSON, R. L. 1997. Superplumes and ridge interactions between Ontong Java and Manihiki Plateaus and the Nova-Canton Trough. *Geology*, **25**, 779–782.

LARSON, R. L., POCKALNY, R. A. *ET AL*. 2002. Mid-Cretaceous tectonic evolution of the Tongareva triple junction in the southwestern Pacific Basin. *Geology*, **30**, 67–70.

LARUE, D. K., TORRINI, R. JR, SMITH, A. L. & JOYCE, J. 1998. North Coast Tertiary Basin of Puerto Rico: From arc basin to carbonate platform to arc-massif slope. *In*: LIDIAK, E. G. & LARUE, D. K. (eds) *Tectonics and Geochemistry of the Northeastern Caribbean*. Geological Society of America, 155–176.

LEAT, P. T. & LARTER, R. D. 2003. Intra-oceanic subduction systems: introduction. *In*: LARTER, R. D. & LEAT, P. T. (eds) *Intra-oceanic Subduction Systems: Tectonic and Magmatic Processes*. Geological Society, London, Special Publications, **219**, 1–17.

LEBRON, M. C. & PERFIT, M. R. 1993. Stratigraphic and petrochemical data support subduction polarity reversal of the Cretaceous Caribbean Arc. *Journal of Geology*, **101**, 389–396.

LEROY, S., MERCIER DE LEPINAY, B., MAUFFRET, A. & PUBELLIER, M. 1996. Structural and tectonic evolution of the eastern Cayman Trough (Caribbean Sea) from seismic reflection data. *American Association of Petroleum Geologists Bulletin*, **80**, 222–247.

LEROY, S., MAUFFRET, A., PATRIAT, P. & MERCIER DE LÉPINAY, B. 2000. An alternative interpretation of the Cayman Trough evolution from a reidentification of magnetic anomalies. *Geophysical Journal International*, **141**, 539–557.

LEVANDER, A., MANN, P., AVE LALLEMENT, H. G. & SCHMITZ, M. 2004. Bolivar: the SE Caribbean Continental Dynamics Project. *EOS Transactions American Geophysical Union*, **85**, Fall Meeting Supplement, Abstract.

LEW, L. R. 1985. *The geology of the Santa Elena Peninsula, Costa Rica, and its implications for the tectonic evolution of the Central America–Caribbean region*. PhD thesis, Pennsylvania State University.

LEWIS, J. F. 1971. Composition, origin, and differentiation of basalt magma in the Lesser Antilles.

In: DONNELLEY, T. W. (ed.) *Caribbean Geophysical, Tectonic and Petrologic Studies*. Geological Society of America Memoirs, **130**, 159–179.

LEWIS, J. F. 1990. Cuba. *In*: DENGO, G. & CASE, J. E. (eds) *The Caribbean Region*. The Geology of North America, **H**. Geological Society of America, 78–93.

LEWIS, J. 2002. Albian unconformities. *16th Caribbean Geological Conference*, Barbados.

LEWIS, J. F. & GUNN, B. M. 1972. Aspects of island arc evolution and magmatism in the Caribbean: geochemistry of some West Indian plutonic and volcanic rocks. *VI Conferencia Geológica del Caribe–Margarita*, Venezuela, Memorias, 171–177.

LEWIS, J. F. & DRAPER, G. 1990. Geology and tectonic evolution of the northern Caribbean margin. *In*: DENGO, G. & CASE, J. E. (eds) *The Caribbean Region*. The Geology of North America, **H**. Geological Society of America, 77–140.

LEWIS, J. F., DRAPER, G., BOWIN, C., BOURDON, L., MAURRASSE, F. & NAGLE, F. 1990. Hispaniola. *In*: LEWIS, J. F. & DRAPER, G. Geology and tectonic evolution of the northern Caribbean margin. *In*: DENGO, G. & CASE, J. E. (eds) *The Caribbean Region*. The Geology of North America, Geological Society of America, 94–112.

LEWIS, J. F., PERFIT, M. R. *ET AL*. 2005. Anomalous granitoid compositions from the northwestern Cayman Trench: implications for the composition and evolution of the Cayman Ridge. *17th Caribbean Geological Conference*, Puerto Rico, Abstracts, 49.

LEWIS, J. G., MATTIETTI, K., PERFIT, M. & KAMENOV, G. 2008. Geochemistry and petrology of three granitoid rock cores from the Nicaragua Rise, Caribbean Sea: implication for its composition, structure and tectonic evolution. *18th Caribbean Geological Conference*, Santo Domingo, Abstracts.

LIDIAK, E. G. 1970. *Volcanic rocks in the Puerto Rican Orogen: international field institute guidebook to the Caribbean Island Arc system*. American Geological Institute (article individually paginated).

LIDIAK, E. G. 2008. Geochemical and tectonic evolution of Albian to Eocene volcanic strata in the Virgin Islands and eastern and central Puerto Rico. *2008 Joint Meeting of the Geological Society of America, American Society of Agronomy, Crop Science Society of America, Gulf Coast Association of Geological Societies with the Gulf Coast Section of the Society for Sedimentary Geology*, Abstracts, paper **128-12**.

LIDZ, B. H. 1988. Upper Cretaceous (Campanian) and Cenozoic stratigraphic sequence, Northeast Caribbean (St. Croix, U. S. Virgin Islands). *Geological Society of America Bulletin*, **100**, 282–298.

LIVERMORE, R., EAGLES, G., MORRIS, P. & MALDONADO, A. 2004. Shackleton Fracture Zone: no barrier to early circumpolar ocean circulation. *Geology*, **32**, 797–800.

LOCKWOOD, J. P. 1971. Detrital serpentinite from the Guajira Peninsula, Colombia. *In*: DONNELLY, T. W. (ed.) *Caribbean Geophysical, Tectonic and Petrologic Studies*. Geological Society of America Memoirs, **130**, 55–75.

LÓPEZ-RAMOS, E. 1975. Geological summary of the Yucatán peninsula. *In*: NAIRN, A. E. M. & STEHLI, F. G. (eds) *The Ocean Basins and Margins*, **3**. Plenum Press, New York, 257–282.

LOWRIE, W. & OPDYKE, N. D. 1975. Paleomagnetism of igneous and sedimentary samples. *In*: EDGAR, N. T. *ET AL*. (eds) *Initial Reports of the Deep Sea Drilling Project*, **15**. US Government Printing Office, Washington, DC, 1017–1021.

LUCAS, S. G., ALVARADO, G. E., GARCÍA, R., ESPINOSA, E., CISNEROS, J. C. & MARTENS, U. 2006. Vertebrate paleontology. *In*: BUNDSCHUH, J. & ALVARADO, G. E. (eds) *Central America, Geology, Resources and Hazards*. Taylor & Francis, Balkema, The Netherlands, Chapter 16, 443–451.

MALIN, P. E. & DILLON, W. P. 1973. Geophysical reconnaissance of the western Cayman Ridge. *Journal of Geophysical Research*, **78**, 7769–7775.

MALFAIT, B. T. & DINKLEMAN, M. G. 1972. Circum-Caribbean tectonic and igneous activity and the evolution of the Caribbean Plate. *Geological Society of America Bulletin*, **83**, 251–272.

MANN, P. 2007. Overview of the tectonic history of northern Central America. *In*: MANN, P. (ed.) *Geologic and Tectonic Development of the Caribbean Plate Boundary in Northern Central America*. Geological Society of America Special Paper, **428**, 1–19.

MANSPEIZER, W. 1988. Triassic–Jurassic rifting and opening of the Atlantic: an overview. *In*: MANZPEIZER, W. (ed.) *Triassic–Jurassic Rifting*, Part A. Elsevier, Amsterdam, 41–79.

MANTON, W. 1996. The Grenville of Honduras, Abstracts. *Geological Society of America*, **28**, 493.

MARESCH, W. V. & GERYA, T. V. 2006. Blueschists and blue amphiboles: how much subduction do they need? *In*: LIOU, J. G. & CLOOS, M. (eds) *Phase Relations, High Pressure Terranes, P–T-Ometry, and Plate Pushing: a Tribute to W. G. Ernst*. Geological Society of America, International Book Series, **9**, 23–37.

MARESCH, W. V., STOCKHERT, B., KRUCKHANS-LUDER, G., TOETZ,A. & BRIX, M. 1993. Structural geology, fabric analysis, petrology and geochronology in concert: how does the Margarita crustal block fit the Caribbean tectonic puzzle? *Geological Society of America Annual Meeting*, Boston, Abstract A-71.

MARTON, G. & BUFFLER, R. T. 1993. Application of simple-shear model to the evolution of passive continental margins of the Gulf of Mexico basin. *Geology*, **21**, 495–498.

MARZOLI, A., RENNE, P. R., PICCIRILLO, E. M., ERNESTO, M., BELLIENI, G. & DE MIN, A. 1999. Extensive 200-million-year-old continental flood basalts of the central Atlantic magmatic province. *Science*, **284**, 616–618.

MASCLE, A., MOORE, J. C. *ET AL*. 1988. Synthesis of shipboard results: Leg 110 transect of the Northern Barbados Ridge. *In*: MOORE, C., MASCLE, A. J. *ET AL*. (eds) *Proceedings of the Ocean Drilling Program, Part A, Initial Reports*, 577–591.

MASCLE, D., LETOUZEY, P. *ET AL*. 1990. *Geological Map of the Caribbean*. IFP, Beicip, Editions Technip, Paris.

MATTIETTI-KYSAR, G. 1999. The role of Paleogene volcanism in the evolution of the northern Caribbean margin. *Penrose Conference: Subduction to Strike–Slip Transitions on Plate Boundaries*, Abstracts, 63–64.

MATTSON, P. H. 1966. Geological characteristics of Puerto Rico. *In*: POOLE, W. H. (ed.) *Continental Margins and Island Arcs*. Geological Survey of Canada Papers, 66–15.

MATTSON, P. H. 1984. *Caribbean Structural Breaks and Plate Movements*. Geological Society of America Memoirs, **162**, 131–152.

MATTSON, P. H. & SCHWARTZ, D. P. 1971. Control of intensity of deformation in Puerto Rico by mobile peridotite basement. *In*: DONNELLEY, T. W. (ed.) *Caribbean Geophysical, Tectonic and Petrologic Studies*. Geological Society of America Memoirs, **130**, 97–106.

MATTSON, P., PESSAGNO, E. A. & HELSEY, C. E. 1972. *Outcropping Later A and A″ Correlatives in the Greater Antilles*. Geological Society of America Memoirs, **132**, 57–66.

MAUFFRET, A. & LEROY, S. 1997. Seismic stratigraphy and structure of the Caribbean igneous province. *Tectonophysics*, **283**, 61–104.

MAURASSE, F. 1981. Relations between the geologic setting of Hispaniola and the origin and evolution of the Caribbean. *In*: MAURASSE, F. *ET AL.* (eds) *Presentations Transactions du ler Colloque sur la Geologie d'Haiti*, Port-au-Prince, 1980, 246–264.

MAURY, R. C., WESTBROOK, G. K., BAKER, P. E., BOUYSSE, Ph. & WESTERCAMP, D. 1990. Geology of the Lesser Antilles. *In*: DENGO, G. & CASE, J. E. (eds) *The Caribbean Region*. The Geology of North America, **H**, 141–166.

MAZE, W. B. 1984. Jurassic La Quinta Formation in the Sierra de Perija, northwestern Venezuela: geology and tectonic environment of red beds and volcanic rocks. *In*: *The Caribbean–South American Plate Boundary and Regional Tectonics*. Geological Society of America Memoirs, **162**, 263–282.

MCCOLLOUGH, C. N. & CARVER, J. A. 1992. The Giant Caño Limon Field, Llanos Basin, Colombia. *In*: HALBOUTY, M. T. (ed.) *Giant Oil and Gas Fields of the Decade 1978–1988*. American Association of Petroleum Geologists Memoirs, **54**, 175–195.

MCHONE, J. G. 2002. Volatile emissions from Central Atlantic Magmatic Province basalts: mass assumptions and environmental consequences. *In*: *The Central Atlantic Magmatic Province*. AGU Monograph, 1–13.

MENÉNDEZ, A. 1966. Tectónica de la parte central de las montañas occidentales del Caribe, Venezuela. *Boletín de Geología*, **8**, 116–139.

MESCHEDE, M. 1998. The impossible Galapagos connection: geometric constraints for a near-American origin of the Caribbean Plate. *Geologische Rundschau*, **87**, 200–205.

MEYERHOFF, A. A. & HATTEN, C. W. 1974. Bahamas salient of North America: tectonic framework, stratigraphy, and petroleum potential. *In*: BURK, C. A. & DRAKE, C. L. (eds) *The Geology of Continental Margins*. Springer, New York, 429–446.

MEYERHOFF, A. A. & MEYERHOFF, H. A. 1972. Continental drift, IV: the Caribbean "Plate". *Journal of Geology*, **80**, 34–60.

MILLS, R. A., HUGH, K. E., FERAY, F. E. & SWOLFS, H. C. 1967. Mesozoic stratigraphy of Honduras. *American Association of Petroleum Geologists Bulletin*, **51**, 1711–1786.

MITCHELL, S. 2005. Cretaceous and Cainozoic evolution of Jamaica. How does it test the current models? *17th Caribbean Geological Conference*, Puerto Rico, Abstracts, 60.

MITCHELL, S. F. 2008. Biostratigraphy and its implications for the early tectonic evolution of the Great Arc of the Caribbean. *2008 Joint Meeting of the Geological Society of America, American Society of Agronomy, Crop Science Society of America, Gulf Coast Association of Geological Societies with the Gulf Coast Section of the Society for Sedimentary Geology*, Abstracts, **128-10**.

MOHRIAK, W. U., BROWN, D. E. & TARI, G. 2008. Sedimentary basins in the central and south Atlantic conjugate margins: deep structures and salt tectonics. World Wide Web Address: http://www.conjugatemargins.com/abstracts/by_session/1.

MOLINA-GARZA, R. S., VAN DER VOO, R. & URRUTIA-FUCUGAUCHI, J. 1992. Paleomagnetism of the Chiapas Massif, southern Mexico: evidence for rotation of the Maya Block and implications for the opening of the Gulf of Mexico. *Geological Society of America Bulletin*, **104**, 1156–1168.

MONTGOMERY, H. 1998. Paleogene stratigraphy and sedimentology, North Coast, Puerto Rico. *In*: LIDIAK, E. G. & LARUE, D. K. (eds) *Tectonics and Geochemistry of the Northeastern Caribbean*. Geological Society of America, 177–192.

MONTGOMERY, H. & KERR, A. C. 2009. Rethinking the origins of the red chert at La Désirade, French West Indies. *In*: JAMES, K. H., LORENTE, M. A. & PINDELL, J. L. (eds) *Origin and Evolution of the Caribbean Plate*. Geological Society, London, Special Publications, **328**, 457–467.

MOORE, G. T. & FAHLQUIST, D. A. 1976. Seismic profiling tying Caribbean DSDP sites 153, 151, and 152. *Geological Society of America Bulletin*, **87**, 1609–1614.

MORA, J., LOUREIRO, D. & OSTOS, M. 1993. Pre-Mesozoic rectangular network of crustal discontinuities: one of the main controlling factors of the tectonic evolution of northern South America. *American Association of Petroleum Geologists/Sociedad Venezolana de Geología International Congress and Exhibition*, Caracas, Abstracts, 58.

MORA, C., CORDOBA, F. *ET AL.* 1996. Petroleum systems of the Middle Magdalena Valley, Colombia. *American Association of Petroleum Geologists/Sociedad Geológica Venezolana International Congress and Exhibition*, Caracas, Abstracts A 32.

MORÓN, S. & JARAMILLO, C. 2008. Miocene Culebra–Cucaracha Formation boundary in Panama. Climatic or tectonic change. *18th Caribbean Geological Conference*, Santo Domingo, Abstracts.

MORRIS, A. E. L., TANER, I., MEYERHOFF, H. A. & MEYERHOFF, A. A. 1990. Tectonic evolution of the Caribbean region; Alternative hypothesis. *In*: DENGO, G. & CASE, J. E. (eds) *The Caribbean Region*. The Geology of North America, **H**, 433–457.

MOSSMAN, W. & VINIEGRA-O, F. 1976. Complex structures in Veracruz province of Mexico. *American Association of Petroleum Geologists Bulletin*, **60**, 379–388.

MOUNTAIN, G. S. & TUCHOLKE, B. E. 1985. Mesozoic and Cenozoic geology of the U.S. Atlantic continental slope and rise. *In*: POAG, C. W. (ed.) *Geologic Evolution of the U. S. Atlantic Margin*. Van Nostrand Reinhold, Stroudsburg, PA, 293–341.

MÜLLER, D., ROEST, W. R., ROYER, J. Y., GALAGHAN, L. M. & SCLATER, J. G. 1997. Digital isochrons of the world's ocean floor. *Journal of Geophysical Research*, **102**, 3211–3214.

MULLER, R. D., ROYER, J.-Y., CANDE, S. C., ROEST, W. R. & MASCHENKOV, S. 1999. New constraints on the Late Cretaceous/Tertiary Plate tectonic evolution of the Caribbean. *In*: MANN, P. (ed.) *Caribbean Sedimentary Basins, Sedimentary Basins of the World*. Elsevier, Amsterdam, 33–59.

MUÑOZ, A., BACA, D., ARTILES, V. & DUARTE, M. 1997. Nicaragua: Petroleum geology of the Caribbean margin. *The Leading Edge*, 1799–1805.

MUTTER, J. C., TALWANI, M. & STOFFA, P. 1982. Origin of eastward-dipping reflectors in oceanic crust off the Norwegian margin by subaerial seafloor spreading. *Geology*, **10**, 353–357.

MYCXYNSKI, R. & ITURRALDE-VINENT, M. 2005. The Late Lower Albian invertebrate fauna of the Río Hatillo Formation of Pueblo Viejo, Dominican Republic. *Caribbean Journal of Earth Science*, **41**, 782–796.

NAGLE, F. 1970. Caribbean geology. *Bulletin of Marine Science*, **21**, 375–439.

NAGLE, F. 1972. Rocks from seamounts and escarpments on the Aves Ridge. *VI Conferencia Geologica Del Caribe*, Margarita, Venezuela, Memorias, 409–413.

NAGLE, F. 1974. Blueschist, eclogite paired metamorphic belts and the early tectonic history of Hispaniola. *Geological Society of America Bulletin*, **85**, 1461–1466.

NAGLE, F., ERLICH, R. N. & CANOVI, C. J. 1978. Caribbean dredge haul compilation: summary and implications. *Geologie en Mijnbouw*, **57**, 267–270.

NAGLE, F., WASSAL, H., TARASIEWICZ, G. & TARASIEWICZ, E. 1982. Metamorphic rocks and stratigraphy of central Tortué Island, Haiti: Transactions. *IX Caribbean Geological Conference*, Santo Domingo, **2**, 409–415.

NANCE, R. D., MILLER, B. V., KEPPIE, J. D., MURPHY, J. B. & DOSTAL, J. 2006. Acatlán Complex, southern Mexico: Record spanning the assemblage and breakup of Pangea. *Geology*, **34**, 857–860.

NELSON, B. K., HERMANN, U. R., GORDON, M. B. & RATSBACHER, L. 1997. Sm–Nd and U–Pb evidence for Proterozoic crust in the Chortís Block, Central America: Comparison with the crustal history of southern Mexico. *Terra Nova*, **9**, Abstract Supplement No 1, 496.

NICHOLLS, I. A., CARMICHAEL, I. S. E. & STORMER, J. C. 1971. Silica activity and Ptotal in igneous rocks. *Contributions to Mineralogy and Petrology*, **33**, 1–20.

NUR, A. & BEN-AVRAHAM, Z. 1983. Displaced terranes and mountain building. *In*: HSU, K. J. (ed.) *Mountain Building Processes*, Academic Press, 73–84.

OKAYA, D. A. & BEN-AVRAHAM, Z. 1987. Structure of the continental margin of southwestern Panama. *Geological Society of America Bulletin*, **99**, 792–802.

ORTEGA-GUTIERREZ, F. & ELIAS-HERRERA, M. 2003. *Wholesale Melting of the Southern Mixteco Terrane and Origin of the Xolapa Complex*. Geological Society of America, abstracts with program, **35**, 66.

ORTEGA-GUTIÉRREZ, F., SOLARI, L. A. *ET AL*. 2007. The Maya–Chortís boundary: a tectonostratigraphic approach. *International Geology Review*, **49**, 996–1024.

OSTOS, M. 2002. The alpine-type Tinaquillo peridotite complex, Venezuela: Fragment of a Jurassic rift zone? *In*: AVÉ LALLEMENT, H. G. & SISSON, V. B. (eds) *Caribbean/South American Plate Interactions, Venezuela*. Geological Society of America, Special Papers, **394**, 207–222.

OSTOS, M. & SISSON, V. B. 2002. Geochemistry and tectonic setting of igneous and metaigneous rocks of northern Venezuela. *In*: AVÉ LALLEMENT, H. G. & SISSON, V. B. (eds) *Caribbean/South American Plate Interactions, Venezuela*. Geological Society of America, Special Papers, **394**, 119–156.

OXBURGH, E. R. 1966. Geology and metamorphism of Cretaceous rocks in eastern Carabobo State, Venezuelan coast ranges. *In*: HESS, H. H. (ed.) *Caribbean Geological Investigations*, Geological Society of America Memoirs, **98**, 241–310.

PAQUETTE, J., SIGMARSSON, O. & TIEPOLO, M. 2006. Continental basement under Iceland revealed by old zircons. *EOS Trans. AGU*, **87**, Fall Meeting Supplement, Abstract V33A-064.

PARDO, G. 1975. Geology of Cuba. *In*: NAIRN, A. E. M. & STEHLI, F. G. (eds) *The Ocean Basins and Margins. The Gulf of Mexico and the Caribbean*. Plenum Press, New York, 553–615.

PAULUS, F. J. 1972. The geology of site 98 and the Bahama Platform. *In*: HOLLISTER *ET AL*. (eds) *Initial Reports of the Deep Sea Drilling Program*, **XI**, 877–897.

PENNINGTON, W. D. 1981. Subduction of the Eastern Panama Basin and seismotectonics of northwestern South America. *Journal of Geophysical Research*, **86**, 10753–10770.

PEQUEGNAT, W. E., BRYANT, W. R. & HARRIS, J. E. 1971. Carboniferous sediments from Sigsbee Knolls, Gulf of Mexico. *American Association of Petroleum Geologists Bulletin*, **55**, 116–123.

PEREIRA, J. G. 1985. Evolucion tectonica de la Cuenca de Carupano durante el Terciario. *VI Congreso Geologica Venezolano*, Caracas, Memoria, **IV**, 2618–2648.

PEREZ DE ARMAS, J. 1999. Transpressional history of the Serrania del Interior Foreland Fold and Thrust Belt, north-central Venezuela: New evidence from apatite fission-track modeling and 2D seismic reflection analysis. *Penrose Conference: Subduction to Strike–Slip Transitions on Plate Boundaries*, Abstracts, 83–84.

PERFIT, M. R. & HEEZEN, B. C. 1978. The geology and evolution of the Cayman Trench. *Geological Society of America Bulletin*, **89**, 1155–1174.

PERFIT, M. R., HEEZEN, B. C., RAWSON, M. & DONNELLY, T. W. 1980. Chemistry, origin and tectonic significance of metamorphic rocks from the Puerto Rico Trench. *Marine Geology*, **34**, 125–156.

PETER, G. & WESTBROOK, G. K. 1976. Tectonics of southwestern North Atlantic and Barbados Ridge Complex. *American Association of Petroleum Geologists Bulletin*, **60**, 1078–1106.

PHAIR, R. L. & BUFFLER, R. T. 1983. Pre-Middle Cretaceous geologic history of the deep southeastern Gulf of Mexico. *In*: BALLY, A. W. (ed.) *Seismic Expression of Structural Styles – a Picture and Work Atlas*. American Association of Petroleum Geologists, Studies in Geology, **15**, 141–147.

PINDELL, J. L. 1991. Geological arguments suggesting a Pacific origin for the Caribbean Plate. *Transactions 12th Caribbean Geological Conference*, St Croix.

PINDELL, J. L. 1993. Regional synopsis of the Gulf of Mexico and Caribbean evolution. *GCSSEOM Foundation 13th Annual Research Conference*, 251–274.

PINDELL, J. L. & BARRETT, S. F. 1990. Geological evolution of the Caribbean region; a plate-tectonic perspective. *In*: DENGO, G. & CASE, J. E. (eds) *The Caribbean Region*. The Geology of North America, **H**. Geological Society of America, 405–432.

PINDELL, J. L. & KENNAN, L. 2009. Tectonic evolution of the Gulf of Mexico, Caribbean and northern South America in the mantle reference frame: an update. *In*: JAMES, K. H., LORENTE, M. A. & PINDELL, J. L. (eds) *Origin and Evolution of the Caribbean Plate*. Geological Society, London, Special Publications, **328**, 1–55.

PINDELL, J. L., HIGGS, R. & DEWEY, J. F. 1998. Cenozoic palinspastic reconstruction, palegeographic evolution, and hydrocarbon setting of the northern margin of South America. *In*: PINDELL, J. L. & DRAKE, C. L. (eds) *Paleogeographic Evolution and Non-Glacial Eustasy, Northern South America*. SEPM Special Publications, **58**, 45–86.

PINDELL, J. L., DRAPER, G., KENNAN, L., STANEK, K. P. & MARESCH, W. V. 2001. Evolution of the northern portion of the Caribbean Plate: Pacific origin to Bahamian collision. *SA Abstracts from the IGCP Project 433 – Caribbean Plate Tectonics*.

PINDELL, J. L., KENNAN, L., MARESCH, W. V., STANEK, K. P., DRAPER, G. & HIGGS, R. 2005. Plate-kinematics and crustal dynamics of circum-Caribbean arc-continent interactions: Tectonics controls of basin development in Proto-Caribbean margins. *In*: AVÉ LALLEMENT, H. & SISSON, V. B. (eds) *Caribbean–South American Plate Interactions, Venezuela*. Geological Society of America Special Papers, **394**, 7–52.

PINDELL, J. L., KENNAN, L., STANEK, K.-P, MARESCH, W. V. & DRAPER, G. 2006. Foundations of Gulf of Mexico and Caribbean evolution: eight controversies resolved. *In*: ITURRALDE-VINENT, M. A. & LIDIAK, E. G. (eds) *Caribbean Plate Tectonics. Geologica Acta*, **4**, 303–341.

PINET, P. R. 1971. Structural configuration of the northwestern Caribbean Plate boundary. *Geological Society of America Bulletin*, **82**, 2027–2032.

PINET, P. R. 1972. Diapirlike features offshore Honduras: implications regarding tectonic evolution of Cayman Trough and Central America. *Geological Society of America Bulletin*, **83**, 1911–1922.

PINET, B., LAJAT, D., LE QUELLEC, P. & BOUYSSE, Ph. 1985. Structure of Aves Ridge and Grenada Basin from Multichannel Seismic Data. *Géodynamique des Caraibes, Symposium*. Editions Technip, Paris, 53–64.

POST, P. 2005. Constraints on the interpretation of the origin and early development of the Gulf of Mexico Basin. *25th Annual Gulf Coast Section SEPM Foundation Bob F. Parker Research Conference, Abstracts*, 46.

PRICE, N. J. 2001. *Major Impacts and Plate Tectonics: A Model for Phanerozoic Evolution of the Earth's Lithosphere*. Routledge, Abingdon.

PROENZA, J. A., DÍAZ-MARTÍNEZ, R. *ET AL*. 2006. Primitive Cretaceous island-arc volcanic rocks in eastern Cuba: the Téneme Formation. *In*: ITURRALDE-VINENT, M. A. & LIDIAK, E. G. (eds) *Caribbean Plate Tectonics. Geologica Acta*, **4**, 103–121.

PSZCZOLKOWSKI, A. 1976. Stratigraphic facies sequences in the Sierra de Rosario, Cuba. *Academie Polonaise des Sciences, Serie des Sciences de la Terre*, **24**, 193–203.

PSZCZOLKOWSKI, A. 1999. The exposed passive margin of North America in Western Cuba. *In*: MANN, P. (ed.) *Caribbean Sedimentary Basins*. Sedimentary Basins of the World. Elsevier, Amsterdam, 93–121.

PSZCZOLKOWSKI, A. & MYCZYNSKI, R. 2003. Stratigraphic constraints on the Late Jurassic–Cretaceous paleotectonic interpretations of the Placetas Belt in Cuba. *In*: BARTOLINI, C. *ET AL*. (eds) *The Circum-Gulf of Mexico and the Caribbean: Hydrocarbon Habitats, Basin Formation, and Plate Tectonics*. American Association of Petroleum Geologists Memoirs, **79**, 545–581.

PUBELLIER, M., MAUFFRET, A., LEROY, S., VILA, J.-M. & AMILCAR, H. 2000. Plate boundary readjustment in oblique convergence: Example of the Neogene of Hispaniola, Greater Antilles. *Tectonics*, **19**, 630–648.

PUDSEY, C. J. & READING, H. G. 1972. Sedimentology and structure of the Scotland Group, Barbados. *In*: *Trench-Forearc Geology; Sedimentation and Tectonics on Modern and Ancient Active Plate Margins*. Geological Society, London Special Publications, **10**, 291–308.

RAMIREZ, Mi. I., DRAPER, G., SMITH, L., HORNAFIUS, J. S., MUNTHE, J. & GORDON, M. 1995. Neotectonic structures and paleostress in south-central Hispaniola. *3rd Geological Conference Geological Society of Trinidad and Tobago, 14th Caribbean Geological Conference, Transactions*, 214.

RAMROOP, C. 1985. Structure and composition of the "acoustic" basement of the North Coast Complex, Trinidad. *First Geological Conference of the Geological Society of Trinidad and Tobago*, 53–66.

REED, J. C., WHEELER, J. O. & TUCHOLKE, B. E. 2005. *Geologic Map of North America*. Decade of North American Geology. Geological Society of America.

RÉMANE, R. 1980. Calpionellids. *In*: HAQ, B. V. & BOERSMA, A. (eds) *Introduction to Micropalaeontology*. Elsevier, New York, 161–170.

RÉVILLON, S., HALLOT, E., ARNDT, N. T., CHAUVEL, C. & DUNCAN, R. A. 2000. A complex history for the

Caribbean Plateau: petrology, geochemistry, and geochronology of the Beata Ridge, South Hispaniola. *Journal of Geology*, **108**, 641–661.

RIGASSI-STUDER, D. 1961. Quelques vues nouvelles sur la géologie cubaine. *Chronique des Mines et de la Recherche Miniere*, **29**, 3–7.

ROBERTS, D. G. 1975. Marine geology of the Rockall Plateau and Trough. *Philosophical Transactions for the Royal Society of London. Series A, Mathematical and Physical Sciences*, **278**, 447–509.

ROBERTS, M., HOLLISTER, C., YARGERAND, H. & WELCH, R. 2005. Regional geologic and geophysical observations basinward of the Sigsbee Escarpment and Mississippi Fan Fold Belt, Central Deep-Water Gulf of Mexico. *25th Annual Gulf Coast Section SEPM Foundation Bob F. Parker Research Conference*, Extended Abstracts, 1190–1199.

ROBINSON, E. 1967. Submarine slides in white limestone group, Jamaica. *American Association of Petroleum Geologists Bulletin*, **51**, 569–578.

RODRIGUEZ, S. E. 1968. Estudio sobre el metamorfismo regional en la Peninsula de Paria, Estado Sucre. *Boletin Informativo, Asociación Venezolana de Geología, Minería y Petróleo*, **11**, 61–88.

ROGERS, R. & MANN, P. 2007. Transtensional deformation of the western Caribbean–North America plate boundary zone. *In*: MANN, P. (ed.) *Geologic and Tectonic Development of the Caribbean Plate Boundary in Northern Central America*. Geological Society of America Special Papers, 37–64.

ROGERS, R. D., MANN, P. & EMMET, P. A. 2007*a*. Tectonic terranes of the Chortís Block based on integration of regional aeromagnetic and geologic data. *In*: MANN, P. (ed.) *Geologic and Tectonic Development of the Caribbean Plate Boundary in Northern Central America*. Geological Society of America, Special Papers, **428**, 65–88.

ROGERS, R. D., MANN, P., EMMET, P. A. & VENABLE, M. M. 2007*b*. Colon fold belt of Honduras: Evidence for Late Cretaceous collision between the continental Chortís Block and intra-oceanic Caribbean Arc. *In*: MANN, P. (ed.) *Geologic and Tectonic Development of the Caribbean Plate Boundary in Northern Central America*. Geological Society of America Special Papers, **428**, 129–149.

ROJAS, C. R. 2004. The Cuban rudist mollusks, an important tool in the biostratigraphical correlation of the Caribbean Cretaceous. *32nd International Geological Conference*, Florence, 2004, IGCP Project 433 Caribbean Plate Tectonics, Abstracts.

ROJAS-AGRAMONTE, Y., KRÖNER, A., GARCÍA-CASCO, A., ITURRALDE-VINENT, M. A., WINGATE, M. T. D. & LIU, D. Y. 2006. Geodynamic implications of zircon ages from Cuba. *Geophysical Research*, Abstracts, **8**.

ROLLINS, J. F. 1965. *Stratigraphy and Structure of the Goajira Peninsula, Northwestern Venezuela and Northeastern Colombia*. University of Nebraska Studies: New Series, **30**.

ROSENCRANTZ, E. 1990. Structure and tectonics of the Yucatán Basin, Caribbean Sea, as determined from seismic reflection studies. *Tectonics*, **9**, 1037–1059.

ROSENCRANTZ, E., ROSS, M. I. & SCLATER, J. G. 1988. Age and spreading history of the Cayman Trough as determined from depth, heat flow, and magnetic anomalies. *Journal of Geophysical Research*, **93**, 2141–2157.

ROSENDAHL, B. R., MEYERS, J. & GROSCHEL, H. 1992. Nature of the transition from continental to oceanic crust and the meaning of reflection Moho. *Geology*, **20**, 721–724.

ROSS, M. I. & SCOTESE, C. R. 1988. A hierarchical tectonic model of the Gulf of Mexico and Caribbean region. *Tectonophysics*, **155**, 139–168.

RUEDA-GAXIOLA, J. 2003. The Origin of the Gulf of Mexico Basin and its petroleum subbasins in Mexico, based on Red Bed and salt palynostratigraphy. *In*: BARTOLINI *ET AL.* (eds) *The Circum-Gulf of Mexico and the Caribbean: Hydrocarbon Habitats, Basin Formation and Plate Tectonics*. American Association of Petroleum Geologists Memoirs, **79**, 246–282.

SACHS, P. M. & ALVARADO, G. E. 1996. Mafic metaigneous lower crust beneath Arenal Volcano (Costa Rica): evidence from xenoliths. *Boletin Observatorio Vulcano Arenal, Año 6*, **11–12**, 71–78.

SALLARES, V., DANOBEITIA, J. J. & FLUEH, E. R. 2001. Lithospheric structure of the Costa Rica Isthmus: effects of subduction zone magmatism on a oceanic plateau. *Journal of Geophysical Research*, **106**, 621–643.

SALVADOR, A. 1991. Triassic–Jurassic. *In*: SALVADOR, A. (ed.) *The Gulf of Mexico Basin*. The Geology of North America. Geological Society of America, 131–180.

SANCHEZ-BARREDA, L. A. 1981. *Geologic evolution of the continental margin of the Gulf of Tehuantepec in southern Mexico*. PhD thesis, University of Texas, Austin, TX.

SANTOS, H. 2002. Stratigraphy and depositional history of the upper Cretaceous strata in the Cabo Rojo-San German structural block, southwestern Puerto Rico. *16th Caribbean Geological Conference*, Barbados, Abstracts, 67.

SAUNDERS, J. B., EDGAR, N. T., DONNELLY, T. W. & HAY, W. W. 1973. Cruise synthesis. *In*: EDGAR, N. T. *ET AL.* (eds) *Initial Reports of the Deep Sea Drilling Project*. US Government Printing Office, Washington, DC, **15**, 1077–1111.

SCHLAGER, W., BUFFLER, R. T. *ET AL.* 1984. Deep Sea Drilling Project, Leg 77, southeastern Gulf of Mexico. *Geological Society of America Bulletin*, **95**, 226–236.

SCHNEIDERMANN, N., BECKMANN, J. P. & HEEZEN, B. C. 1972. Shallow water carbonates from the Puerto Rico Trench region. *VI Conferencia Geología del Caribe*, Margarita, Venezuela, Memorias, 423–425.

SCHUCHERT, C. 1935. *Historical Geology, Antillean – Caribbean Region*. Wiley, Chichester.

SEIDERS, V. M. 1965. Geología de Miranda Central, Venezuela. *Ministerio de Minas e Hidrocarburos Boletin Geologico*, **6**, 289–416.

SENN, A. 1940. Paleogene of Barbados and its bearing on history and structure of Antillean–Caribbean region. *Bulletin American Association of Petroleum Geologists*, **24**, 1548–1610.

SENN, A. 1944. *Inventory of the Barbados Rocks and Their Possible Utilization*. Department of Science and Agriculture, Barbados, Bulletin **1**, 1–40.

SHARP, W. D. 1988. Tobago, West Indies, geochronological study of a fragment of a composite mesozoic oceanic island arc. *Annual Geological Society of America Centennial Celebration Meeting*, Abstracts, **11964**.

SHAUB, F. J. 1983. Origin of the Catoche Tongue. *In*: BALLY, A. W. (eds) *Seismic Expression of Structural Styles – A Picture and Work Atlas*. American Association of Petroleum Geologists Studies in Geology, **15**, 129.

SHERIDAN, R. E., CROSBY, J. T., BRYAN, G. M. & STOFFA, L. 1981. Stratigraphy and structure of southern Blake Plateau, northern Florida Straits, and northern Bahamas Platform from multichannel seismic reflection data. *American Association of Petroleum Geologists Bulletin*, **65**, 2571–2593.

SHURBET, G. L., WORZEL, J. L. & EWING, M. 1956. Gravity reconnaissance survey of Puerto Rico. *Geological Society of America Bulletin*, **67**, 511–534.

SIGURDSSON, H., LECKIE, R. M. & ACTON, G. D. 1996. *Caribbean Ocean History and the Cretaceous/Tertiary Boundary Event*. Ocean Drilling Program, Leg 165 Preliminary Report.

SINTON, C. W., SIGURDSSUN, H. & DUNCAN, R. A. 2000. Geochronology and petrology of the igneous basement at the lower Nicaraguan Rise, Site 1001. *Proceedings of the Ocean Drilling Program*, Scientific Results, Leg 165, 233–236.

SISSON, V. B. & AVÉ LALLEMENT, H. G. 1992. Burial and ascent of blueschists and eclogites, Venezuela, part 1: petrologic constraints. *Geological Society of America Annual Meeting*, Abstracts, A149.

SISSON, V. B., AVÉ LALLEMENT, H. G. *ET AL.* 2005. Overview of radiometric ages in three allochthonous belts of northern Venezuela: old ones, new ones, and their impact on regional geology. *In*: AVÉ LALLEMENT, H. G. & SISSON, V. B. (eds) *Caribbean–South America Plate Interactions, Venezuela*. Geological Society of America Special Papers, **394**, 91–117.

SKERLEC, G. M. & HARGRAVES, R. B. 1980. Tectonic significance of paleomagnetic data from northern Venezuela. *Journal of Geophysical Research*, **85**, 5303–5315.

SMITH, A. L., SCHELLEKENS, J. H. & DÍAZ, A-L. M. 1998. Batholiths as markers of tectonic change in the northeastern Caribbean. *In*: LIDIAK, E. G. & LARUE, D. K. (eds) *Tectonics and Geochemistry of the Northeastern Caribbean*. Geological Society of America, 99–122.

SNOKE, A. W. 1990. An evaluation of the petrogenesis of the accreted Mesozoic Island Arc of the southern Caribbean. *Second Geological Conference of the Geological Society of Trinidad and Tobago, Transactions*, 222–243.

SNOKE, A. W. 2003. *Tobago, West Indies, as a Guide for the Mesozoic Evolution of the Great Arc of the Caribbean*. Geological Society of America Abstracts with Program, **35**, paper no. 33-1.

SNOKE, A. W., YULE, J. D., ROWE, D. W., WADGE, G. & SHARP, W. D. 1990. Stratigraphic and structural relationships on Tobago and some tectonic implications. *In*: LARUE, D. K. & DRAPER, G. (eds) *Transactions of the 12th Caribbean Geological Conference*, St Croix, 7–11 August 1989, 393–403.

SNOKE, A. W., YULE, J. D., ROWE, D. W., WADGE, G. & SHARP, W. D. 2001. *Geologic History of Tobago, West Indies*. Geological Society of America Special Papers, **354**.

SOMIN, M. L., LEPEKHINA, E. N. & TOLMACHEVA, E. V. 2006. El Guaybo gneiss sialic basement boulder in western Cuba. *Geophysical Research Abstracts*, **8**, 03377.

SOMOZA, R. 2008. Paleomagnetic data from the Americas admit the possibility of an extensional origin for the Caribbean LIP. World Wide Web Address: http://www.mantleplumes.org/CaribbeanPMag.html.

SPEED, R., RUSSO, R., WEBER, J. & ROWLEY, K. C. 1991. Evolution of southern Caribbean Plate boundary, vicinity of Trinidad and Tobago: discussion. *American Association of Petroleum Geologists Bulletin*, **75**, 1789–1794.

STAINFORTH, R. M. 1966. Gravitational deposits in Venezuela [Depositos gravitationales en Venezuela]. *Boletin Informativo, Asociacion Venezolana de Geologia, Mineria y Petroleo*, 277–287.

STAINFORTH, R. M. 1969. The concept of sea-floor spreading applied to Venezuela. *Associacion Venezolana Geología, Minería y Petróleo, Boletin Informativo*, **12**, 257–274.

STANEK, K. P. & MARESCH, W. V. 2006. The geotectonic story of the Great Antillean Arc – implications of structural and geochronological data from Central Cuba. *In*: JAMES, K. H. & LORENTE, M. A. (convenors), *Geology of the Area between North and South America, with Focus on the Origin of the Caribbean Plate: an International Research Conference*, Sigüenza, Spain, Abstracts.

STANEK, K. P., MARESCH, W. V. *ET AL.* 2005. Contrasting high-pressure and low-pressure P-T-t-d paths in a single nappe pile: a case study from the Cuban collisional suture. *17th Caribbean Geological Conference*, Puerto Rico, abstracts, 84.

STANEK, K. P., MARESCH, W. V., GRAFE, F., GREVEL, CH. & BAUMANN, A. 2006. Structure, tectonics and metamorphic development of the Sancti Spiritus Dome (eastern Escambray Massif, Central Cuba). *In*: ITURRALDE-VINENT, M. A. & LIDIAK, E. G. (eds) *Caribbean Plate Tectonics. Geologica Acta*, **4**, 151–170.

STANEK, K. P., MARESCH, W. V. & PINDELL, J. L. 2009. The geotectonic story of the northwestern branch of the Caribbean Arc: implications from structural and geochronological data of Cuba. *In*: JAMES, K. H., LORENTE, M. A. & PINDELL, J. L. (eds) *Origin and Evolution of the Caribbean Plate*. Geological Society, London, Special Publications, **328**, 361–398.

STEINER, M. B. 2005. Pangean reconstruction of the Yucatán Block: its Permian, Triassic, and Jurassic geologic and tectonic history. *In*: ANDERSON, T. H. *ET AL.* (eds) *The Mojave–Sonora Megashear Hypothesis*. Geological Society of America Special Papers, **393**, 457–480.

STOCKHERT, B., MARESCH, W. V. *ET AL.* 1995. Crustal history of Margarita Island (Venezuela) in detail: constraint on the Caribbean Plate-tectonic scenario. *Geology*, **23**, 787–790.

SUMMA, L. L., GOODMAN, E. D., RICHARDSON, M., NORTON, L. O. & GREEN, A. R. 2003. Hydrocarbon systems of northeastern Venezuela: plate through molecular scale-analysis of the genesis and evolution of the eastern Venezuela Basin. *Marine and Petroleum Geology*, **20**, 323–349.

SZATMARI, P. 1983. Amazon rift and the Pisco-Juruá Fault: their relation to the separation of North America from Gondwana. *Geology*, **11**, 300–304.

TARDY, M., LAPIERRE, H. *ET AL*. 1994. The Guerrero suspect terrane (western Mexico) and coeval arc terranes (the Greater Antilles and the Western Cordillera of Colombia): a Late Mesozoic intra-oceanic arc accreted to cratonal America during the Cretaceous. *Tectonophysics*, **230**, 49–73.

TEN BRINK, U. S., COLEMAN, D. F. & DILLON, W. P. 2003. The nature of the crust under Cayman Trough from gravity. *Marine and Petroleum Geology*, **19**, 971–987.

TOMBLIN, J. F. 1970. *Field Guide to the Grenadines, Lesser Antilles: International Field Institute Guidebook to the Caribbean Island-Arc System*. American Geological Institute (article individually paginated).

TOMBLIN, J. F. 1975. The Lesser Antilles and Aves Ridge. *In*: NAIRN, A. E. M. & STEHLI, F. G. (eds) *The Ocean Basins and Margins*, **3**. Plenum Press, New York, 467–500.

TOMMASI, A. & VAUCHEZ, A. 2001. Continental rifting parallel to ancient collisional belts: an effect of the mechanical anisotropy of the lithospheric mantle. *Earth and Planetary Science Letters*, **185**, 199–210.

TOURNON, J., TRIBOULET, C. & AZEMA, J. 1989. Amphibolites from Panama: anticlockwise *P–T* paths from a pre-Upper Cretaceous metamorphic basement in Isthmian Central America. *Journal of Metamorphic Geology*, **7**, 539–546.

TRECHMANN, C. T. 1925. The Scotland beds of Barbados. *Geological Magazine*, **62**, 481–504.

TRECHMANN, C. T. 1937. The base and top of the coral-rock in Barbados. *Geological Magazine*, **LXXIV**, 337–359.

URBANI, F. 2004. New geological map of the Cordillera de la Costa, Northern Venezuela. *32nd IGC*, Florence, 2004. IGCP Project 433 Caribbean Plate Tectonics, abstracts.

VAN DER HILST, R. 1990. Tomography with P, PP and pP delay-time data and the three dimensional mantle structure below the Caribbean region *Geologica Ultraiectina*, Mededelingen van de Faculteit Aardwetenscahppen der Rijsuniversiteit te Utrecht, **67**, 250p.

VAN DER HILST, R. & MANN, P. 1994. Tectonic implications of tomographic images of subducted lithosphere beneath northwestern South America. *Geology*, **22**, 451–454.

VAN GESTEL, J. P., MANN, P., GRINDLAY, N. R. & DOLAN, J. F. 1999. Three-phase tectonic evolution of the northern margin of Puerto Rico as inferred from an integration of seismic reflection, well, and outcrop data. *Marine Geology*, **16**, 257–286.

VAUGHAN, T. W. & WELLS, J. W. 1945. *American Old and Middle Tertiary Larger Foraminifera and Corals*. Geological Society of America Memoirs, **9**.

VENABLE, M. E. 1993. An interpretation of the tectonic development of N. E. Nicaragua. *Geological Society of America Abstracts*, **25**, A-286.

VIVAS, V. & MACSOTAY, O. 2002. Cretaceous (Senonian)–Paleocene paleoceanographic continuity between the Caribbean Plate's abyssal facies (Venezuelan Basin) and the South American Plate's slope and shelf facies (northern Venezuela). *16th Caribbean Geological Conference*, Barbados, Abstracts, 70.

VOGEL, T. A., PATINO, L. C., ALVARADO, G. E. & GANS, P. B. 2004. Silicic ignimbrites within the Costa Rican volcanic front: evidence for the formation of continental crust. *Earth and Planetary Science Letters*, **226**, 149–159.

VOGEL, T. A., PATINO, L. C., ALVARADO, G. E. & ROSE, W. I. 2007. Petrogenesis of ignimbrites. *In*: BUNDSCHUH, J. & ALVARADO, G. E. (eds) *Central America: Geology, Resources and Hazards*. Taylor & Francis/Balkema, The Netherlands, 591–618.

WADGE, G. & MACDONALD, R. 1985. Cretaceous tholeiites of the northern margin of South America: the Sans Souci Formation of Trinidad. *Journal of the Geological Society, London*, **142**, 297–308.

WEBER, J. C., DIXON, T. H. *ET AL*. 2001. GPS estimate of relative motion between the Caribbean and South American plates, and geologic implications for Trinidad and Venezuela. *Geology*, **29**, 75–78.

WEHRMANN, M. 1972. Geologia de la region de Guatire-Colonia Tovar. *IV Congreso Geologico Venezolano, Caracas, Memoria, Boletín Geología*, Publicación Especial, **5**, 2093–2219.

WESTBROOK, G. K. 1990. Gravity anomaly map of the Caribbean. *In*: DENGO, C. & CASE, J. E. (eds) *The Caribbean Region*. The Geology of North America, **H**. Geological Society of America, plate 7.

WESTERCAMP, D. 1988. Magma generation in the Lesser Antilles: geological constraints. *Tectonophysics*, **149**, 145–163.

WESTERCAMP, D., ANDREIEFF, P., BOUYSE, Ph., MASCLE, A. & BAUBRON, J. C. 1985. The Grenadines, Southern Lesser Antilles. Part 1. Stratigraphy and volcano-structural evolution. *Géodynamique des Caraîbes*, Symposium, Édition Technip, 109–118.

WIEDMANN, J. 1978. Ammonites from the Curaçao Lava Formation, Curaçao, Caribbean. *Geologie en Mijnbouw*, **57**, 361–364.

WILSON, H. H. & MEYERHOFF, A. A. 1978. Paleomagnetic results from Cretaceous sediments in Honduras: Tectonic implications: Comments and reply. *Geology*, **6**, 440–442.

WILSON, J. T. 1966. Did the Atlantic close and then re-open? *Nature*, **211**, 676–681.

WITHJACK, M. O. & SCHLISCHE, R. W. 2005. A review of tectonic events on the passive margin of eastern North America. *25th Annual Gulf Coast Section SEPM Foundation Bob F. Parker Research Conference*, Extended Abstracts, 203–235.

WORZEL, J. L., BRYANT, W. *ET AL*. 1973. *Initial Report of the Deep Sea Drilling Project*, **S**. US Government Printing Office, Washington, DC.

WRIGHT, J. E. 2004. Aruba and Curaçao: remnants of a collided Pacific oceanic plateau? Initial geologic results from the BOLIVAR project. *EOS Transactions of the American Geophysical Union*, **85**, Fall Meeting Supplement, Abstract.

YSACCIS, R. 1997. *Tertiary Evolution of the Venezuelan Northeastern Offshore*. PhD thesis, Rice University, Houston.