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Caribbean Plate margin evolution: constraints and current problems

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ABSTRACT

Oceanic crust was generated at multiple spreading centres during the Jurassic and Early Cretaceous, forming a "proto-Caribbean" oceanic domain. During the Cretaceous, part of that crustal domain thickened into an oceanic plateau, of petrologic Mid-Ocean Ridge (MOR) to Ocean Island Basalt (OIB) affinity. Simultaneously, the South and North American continental plates developed rifting and tholeiitic magmatism in the Middle America region (Venezuela and Cuba). The rifting created space for the proto-Caribbean oceanic domain. Petrological and regional correlations suggest that, beginning in the Cretaceous, the proto-Caribbean domain was involved into two main stages of subduction, referred to as first and second "eo-Caribbean" phases. Each phase is characterized by oblique convergence. The older (mid-Cretaceous) stage, involved in subduction (probably eastward dipping) of thin proto-Caribbean lithosphere, with generation of Island Arc Tholeiitic (IAT) and Calc-Alkaline (CA) magmatism, accompanied by high pressure - low temperature (HP - LT) metamorphic effects, and formation of arc units and ophiolitic melanges (Guatemala, Cuba, Hispaniola and Puerto Rico, in the northern margin; Venezuela in the southern). The Late Cretaceous second stage consisted of westward dipping intra-oceanic subduction; it is recorded by tonalitic arc magmatism related to the onset of the Aves - Lesser Antilles arc system. Since the Late Cretaceous, the inner undeformed portions of the Caribbean oceanic plateau (i.e. the Colombian and Venezuelan Basins) were trapped east of the Pacific subduction of the Chortis, Chorotega and Choco blocks, ultimately building the Central American Isthmus. From Tertiary to Present, continuous eastward movement of the Caribbean Plate with respect to the Americas, gave rise to transpression along both the northern and southern margins, marked by scattered and dismembered ophiolitic terranes.

KEYWORDS **Caribbean Plate. Ophiolites. Tectono-magmatic setting. Geodynamic evolution. Plate-tectonic models.**

INTRODUCTION

The Caribbean Plate consists of a nearly undeformed central portion (Colombia and Venezuela Basins) bounded by active margins (Fig. 1). The active northern (from Guatemala to Greater Antilles) and southern (northern Venezuela) margins mainly consist of shear zones within Jurassic/Cretaceous deformed terranes, bounded by east-west trending sinistral and dextral strike-slip faults respectively. The western and eastern margins are represented by convergent systems and related magmatic arcs (Central American Isthmus and Lesser Antilles). Deformed and dismembered Jurassic/Cretaceous ophiolitic terranes crop out along suture zones and strike-slip faults at the northern, southern and western edges of the Caribbean Plate; they represent fundamental tectono-stratigraphic elements related to the origin and evolution of the Caribbean Plate.

Systematic structural and petrological investigations carried out in the last decade by an Italian-Caribbean research group, within the framework of the IGCP Projects 364 and 433, are reviewed in this paper, with the aim of integrating the acquired results with the available data, and pointing out how the new information bears upon current problems.

The knowledge of the complex structural setting of the peri-Caribbean terranes (Beccaluva et al., 1996, 1999; Giunta et al., 1997, 2002a, b, c, d, 2003a,b) allows a better definition of the tectonic processes which involved some first-order geotectonic elements, originated in different paleo-domains. These geotectonic elements and related units (Fig. 2) are the following: (1) continental margins of North and South America, and minor blocks (Maya and Chortis in Central America, Escambray in Cuba, Cordillera de la Costa in Venezuela); (2) rifted continental margins related to the main continental plates (Escambray in Cuba, Caucagua-El Tinaco and Tinaquillo in Venezuela) with Jurassic-Early Cretaceous Within Plate Tholeiitic (WPT) magmatism; (3) Jurassic-Cretaceous oceanic domain (proto-Caribbean) evolving to a thickened plateau structure with Mid Ocean Ridge (MOR) (Santa Elena in Costa Rica, North and South Motagua in Guatemala, Northern Ophiolite in Cuba, Northern Cordillera and Loma Caribe in Hispaniola, Loma de Hierro and Franja Costera in Venezuela) and to Ocean Island Basalts (OIB) magmatic affinities (Matapalo and Esperanza in Costa Rica, Central Cordillera and Massif de la Hotte in Hispaniola, Dutch-Venezuelan Islands). These rock assemblages record the so-called proto-Caribbean process of oceanic crust generation; (4) mid-Cretaceous intra-oceanic subduction zones (and HP-LT subduction complexes) and related volcanic arcs, with Island Arc Tholeiitic (IAT) and Calc- Alkaline (CA) affinities (Sierra Santa Cruz and Juan de Paz in Guatemala, Mabujina and Cretaceous Arc in Cuba, Villa de Cura and Dos Hermanas in Venezuela); (5) mid-Cretaceous sub-continental

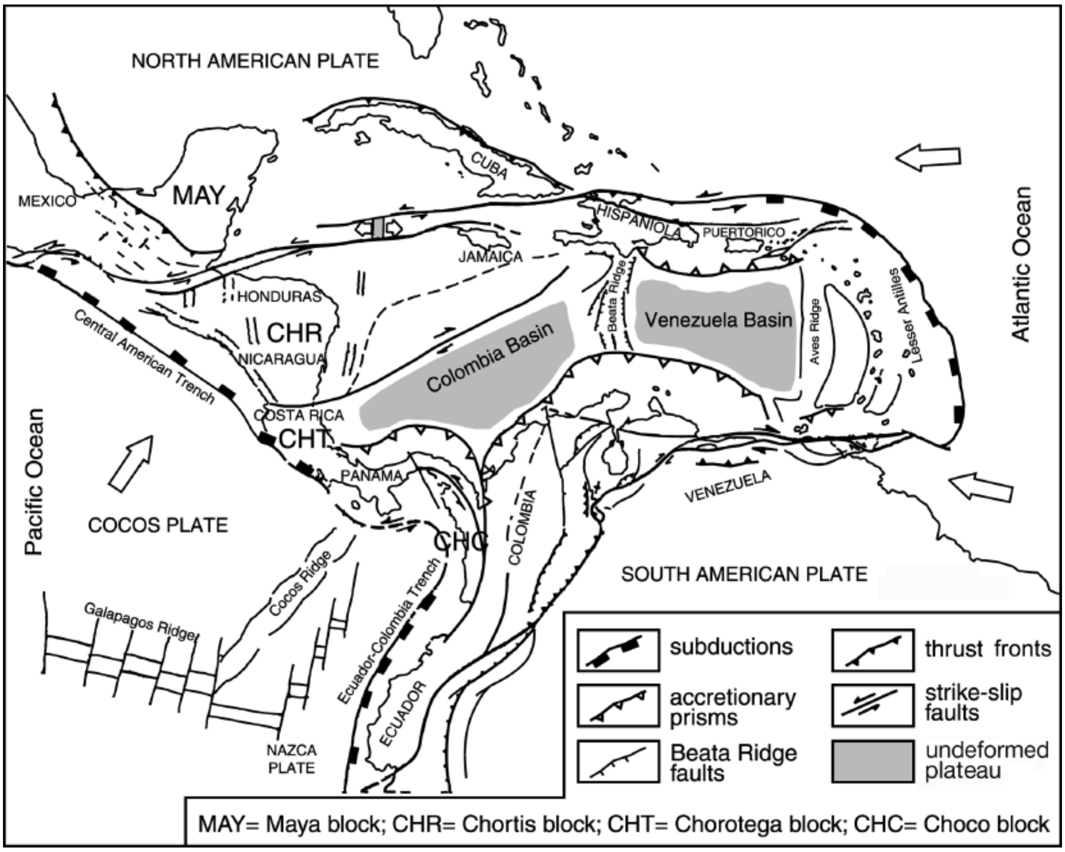

FIGURE 1 **Structural sketch map of the Caribbean area (modified from Beccaluva et al., 1996). Arrows show the drifting directions of the main plates.**

subductions with formation of HP-LT metamorphosed ophiolitic melanges, including mafic blocks with MORB affinity (Northern Ophiolite in Cuba, Northern Cordillera in Hispaniola, Franja Costera in Venezuela); Both (4) and (5) are proposed to be related to the eo-Caribbean first stage of subduction; (6) Late Cretaceous intra-oceanic subduction zones characterized by Tonalitic Arc magmatism (intruding: South Motagua in Guatemala, Mabujna and Arc Cretaceousin Cuba, Cordillera Central in Hispaniola, Dutch-Venezuelan Islands and part of Caucagua-El Tinaco in Venezuela), related to the so called 2nd eo-Caribbean stage of subduction; and (7) foredeep basins developed onto both the North America (NOAM) and South America (SOAM) continental margins since the latest Cretaceous.

The spatial-temporal distribution and regional correlation of the tectono-magmatic and structural characters of the main studied units are reported in Fig. 3. The timeline of the major Caribbean events is characterized by different tectonic regimes (Giunta et al., 2003a), including 1) the proto-Caribbean stage of oceanization; 2) the first and second eo-Caribbean stages of subduction (either intra-oceanic or sub-continental); and 3) the collisional stage leading to the present Caribbean Plate (Fig. 4).

The geodynamic evolution of the Caribbean Plate is discussed from the perspective of our new results, and a general model is proposed that incorporates important constraints recognized in the last years, as well as those of the previous reconstructions of the Caribbean Plate (Pindell and Barrett, 1990; Pindell, 1994, Beccaluva et al., 1996, 1999; Meschede and Frisch, 1998; Giunta et al., 2002a, b, c, d; 2003a, b). The crucial points in our paleogeographic restorations are: 1) the original "near mid-America" location of the Mid Jurassic-Early Cretaceous oceanization (proto-Caribbean), probably located at the westernmost corners of the American Plates); 2) the polarity of the two Cretaceous subduction zones; 3) the paleogeography, as well as the number of magmatic arcs, connected with the first and the second eo-Caribbean subduction stages respectively; and 4) the possibility of a subduction polarity reversal: eastward in the first stage (mid-Cretaceous), westward in the second stage (Late Cretaceous).

PROTO-CARIBBEAN OCEANIZATION

During the Jurassic, extension related to the central Atlantic opening and induced by the separation of North and South American Plates, led to the formation of the proto-Caribbean oceanic crust between the two Americas (Fig. 5A). The early creation of this oceanic crust was probably related to multiple spreading centres generating basaltic and gabbroic sequences, with MORB affinity (Beccaluva et al., 1999; Giunta et al., 2002a, b, c). These sequences are observed in: Santa Elena (SE) and Matapa-

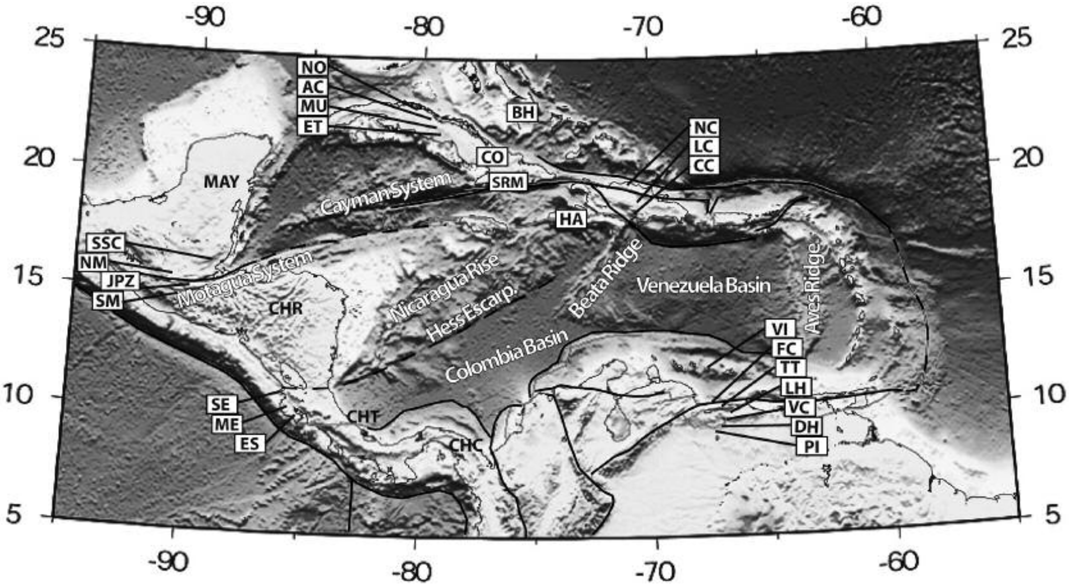

FIGURE 2 **Location map of the studied peri-Caribbean tectonic units. Northern margin units: SSC: Sierra Santa Cruz; JPZ: Juan de Paz; NM: North Motagua; SM: South Motagua (Guatemala); NO: Northern Ophiolite; AC: Arc Cretaceous; MU: Mabujna; ET: Escambray; CO: Cuba Oriental; SRM: Sierra Maestra (Cuba); BH: Bahamas (NOAM); NC: Northern Cordillera; LC : Loma Caribe; CC: Central Cordillera; HA: Dumisseau and Massif de la Hotte (Hispaniola). Southern margin units: VI: Dutch and Venezuela Islands; FC: Franja Costera; TT: Caucagua-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: Chortis; CHT: Chorotega, CHC: Choco.**

lo (ME) complexes in Costa Rica, South Motagua (SM) and the lower North Motagua (NM) units in Guatemala, Northern Ophiolites (NO) in Cuba, Loma de Hierro (LH) and Franja Costera (FC) in Venezuela, Northern Cordillera (NC), Loma Caribe (LC) and the oldest portions of the Duarte Complex, Central Cordillera (CC) in Dominican Republic (Fig. 2). This tholeiitic magmatism is characterized by flat or slightly light rare earth elements (LREE)-enriched to LREE-depleted patterns, suggesting that it was mostly generated by high-degree partial melting of undepleted to slightly depleted MORB mantle sources (Beccaluva et al., 1999; Giunta et al., 2002b, and references therein). The unusual abundance of Fe-Ti-enriched basaltic and gabbroic differentiates, recognized in the ophiolites of northern Costa Rica and Duarte complex in Dominican Republic is strongly comparable to those of the propagating spreading centers (e.g. Galápagos; Christie and Sinton, 1981); this suggests that crustal generation at spreading ridges may have been accompanied by overthickening due to excess eruptions of Fe-basaltic magmas, as proposed by Saunders et al. (1996) for the Icelandic-type oceanic plateaus**.**

The proto-Caribbean oceanic crust thickened at its westernmost end during the Cretaceous (91-88 Ma; Sinton et al., 1998), becoming structurally and petrologically comparable to typical oceanic plateaus (Burke, 1988; Case et al., 1990; Storey et al., 1991; Mahoney et al., 1993; Hill, 1993; Kerr et al., 1996; Beccaluva et al., 1999; Giunta et al., 2002a, b, c). The resulting rocks are tholeiitic basalts with flat REE patterns, sometimes associated with picrites, such as those recorded at Curaçao (Kerr et al., 1996; Giunta et al., 2002a), Aruba (White et al., 1999), Los Roques (Giunta et al., 1997, 2002a), the Tortugal komatiitic suite in Costa Rica (Alvarado et al., 1997), Central Cordillera of Dominican Republic (Lapierre et

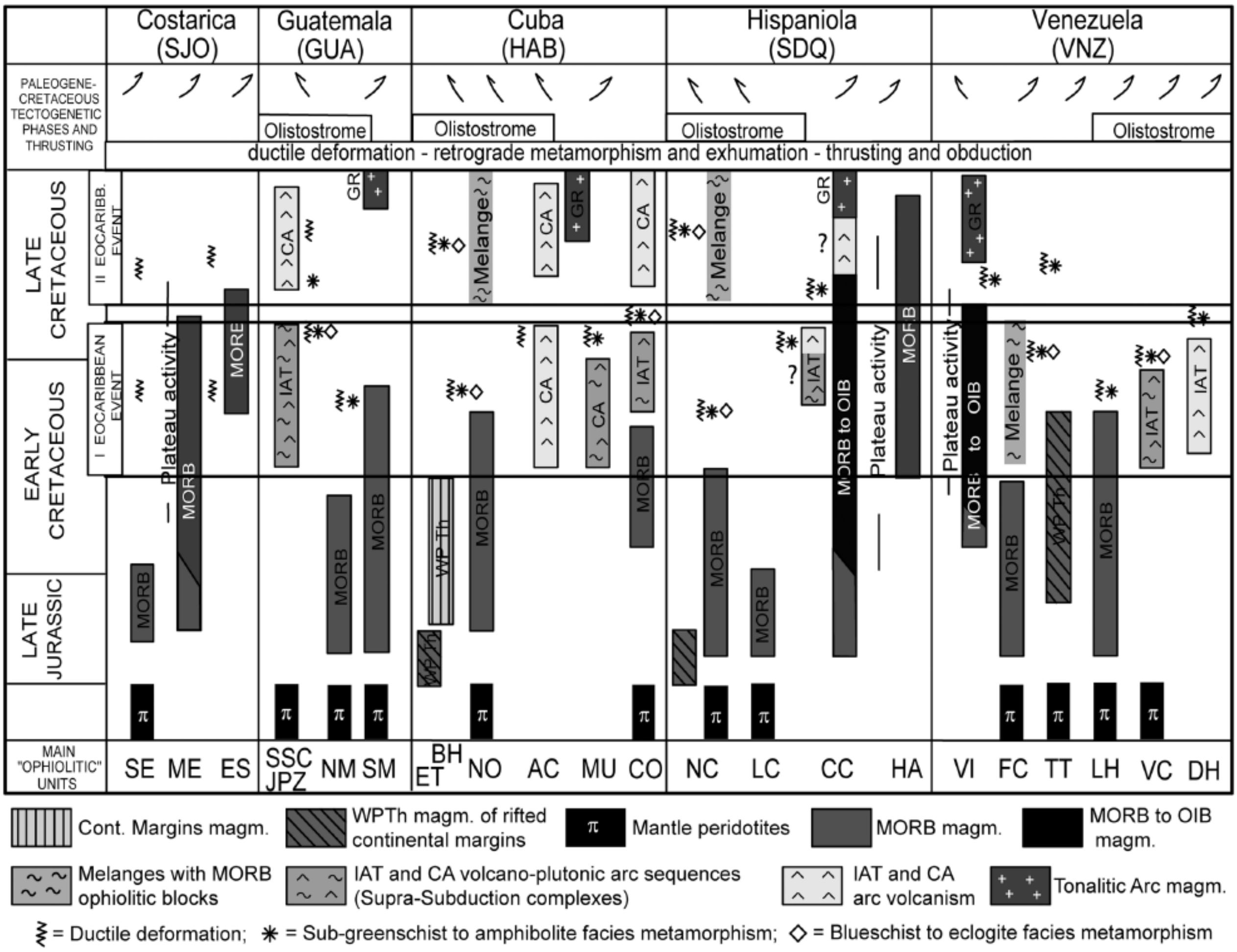

FIGURE 3 **Tectono-magmatic grid of the main peri-Caribbean igneous units (modified from Giunta et al., 2002b). SE=Santa Elena; ME=Metapalo; ES=Esperanza; SSC=Sierra Santa Cruz; JPZ=Juan de Paz; NM=North Motagua; SM=South Motagua; BH=Bahamas; ET=Escambry; NO=Northem Ophiolites; AC=Cretaceous Arc; MU=Mabujina: CO=Cuba oriental; NC Northern Cordillera; LC=Loma caribe; CC=Central Cordillera; Ha=Haiti; VI=Venezuelan Islands; FC=Franja Costera; TT=Caucagua-El Tinaco; LH=Loma de Hierro: VC=Villa de Cura; DH=Dos; π=Peridoitite; MORB=Mid Ocean Ridge Basalt; OIB=Ocean Islands Basalt; IAT=Island Arc Tholeiite; CA=Island Arc Calcalkaline; GR=Tonatitic arc magmatism (Gabbroid to Granitoid); WPTh=Within Plate Tholeiite.**

al., 2000; Lewis et al., 2002; Giunta et al., 2002a, b), and the western Colombian ophiolites (Spadea et al., 1989; Kerr et al., 1997). Crustal accretion by vertical overthickening (both intrusive and extrusive) was probably predominant at this stage, with the production of large amounts of basaltic magmas and picrites. This process suggests high degree of partial melting of compositionally analogous (MORB), but comparatively hotter and deeper mantle sources, which underwent adiabatic upwelling (McKenzie and Bickle, 1988; Kerr et al., 1996). Upwelling and melting could have resulted from the rise of a hot plume-head in the upper mantle plume region, near or at previous spreading centers (Sen et al., 1988; White and McKenzie, 1989; Kent et al., 1992).

Some basaltic lava units of the Duarte and Tireo complexes in Santo Domingo (Giunta et al., 2002b, c), the Curaçao dikes (Giunta et al., 2002a), and Site 151 in the Beata Ridge (DSDP - Leg 15, Sinton et al., 1998), are comparable with the lavas of ocean islands (OIB), and Iceland- and Galapagos-type central volcanoes (Christie and Sinton, 1981; Furman et al., 1992; Geist et al., 1995). Their LREE-enriched and positively fractionated heavy rare earth element (HREE) patterns indicate that they were generated from mantle sources enriched in incompatible elements with respect to MORB sources, similar to those related to a magmatism in a plume region. These basaltic rocks generally occurring as seamounts, further contributed to the thickening of the Caribbean oceanic crust.

Geological evidences and petrologic characteristics of the Jurassic-Cretaceous rocks from the tectonic units of Guatemala, Cuba, Hispaniola, and Venezuela, strongly suggest that a spatial continuity existed with the Bahamas, Maya and Chortis continental margins to the north, and the Guayana shield to the south. Portions of these continental margins were affected by Late Jurassic- Early Cretaceous rifting with production of within plate tholeiitic (WPT) magmatism, well documented both in the northern (Cuba) and in the southern (Venezuela) peri-Caribbean belts (Giunta et al., 1997, 2002a, b; Seyler et al., 1998; Kerr et al., 1999). This WPT magmatism may suggest a physical continuity between the oceanic crust and the continental margins, supporting the near mid-American original location of the proto-Caribbean oceanic domain, already proposed by several authors (Giunta, 1993; Beccaluva et al., 1996, 1999; Meschede and Frisch, 1998; Giunta et al., 2002a, b, c, 2003; Iturralde-Vinent, 2003; James, 2003). This model is therefore favoured with respect to the classic hypothesis of the Caribbean Plate as a "Pacific promontory" between the two Americas (Duncan and Hargraves, 1984; Burke, 1988; Pindell and Barrett, 1990; Pindell, 2003).

SUBDUCTION EVENTS

Two main stages of intra-oceanic subduction, marked by formation of supra-subduction igneous and metamorphic complexes, have been recognized in several Cretaceous ophiolitic units of the peri-Caribbean deformed terranes; some HP-LT metamorphosed ophiolitic melanges are also considered as related to sub-continental subduction zones. The main stages of intra-oceanic convergence, referred to as first and second eo-Caribbean phases (Giunta, 1993), are represented by: (1) volcano-plutonic sequences (mid-to-Late Cretaceous) with IAT or CA affinities, in places affected by HP-LT metamorphism, and (2) unmetamorphosed tonalitic arc magmatism (Late Cretaceous), ranging from gabbroid to granitoid intrusives. The overall petrological and structural features of all these complexes, according to Beccaluva et al. (2004), are typical of "Cordilleran" ophiolites, being characterized by dismembered volcano-plutonic arc sections with tholeiitic to calc-alkaline magmatic affinity and acidic differentiates, commonly associated with metamorphic subduction complexes within polygenetic terranes.

1° eo-Caribbean phase of subduction

During the mid-Cretaceous intra-oceanic and subcontinental subduction processes took place with associated tholeiitic and calc-alkaline arc magmatism, as well as HP-LT metamorphic effects recorded in several units of the Caribbean deformed margins. The onset of the compressional conditions were induced by the South Atlantic opening with westward and north-westward motion of the American plates (Figs. 5B and 6). Remnants of magmatic arcs and subduction complexes are represented by mantle rocks, intrusives, and volcanic sequences (Giunta et al., 2002a, b, c, d) of: (1) the Sierra Santa Cruz (SSC), Juan de Paz (JPZ), and Baja Verapaz units (Guatemala), the Cretaceous Arc (AC) and Mabujina (MU) units (Cuba), as well as in Jamaica, to the north; (2) the Villa de Cura (VC), Dos Hermanas (DH), and Franja Costera (FC) units (Venezuela), to the south. Moreover, portions of the

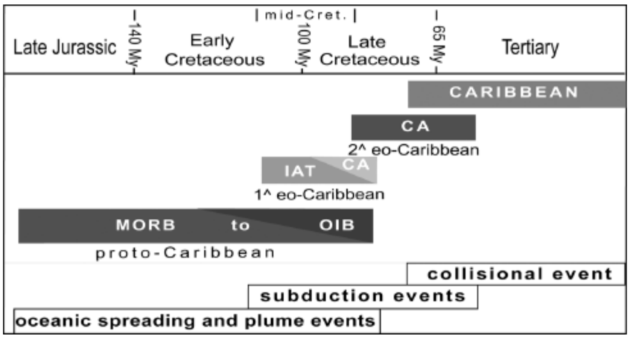

FIGURE 4 **Timeline of major Caribbean events. Abbreviations as in Fig. 3.**

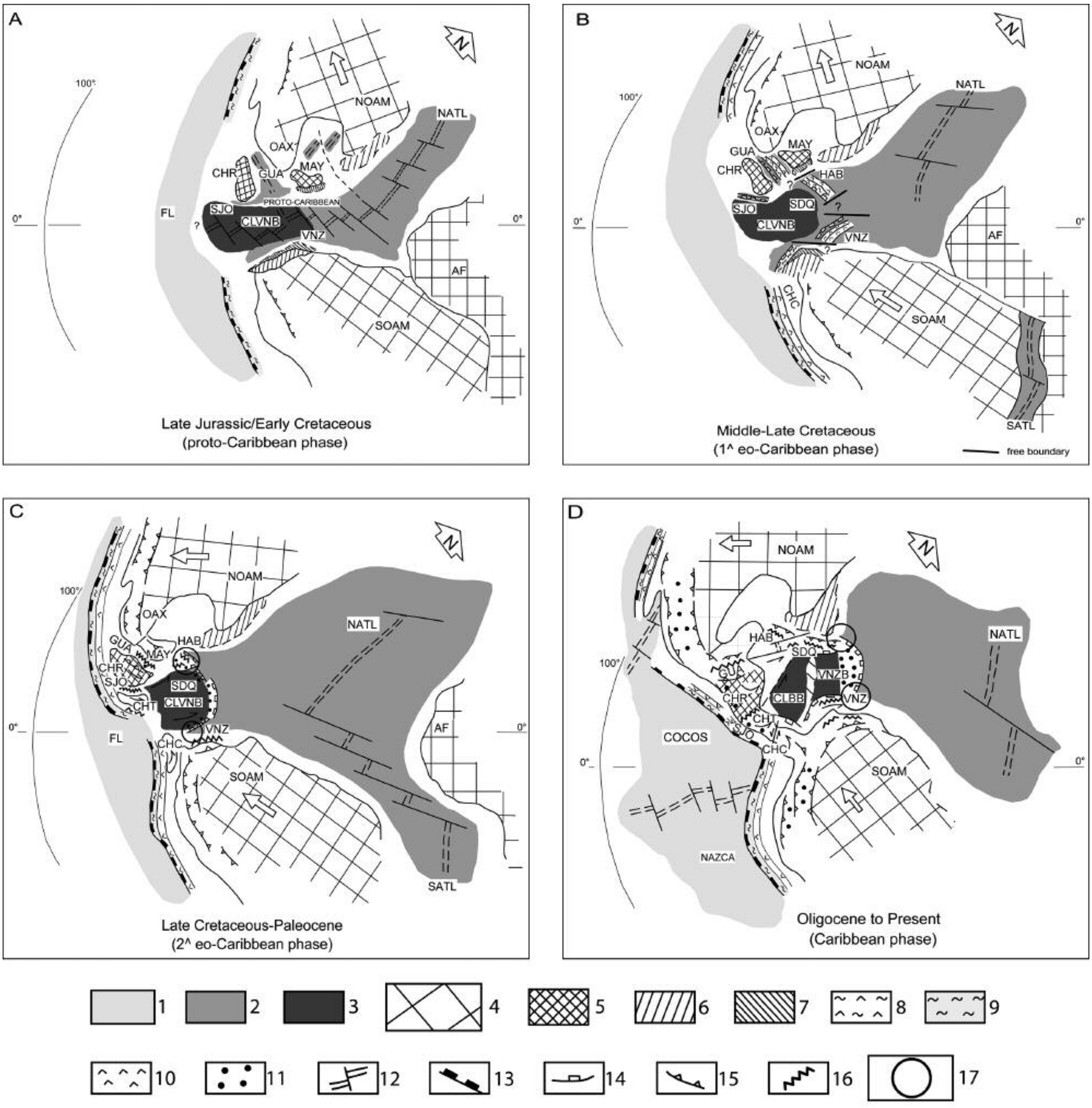

FIGURE 5 | **Tentative paleogeografic reconstruction and kinematic evolution of the Caribbean Plate, from Late Jurassic to Tertiary (modified from Giunta et al., 2002b).**

Numbers in legend: 1: Oceanic crust of the Farallon Plate. 2: Proto-Caribbean-Atlantic oceanic crust (Loma de Hierro unit, blocks in Franja Costera unit, in Venezuela; North Motagua unit, South Motagua unit, in Guatemala; Northern Ophiolites unit, in Cuba; Northern Cordillera units, Loma Caribe unit, in Hispaniola). 3: Proto-Caribbean oceanic area undergoing crustal thickening (Santa Elena units, Metapalo unit, Esperanza unit, in Costa Rica; Duarte-Tireo units, in Hispaniola; Dutch Antilles and Venezuelan Is. units, in Venezuela). 4: North American, South American and African continental plates. 5: Minor continental blocks. 6: Continental margins (Bahamas (NOAM) and Cordillera de la Costa (Venezuela) units). 7: Rifted continental margins (Escambray Terranes, Cuba, and Caucagua el Tinaco units, in Venezuela). 8: Volcano-plutonic arc sequences (Mabujina unit, in Cuba, Villa de Cura units, in Venezuela). 9: Ophiolitic melanges (Franja Costera unit, in Venezuela, and Pacific margins). 10: Cretaceous arc volcanism of the Caribbean area (Arc Cretaceous units, in Cuba; Dos Hermanas unit, in Venezuela; Sierra Santa Cruz units, Juan de Paz unit, in Guatemala, and Pacific margins). 11: Tonalitic magmatism (gabbroid to granitoid) and volcanic arcs. 12: Oceanic spreading centers. 13: Subductions of the Farallon-Pacific oceanic lithosphere. 14: Intra-oceanic subductions in the Caribbean area. 15: Main overthrust fronts. 16: Deformed and thrust belts, including suture zones, accretionary prisms, melanges and olistostromes. 17: Triple-junctions.

Abbreviations: FL: Farallon; NOAM: North America; SOAM: South America; AF: Africa; NATL: Northern Atlantic; SATL: South Atlantic; OAX: Oaxaca; MAY: Maya; CHR: Chortis; CHT: Chorotega; CHC: Choco; SJO: Costa Rica; GUA: Guatemala; SDQ: Hispaniola; HAB: Cuba; VNZ: Venezuela; CLVNB: Colombia and Venezuela Basins; CLBB: Colombia Basin; VNZB: Venezuela Basin.

previously rifted continental margins were also involved in the subduction zones (e.g., La Rinconada Formation of the Caucagua-El Tinaco (TT) unit in Venezuela; Escambray in Cuba), sometimes reaching the amphibolite-eclogite facies. As reported by Giunta et al. (2003b, and references therein), the age of the 1º eo-Caribbean phase should correspond to the peak of HP-LT metamorphism in the arc unit of Villa de Cura (Venezuela), dated at 96.3±0.4 Ma. This is consistent with the oldest age range (79.8±0.4 - 84.5±0.2 Ma) of retrograde metamorphic conditions, whereas the HP-LT metamorphism of La Rinconada continental unit (Venezuela) is younger than 114-105 Ma (probable age range of magmatism). Hence, at least a mid-Cretaceous age for the early convergence in the Caribbean realm is suggested.

To reconstruct the eo-Caribbean phase of subduction, several important points have to be considered (Giunta et al., 2003), including: 1) The location and polarity of the subduction, either intra-oceanic or sub-continental. The intra-oceanic convergence of the 1º subduction is supposed to have affected the eastern sector of the proto-Caribbean domain, where the older, thinner and denser portions of this oceanic lithosphere was in the more favourable condition to be subducted; at the same time, the western sector of the oceanic domain was undergoing progressive crustal thickening. This view, suggesting the location of trench zones in the eastern sector of the proto-Caribbean realm close to the American plates, is significantly different from the model proposed by Pindell and Barrett (1990) and Pindell (1994, 2003). They proposed that during Barremian-Albian time a continuous subduction zone was located along the present Central American Isthmus. 2) The ocean floor or back-arc origin of the MOR-type ophiolitic units (e.g. South and North Motagua (SM, NM) units in Guatemala, blocks in the Nortern Ophiolite (NO) in Cuba, Loma Caribe (LC) in Hispaniola, Loma de Hierro (LH) unit and blocks in the Franja Costera (FC) unit in Venezuela). 3) The atypical evolution of some of the volcanic arc units, which were involved at least in part (e.g. Juan de Paz (JPZ) in Guatemala, Villa de Cura (VC) in Venezuela) in subduction processes. In fact, the HP-LT metamorphism affecting those units raises the problem of how arc complexes, generally floating in the upper plate could have been deeply involved in subduction processes; this may be explained by tectonic erosion during the last steps of the first phase of oceanic convergence, in the mid-Cretaceous. 4) The coexistence of both arc complexes and continental crust sections involved in subduction (intra-oceanic or sub-continental) processes (e.g. Juan de Paz (JPZ) unit in Guatemala, Mabujna (MU) and Escambray units in Cuba, Villa de Cura (VC), Dos Hermanas (DH) and Caucagua-El Tinaco (TT) units in Venezuela). 5) The HP-LT metamorphism recorded in continental margin units (e.g. Caucagua-El Tinaco in Venezuela) requires subduction mechanisms more complex than those commonly considered for the sinking of the denser oceanic lithosphere, such as tectonic erosion, or underthrusting of thinned continental crust or flakes during continental collision.

The cartoon model of Fig. 5B is not intended to resolve the controversial points reported above, but to propose several possible models (Fig. 7), each of which needs kinematic free-boundaries (strike-slip faults). The models of Fig. 7, proposed in particular for the evolution of the southern Caribbean plate margin (Giunta et al., 2003b), imply an oblique convergence regime.

In the first model (Fig. 7A), an east-west trending strike-slip system separating two simultaneous opposite dipping subduction zones, is located inside the oceanic domain, in addition to the presence of micro-continents. The second model (Fig. 7B), where the oceanic domain is located between the main free-boundaries, requires the occurrence of both a west- dipping subduction and a complicated continental margin morphology (e.g. continental promontories). In the third model (Fig. 7C), the occurrence of a single east-dipping convergence boundary allows the contemporaneous existence of intra-oceanic and sub-continental subduction zones.

On the whole, the available data confirm that the first eo-Caribbean phase ended in the Late Cretaceous, when the thickened oceanic plateau was about to be involved in the subduction. However, because of buoyancy forces this process was interrupted and a new subduction took place below the plateau. This implies a flip of the intra-oceanic subduction direction with reverse westward lithospheric sinking (White et al., 1999), north of the Venezuelan margin, as shown in Fig. 7C.

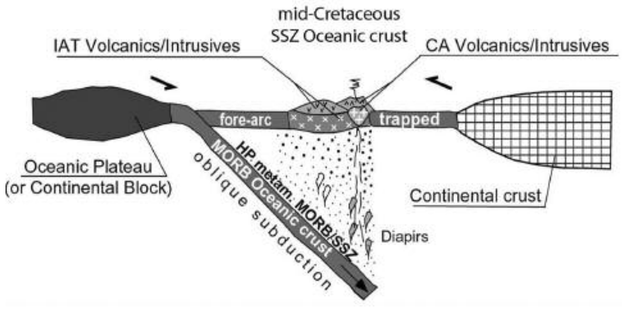

FIGURE 6 **Generalized cross-section across the intra-oceanic subduction zones of the 1° eo-Caribbean phase (mid-Cretaceous).**

2° eo-Caribbean phase of subduction

In the Late Cretaceous, the Caribbean oceanic plateau (Colombia and Venezuela Basins) continued eastward movement relative to the Americas. Westward dipping subduction of the proto-Caribbean-Atlantic oceanic lithosphere below the plateau generated the Aves-Lesser Antilles magmatic arc system (Fig. 5C) moving eastward. At the same time, along both the northern and southern plate margins oblique subduction processes of the oceanic

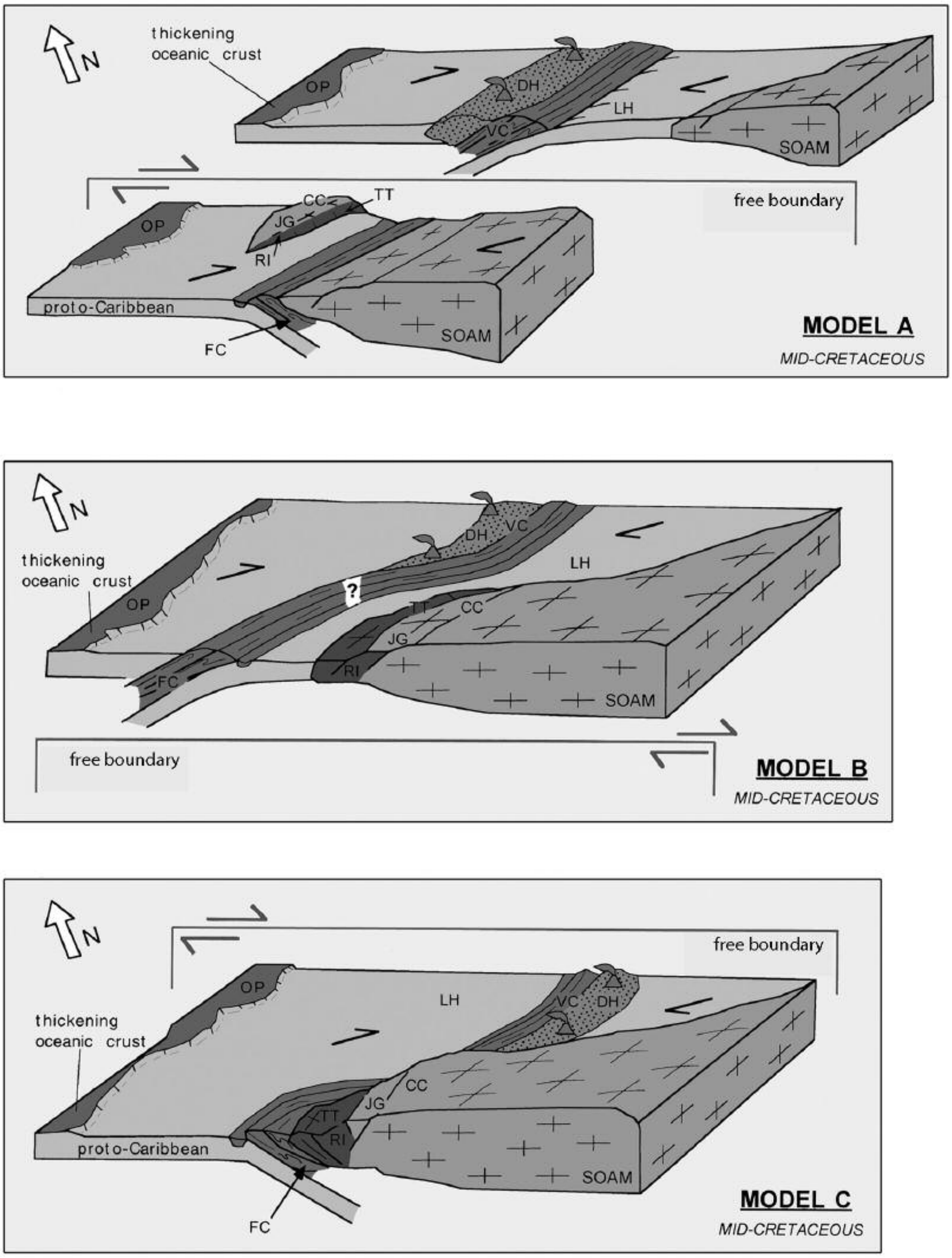

FIGURE 7 **Possible evolutionary models of the southern Caribbean plate margin (Venezuela), during the first (mid-Cretaceous) eo-Caribbean phase (modified from Giunta et al., 2003b). SOAM: South America Plate; JG and CC: continental margin of the Juan Griego and Cordillera de la Costa groups; RI and TT: sub-continental mantle and crust of rifted margins of La Rinconada and Caucagua-El Tinaco units characterized by WPT magmatism; FC and LH: MORB 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.**

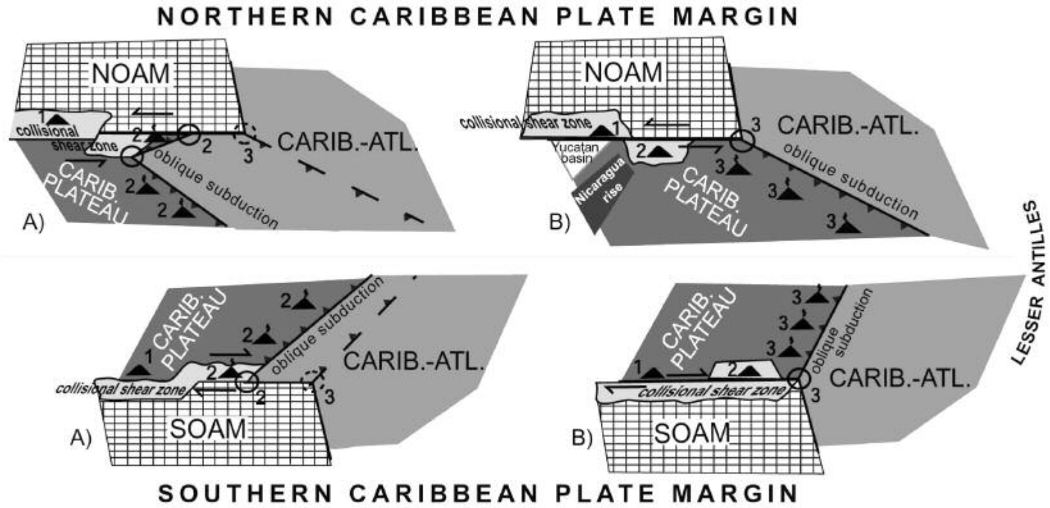

FIGURE 8 | **Tentative evolutionary models for the northern and southern Caribbean Plate Margins since the Late Cretaceous, related to the eastward shifting of two triple-junctions (modified from Giunta et al., 2003a). The cartoons show the supposed evolution of both northern (upper part of the figure) and southern (lower part of the figure) margins, from Late Cretaceous (A) to Paleogene (B). The numbers indicate the volcanic arcs connected with the subduction (progressively active from 1 to 3), both related to triple-junctions (circles).**

lithosphere took place beneath the plateau and/or the previous magmatic arcs, giving rise to: (1) the widespread predominantly tonalitic (gabbroid to granitoid) arc magmatism of the northern and southern Caribbean plate margins (in Guatemala, Cuba, Hispaniola, Puerto Rico, Dutch Antilles, Venezuelan Islands, and Venezuela); and (2) the amphibolite/HP-LT metamorphism in some ophiolitic units of the northern Caribbean margin, as in Cuba, Hispaniola and Puerto Rico (Iturralde-Vinent, 1998; White et al., 1999; Giunta et al., 2002a, b, c , d; Lewis et al., 2002; Kerr et al., 2003).

In the cartoon model of Fig. 8 the kinematics of the Caribbean Plate is supposed to be related to triple-junctions located in both the northern and southern (Giunta et al., 2003a) margins. The progressive shift eastward of these triple-junctions gave rise to a transpressional tectonic regime, which allowed lateral dismembering and dispersion of the older subduction and supra-subduction complexes (originated in the mid-Cretaceous subduction phase), as well as progressive bending of the Aves-Lesser Antilles arcs.

In this scenario significant differences between the two margins can be pointed out. Along the northern margin, from the Late Cretaceous the tonalitic arc magmatism generally intruded (Fig. 9) both the deformed older arc complexes and the new eastward migrating accretionary wedge, which started to collide against the NOAM from the west (Motagua Suture Zone of Guatemala) to the east. The Paleocene-Eocene volcanic arc of the Sierra Maestra in eastern Cuba (Iturralde-Vinent, 1998; Kerr et al., 1999) may be related with a second-order triple-point (Giunta et al., 2003a) shifting south-eastward, while the Late Cretaceous magmatic arc–accretionary wedge couple (western and central Cuba) collided against the NOAM becoming progressively inactive (Fig. 8).

Along the southern margin the tonalitic magmatism intruded (85-82 Ma at Aruba; White et al., 1999) both the undeformed oceanic plateau (Dutch Antilles) and its deformed portions (Venezuela Islands), as well as some metamorphic complexes related to the northernmost rifted continental margin (e.g. Caucagua-El Tinaco unit in Margarita Island). By contrast, no younger tonalitic magmatism is recorded in the deformed units related to the first eo-Caribbean subduction phase (e.g. Franja Costera, southernmost Caucagua-El Tinaco, Loma de Hierro, Villa de Cura, Dos Hermanas units in Venezuela) (Fig. 8). This implies that this older portion of the deformed belt, was geodynamically disconnected from the Late Cretaceous active subduction (second eo-Caribbean phase). Later on (latest Cretaceous-to-Paleocene), both the previous decoupled portions of the deformed belt were juxtaposed as independent terranes along the west-east southern margin of the Caribbean plate (Giunta et al., 2002a, 2003a, b).

Some constraints support the proposed tectonic evolution of the peri-Caribbean terranes (Giunta et al., 2003b, and references therein), as the apparent contrasts in the decompressional evolution recorded in several HP-LT metamorphic units, which indicate that the converging zones, since the Late Cretaceous, were subdivided into sectors characterized by different tectonic settings. In fact, various deformation phases developed under P-T retrograde conditions during exhumation. The beginning of exhumation, referable to a second tectono-metamorphic

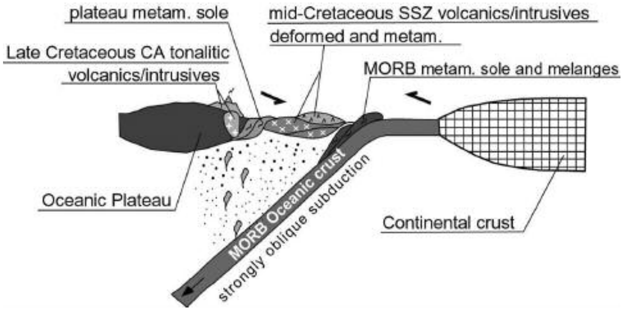

FIGURE 9 | **Generalized cross-section across the northern Caribbean accretionary system during the 2° eo-Caribbean phase (Late Cretaceous).**

event, is characterized by a well-developed axial-plane foliation showing mineral and stretching lineations. The east-west trending L2 lineations suggest that displacement during the early stage of exhumation was nearly perpendicular to the subduction direction, which in turn is characterized by north-south trending L1 lineations, roughly parallel to the plate boundaries. These structural features demonstrate that strike-slip tectonics have largely ruled the geodynamics of the Caribbean margins, controlling their tectonic evolution since at least the beginning of exhumation of the HP-LT units in the mid- Late Cretaceous.

The end of the second eo-Caribbean accretionary phase is marked by the Late Cretaceous-Paleogene collision and/or obduction of the proto- and eo-Caribbean complexes against or onto the NOAM and SOAM continental margins, with formation of suture zones through the development of flakes and wedges in the deformed units, controlled by east-west strike-slip tectonic regime. In the meantime the Caribbean oceanic plateau was trapped to the west by the intervening of the Chortis, Chorotega and Choco blocks (Beccaluva et al., 1999; Giunta et al., 2002b), which progressively rotate allowing the construction of the western plate margin (Central American Isthmus; Fig 5C).

COLLISIONAL EVENT

From Late Cretaceous to Present, the Caribbean Plate eastward drift was enhanced, resulting in the collision of its margins against the NOAM and SOAM (Figs. 5D and 10). Meanwhile, it was trapped westward by the intervening Pacific subduction (building the Central American Isthmus), and eastward by the Aves-Lesser Antilles arc-back arc systems. As a result, both the northern and southern boundaries of the Caribbean correspond to two wide shear zones, where, since the Late Cretaceous, the large-scale tear faulting favoured eastward dispersion and uplifting of the tectonic units, juxtaposing them within deformed terranes (Giunta et al., 2003a, b).

During this collisional event, fore- or back-arc and piggyback basins laying on the deforming plate borders, were filled by clastic sediments and volcanoclastics. In particular, on the NOAM and SOAM continental margins, foredeep systems (Sepur Basin in Mexico-Guatemala; Foreland Basin in Cuba; Piemontine Basin in Venezuela) developed at the thrust belt front (Giunta et al., 2002d, 2003b).

Since the Tertiary, continuous westward drifting of the two Americas resulted in further encroachment on the Caribbean Plate, enhancing either the bending of the Lesser Antilles arc or the collisional processes through transpressional tectonics at the northern and southern margins. This led to a geometry of the plate borders substantially similar to the present configuration**,** where sinistral or dextral shear zones respectively, allowed a gradual dismembering and scattering of the eo-Caribbean terranes along regional faults (e.g. Motagua-Polochic fault system in Guatemala, Cayman Ridge system, Bartlett fault, and Oca, Bocono, S. Sebastian, La Victoria, El Pilar fault zones in Colombia and Venezuela). Along the western border of the plate, the northwest-southeast compressional stress field affecting the deformed borders of the Mid-American Trench produced adjustments and different rotations (Beccaluva et al., 1999; Giunta et al., 2002b, c) of the Chorotega and Choco blocks through strike-slip fault zones (e.g. the Hess Escarpment and Panamá Canal).

The continuous convergence between the two Americas generated new accretionary prism systems along the internal side of the Caribbean plate borders**,** which progressively involved crustal portions of the Colombian and Venezuelan Basins (Los Muertos in Hispaniola, Venezuela-Colombia and Panama accretionary prisms). The Dumisseau Formation (HA) of the Massif de la Hotte in Haiti may represent the northeastern portion of the oceanic plateau, inserted between the Beata Ridge and the Hess Escarpment, and deformed against the Hispaniola thrust-belt and Los Muertos accretionary prism, in relation to the anticlockwise rotation of the Nicaragua Rise and Colombia Basin (Giunta et al., 2003a). At the same time, the plate continued to migrate slowly (1-2 cm/yr or less) eastward, overriding the Atlantic lithosphere, devel-

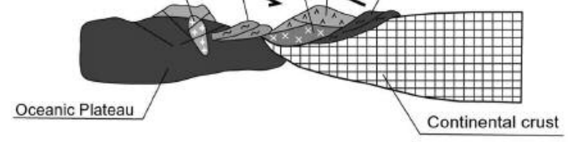

FIGURE 10 | **Generalized cross-section of the peri-Caribbean collisional belts (Late Cretaceous-Paleogene).**

oping the Lesser Antilles arc-backarc system and related Barbados accretionary prism.

CONCLUDING REMARKS

Researches carried out on the main tectonic units of the Caribbean margins, based on structural, magmatic, and metamorphic characteristics and their regional correlations, have provided important contributions for the geodynamic evolution of the Caribbean plate margins. Among these are: the origin and evolution of the proto-Caribbean oceanic crust, the beginning of the convergence during the Early-mid-Cretaceous, the two-stage arc magmatism (mid- and Late Cretaceous), the different subduction settings (intra-oceanic and sub-continental), the HP-LT assemblages in both oceanic and continental lithospheres, the atypical evolution of the supra-subduction system during the mid-Cretaceous, the different distribution of the second arc magmatism (Late Cretaceous), the differences in retrograde evolutions and the exhumation histories of the HP-LT units, the role of the strike-slip tectonics since the mid-Cretaceous. An evolutionary model has been proposed pointing out some important aspects of the Caribbean Plate geodynamic history.

The hypothesis that the Late Jurassic-Early Cretaceous proto-Caribbean oceanic plate formed near mid-America and evolved during Cretaceous into a plateau, has been gradually gaining ground although it is still under debate (Duncan and Hargraves, 1984; Pindell and Barrett, 1990; Giunta, 1993; Beccaluva et al., 1996, 1999; Meschede and Frisch, 1998; Giunta et al., 2002a, b, c, 2003a, b; Iturralde-Vinent, 1998, 2003; Kerr et al., 2003; James, 2003; Pindell, 2003). Major uncertainties concern the Jurassic-Early Cretaceous paleogeography of the continental margins of the NOAM, SOAM and minor blocks and their paleo-tectonic relationships with the oceanic realm.

Some unsolved problems concern the mid-Cretaceous geodynamics, with respect to location and polarity of the intra-oceanic and sub-continental subductions, as well as the involvement of island arc and continental crust fragments in the subduction. This difficulty arises from both insufficient geological data and the extensive obliteration of the structural and tectonic features by the subsequent deformational events. At least three models would fit the data, depending on the location of free-boundaries (e.g. strike-slip paleo-tectonic faults) that create different tectonic settings during the eo-Caribbean phase of subduction.

On the contrary, a general agreement exists that the Late Cretaceous-Present geodynamic evolution of the Caribbean plate have mainly been driven by the eastward movement of the Caribbean plateau (Colombia and Venezuela basins) with respect to the NOAM and SOAM plates along two wide east-west shear zones. These, in the proposed model, are supposed to be produced by the shifting of two opposite main triple-junctions.

In particular, similarities between the northern and southern Caribbean plate margins are: 1) the strike-slip fault systems that are active both in the north (e.g., Motagua-Polochic fault system in Guatemala), and in the south (El Pilar fault system in Venezuela); 2) in the present-day tectonic setting both margins are composed by terranes, bordered and displaced by strike-slip faults; 3) within northern and southern terranes, the tectonic units are often the result of the deformation of similar geotectonic elements, represented by rocks with the same tectono-magmatic features, as oceanic or back-arc, subduction, supra-subduction, magmatic arc, continental margin, foredeep, etc; and 4) the tectonic units within the deformed belts commonly overthrust, in a flower-like structure, the foredeep basins of the NOAM and SOAM continental margins, minor continental blocks (e.g., Chortis), as well as the deformed portions of the oceanic plateau (e.g., Los Muertos, southward of Hispaniola, and Colombia-Venezuela accretionary prisms).

Significant differences in the evolution of the northern and southern Caribbean margins are also recognized, as for instance, the non-uniform distribution of Late Cretaceous magmatism. In the northern marginal belt, from Guatemala to Puerto Rico, Late Cretaceous tonalitic arc magmatism intruded active accretionary complexes, composed by deformed and metamorphosed units of oceanic, island arc and continental origin (e.g., in Guatemala, Cuba, Hispaniola, and Puerto Rico). By contrast, in the southern margin the deformed belt (Venezuela) was decoupled (perhaps due to a strong clockwise rotation of the mid-Cretaceous accretionary complexes toward the south), and subsequently the Late Cretaceous tonalitic magmatism is recorded only in the Dutch-Venezuelan Island oceanic plateau and subordinately in the Caucagua-El Tinaco units of the Margarita Island. This distribution of the magmatism indicates that, during the Late Cretaceous, the previous subduction and accretionary complexes were variably located with respect to the active northern and southern Caribbean margins, in relation to the west-dipping subduction zones which produced the tonalitic arc magmatism.

The evolutionary model proposed in this paper lacks unequivocal interpretation. Acquisition of more detailed multidisciplinary data and their careful integration on a regional scale are therefore needed to achieve major advances in the reconstruction of the Caribbean Plate geodynamics, from its early generation to subduction and collisional processes.

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