Some remarks on the Caribbean Plate kinematics: facts and remaining problems

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Abstract: Caribbean Plate margins are assemblages of terranes located, since the Mid-Cretaceous, along transform boundaries between the Caribbean, North and South America and the Pacific and Atlantic oceans. Litho-stratigraphic, petrological and metamorphic features of the main units and their regional correlations allow definition of the main geotectonic elements (continental margins, oceanic basins, subduction zones, magmatic arcs) involved in the evolution of Caribbean Plate margins. They provide valuable constraints on plate evolution since the Jurassic. This involved proto-Caribbean ocean opening, thickening into an oceanic plateau, beginning of convergence in the Early Cretaceous, atypical evolution of a supra-subduction system during the Mid-Cretaceous, subduction of rifted continental margins, Late Cretaceous convergence related to eastward migration of two opposite triple-junctions and strike–slip tectonics. Using these data, we compare different models and suggest improvements.

The Caribbean Plate (Fig. 1) is an independent lithospheric element of more than 4000 km², consisting of undeformed or little deformed Cretaceous oceanic plateau crust (Colombia and Venezuela Basins; almost 1000 km²) and the Palaeozoic–Mesozoic Chortís continental block (about 700 000 km²). These are bounded by deformed marginal belts (about 2300 km²) resulting from Mesozoic to Present interactions with the adjacent Nazca, Cocos and Americas plates. The northern (Guatemala and Greater Antilles) and southern (northern Venezuela) plate margins consist mainly of ophiolitic decorated shear zones that represent collisional sutures between the plate and North and South America. Magmatic arcs of the Central American Isthmus and the Lesser Antilles characterize the western and eastern convergent boundaries with the Pacific and Atlantic Plates. Jurassic–Cretaceous ophiolitic terranes comprise about 40–50% of these belts. These assemblages record several compressional episodes, beginning in the Cretaceous, followed by tensional and/or strike–slip tectonics. More internal Caribbean marginal areas in Venezuela, Colombia, Panama and Hispaniola were involved in accretionary prisms (Stephan et al. 1986). Fragments of original Caribbean lithosphere are now accreted on adjacent plate margins.

Bivergent ‘flower structures’ exist along the northern and southern Caribbean margins where diachronous oblique movements have occurred along the Cenozoic.

Structure of the Caribbean Plate margins

Caribbean marginal belts are the product of complex interaction between several first-order geotectonic elements, characterized by different tectono-magmatic features and formed in different areas, that now lie fragmented and dispersed along the margins. They include continental margins, rifted continental margins, oceanic crust, oceanic plateau, intra-oceanic and sub-continental subduction zones and foredeep basins. The most important geological features are reported below.

Costa Rica

The western margin of the Caribbean Plate involves tectonic juxtaposition of three main composite blocks, Chortís, Chorotega and Chocó, of the Central American Isthmus. Accreted terranes are overlain by recent volcanic (Kuijpers 1980; Azema et al. 1984; Dengo 1985; Sinton et al. 1998; Beccaluva et al. 1999; Giunta et al. 2002a; Baumgartner & Denyer 2006; Denyer et al. 2006; Gazel et al. 2006). They form part of the Chortís continental block and most of Chorotega and Chocó.

The Santa Elena and Nicoya complexes of Costa Rica (Fig. 2) are two of the most important ophiolitic occurrences in the western margin of the Caribbean Plate. The first consists mainly of a peridotitic body, cut by a number of doleritic dykes and with subordinate breccias, thrusted onto basaltic rocks in the southwesternmost part of the

The Nicoya complex consists of an intrusive suite (gabbros, Fe-gabbros, Fe-diorites and plagiogranites) and basaltic rocks (basalts and dolerites), discontinuously covered by radiolarites. This complex was originally divided into two main units, Metapalo (ME) and Esperanza (ES). The older ME consists of basalts with scarce gabbros (Potrero intrusives) and sills, overlain by radiolarites of Late Jurassic (?) to Early Cretaceous age (Punta Conchal Fm). The ES, dated Mid- to Late Cretaceous, consists of basalts and diabases with widespread gabbroic (Potrero) and plagiogranitic intrusions, with scattered radiolaritic cover. Several décollements affect the complexes though locally the contact between the units can be interpreted as high-angle faults. These units are unconformably overlain by the Campanian to Cenozoic turbiditic sandstones, andesite and carbonate rocks of the Sabana Grande, El Viejo, Rivas, Las Palmas, Samara and Barraonda Fms.

Fig. 1. Location map of the studied peri-Caribbean tectonic units. Northern margin units: BVP, Baja Verapaz; SSC, Sierra Santa Cruz; JPZ, Juan de Paz; NM, North Motagua; SM, South Motagua (Guatemala); BH, Bahamas; NO, Northern Ophiolite; AC, Cretaceous Arc; MU, Mabujua; ET, Escambray; MB, Mayari–Baracoa; SRM, Sierra Maestra (Cuba); NC Northern Cordillera; LC, Loma Caribe; CC, Central Cordillera; HA, Dumisseeau and Massif de la Hotte (Hispaniola); SB, Sierra Bermeja (Puerto Rico). Southern margin units: VI, Dutch and Venezuelan Islands; FC, Franja Costera; TT, Caucauca–El Tinaco; LH, Loma de Hierro; VC, Villa de Cura; DH, Dos Hermanas; PI, Piemontine (Venezuela). Western margin units: SE, Santa Elena; ME, Metapalo; ES, Esperanza (Costa Rica). Minor blocks: MAY, Maya; CHR, Chortí’s; CHT, Chorotega; CHC, Choco’.

Fig. 2. Cross section of Guanacaste province of Costa Rica (modified from Beccaluva et al. 1999). Main units: SE, Santa Elena; ME, Metapalo; ES, Esperanza. Legend: 1, Recent deposits; 2, terrigenous and carbonatic sequences (Late Cretaceous–Cenozoic); 3, basalts and diabases with MOR affinity (Late Jurassic–Late Cretaceous); 4, gabbroic and scattered plagiogranitic intrusions with MOR affinity; 5, serpentnized mantle peridotites with doleritic dykes.
Guatemala

The present northwestern margin of the Caribbean Plate crops out along the Motagua Suture Zone (Fig. 3) in Guatemala, which links the Middle-American trench with the Cayman Trough extensional system (Muller 1980; Rosenfeld 1981; Finch & Dengo 1990; Beccaluva et al. 1995; Giunta et al. 2002a; Valls Alvarez 2006). The suture is a sinistral shear-zone between the Maya and Chortís continental blocks, consisting of east–west and ENE–WSW strike–slip fault systems (Polochic, Motagua, Cabañas, Yucatán). Remarkable west–east trending uplift structures (Sierra Chuacus, Sierra de Las Minas, Montañas del Mico), pull-apart basins (Izabal Lake, Banañeras) and grabens elongated in a prevalent north–south direction (Guatemala, Chiquimula), occur in this zone, which is a typical transpressional ‘flower structure’, with north and south vergence. The following are the main components:

1. the Sierra Santa Cruz (SSC) and Baja Verapaz (BVP) units overthrust northward onto the Maya Block, the former onto the Late Cretaceous–Eocene carbonatic–terrigenous sequences of the Sepur formation, the latter onto Paleozoic metamorphites of the Chuacus Group or the Mesozoic evaporitic–terrigenous–carbonatic deposits of the Todos Santos, Coban and Campur formations;
2. the Juan de Paz unit (JPZ) overthrusts the Paleozoic metamorphic basement of the Sierra de Las Minas and Montañas del Mico;
3. the South Motagua (SM) and North Motagua (NM) units overthrust both the Paleozoic continental basement (Las Ovejas and San Diego formations) of the Chortís Block to

Fig. 3. Cross section of the Motagua suture Zone (MSZ), in Guatemala (modified from Beccaluva et al. 1995). Main units: MAY, Maya Cont. Block; BVP, Baja Verapaz; SSC, Sierra Santa Cruz; JPZ, Juan de Paz; NM, North Motagua; SM, South Motagua; GR, Zacapa granitoids; CHR, Chortís Cont. Block. Legend: 1, Cenozoic–Quaternary volcanics; 2, flysch and molassic deposits, Late Cretaceous–Eocene (Subinal Fm); 3, arc tonalitic magmatism, Cretaceous (Zacapa granitoids, GR); 4, Late Cretaceous–Paleocene pre-flysch and flysch (Sepur Fm); 5, Late Jurassic–Cretaceous terrigenous and carbonatic covers; 6, Paleozoic continental basement; 7, Mid–to Late Cretaceous basalts, limestones and andesitic basalts; 8, gabbros and dolerites; 9, peridotites; 10, Late Jurassic–Early Cretaceous basalts, radiolarites, phyllites and metalimestones; 11, gabbros; 12, peridotites; 13, Paleozoic continental basement and Mesozoic sedimentary covers.
the south (SM), and the Palaeozoic metamorphic terranes of the Sierras de Chuacus and Las Minas of the Maya Block (?) to the north (NM). These units are imbricated with ‘out of sequence’ basement slices.

The SSC, BVP and JPZ units consist of generally serpentinitized mantle harzburgites, layered gabbros, dolerites and andesitic basalts. The SSC is locally covered by small outcrops of terrigenous and volcanoclastic sequences including andesitic and dacitic fragments (Cretaceous Tzumuy Fm), while the JPZ is covered by basic volcanoclastic and andesitic breccias passing up to carbonatic breccias and calcarenites, with sandstone and microconglomerates containing acid volcanic fragments (Late Cretaceous Cerro Tipon Fm).

The SM and NM consist of the so-called El Tambor Group, made-up of serpentinitized peridotites and foliated gabbros, followed by a thick basaltic pillow lava sequence, radiolarian cherts, metasiltites and metarenites with intercalations of basaltic flows, in places metamorphosed to blueschist and eclogite facies. The top of the sequence is formed by phyllicit metasiltites alternating with marbles and metacalcarenites (Mid- to Late Cretaceous Cerro de La Virgen limestones). Along the Motagua Valley the JPZ, SM and NM units are unconformably overlain by the Eocene continental molasse of the Subinal Fm.

Cuba

The northernmost portion of the original Caribbean Plate margin crops out in Cuba, overthrust onto the southern edge of the North American Plate (Pardo 1975; Iturralde-Vinent 1989, 1999, 2000; Beccaluva et al. 1996; Cobiella-Reguera 2005; Marchesi et al. 2006; Meschede et al. 2006; Stanek et al. 2006). It is separated from the rest of the Greater Antilles by the Bartlett sinistral strike-slip structure, which represents the present-day northern boundary of the Caribbean Plate. The plate boundary shifted from the Cuba area to the Cayman Trough in the Eocene (e.g. Pindell 2006).

The Cuban thrust belt (Fig. 4) includes two continental elements: the northern Bahamas Platform and the southern Guaniguanico–Piños–Escambray (ET). They are overthrust by oceanic elements of the Northern Ophiolite (NO), a Cretaceous Arc (AC) and a Palaeogene Arc. The deformation front extends onto a Palaeogene foredeep as a series of north-vergent slices with associated flyschoid sequences and olistostromes.

(1) The Bahamas units (BH) are structurally the lowest in the folded system and consist of at least four tectonic sheets, Cayo Coco, Remedios, Camajunı` and Placetas, which represent the original edge of the North American margin. In the Placetas Unit, Late Jurassic tholeiitic lavas are also present. A Paleocene–Eocene foredeep basin overlying the Bahamas margin dates the collision of the Northern Ophiolite and Cretaceous Arc against NOAM.

(2) The NO unit is a metamorphic mélangé which includes blocks of peridotites and cumulate gabbros cut by dykes of diabases and overlain by basaltic lavas, hyaloclastites, radiolarites and volcanoclastites. In eastern Cuba the NO consists of peridotitic and gabbroic massifs, such as Holguin and Mayarı`-Baracoa, and big bodies of metamorphic rocks (Pural, Asuncion, Sierra del Convento).

(3) The AC units overlie the ophiolitic mélangé to the north and the Escambray Terranes to the north.
south. They consist of lava flows, pyroclastites and volcanoclastic rocks, sometimes unconformably overlain by carbonate and terrigenous sequences. Rudist-bearing limestone horizons of Late Albian, Santonian and Early Campanian ages are present in this unit.

(4) The Mabujina subduction complex (MU) consists of metavolcanics and metaplutonics with calc-alkaline magmatic affinity; it underlies the Cretaceous Arc units and overthrusts the Escambray continental terranes.

(5) Different plutonic complexes intrude the AC and the MU units, with variably thick cornubianitic aureoles, made up of locally foliated granitoid and tonalitic bodies, from Aptian to Campanian age. Palaeogene volcanic and intrusive rocks occur in the Sierra Maestra.

(6) The ET, considered to be equivalent to the Guaniguanico and Los Piños terranes, tectonically underlies the Mabujina unit and crops out as a complex thrust system in a large dome-shaped structure. The sequence generally consists of metamorphosed Mesozoic terrigenous and carbonate deposits of continental margin origin. Slices of metavolcanites, meta-gabbros and serpentininites have been reported in some localities, together with a metamorphic mélangé.

**Hispaniola**

Hispaniola represents a transpressional shear zone (Lewis & Draper 1990; Draper & Nagle 1991; Draper et al. 1994; Escuder-Viruete et al. 2002) with terranes of the Central Cordillera juxtaposed against Northern Cordillera ophiolites to the NE and a portion of emerged oceanic plateau to the SW (Massif de la Hotte-Bahoruco, Southern Peninsula of Haiti). Large, sinistral strike–slip faults (Septentrional, Enriquillo, Hispaniola) separate these sectors (Fig. 5).

(1) the Northern Cordillera (NC) is a heterogeneous ophiolitic terrane where the following tectonic units have been recognized:

(a) the Puerto Plata complex of variably sized bodies of serpentinized peridotites, layered metagabbros and pillowered metabasalts, with scattered Early Cretaceous radiolarites;

(b) the Rio San Juan complex, composed of

(i) the Gaspar Hernandez serpentinites,

(ii) the Hicotea and Puerca Gorda schists,

(iii) the Jagua Clara Mélangé, with several high pressure metamorphic blocks in an ultramafic matrix,

(iv) the Cuaba amphibolites and the Rio Boba gabbroic layered sequences.

(c) the Samanà-Punta Balandra complex, consisting of a continuous sequence of foliated marbles with intercalations of micaschists, including boudins of metabasalts and metadolerites metamorphosed into blueschist and eclogite facies.

(2) the Central Cordillera (CC) terrane, consisting mainly of the Duarte and Tireo complexes,
overthrusts northeastward above the Loma Caribe–Ortega (LC) unit, which in turn overthrusts the Maimon–Amina and Los Ranchos units, which are separated by the Hatillo Thrust. Southwestward the CC overthrusts the Late Cretaceous–Palaeogene terrigenous sequences of the Trois Rivieres belt. The generalized stratigraphical sequence of the CC, reconstructed from the dismembered components, consists of basal serpentinitized harzburgites (LC), covered by metadolerites and frequently pillowved metabasalts with intercalation of Late Jurassic–Early Cretaceous radiolarites (Duarte), and basalts, tuffs and volcanoclastites locally associated with Late Cretaceous and Jurassic radiolarites and siltstones (Tireo). The Amina–Maimon and Los Ranchos units are respectively composed of ducitic metatuffs intercalated with metasediments and of pillowed basalts and breccias with ducitic and phyllic composition, the latter underlying reeal limestones of the Middle Cretaceous. Several gabbroic and tonalitic plutons intrude into Duarte–Tireo complex of the Central Cordillera.

Puerto Rico

Most of Puerto Rico is made up of volcanic arc ‘strata’ (lavas, tuffs and volcanoclastic products) of Aptian to Eocene age (Jolly et al. 1998; Mitchell 2006). This complex, intruded by granitoid plutons since the Late Cretaceous, may be subdivided into three main districts separated by sinistral NW–SE strike–slip faults.

The southwesternmost portion of the island consists of the Sierra Bermeja complex, a tectonic assemblage of serpentinitized harzburgites, metabasalts and amphibolites (Las Palmas unit) and scattered pelagic sediments with Cretaceous radiolarites (Mariquita Fm).

Much of western Puerto Rico is characterized by tectonic slices with variable vergence, separated by at least three NW–SE elongated peridotitic bodies (Monte del Estado, Rio Guanajibo, Sierra Bermeja).

The central and eastern district of the island is mainly made by Late Cretaceous–Early Cenozoic volcanic sequences and plutonic bodies.

Venezuela

The Dutch–Venezuelan islands, the Coastal Cordillera of Venezuela and the Northern Range of Trinidad form the southern margin of the Caribbean Plate, extending from the Barquisimeto depression, in the west, to Trinidad and Tobago in the east (Bellizzia 1986; Stephan et al. 1986; Beccaluva et al. 1996; Giunta et al. 1997, 2002c). The northern uplifts are bounded to the south by the Interior and Central Ranges of Venezuela and Trinidad, which overthrust the Guayana continental foreland of the South American Plate. Further west the north-vergent South Caribbean Deformed Belt ‘accretionary prism’ of Colombia and Venezuela forms the Curaçao Ridge, while to the south the Gulf of Venezuela, Maracaibo and Falcón pull-apart/intermontane basins lie between uplifts of the Guajira and Paraguaú peninsula, the Sierra de Perijá and the Mérida Andes (James 2006a). The whole belt (Fig. 6) consists of imbricated tectonic units, highly dismembered and affected by severe brittle and ductile/brittle deformation, related to a west–east dextral shear zone with strike–slip faults (Oca, San Sebastian, El Pilar) and associated synthetic (Tacata, Charrallave, Urica, San Juan) and subordinate antithetic fault systems.

The CC consists of pre-Mesozoic continental basement covered by Late Jurassic–Cretaceous metamorphosed carbonate–terrigenous sediments (with local volcanic intercalations). The CC is overthrust by the ophiolitic mélangé of the Franja Costera (FC) unit and part of the Cauca–El Tinaco units (TT) to the north, and by the Cauca–El Tinaco, Loma de Hierro (LH), Villa de Cura, (VC) and Dos Hermanas (DH) units to the south:

(1) The Franja Costera (FC) consists of a Cretaceous metamorphic volcano-sedimentary and carbonate-terrigenous sequence with boudins of serpentinitized peridotites, metagabbros and eclogites.

(2) The TT units, south of the CC terrane, consist of pre-Mesozoic basement (El Tinaco complex) covered by a Cretaceous metavolcano-sedimentary sequence (Tucutunemo Fm), including Los Naranjos basalts and Sabana Larga dolerites and gabbros. They are overlain by the Tinaquillo thrust sheets, which consist of serpentinitized mantle lherzolites and meta-gabbros. On Margarita Island, north of CC, Mesozoic continental basement (Juan Griego Complex) is intruded by layered meta-gabbros (La Rinconada Fm). These overthrust the metacarbonatic–terrigenous sequence of the Cretaceous Los Robles Fm, overlain by the Cerro Matasiete peridotites. Late
Cretaceous granitoid bodies (El Salado) intrude the previous formations.

(3) The Loma de Hierro (LH) unit consists of serpentinized mantle peridotites, layered gabbroic cumulates (Rio Mesia), and basaltic lavas and dolerites (Tiara Fm), discontinuously covered by Late Jurassic–Early Cretaceous radiolarites (Capas Rio Guare), and Cretaceous silicified metalimestones and siltites (Paracotos Fm).

(4) The Villa de Cura (VC) units consist of serpentinized mantle peridotites and wehrlite–clinopyroxenite cumulates (Chacao complex), massive metabasalts (El Carmen Fm), metaturfis and subordinate metalavas (El Chino–El Cano Fm) and an Early–Mid-Cretaceous metavolcano–sedimentary sequence, prevalently comprising rhyolites, siltstones and cherts (S. Isabel Fm). High pressure/low temperature (HP/LT) metamorphism (blue-schist facies) characterizes several tectonic slices.

(5) The Dos Hermanas (DH) unit is represented by less metamorphic basaltic–andesitic lava breccias and volcanoclastites. The LH, VC and DH units were thrust southwards onto the Piemontine foredeep-terrigenous units in the Late Cretaceous–Early Cenozoic.

(6) The Dutch–Venezuelan Islands (VI) unit, off northern Venezuela, include a basement made up of basaltic and picritic lavas, dolerites and gabbros, intruded by Late Cretaceous tonalitic plutons and rhyolitic dykes. The tectonic relationship between the VI and the rest of the orogen is poorly known. It probably involves dextral strike–slip high angle faults.
Fig. 7. Regional correlations between the main sedimentary, magmatic, metamorphic, and deformational events recorded in the peri-Caribbean terranes. Abbreviations: SJO, Costa Rica; GUA, Guatemala; HAB, Cuba; SDQ, Hispaniola; HA, Haiti; PRC, Puerto Rico; VNZ, Venezuela; WPT, within-plate tholeiite; MOR, mid-ocean ridge; OIB, ocean islands basalt; IAT, island arc tholeiite; CA, island arc calc-alkaline; GR, tonatitic arc magmatism (gabbroid to granitoid). 1–27: most representative formations. Continental margins: 1, Sebastopol complex (VNZ): continental metamorphic basement (mainly gneiss), with granitic intrusions; 2, Las Brisas (VNZ): phyllite, metasiltites and meta-arenites, with intercalations of metacalcarenites; Todos Santos (GUA): reddish arenites and siltites, with intercalations of limestones and polygenic conglomerates; 3, Antimano (VNZ): metacalcarenites and marbles, with intercalations of amphibolites and metabasites; 4, Las Mercedes (VNZ): phylilit, metasiltites and meta-arenites, with intercalations of marbles; Chuspita (VNZ): meta-arenites, metasiltites and metacalcarenites, with intercalations of marbles; Coban (GUA): evaporites, dolomites and limestones; 5, Campur (GUA): limestones, with intercalations of siltites. Rifted continental margins: 6, Tinaquillo, Cerro Matasiete (VNZ): serpentinized lherzolites; 7, El Tinaco complex (VNZ): continental basement made by gneiss with few amphibolites, phyllites, metagabbro cumulates and meta-arenites; 8, Juan Griego (VNZ): continental crystalline (quartz, feldspar, rich schist and ortho or paragneisses) basement; 9, Rinconada, Tinaquillo p.p. (VNZ): metagabbro cumulates intruded and overlying the 8; 10, Sabana Larga (VNZ): basalts (mainly pillow lavas), dolerites and gabbro breccias; 11, Tucutunemo, Los Naranjos, Los Robles (VNZ): metagabbro cumulates and metasiltites with basaltic pillow lavas. Proto-Caribbean ocean: 12, Gaspar Hernandez (SDQ), Monte del Estado (PRC): serpentinitized peridotites; 13, Cuaba (SDQ), Rio Mesia (VNZ): layered gabbros; 14, El Tambor group (GUA), Punta Balandra (SDQ), Sierra Bermeja (PRC), Tiara (VNZ): metagabbro cumulates, metasiltites, metacalcarenites, with intercalations of basaltic (flows or pillow lavas) and radiolarian cherts; 15, Cerro de la Virgen (GUA): metacalcarenites and metacalcisiltites with breccia and silicic intercalations. Proto-Caribbean oceanic plateau: 16, Loma Caribe (SDQ): serpentinitized peridotites; 17, Potero (SJO): gabbro cumulates, Fe-gabbros, Fe-diorites and subordinate plagiogranites; 18, Punta Conchal (SJO): radiolarites intercalated in pillow and massive basals; 19, Duarte complex (SDQ), Lava (CUR): pillow and massive basalts with intercalations of radiolarites and volcanoclastites; 20, Siete Cabezas (SDQ), Knip group (CUR): volcanoclastites, radiolarites; pillow and massive basalts; 19, 20, Dumissieu (HA): pillow and massive basalts, volcanoclastites, with intercalations of radiolarites. First eo-Caribbean SSZ and volcanic arc: 21, serpentinitized peridotites; 22, layered gabbros with scattered intrusions of granites; Chacao complex 21 + 22 (VNZ), Mayari Baracoa (HAB); 23, Mabujina, Purial (HAB), El Carmen, El Chino, El Cano, S. Isabel (VNZ): metabasalts (mainly pillow lavas), metadolerites and meta-andesites; 24, Hatillo (SDQ): reefal limestones; 25, Tzumuy, Cerro Tipon (GUA): calcarenites and carbonate breccias.
After Giunta et al. (1997), the VI is an independent unit, in disagreement with some authors, who consider it a westward continuation of the Villa de Cura unit, following Stephan et al. (1986).

Regional correlations

The peri-Caribbean tectonic units and their numerous formations described above can be grouped into at least six litho-stratigraphic sections with similar lithological characteristics but very different tectonic origins, mainly based on the petrological data characterizing the geochemical affinities of the magmatic lithotypes. As shown in Fig. 7, each is the litho-stratigraphic product of different tectono-magmatic environments (Giunta et al. 2002b; Lewis et al. 2002; Lewis et al. 2006a, b; Cobiella-Reguera 2005):

1. Mesozoic continental margins (Bahamas Platform, northern South America, the Maya and Chortís Blocks of Central America, Guaniguano in Cuba, Cordillera de la Costa in Venezuela), including a pre-Mesozoic basement;
2. rifted continental margins (Escambray in Cuba, Cauca-gua El Tinaco and Tinalguillo in Venezuela) related to Jurassic-Early Cretaceous tensional episodes which continued to affect the continental margins, characterized by within-plate tholeiitic (WPT) magmatism;
3. Jurassic-Early Cretaceous oceanic crust, with mid-ocean ridge (MOR) affinity (North and South Motagua in Guatemala, Northern Ophiolite in Cuba, Northern Cordillera in Hispaniola, Sierra Bermeja in Puerto Rico, Loma de Hierro and Franja Costera in Venezuela);
4. ‘thin’ oceanic crust, in places evolved into an oceanic plateau structure with related ocean island basalts (OIB) during the Cretaceous (Santa Elena, Matapalo and Esperanza in Costa Rica, Loma Caribe, Central Cordillera and Massif de la Hotte in Hispaniola, Dutch-Venezuelan Islands);
5a. Mid-Cretaceous intra-oceanic supra-subduction zones (SSZ) and related volcanic arc magmatism, with island arc tholeiitic (IAT) and/or calc-alkaline (CA) affinities (Sierra Santa Cruz, Baja Verapaz and Juan de Paz in Guatemala, Mabujina, Cretaceous Arc, Mayarí-Baracoa and Purial in Cuba, Maimon–Los Ranchos in Hispaniola, Villa de Cura and Dos Hermanas in Venezuela), in places affected by HP/LT metamorphism;
5b. Mid-Cretaceous, sub-continental subduction, HP/LT metamorphosed ophiolitic melanges, including mafic blocks with MOR affinity (Franja Costera in Venezuela);
6. Late Cretaceous tonalitic arc magmatism with CA affinity (intruding: South Motagua in Guatemala, Mabujina and Cretaceous Arc in Cuba, Cordillera Central in Hispaniola, Dutch-Venezuelan Islands and part of Cauca-gua–El Tinaco in Venezuela);
7. Late Cretaceous mélanges (Northern Ophiolite in Cuba, Northern Cordillera in Hispaniola), followed by Palaeogene olistostromes, involving blocks of different origin (MOR, SSZ) in the deformation fronts, colliding against the NOAM and SOAM continental plates, through the progressive activation of foredeep basins (Sepur in Guatemala, Piemontine in Venezuela).

Constraints

The time-space distribution and regional correlation of the main peri-Caribbean units provide important geological constraints for reconstruction of the history of the Caribbean Plate. This is summarized the following different stages.

- **Continental margin rifting** – Pangaeang breakup and separation of South and North America, Maya and Chortís continental blocks favoured rifting and tholeiitic magmatism (WPT), from Triassic–Early Jurassic.
- **Oceanization** – MOR oceanic crust formed at multiple spreading centres during the Jurassic and Early Cretaceous, forming the ‘proto-Caribbean’ ocean.
- **Oceanic plateau** – during the Cretaceous, parts of the oceanic crustal domain thickened into an oceanic plateau of MOR to OIB affinity.
- **Subduction** – several lines of geological evidence, such as relict HP/LT distribution, record different subduction complexes (eo-Caribbean stage), both intra-oceanic (IAT and CA arc magmatism associated with SSZ) and/or sub-continenental (mélanges). They also indicate trapped or back-arc oceanic crust.

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**Fig. 7. (Continued)** (with andesitic fragments) and andesitic volcanoclastites. Second eo-Caribbean volcanic arc: 26, Yautia (SDQ): tonalites, quartzo-diorites and granites, with gabbroic and mafic differentiates; 27, Tireo (SDQ), Washikemba (BON): volcanoclastites and sedimentary layers, basalts, basalt–andesites and rhyolites. Bars: HP/LT (blueschist to eclogite facies) subduction related metamorphism and ductile deformation; : green schist to amphibolite facies metamorphism and ductile deformation; : ductile deformation.
• Early convergence – onset of the accretionary stage seems to have been diachronous, between 115 and 95 Ma (Smith et al. 1999; Escuder-Viruete et al. 2006; Giunta et al. 2003b), according to HP/LT assemblages related to ocean–ocean subduction and to ocean–continent subduction that locally reached eclogite facies.

• Double-arc magmatism – Mid-Cretaceous (100–95 Ma) and Late Cretaceous (85–75 Ma) peaks of IAT and CA arc magmatism associated with the SSZ occurred in the eo-Caribbean accretionary stage, which has been separated in first and second eo-Caribbean phases of subduction.

• HP/LT assemblages – widespread occurrences of blueschist and eclogite assemblages (Garcia-Casco et al. 2006a, b) in both oceanic and continental terranes of the Caribbean Plate margins requires a geodynamic model where portions of both oceanic and continental lithospheres were simultaneously subducted. Development of HP/LT conditions in MOR-type units is commonly related to subduction of oceanic lithosphere in either sub-continental or intra-oceanic settings. Metamorphism of continental margin elements requires more complex subduction mechanisms (e.g. continental collision, tectonic erosion) that allow underthrusting of thinned continental crust. There is also the possibility that minor continental terranes, formed during breakup and proto-Caribbean formation, were involved in subduction, as suggested by Ave Lallemant & Sisson (2005). Moreover, if large rivers delivered continental sediments to the ocean, these also could be subducted (Cardona, pers. comm.).

• Atypical evolution of the older volcanic arc – the Mid-Cretaceous island-arc system was frequently deeply subducted and metamorphosed to blueschist facies. In general, supra-subduction zone units obduct onto continental margins and only locally become involved in the deep subduction. In these cases an unusual geodynamic evolution must be imagined, such as subduction polarity reversal following subduction blocking or ‘tectonic erosion’ of the overriding plate. It has been also proposed that intra-oceanic arcs can be subducted, mainly controlled by lithosphere thickness (Boutelier et al. 2003).

• Diachronous tonalitic magmatism – the second calc-alkaline magmatic arc, mainly tonalitic, seems to have been diachronously connected to the Aves–Lesser Antilles arc system since 85 Ma. In the north the tonalitic magmatic arc generally rests on both older arc systems and oceanic plateau. In the south it is tectonically decoupled from the older arc and is intruded into both undeformed and deformed oceanic plateau and into rifted continental margin units.

• Strike–slip tectonic regime – contrasts in the P–T paths of various HP/LT metamorphic units (Sisson et al. 1997; Garcia-Casco et al. 2006a) probably indicate that converging zones were subdivided into different tectonic sectors during the Mid-Cretaceous. According to Giunta et al. (2003a and references therein), some eclogites and blueschists followed an ‘Alpine-type’ retrograde trajectory, suggesting that shut-off of subduction occurred before the beginning of exhumation. In contrast, blueschists locally show a ‘Franciscan-type’ path, which commonly characterizes decompression in intra-oceanic settings during still active subduction processes.

On the Venezuelan Caribbean margin deformation occurred under retrograde P–T conditions during exhumation from the Campanian onwards. The beginning of exhumation is often characterized by well-developed foliation showing mineral or stretching lineations and transected folds. The present more or less east–west trend of the second lineations suggests that displacement during the first stage of exhumation was nearly orthogonal to the north–south axis of subduction, as demonstrated by the trend of L1 lineations sub-parallel to the Caribbean–NOAM–SOAM plate boundaries. According to Ave Lallemant (1997), these structural features can be explained by an exhumation dominated by strike–slip tectonics.

Remarks and models comparison

The above observations allow reconstruction of Caribbean Plate evolution (Beccaluva et al. 1999; Giunta et al. 2002a–c, 2003a, b, 2006) that differs in some aspects from models proposed by others (Iturralde-Vinent 1989, 1994, 2003; James 2003, 2006a, b; Pindell 2003; Draper & Pindell 2006).

Major Caribbean events (Fig. 8) occurred in different tectonic regimes (riifting, spreading, plume, accretion, collision), from the early proto-Caribbean stage of oceanization through two eo-Caribbean accretionary stages of subduction to the collisional stage leading to the present Caribbean Plate.

During the Jurassic, tensional and transtensional stress related to Central Atlantic opening and separation of North (NOAM) and South (SOAM) American plates produced several spreading centres, offset by transform faults, forming a proto-Caribbean oceanic realm, between the Atlantic and Pacific. During the Cretaceous, proto-Caribbean oceanic crust thickened at its westernmost end, becoming structurally and petrologically
comparable to typical oceanic plateaus (e.g. Ontong–Java). The resulting rocks are tholeiitic basalts with flat REE patterns, sometimes associated with picrites, such as those recorded at Curacao (Kerr et al. 1996; Giunta et al. 2002c), Aruba (White et al. 1999), Los Roques (Giunta et al. 1997, 2002c; Kerr & Hastie 2006), the Tortugal komatiitic suite in Costa Rica (Alvarado et al. 1997), Central Cordillera of Dominican Republic (Lapierre et al. 2000; Lewis et al. 2002; Giunta et al. 2002a) and the western Colombian ophiolites (Kerr et al. 1997).

Crustal accretion by vertical overthickening (intrusive and extrusive) was probably predominant, with production of large amounts of basaltic magmas and picrites. Some basaltic rocks, occurring as seamounts, further contributed to thickening of the Caribbean oceanic crust (Kerr & Hastie 2006).

Since Late Jurassic–Early Cretaceous nucleation this oceanic domain separated the Bahamas, Maya and Chortis continental margins to the north from the Guayana shield to the south, developing through rifted continental margins with WPT magmatism, which created space for the proto-Caribbean oceanic domain. This scenario supports the proposed ‘near American’ location of the proto-Caribbean ocean (Giunta 1993; Meschede & Frisch 1998; Beccaluva et al. 1999; Giunta et al. 2002a, c, d, 2003a, b, 2006; Itrurralde-Vinent 2003; James 2003, 2006a, 2009) and is favoured over the classic idea that the Caribbean Plate is a ‘Pacific promontory’ (Duncan & Hargraves 1984; Burke 1988; Pindell & Barrett 1990; Pindell 2003; Draper & Pindell 2006; Maresch 2009; Stanek & Maresch 2006, 2009).

The original location of the proto-Caribbean is still debated. It could be thought of as a westward projection of the Tethyan ocean, forming an Atlantic–Pacific link. It would be ‘inter-American’ because it formed during Pangaean separation of the Americas. The controversy concerns the location of oceanic crust thickening – inter- or extra-American.

The proto-Caribbean realm constituted a Large Igneous Province (LIP) that has partly been subducted, so its original extension is unknown. The relationship between thin and thickened oceanic crust, with part of the first evolving to the latter, depends on the original distance between them. Close proximity suggests a near mid-American location. Distance suggests the Pacific model.

Ophiolites on Caribbean Plate margins, relics of Mid- to Late Cretaceous tectonic phases, indicate that the original LIP experienced two main stages of intraoceanic subduction and subordinate continental interaction with mélange formation and HP/LT metamorphism, involving both the proto-Caribbean oceanic lithosphere and/or supra-subduction complexes. These two stages, called eo-Caribbean phases (Giunta 1993), are respectively recorded by volcano–plutonic sequences with IAT or CA affinities and tonalitic intrusions of CA affinity. The two phases are recorded in several places along the plate margins. The first occurred in the Mid-Cretaceous (before 96 Ma); the second in the Late Cretaceous (from 86 Ma). One of the main problems of Caribbean geology is whether these record a single system continuously evolving in the Mid- and Late Cretaceous (Great Volcanic Arc model), or separate arcs (first and second eo-Caribbean).

Beginning in the Early Cretaceous, South Atlantic opening and westward–northwestward motion of the American plates led to ocean–ocean and ocean–continent plate convergence (first eo-Caribbean phase), producing several Cordilleran-like ophiolites.
(Beccaluva et al. 2004) related to SSZ and magmatic arcs (Fig. 9). Evidence of involvement of proto-Caribbean oceanic lithosphere in subduction zones comes from the above-mentioned HP/LT metamorphosed units of the plate margins. They formed during ocean–ocean subduction or, subordinately, an ocean–continent subduction. Parts of the previously rifted continental margins were also subducted, reaching eclogite facies in places. Subduction models have been proposed by Garcia-Casco et al. (2006a, b), Escuder-Viruete et al. (2006) and Maresch (2006, 2009). According to Giunta et al. (2003b, and references therein), the oldest available radiometric age for the HP/LT metamorphic climax is 96.3 ± 0.4 Ma. Since some units (e.g. Villa de Cura, Venezuela) formed in a supra-subduction setting, subduction must have commenced earlier than this HP/LT event. Peak HP/LT metamorphism of some rifted continental margin units (e.g. La Rinconada Fm of the Caucagua–El Tinaco complex in Venezuela) was probably younger than 114–105 Ma. A time span of about 11–16 Ma, during which the subduction continued, is suggested by the younger radiometric ages of climax conditions (79.8 ± 0.4 Ma), as well as the oldest radiometric ages of retrogradation (84.5 ± 0.2 Ma).

The Mid-Cretaceous accretionary stage is interpreted in different ways and is the most controversial of Caribbean evolution. The main features and problems are:

1. **Locations of either ocean–ocean or ocean–continent convergence.** The oldest intra-oceanic convergence probably involved the eastern proto-Caribbean, where thinner oceanic lithosphere favoured subduction. Simultaneously the western part of the plate was thickening to an oceanic plateau (Late Cretaceous). At the same time subduction occurred below the continental crust of the main plates and minor blocks, recorded by metamorphic mélanges and continental-derived units. Various models propose several magmatic arcs in a near mid-American area. Others propose a single great arc located in the Pacific, far from the present Central America Isthmus.

2. **Both volcanic arc complexes and thinned continental crust were involved in subduction.** Geology indicates existence of two coeval subduction settings: intra-oceanic and sub-continental. HP/LT assemblages (blueschist and eclogitic) in both oceanic and continental lithosphere require deep subduction. As mentioned earlier, HP/LT metamorphism of arc complexes (e.g. Villa de Cura), and in particular continental margin units (e.g. Caucagua–El Tinaco, Venezuela) requires more complex subduction than sinking of dense oceanic lithosphere. It could have involved tectonic erosion (likely) or underthrusting of thinned continental crust or flakes during continental collision.

3. **Ocean floor or back-arc origin of MOR-type ophiolitic units.** This problem is very difficult to resolve with petrological data alone. Depending on the location of the SSZ in different models, data suggest that some units better fit an intra- or back-arc supra-subduction origin or originated as trapped oceanic fragments. How many ophiolitic units can be referred to the un-thickened oceanic proto-Caribbean crust is difficult to establish.
Sinking direction of oceanic slabs in ocean–ocean or ocean–continent convergences – eastward or westward. In an attempt to accommodate all recognized constraints, at least three models have been proposed (Giunta et al. 2003a, b, 2006), with strike-slip boundaries separating accretionary–subduction environments (Fig. 10). Palaeomagnetic data may distinguish between these models.

The models differ in strike-slip fault locations. In model A, more or less east–west trending transform faults separate subduction zones with different dipping directions (westward in intra-oceanic convergence, eastward in sub-continental convergence). These are seen to have been located inside the oceanic domain, with micro-continentals present. In model B, all the oceanic domains could have been located between the main transform boundaries. This reconstruction requires both west-dipping subduction and very complicated continental margin morphology of continental promontories. Both these models can explain the early evolution of the so-called Great Volcanic Arc of Draper & Pindell (2006) and Pindell (2006). They differ in the Pacific or near mid-American origin of the arc system and the geometrical relationships of intra-oceanic and sub-continental subduction. Model C proposes widespread east-dipping subduction. Transform faults allowed coeval intra-oceanic and sub-continental subduction. Back-arc origin of some MOR-type units is also easily explained. Since few, dismembered arc portions have been referred to the first eo-Caribbean accretionary stage, doubts remain that they formed one original single arc. The first eo-Caribbean accretionary phase ended in the Late Cretaceous when the un-thickened oceanic realm was involved in westward subduction below the oceanic plateau (e.g. Burke 1988; Lewis & Draper 1990; Lewis et al. 2002; Meschede & Frisch 1998; Beccaluva et al. 1999; Giunta et al. 2002b, c, 2003b). This implies a flip of intraoceanic subduction polarity in model C (Kerr et al. 1996, 1999; White et al. 1999) or continuous westward subduction in models A and B.

Late Cretaceous kinematics (Fig. 11; second eo-Caribbean) involved eastward drift of the proto-Caribbean oceanic plateau, resulting in diachronous tonalitic magmatism (from 85 Ma) associated with westward-dipping oblique subduction of proto-Caribbean-Atlantic ocean floor and eastward youngling obduction of dismembered subduction complexes along northern and southern, east–west trending continental margins. This seems to be the consequence of eastward migration of northern and southern triple-junctions, resulting in bending of the Aves–Lesser Antilles arc (Giunta et al. 2003a, 2006). Tonalitic arc magmatism along the northern margin intruded both deformed older arc complexes and a new accretionary wedge migrating from the west (Motagua Suture Zone of Guatemala) to east (Cuba and Hispaniola). The Paleocene–Eocene volcanic arc of the Sierra Maestra in eastern Cuba (Iturralde-Vinent 2000; Kerr et al. 1999; Rojas-Agramonte et al. 2006b) may be connected with northward subduction of ‘residual’ oceanic crust below the older volcanic arc, as a second-order segment of the triple-point (Giunta et al. 2003b). At the same time the Late Cretaceous magmatic arc–accretionary wedge couple (western and central Cuba) collided against the NOAM, becoming progressively inactive.

Along the southern margin, tonalitic magmatism intruded both undeformed (85–82 Ma, Aruba; White et al. 1999) and deformed (Venezuelan islands) oceanic plateau, as well as the northernmost metamorphic complexes of rifted continental margin terrane (Caucagua–El Tinaco unit, Margarita island). No younger tonalitic magmatism is recorded in deformed units of the first eo-Caribbean volcanic arc. This implies that the older portion of the deformed belt was disconnected from Late Cretaceous active subduction. During Late Cretaceous–Paleocene collision the previously decoupled portions of the deformed belt were juxtaposed along the west–east southern margin of the Caribbean Plate (Giunta et al. 2002c, 2003a, b).

The proposed models for Late Cretaceous evolution differ in important aspects, as follows:

1. **Flip or no flip of the intra-oceanic subduction direction between first and second eo-Caribbean stages.** In Pacific models early subduction direction of the leading edge arc is supposed to have dipped westward. This changed to eastward dip after collision of the Caribbean plateau with the subduction zone. The change would have to have occurred in a very short time interval.

2. **Timing of plateau insertion into the mid-American area, and onset of two triple-junctions.** The Coniacian (85 Ma) seems a probable age of eastward drifting of the plateau and related triple-junctions, followed by collisional and suture zones from the west. The triple-junctions model can explain the evolution of the plate margins since at least the Late Cretaceous. The problem is to measure the distance travelled by the plateau. In some Pacific models this was more than 1000 km. ‘In-place’ models do not invoke plateau insertion and movement of the Caribbean Plate relative to its North and
Possible evolutionary models during the first (Mid-Cretaceous) eo-Caribbean phase related to the southern Caribbean Plate margin of Venezuela, depending on different locations of first-order free-boundaries (modified from Giunta et al. 2003b). These models could be proposed also for northern Caribbean margin, in a left-lateral convergence. Abbreviations: SOAM, South American Plate; JG and CC, continental margin of the Juan Griego and Cordillera de la Costa groups; RI and TT, sub-continental mantle and crust of rifted margins of La Rinconada and Caucagua-El Tinaco units characterized by WPT magmatism; FC and LH, MOR oceanic lithosphere of the Franja Costera group and Loma de Hierro unit; VC and DH, island arc showing IAT magmatism of the Villa de Cura and Dos Hermanas units; OP, thickening oceanic lithosphere (future Caribbean Plateau). See text for details and more explanations of models A, B, and C.
South American neighbours might have been as little as 300 km (James 2006a, b). If the western Colombian terranes are considered as remnants comparable to the Caribbean Plate, there is some palaeomagnetic data that suggests significant latitudinal displacement.

(3) Driving forces induced by the plateau. From the Late Cretaceous, the three models of Figure 10 converge, with eastward motion of the Caribbean Plateau driving evolution of the Caribbean margins (Escuder-Viruete & Pérez-Estaín 2006). Exhumation of HP/LT units and retrograde tectono-metamorphism occurred from the Campanian onward, with uplift related to displacement in shear zones sub-parallel to the plate boundaries. Strike–slip led to progressive dismembering of the orogenic system and development of separate accreted terranes.

(4) Timing of granitoid and tonalitic magmatism. In the model of Beccaluva et al. (1999), and Giunta et al. (2002a, c, d, 2003a, b) arc intrusions are divided in two main peaks of activity, connected with Mid-Cretaceous (first eo-Caribbean) and Late Cretaceous (second eo-Caribbean) intra-oceanic subduction. In contrast, Stanek & Maresch (2009) reconstruct continuous (110–73 Ma) arc activity in Cuba, supporting the existence of a single Great Volcanic Arc. Other arc regions (e.g. Andes or North American Cordilleras) may show the fact that, although magmatism can be continuous, there are some peaks where the magmatic volume is more significant, related to major tectonic changes. Diachronism of tonalitic magmatism, younging from the west since the Late Cretaceous, supports both the shifting of triple...
Eastward drift of the Caribbean Plateau continued from Late Cretaceous to Present, enhancing the Lesser Antilles arc by eastward shift of the two triple-junctions to their present-day positions, north of Puerto Rico and east of Tobago. The end of the second eo-Caribbean accretionary phase was marked by Late Cretaceous–Palaeogene collision and/or obduction of the proto- and eo-Caribbean complexes against or onto NOAM and SOAM continental margins. Suture zones formed along east–west strike–slip zones (Fig. 12). As a result, both the northern and southern boundaries of the Caribbean Plate are collisional belts that followed the eastward migrating triple-junctions. They are broad zones where large-scale tear faulting (still seismologically active) facilitates eastward dispersion and uplift of tectonic units, juxtaposing them within deformed terranes (Giunta et al. 2003a,b, 2006; Guzman-Speziale et al. 2006).

The Caribbean oceanic plateau became defined to the east by the Aves–Lesser Antilles arc-back arc system and to the west by the Chortís, Chorotega and Chocó blocks (Beccaluva et al. 1999). Fore-arc, back-arc and piggy-back basins on the deforming plate borders were filled with clastic and volcaniclastic sediments. Foredeep systems (Sepur Basin in Mexico-Guatemala; Foreland Basin in Cuba; Piemontine Basin in Venezuela) developed at thrust fronts (Giunta et al. 2002b, 2003a).

Models of Cenozoic–Present Caribbean kinematics are generally similar. Minor differences at the large scale concern the role of the strike–slip tectonics in plate margin evolution since at least the Mid-Cretaceous exhumation of HP/LT units. The Motagua zone of Guatemala is perhaps the best example of collisional belt evolution (Giunta et al. 2002b) in a strike–slip tectonic regime.

Conclusions

In order to compare different geodynamic models of the Caribbean Plate, facts and unresolved problems are distinguished and considered. Major disagreements currently concern: (a) the original location of the ‘proto-Caribbean’ oceanic realm or realms; (b) the Early Cretaceous palaeogeography and morphology of North and South American continental margins and minor blocks, in particular original locations of the latter; (c) polarity of the Cretaceous subduction zones; (d) the locations of and relationships between coeval intra-oceanic and sub-continental subduction zones; (e) the progressive insertion of rifted continent and supraduction complexes in subduction; (f) the possible subduction polarity reversal; and (g) the number of magmatic arcs and their peaks of activity.

From the Jurassic–Early Cretaceous until the Present plate evolution involved ocean spreading and plume activity, accretionary and collisional tectonics, dominated by a strongly oblique tectonic regime, constraining seafloor spreading, subduction, crustal exhumation, emplacement and dismembering processes, the evidence of which has been recorded in the oceanic remnants of a lost large igneous province.

A recent conference, held in Sigüenza, Spain, discussed in detail current regional problems. Although there are sufficient data to unravel an evolution outline, many different order problems remain open or insufficiently explained, so that current models seem to be far too speculative. The detailed new data that are being obtained by the Caribbean geological community certainly will show a more realistic picture of both plate convergence and ocean dynamics.

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