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The Caribbean Plate Evolution: Trying to Resolve a Very Complicated Tectonic Puzzle

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1. Introduction

The Caribbean Plate is an independent lithospheric element of more than 4 Mkm2, characterized today by the un-deformed or less deformed Cretaceous oceanic plateau of Colombia and Venezuela Basins (almost 1 Mkm2), and the Palaeozoic-Mesozoic Chortis continental block (about 700,000 km2), both bounded by deformed marginal belts (about 2,3 Mkm2), resulting from the Mesozoic to Present interactions with the adjacent Nazca, Cocos, and Americas Plates (Fig.1).

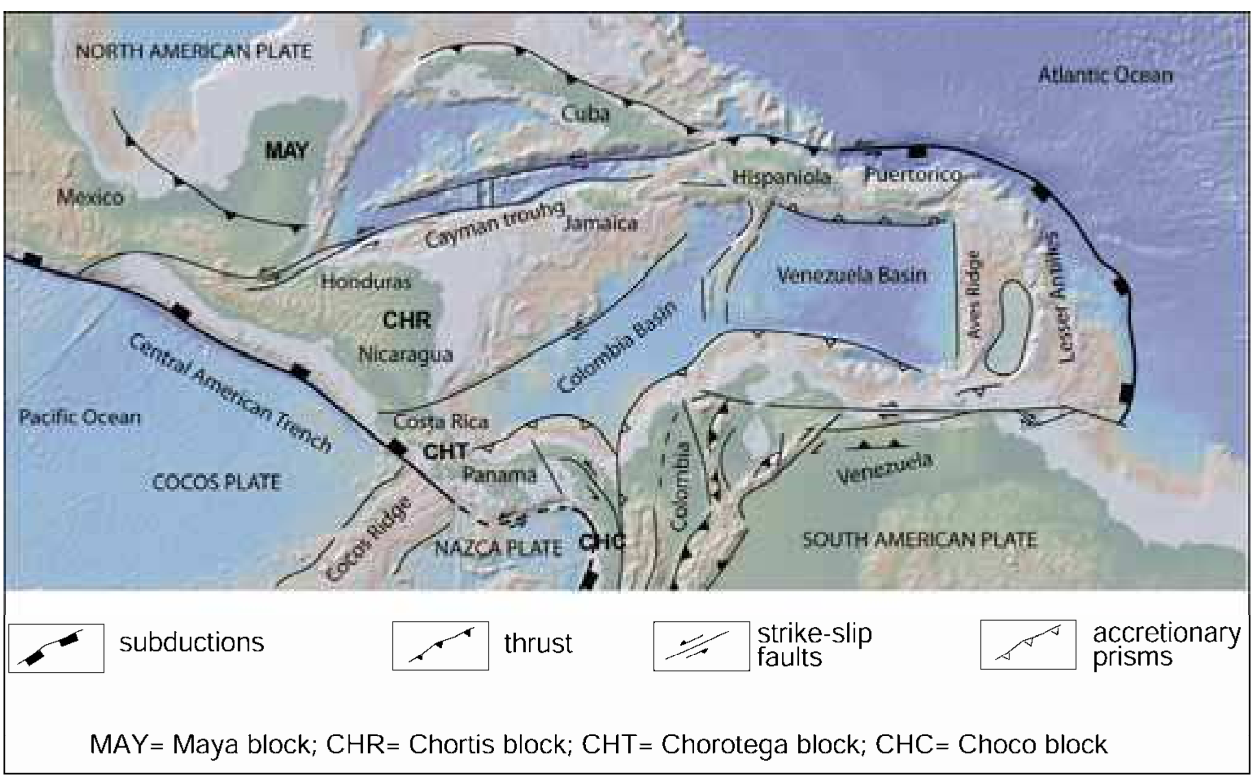


Fig. 1. Tectonic sketch map of the Caribbean area

The crustal thickness of the Caribbean Plate varies from, 6-8 km, west of the Beata Ridge, to 20 km between the Central Venezuelan and the western part of the Beata Ridge until, 3-5 km in the southeast of the Venezuela Basin (Diebold & Driscoll, 1999). The crust varies also in thickness from Yucatán Basin (8-9 km, Hall 1995) to Colombian and Grenada Basins. The thickness of the marginal belts ranges from 10 - 22 km to 18 km (Case et al., 1990).

The Caribbean lithosphere has been deformed and tectonically emplaced over the Pacific and Atlantic oceanic crusts producing the western and eastern arc systems of the Central American Isthmus and Lesser Antilles. It has also been squeezed against the North and South American continental crusts, thereby originating suture zones in the Cordilleras of Guatemala, Greater Antilles and Venezuela. More internal Caribbean marginal areas in Venezuela, Colombia, Panama and Hispaniola are shortened forming "accretionary prisms" with a centripetal vergence (Stephan et al., 1986).

Bivergent "flower structures" exist along the northern and southern Caribbean margins where diachronous oblique movements have occurred from the Cretaceous until present time. The active northern (Guatemala and Greater Antilles) and southern (northern Venezuela) plate margins are mainly made by deformed terranes in shear zones bounded by east-west trending sinistral and dextral strike-slip faults respectively. The western (Central America Isthmus) and eastern (Lesser Antilles) are represented by convergent systems and related magmatic arcs. The Caribbean marginal belts are the product of complex interaction between several first-order geotectonic elements, characterized by different tectono-magmatic features and originated in different paleo-domains, that now lie fragmented and dispersed along the margins. The paleo-domains include continental margins, rifted continental margins, thin oceanic crust, oceanic plateau, intra-oceanic and sub-continental subduction zones and foredeep basins.

The interaction between portions of these domains produced the present-day settlement of the plate, recording same important compressional episodes, beginning in the Cretaceous, followed by tensional and/ or strike-slip tectonics; the reconstruction of the evolution of which encounters several problems mainly related to unresolved facts (Giunta & Oliveri, 2009).

2. The Caribbean terranes

The Caribbean Plate margins include several terranes, in particular Jurassic-Cretaceous ophiolitic complexes, exposed along suture zones or as accreted terranes on the northern, southern and western sectors of the plate, and subordinately in the eastern one (Fig.2).

These terranes, bounded by regional strike-slipe faults, are made up by several tectonic units, which have been reconstructed in terms of tectono-stratigraphic evolution, and correlated at the plate scale.

The peri-Caribbean tectonic units and their numerous formations can be grouped into at least six litho-stratigraphic sections with similar lithologic characteristics but very different tectonic origins, mainly based on the petrologic data characterizing the geochemical affinities of the magmatic lithotypes (Fig.3.). Each unit corresponds to the litho-stratigraphic development of related geodynamic elements, characterizing different tectono-magmatic environments (Cobiella-Reguera, 2005; Giunta et al., 2002b; Lewis et al., 2002, 2006a, 2006b) as:

1. Mesozoic continental margins (Bahamas Platform, northern South America, the Maya and Chortis blocks of Central America, Guaniguanico in Cuba, Cordillera de la Costa in Venezuela), including a pre-Mesozoic basement;
2. rifted continental margins (Escambray in Cuba, Caucagua-El Tinaco and Tinaquillo in Venezuela) related to Jurassic-early Cretaceous tensional episodes which continued to affect the continental margins, characterized by Within Plate Tholeiitic (WPT) magmatism;

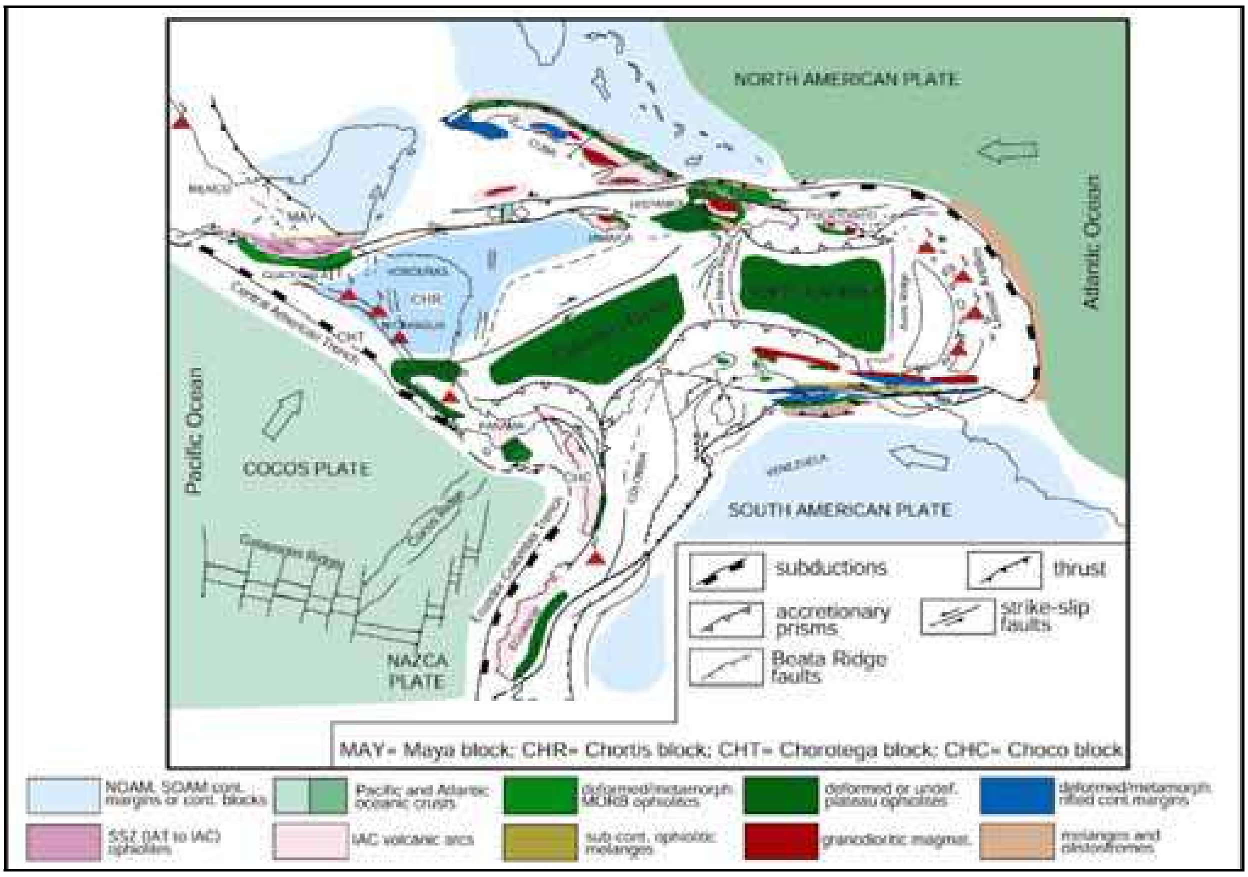


Fig. 2. Tectonic sketch map of the Caribbean area

3. Jurassic-Early Cretaceous oceanic crust, with Mid Ocean Ridge (MORB) 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, Mayarì-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 subductions, with formation of HP-LT metamorphosed ophiolitic melanges, including mafic blocks with MOR affinity (Franja Costera in Venezuela);

6. Late Cretaceous to Eocene Tonalitic Arc magmatism with calc-alkaline (CA) affinity (intruding: South Motagua in Guatemala, Mabujna and Cretaceous Arc in Cuba, Cordillera Central in Hispaniola, Dutch-Venezuelan islands and part of Caucagua-El Tinaco in Venezuela);
7. Late Cretaceous mélanges (Northern Ophiolite in Cuba, Northern Cordillera in Hispaniola), followed by Paleogene 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).

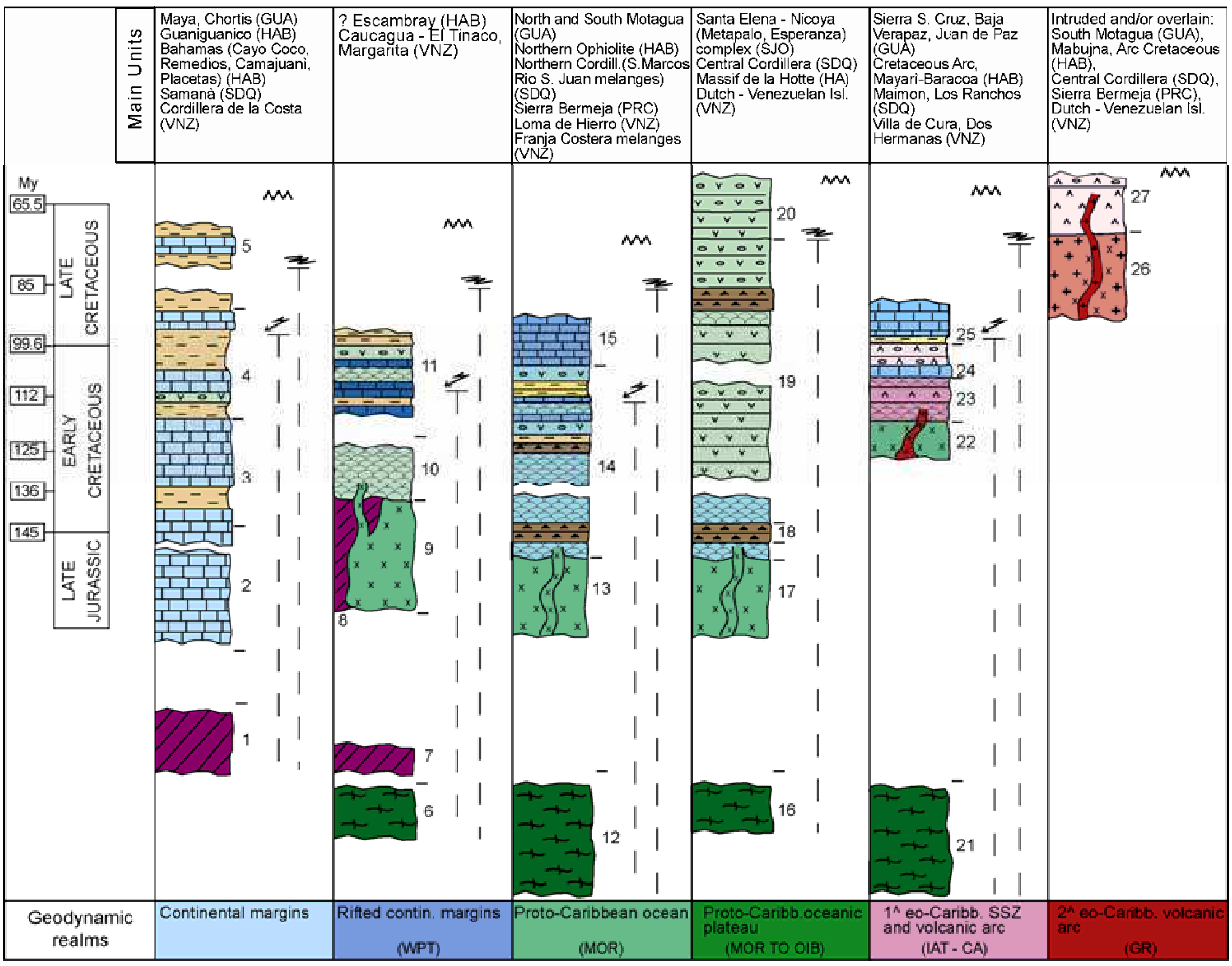


Fig. 3. Regional correlations between the main sedimentary, magmatic, metamorphic, and deformational events recorded in the peri-Caribbean terranes. Abbreviations: SJO, Costa Rica; GUA, Guatemala; HAB, Cuba; SDQ, Hispaniola; HA, Haiti; PRC, Puerto Rico; VNZ, Venezuela; WPT, within-plate tholeiite; MOR, 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 poligenic conglomerates; 3, Antimano (VNZ): metacalcarenites and marbles, with intercalations of amphibolites and metabasites; 4, Las Mercedes (VNZ): graphitic phyllites, metacalcarenites, with scarce intercalations of metabasites; Chuspita (VNZ): meta-arenites, metasiltites and metaconglomerates, 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, phillites, metaconglomerates 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): metalimestones and metasiltites with basaltic pillow lavas. Proto-Caribbean ocean: 12, Gaspar Hernandez (SDQ), Monte del Estado (PRC): serpentinized peridotites; 13, Cuaba (SDQ), Rio Mesia (VNZ): layered metagabbros; 14, El Tambor group (GUA), Punta Balandra (SDQ), Sierra Bermeja (PRC), Tiara (VNZ): metasiltites, meta-arenites, metacalcarenites, with intercalations of basaltic (flows or pillow lavas) and radiolarian cherts; 15, Cerro de la Virgen (GUA): metacalcarenites and metacalcasiltites with breccia and siltitic intercalations. Proto-Caribbean oceanic plateau: 16, Loma Caribe (SDQ): serpentinized peridotites; 17, Potrero (SJO): gabbro cumulates, Fe-gabbros, Fe-diorites and subordinate plagiogranites; 18, Punta Conchal (SJO): radiolarites intercalated in pillow and massive basalts; 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, serpentinized peridotites; 22, layered gabbros with scattered intrusions of granites; Chacao complex 21 þ 22 (VNZ), Mayarı` 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 carbonatic breccias.
= HP-LT (blueschist to eclogite facies) subduction related metamorphism and ductile deformation;
= greenschist to amphibolite facies metamorphism and ductile deformation;
= ductile deformation.

The present-day tectonic characters of the plate margins are shown in the cartoon cross-section of the Fig. 4, where the Caribbean Plateau (Colombia and Venezuela Basins) obduces the Atlantic and Pacific crusts, along the Barbados accretionary prism and Central America trench respectively, and is collided against the North and South America continental crusts with the intermediate of some ophiolitic terranes, along left-lateral and right-lateral fault aligneament respectively.

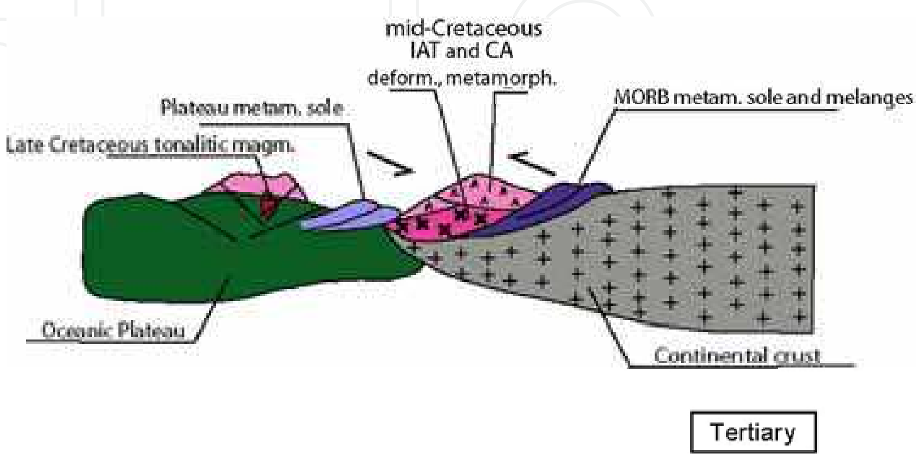


Fig. 4. Generalized cross-section of the peri-Caribbean collisional belts (Late Cretaceous-Paleogene)

3. Origin, growth and evolution

The correlations of above mentioned main units involved in the Caribbean terranes showing different characteristics, point-up some important times related to origin, growth and evolution of the Plate, which represent the fundamental constraints for elaborate any evolutionary model.

Triassic-Early Jurassic (250-180 My)

The Pangea breakup and related split of South and North American, Maya and Chortis plates or blocks, favoured rifting and tholeiitic magmatism (WPT), along extensional faults cutting the continental crust, corresponding to the inferred continental margins units.

Jurassic - Early Cretaceous (180- 130 My)

Mid-Ocean Ridge (MOR) oceanic crust formed at multiple spreading centres during the Jurassic and Early Cretaceous, forming the "proto-Caribbean" ocean, corresponding to ocean floor units.

Cretaceous

During the Cretaceous, parts of the oceanic crustal domain thickened, forming an oceanic plateau structure, of petrologic MOR to Ocean Island Basalt (OIB) affinity, represented by the oceanic plateau units.

Early Cretaceous – Late Cretaceous (130 -65 My)

Several lines of geological evidence, as relict HP-LT distribution, record the occurrence of different subduction complexes (eo-Caribbean stages), both intra-oceanic (IAT and CA arc magmatism associated to SSZ) and/or sub-continental (mélanges), maybe coupled with trapped or back-arc oceanic crust. In both mid- (120-95 My) and Late Cretaceous (85-70 My) peaks of IAT and CA arc magmatism associated with the SSZ occurred in the eo-Caribbean accretionary stage, which has been separated in 1^ and 2^ eo-Caribbean phases of subduction.

Early-mid Cretaceous (115-95 My) and Late Cretaceous (85-65 My)

The beginning of the accretionary stage seems to have been diachronous, between 115 and 95 My (Escuder-Viruete & Pérez-Estaún 2006b; Giunta et al., 2003b; Smith et al., 1999), according to HP/LT assemblages related to ocean-ocean subduction and to ocean-continent subduction that locally reached eclogite facies, which demonstrate the early convergence in the Caribbean.

During the Cretaceous have been recognized two main SSZ related magmatism: the resulting double-arc magmatism is associated, the first (mid-Cretaceous), with subduction related to metamorphism; the second (Late Cretaceous) with subduction exhumation related to metamorphism. Both events occurred in the eo-Caribbean accretionary stage, which has been separated in 1^ and 2^ eo-Caribbean phases of subduction.

Widespread occurrences of blueschist and eclogite assemblages (García-Casco et al., 2006b; Rojas-Agramonte et al., 2006a) 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.

The older volcanic arc presents an atypical evolution: in fact the mid-Cretaceous island-arc system was frequently deeply subducted and affected by blueschist facies metamorphism. In general, supra-subduction zone units obduct onto continental margins and only locally become involved in the deep part of the subduction complex; in these cases an unusual geodynamic evolution must be supposed.

Contrasts in the P-T paths of various HP-LT metamorphic units (Garcia-Casco et al., 2006a; Sisson et al., 1997) probably indicate that converging zones were subdivided into different sectors, characterized by different tectonic settings, during the mid-Cretaceous. This may be reflecting a more realistic issue on the physical parameters of the subduction zones, that should show a variable thermobaric structure. According to Giunta et al. (2003a and references therein), some eclogites and blueschists followed an “Alpine-type” retrograde trajectory, suggesting that shut-off of the 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.

In the Late Cretaceous, the distribution of the second calcalkaline magmatic arc, mainly tonalitic, seems to be diachronously connected to the Aves-Lesser Antilles arc system since 85 My. Differences in the northern and southern Caribbean margins are noted. 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 some rifted continental margin units.

On the base of the available data the evolution of the Caribbean Plate followed some steps (Fig.5), as:

- proto- Carribean event: oceanic spreading and plume events;
- 1° eo-Caribbean phase of subduction: volcano-plutonic sequence with IAT or CA affinities, in places affected by HP-LT metamorphism;
- 2° eo-Caribbean phase of subduction: un-metamorphosed tonalitic arc magmatism, ranging from gabbroid to granitoid intrusives, and volcanics;
- Carribean phase: collisional event.

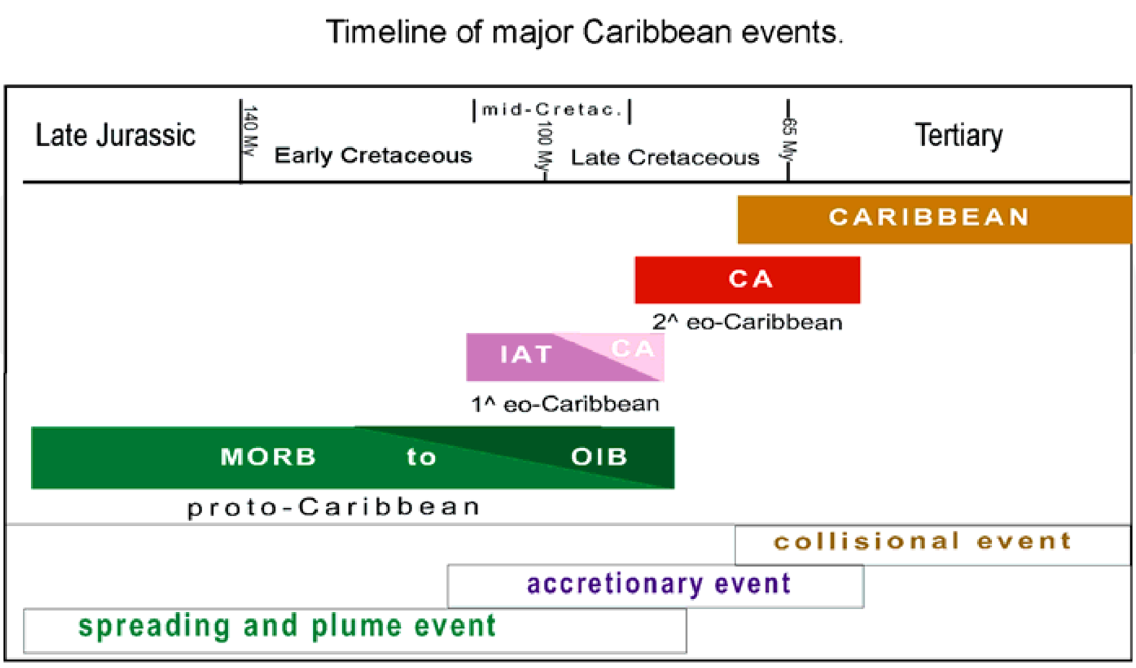


Fig. 5. Timeline of major Caribbean events. Abbreviations: MORB=Mid Ocean Ridge; OIB=Ocean Islands Basalt; IAT=Island Arc Tholeiite; CA=Island Arc Calcalkaline

4. Discussion on the evolution of the Caribbean Plate

The acquired facts and the open problems are necessary leading whatever discussion on the Caribbean puzzle reconstruction.
From the Jurassic-Early Cretaceous until the Present times, the Plate evolution was realized through spreading or plume, 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 (LIP).
We describe the main steps of the Caribbean Plate evolutionary history, stressing much more the unresolved problems than the acquired ones.

proto-Caribbean event

The proto-Caribbean oceanization has been realized through three steps, as the rifting of continental margins, the oceanization "strictu sensu", and the oceanic plateau thickening.
Firstly, the South and North American continental plates developed rifting and tholeiitic magmatism, which created space for the "proto-Caribbean" oceanic domain.
The oceanic crust was generated at multiple spreading centres during the Jurassic and Early Cretaceous, forming the "proto-Caribbean" ocean. 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 (Fig.6).
Starting from Jurassic, tensional and transtensional stress-fields related to the central Atlantic opening and induced by separation of the North (NOAM) and the South (SOAM) American Plates, produced several spreading centers, offset by transform faults, developed in mid-American areas, leading to a proto-Caribbean oceanic realm between the Central Atlantic and Pacific Farallon Plate. Its accretion was initially related to multiple spreading centres (LREE-depleted MORB, in Venezuela, Costa Rica, Cuba, Guatemala, Hispaniola), evolving during the Cretaceous to a thickened oceanic plateau in its westernmost ending (REE-flat MORB locally associated with picrites, in Costa Rica, Hispaniola, Venezuela, Dutch and Venezuelan Islands). Geological evidences from Guatemala, Cuba, Hispaniola, and Venezuela strongly suggest a spatial continuity of this oceanic domain with the Bahamas, Maya and Chortis continental margins to the north, and the Guayana shield to the south, through rifted continental margins with WPT magmatism inferred in both the northern and southern peri-Caribbean belts. How many ophiolitic units can be referred to the unthickned oceanic proto Caribbean crust is difficult to establish because several data suggest that some units should better fit an intra- or back-arc supra-subduction (SSZ) origin. In any case, the near American point of view already put forward by several authors (Beccaluva et al., 1996; 1999; Meschede & Frisch, 1998; Giunta, 1993; Giunta et al., 2002 a, 2002b), is therefore favoured with respect to the classic hypothesis of the Caribbean Plate as a "Pacific promontory" (Burke, 1988; Draper & Pindell 2006; Duncan & Hargrave, 1984; Maresch et al., 2009; Pindell & Barrett, 1990; Pindell 2003; Stanek & Maresch 2006, 2009) (Fig.7).
In order to compare the various models of the literature (James, 2009 and references therein; lavori vari), some problems need a better resolution for this tectonic phase:

1. Original location of the proto-Caribbean: three models are possible as (i) Pacific origin; (ii) in situ origin; (iii) near mid-American origin. The most accepted Pacific origin

sometime implies a very far original location from Central America, opposite to the in situ model which considers the proto-Caribbean ocean formed in the same place of today. In the palaeo-geographic reconstruction results almost clearly that the proto-Caribbean represented a by-pass between Atlantic and Pacific Jurassic oceans, then the near mid-American location seems to be the best choose resolving this problem, even if their growth steps and size are poorly known.

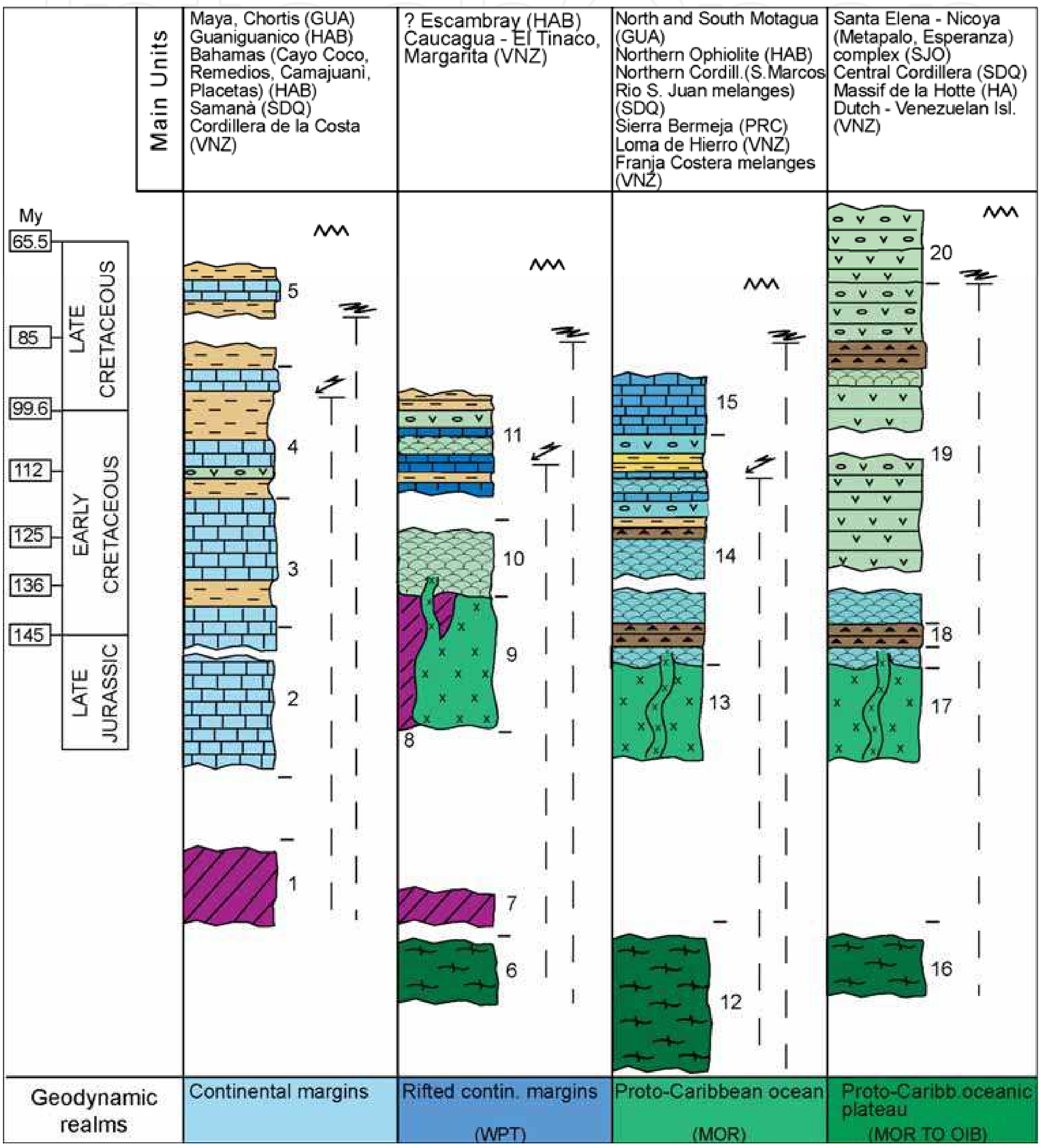


Fig. 6. Main units related to continental margin, rifted continental margin (WPT), Proto-Caribbean ocean (MOR) and Proto-Caribbean ocean plateau (MOR to OIB). For more details and captions see also fig.3

2. From the above mentioned controversy derives the problem of the real extension of the proto-Caribbean realm; being impossible to restore the volume of the subduced oceanic lithosphere.
3. The thickening of proto-Caribbean crust, of MOR oceanic to OIB plateau began later in the Late Jurassic (?) early Cretaceous by the repeated plume events. From the paleogeographic point of view the models differ particularly on the location of the thickening: - the "Pacific " model foresees the thin oceanic crust in a mid-American location connecting by rifting the Atlantic and Pacific ocean, whereas places the proto-Caribbean plateau far from it, offshore from the South America, thus separating both elements in term of space and time; - the in situ model considers that the thickening occurred all above the thin oceanic crust; - the near mid-American model, on the contrary, infers the thickening of the westernmost portion of the thin oceanic crust.
   In all cases it is not clear the original relationships between thin and thickened crusts. Even if all models agree to compare the proto-Caribbean plateau portion with Ontong-Java plateau of the western Pacific, the major discussion, depending from the location, concerns the significance of the term proto-Caribbean, because for examplein the "Pacific" model it would be only the plateau, located far from the central American regions.
4. An other important controversy concerns the physical original relationships between the proto-Caribbean and the continental margins. Even if the rifting of the continental margin, corresponding to some tectonic units, seems to be demonstrated it is not generally accepted, because several authors consider these units as oceanic and not as sub-continental. The last case places the possibility of the original location of the proto-Caribbean ocean very close to continental margin, then in a near mid-American location.

Subduction events

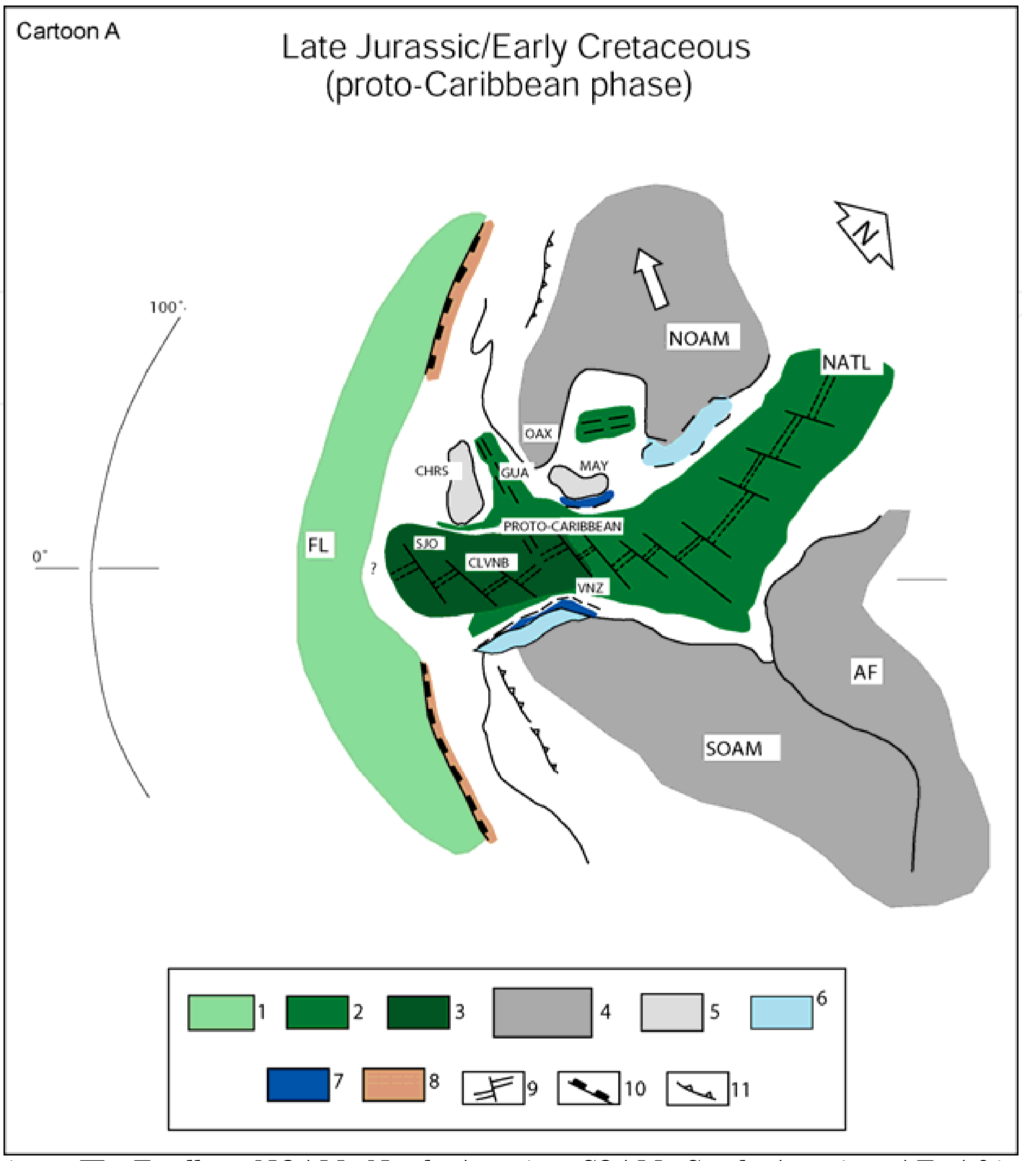
Petrological and tectonic regional correlations suggest that the "proto-Caribbean" crust was involved into two main stages of subduction, referred to as first and second "eo- Caribbean" stages of Giunta (1993).

These 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.

1^ "eo-Caribbean" phase

This period corresponds to the beginning of the compressional conditions in central America area characterized by intraoceanic subduction systems with associated IAT and CA arc magmatism, and in places sub-continental.

Starting from the Early Cretaceous, the South Atlantic opening and related westward and north-westward motion of the American plates led to ocean-ocean and ocean-continent intra/ or plate convergences, producing several SSZ and magmatic arcs. Remnants of magmatic arcs and subduction complexes are represented by mantle rocks, intrusives, and volcanic sequences (Giunta et al., 2002a, 2002b, 2002c, 2002d) 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 (Fig.8).



Abbreviations: FL: Farallon; NOAM: North America; SOAM: South America; AF: Africa; NATL: Northern Atlantic; OAX: Oaxaca; MAY: Maya; CHR: Chortis; SJO: Costa Rica; GUA: Guatemala; VNZ: Venezuela; CLVNB: Colombia and Venezuela Basins.

Fig. 7. Tentative paleogeografic reconstruction and kinematic evolution of the Caribbean Plate, from Late Jurassic to Early Cretaceous (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: Ophiolitic melanges (Franja Costera unit, in Venezuela, and Pacific margins).
9: Oceanic spreading centers. 10: Subductions of the Farallon- Pacific oceanic lithosphere.
11: Main overthrust fronts

The involvement of the proto-Caribbean oceanic lithosphere in subduction zones is also demonstrated by the HP/LT metamorphosed units, outcropping in the peri-Caribbean terranes, related to an ocean-ocean subduction or subordinately to an ocean-continent subduction. Moreover, portions of the previously rifted continental margins were also involved in the subduction zones, reaching in places the eclogite facies. On the whole, several geological evidences indicate the contemporaneous presence of two subduction settings developed in an intra-oceanic convergence the first and in a sub-continental setting the latter.

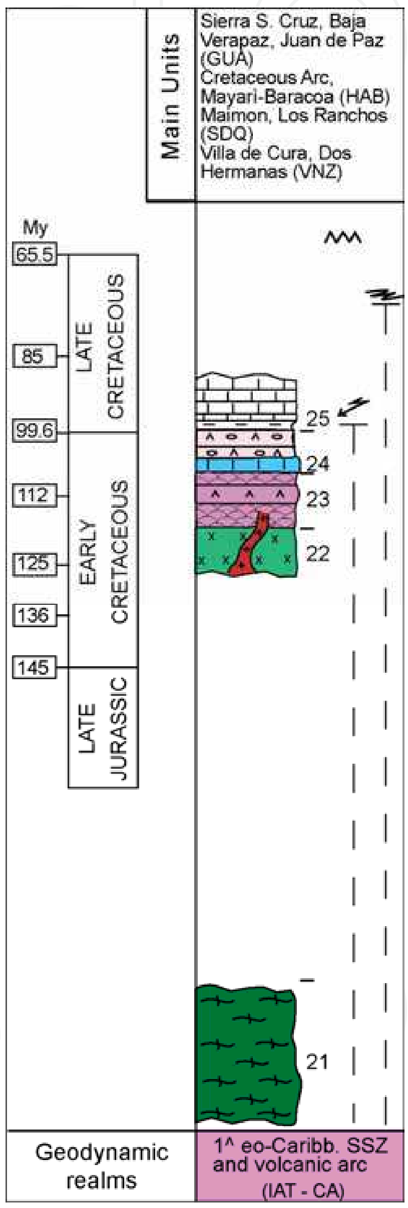
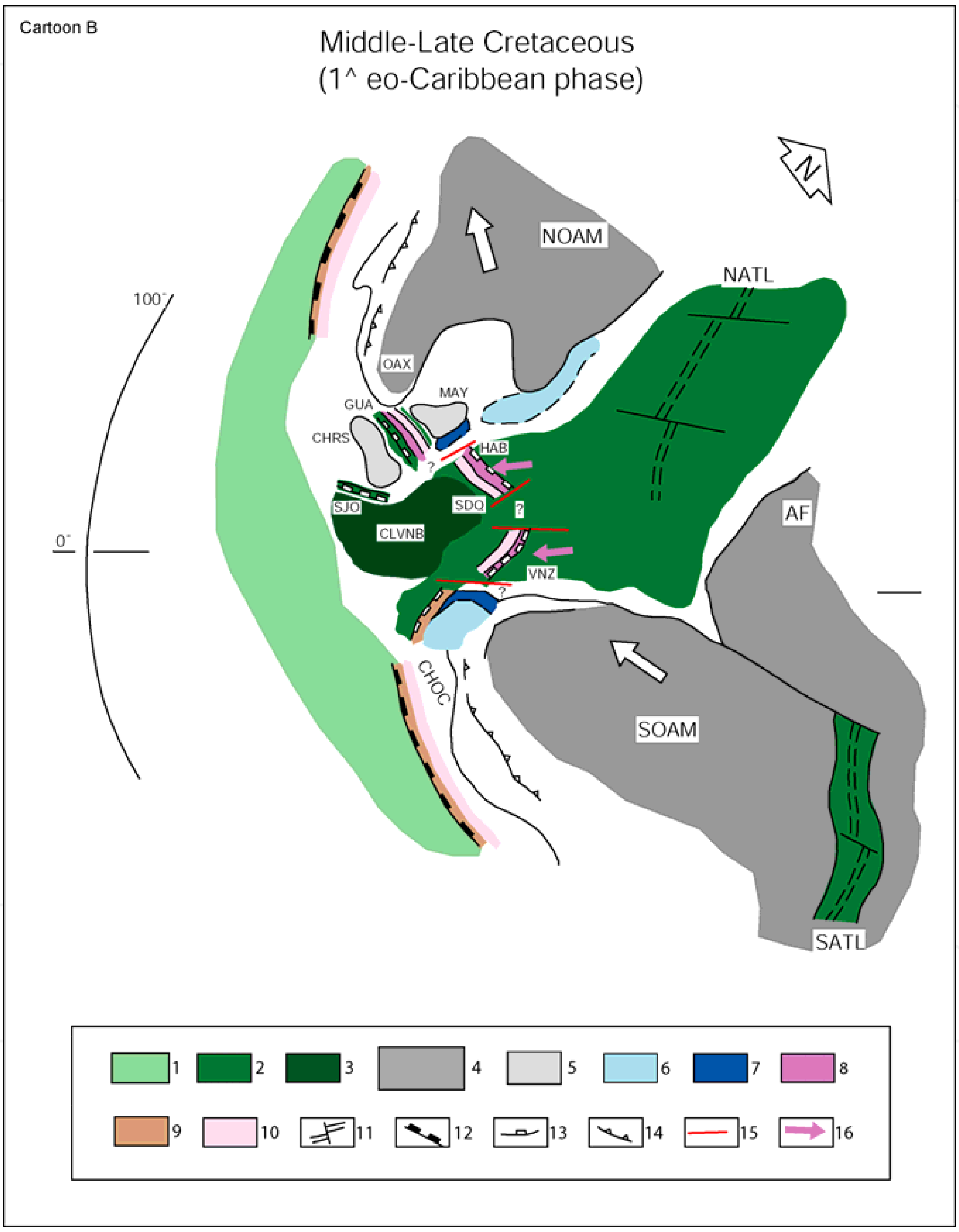


Fig. 8. Main units related to 1^ eo-Caribbean SSZ and volcanic arc (IAT to CA).). For more details and captions see also fig.3

The first "eo-Caribbean" phase reconstruction (Fig.9) encounters several problems, the solutions of which not sufficiently supported by the data, are object of the researches of the last years in particular: a) relationships between thin and thickened oceanic crusts; b) locations of either ocean-ocean or ocean-continent convergences; c) subduction directions of the oceanic slab, if eastward or westward; d) how many arc portions can be recognized, not well defined as one single arc; e) ocean floor or back-arc pertinence of the MOR-type ophiolitic units; f) both the volcanic arc complexes and thinned continental crusts involvement in subduction zones; g) no subduction related magmatism has been found in the sub-continental subduction.



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

Fig. 9. Tentative paleogeografic reconstruction and kinematic evolution of the Caribbean Plate, during middle- Late Cretaceous (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: Oceanic spreading centers. 12: Subductions of the Farallon- Pacific oceanic lithosphere. 13: Intra-oceanic subductions in the Caribbean area. 14: Main overthrust fronts. 15: free boundary. 16: subduction direction (problematic if eastward or westward)

Reviewing the different available models the convergence has the characteristics of an intra-oceanic subduction that is likely supposed to affect the eastern sector of the proto-Caribbean domain, where the thinner portions of the oceanic lithosphere were in more favorable conditions to be subducted, while at the same time the western sector was undergoing progressive crustal thickening, ultimately (Late Cretaceous) leading to a well defined oceanic plateau structure (Fig.10).

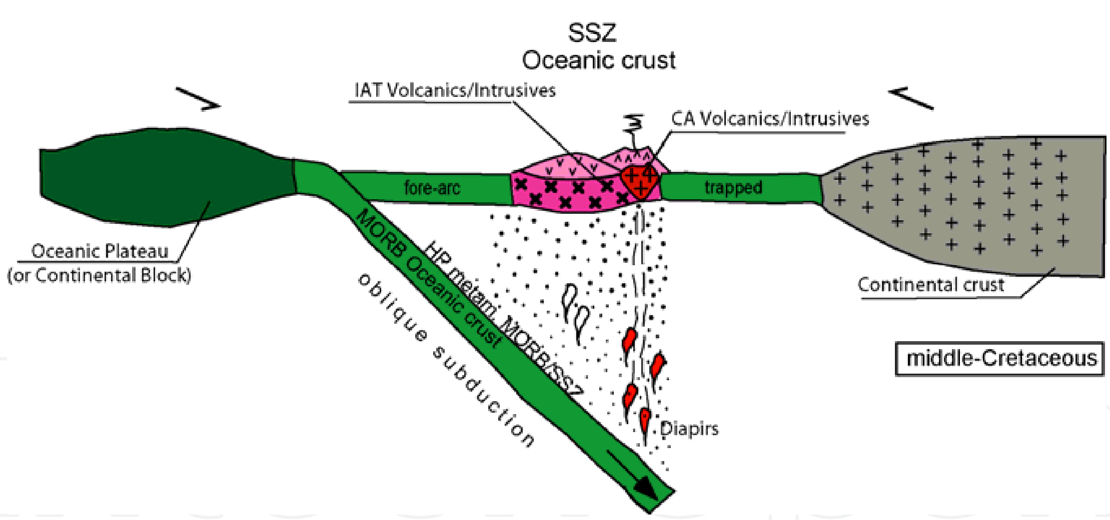


Fig. 10. Main units related to 2^ eo-Caribbean volcanic arc (GR). For more details see also fig.3

The location of these intra-oceanic convergence has been inferred either in intra-middle American area or within the eastern Pacific one, both able to produce cordilleran-like ophiolites and volcanic arcs, in turn involved in subduction zone, with the subduction direction of the slab either eastward or westward.
The consequences of these various scenarios could be firstly the onset and growth of the so-called Great Volcanic Arc and also its relationships with thickening oceanic plateau, if close to the subduction trench or far from it, as placed in the different models.
It is unlikely that the Great Volcanic Arc began its activity at that time, while at the moment there are several difficulties to connect the recognized portions of volcanic arc in a continues

one. From the palaeo-geographic point of view is also not clear the relationship between the ocean-ocean and the ocean-continent convergences in some areas, as for example the northern Venezuela: at least three models can be proposed, depending on some strike-slip faults playing as free boundaries between the different geodynamic environments differing from the strike-slip fault locations, dividing subduction areas with either opposite dipping directions or very complicated paleogeographical morphology.

Moreover, the metamorphism of the ophiolitic rocks demonstrates that it ranges until the eclogitic phases, in relatively fast span of time, also followed by the involvement in the subduction slab of portions of the volcanic arc and in places rifted continental margins both ranging eclogitic phases. HP-LT assemblages (blueschist and eclogitic) in both oceanic and continental lithospheres require a geodynamic model where these both oceanic and continental lithospheres have been deeply involved in the subduction zones. The development of HP-LT conditions in MORB-type units is commonly related to the subduction of dense oceanic lithosphere, in either sub-continental or intra-oceanic settings. The metamorphism of units that represent remnants of continental margin requires more complex subduction mechanisms (e.g., continental collision, tectonic erosion) that include underthrusting of more or less thinned continental crust. Moreover, the atypical evolution of the early volcanic arc should be resolved (tectonic erosion?), because some arc units (in Cuba and Venezuela) were deeply subducted and early affected by blueschist facies metamorphism. The supra subduction zone complexes generally obduce, floating and escaping from involvement in the deep part of the subduction slab; only a amphibolitic sole often develops in a narrow zone below the obducing, relatively hot, slab.

An other problem is the un-established pertinence of the MOR-type ophiolitics rocks if at an original ocean floor or back-arc systems which could help the solution of the problem of the subduction slab direction. The whole geological data confirm that the first “eo-Caribbean” accretionary stage ends in the Late Cretaceous, when the un-thickened oceanic crust was involved in subduction below the thicker oceanic plateau, with a likely westward sinking of the lithospheric slab corresponding with the more likely onset of the Great Volvanic Arcs system.

2^ “eo-Caribbean” phase

During the second eo-Caribbean stage, (Late Cretaceous) a new intraoceanic subduction took place, giving rise to (1) the widespread tonalitic arc magmatism of the northern and southern Caribbean plate margins (in Guatemala, Cuba, Hispaniola, Puerto Rico and Venezuela), (2) the HP/ LT and amphibolitic metamorphic effects in both the ophiolitic units and continental margins (Cuba, Hispaniola and Puerto Rico) (Fig.11), as well as (3) the onset of the Aves/ Lesser Antilles magmatic arc system, and the evolution of portions of magmatic arc facing the Middle American trench.

Since the Late Cretaceous, the kinematics of the Caribbean plate is closely related to the eastward drifting of the “proto-Caribbean” oceanic plateau (Colombia and Venezuela Basins), producing both the subduction of the oceanic lithosphere beneath the oceanic plateau and the previous magmatic arcs, and associated diachronous tonalitic magmatism.

This corresponds to the onset of the Aves - Lesser Antilles arc system, in the central part of the so-called Great Volcanic Arc, connected with a westward dipping strongly oblique subduction of the proto-Caribbean-Atlantic ocean floor below the plateau, and an opposite dismembering of subduction complexes of different ages along an E-W trend (north and south Caribbean margins) (Fig.12).

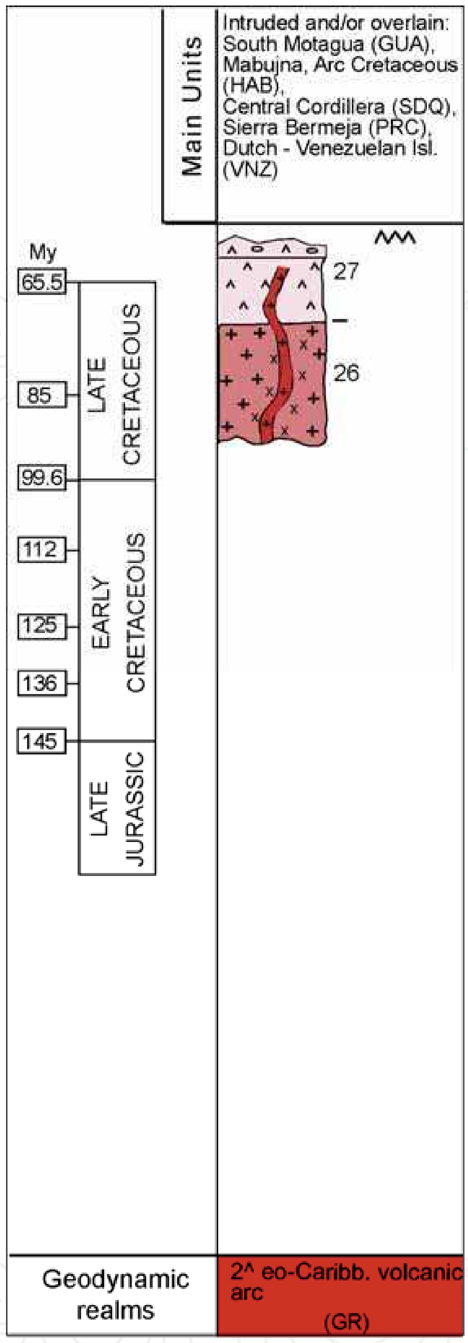
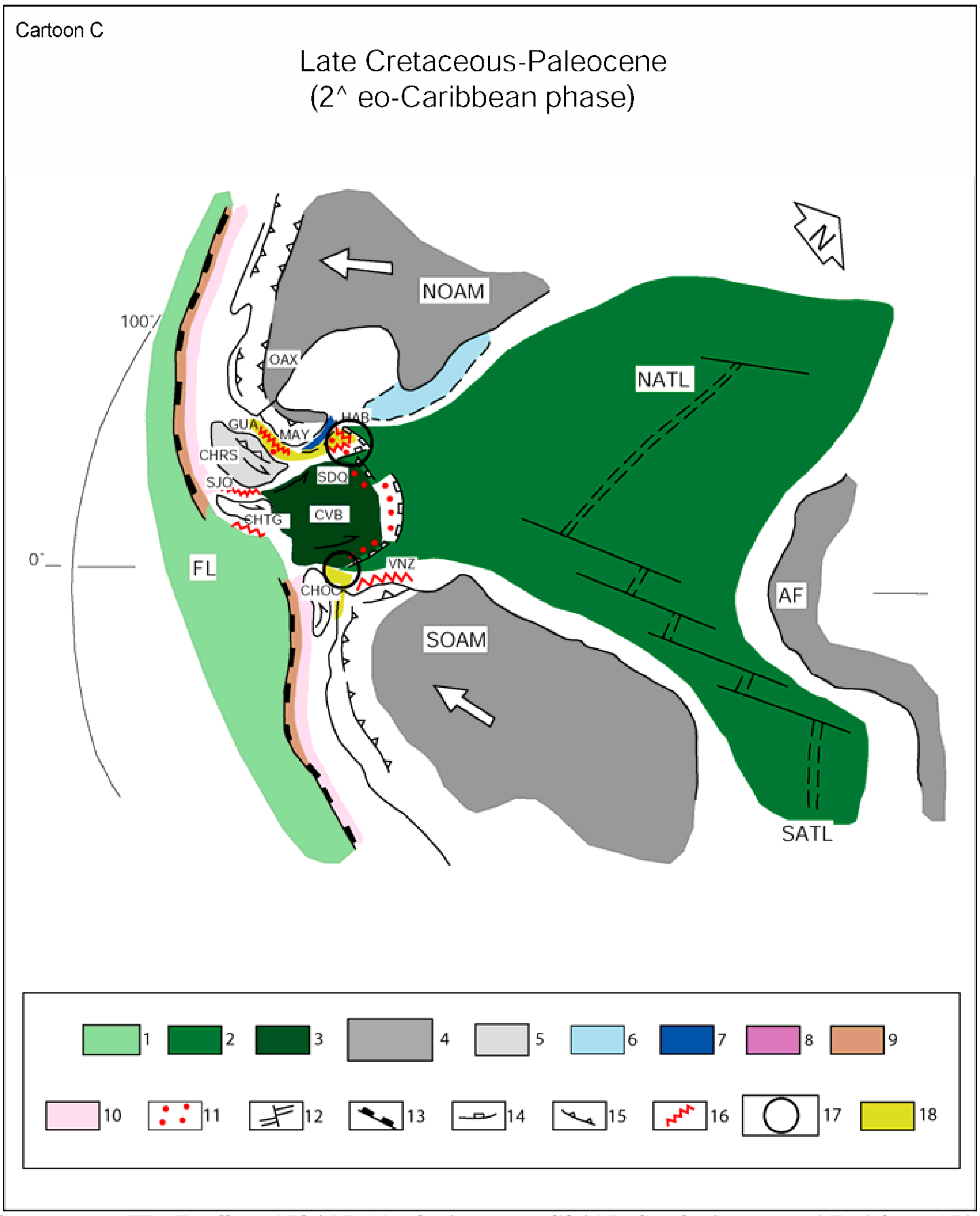


Fig. 11. Main units related to 2^ eo-Caribbean volcanic arc (GR). For more details and captions see also fig.3

This event corresponds to the onset of the Aves - Lesser Antilles arc system, in the central part of the so-called Great Volcanic Arc, connected with a westward dipping strongly oblique subduction of the proto-Caribbean-Atlantic ocean floor below the plateau, and an opposite dismembering of subduction complexes of different ages along an E-W trend (north and south Caribbean margins) (Fig.12)

A very detailed and more accepted reconstruction of the Late Cretaceous Caribbean evolution necessary gets thought the following main points: a) Timing of the plateau insertion and related subduction and collisional belts; b) Flip or no flip of subduction direction; c) Diachronism of granitoid magmatism; d) Metamorphism and exhumation; e)

Triple-points of junctions; f) Suture zones along collisional belts; g) Rotations of the mid-American blocks, along the Pacific subduction.



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.

Fig. 12. Tentative paleogeografic reconstruction and kinematic evolution of the Caribbean Plate, from Late Cretaceous to Paleocene (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

The age of the plateau drifting, likely related to the Late Cretaceous, has had the consequence of the onset of subduction of the proto-Caribbean thinner oceanic crust below the Caribbean plateau itself, presumably with the westward direction. In the interpreting model the first “eo-Caribbean” subduction eastward could be necessary a flip of subduction direction from the first to the second “eo-Caribbean” stage. The subduction system (Fig.13) connected with the Great Volcanic Arc has been realized in a very strong transpressional tectonic regime, more and more increasing from the central toward the ending of the arc, constraining also the collisional belts building from west to east.

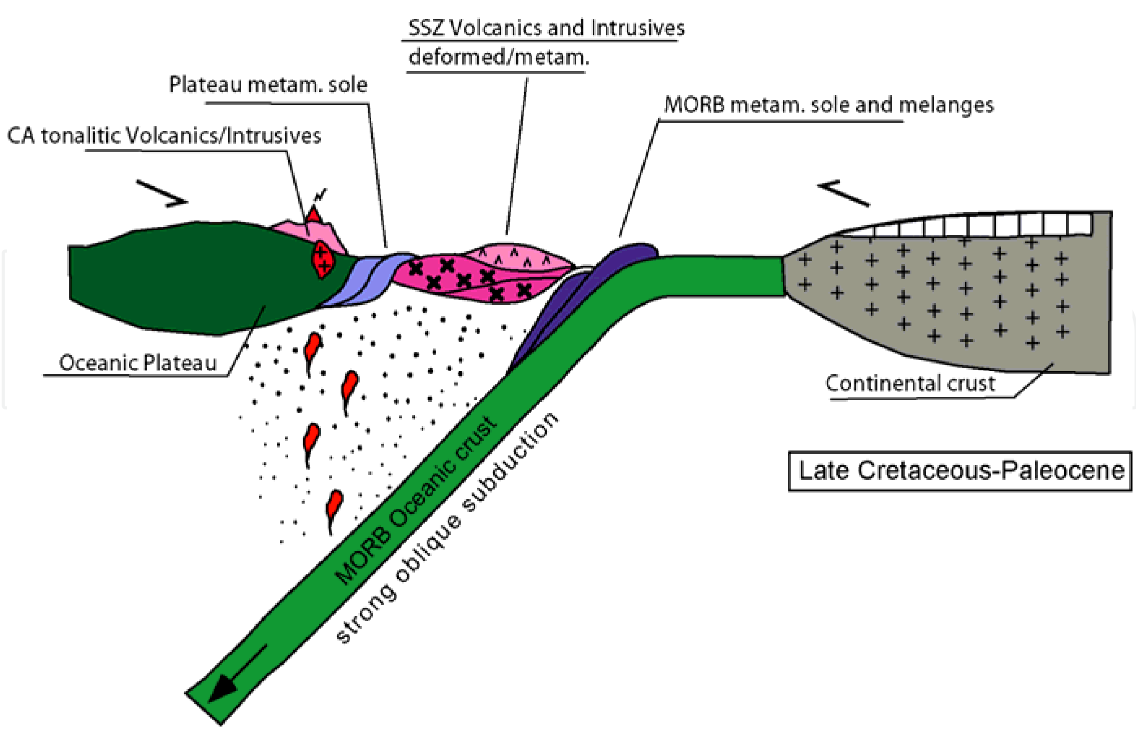


Fig. 13. Second eo-Caribbean phase (Late Cretaceous): generalized cross-section across the northern Caribbean accretionary system

The related metamorphism and deformation more or less fit in age and geometry this scenario, also constraining the exhumation of the metamorphic or poli-matamorphic units, followed by emplacement in the collisional belts forming very complex suture zones. In the peri-Caribbean metamorphic units are generally present two main deformation geometries, the first showing a syn-metamorphic foliation associated to a mineral lineation and rare rootless isoclinal fold; the second by a new well developed foliation and isoclinal folds acquired under retrograde metamorphic conditions. These geometries are followed by a widespread crenulation cleavage connected with open to tight folds, normally without important metamorphic imprint. At that time, several problems exist mainly related to the northern, southern and western plate margins as shown ahead. The present-day trending of the structural lineations suggests that displacement during early stage of the exhumation was high angle with respect to the subduction direction, as well as roughly parallel to the plate boundary between the Caribbean plate and both the NOAM and SOAM. Moreover, a complex decompression evolution is recorded in several HP/ LT metamorphic units; the deformation phases, developed under P-T retrograde conditions during exhumation, demonstrate that the uplifting was characterized by a well developed ductile geometries.

As above mentioned, the second "eo-Caribbean" phase has been strictly related to insertion in Central American area of the proto-Caribbean plateau producing the Great Volcanic Arc activity, running from north to south, including the Aves Lesser Antilles onset.

The model that shifting of the triple-points of junctions from west to east could be demonstrated, also by the diachronism of tonalitic and granodioritic plutonism, intruding the northern and southern plate margins.

Transpressional tectonics along the northern and southern margins of the Caribbean plate caused the lateral dispersion and opposite rotation (sinistral vs. dextral, respectively) of the older structural elements. This resulted in significant differences between the two margins. Along the northern margin the younger (tonalitic) magmatic arc generally rests on the deformed belt, which includes both the older arc systems and the eastward migrating front of the new accretionary wedges. The Paleocene-Eocene volcanic arc in eastern Cuba (Sierra Maestra) may be related with a second-order shifting of a triple-point of junction southeastward, while the Late Cretaceous arc connected to the northwestern one already collided against the NOAM, becoming inactive. Along the southern margins the tonalitic magmatism is decoupled from the older arc, being intruded in both undeformed and deformed oceanic plateau and in part in the rifted continental margin units.

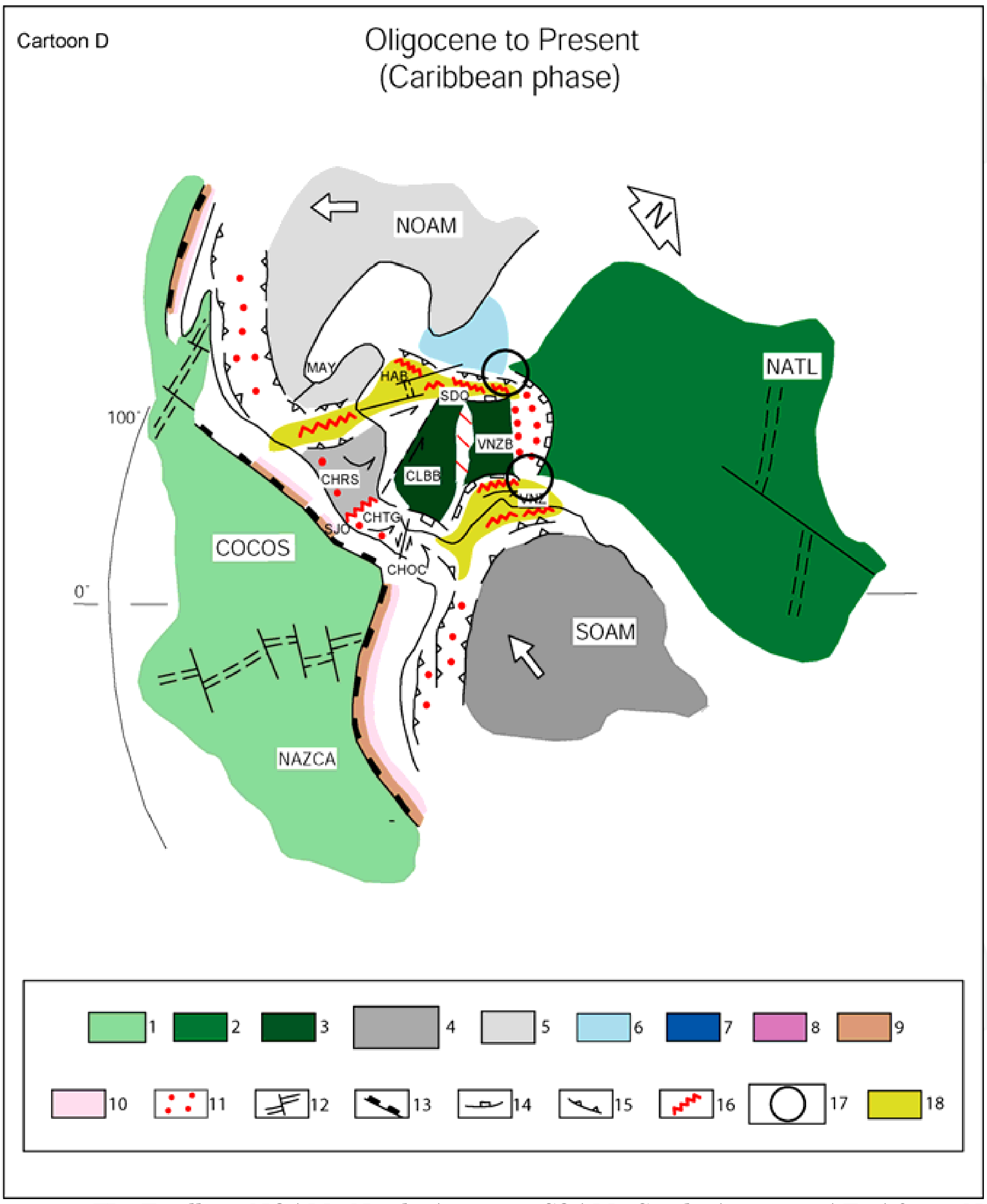
Moreover, the developing of the subduction of the Pacific crust below the Caribbean Plateau could have induced different rate rotations in the Central America blocks, more and more building the present-day arrangement, involving in accretionary wedges portion of the Caribbean Plateau, obducing westward and southwestward the Pacific crust.

The end of the eo-Caribbean accretionary phase is progressively older going westward marking the Late Cretaceous-Paleogene collision and/ or obduction of the proto- and eo-Caribbean ophiolitic units against or onto the NOAM and SOAM continental margins, as suture zones in flake and wedge geometry. These structural features can be explained in a strike-slip tectonic regime which has largely ruled the geodynamics of the Caribbean boundaries, controlling their evolution since at least the beginning of exhumation of the HP-LT units in the mid-Late Cretaceous.

Collisional event

The Late Cretaceous-to-Present geodynamics of the Caribbean plate has been mainly driven by the further eastward drift of the Caribbean plateau with respect to the North and South

America plates, with the consequence that it has been trapped in the Colombia and Venezuela basins by the intervening Atlantic and Pacific subductions and related volcanic arcs, producing eastward the Aves-Lesser Antilles arc, and westward the Central American Isthmus as a mosaic of different blocks reciprocally juxtaposed and facing the Middle American Trench (Fig.14).



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.

Fig. 14. Tentative paleogeografic reconstruction and kinematic evolution of the Caribbean Plate, from Oligocene to Present (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. 18: collisional belts

This seems to be the consequence of the eastward shifting of both northern and southern triple junctions, allowing to the progressive bending of the Aves- Lesser Antilles arc (Fig.15).

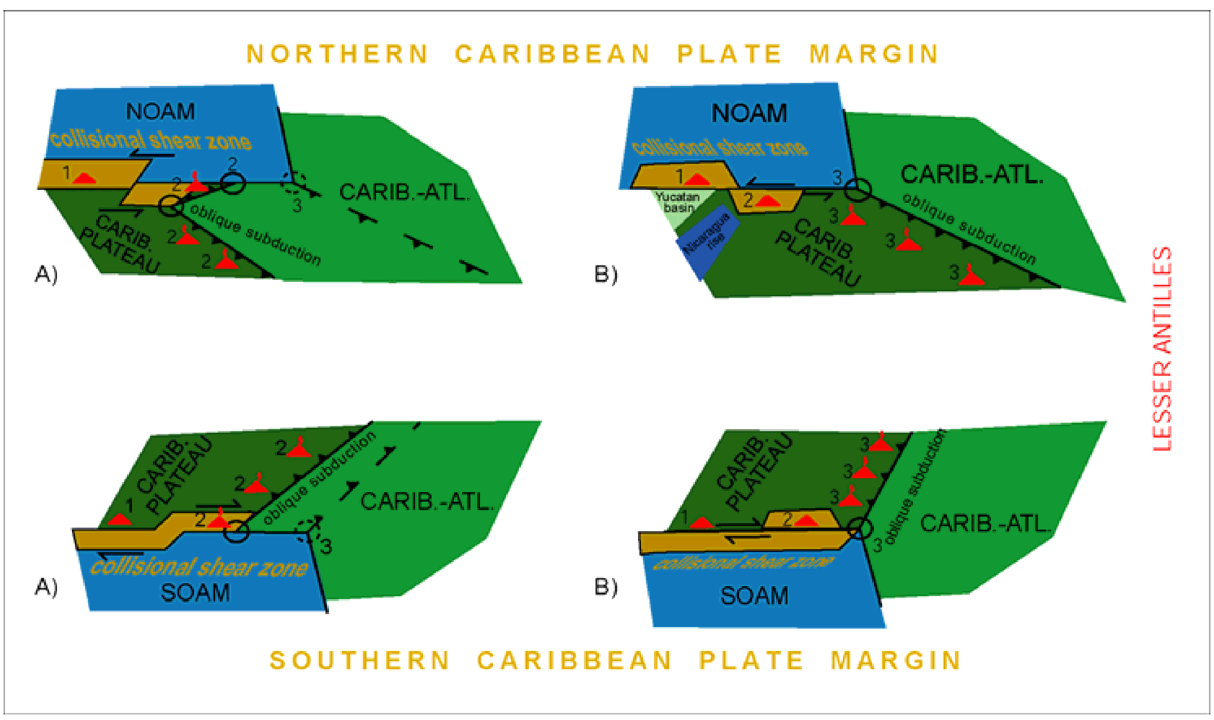


Fig. 15. Tentative evolutionary models for the northern and southern Caribbean Plate Margins since the Late Cretaceous, related to the eastward shifting of two triple-junctions (modified from Giunta et al., 2003a). The cartoons show the supposed evolution of both northern (upper part of the figure) and 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)

Westward, the Caribbean oceanic plateau was trapped by different rotation rates of the Chortis, Chorotega and Choco blocks during the construction of the western plate margin (Fig.16) (Central American Isthmus).
As a result, both the northern (Fig.17) and southern (Fig.18) boundaries of the Caribbean correspond, since the Late Cretaceous, to two wide shear zones, where, during Late Cretaceous-Tertiary, large-scale tear faulting, still extensively active and seismogenic (e.g., Motagua fault in Guatemala, El Pilar fault in Venezuela), favoured eastward dispersion and uplifting of the previous subduction accretion systems.

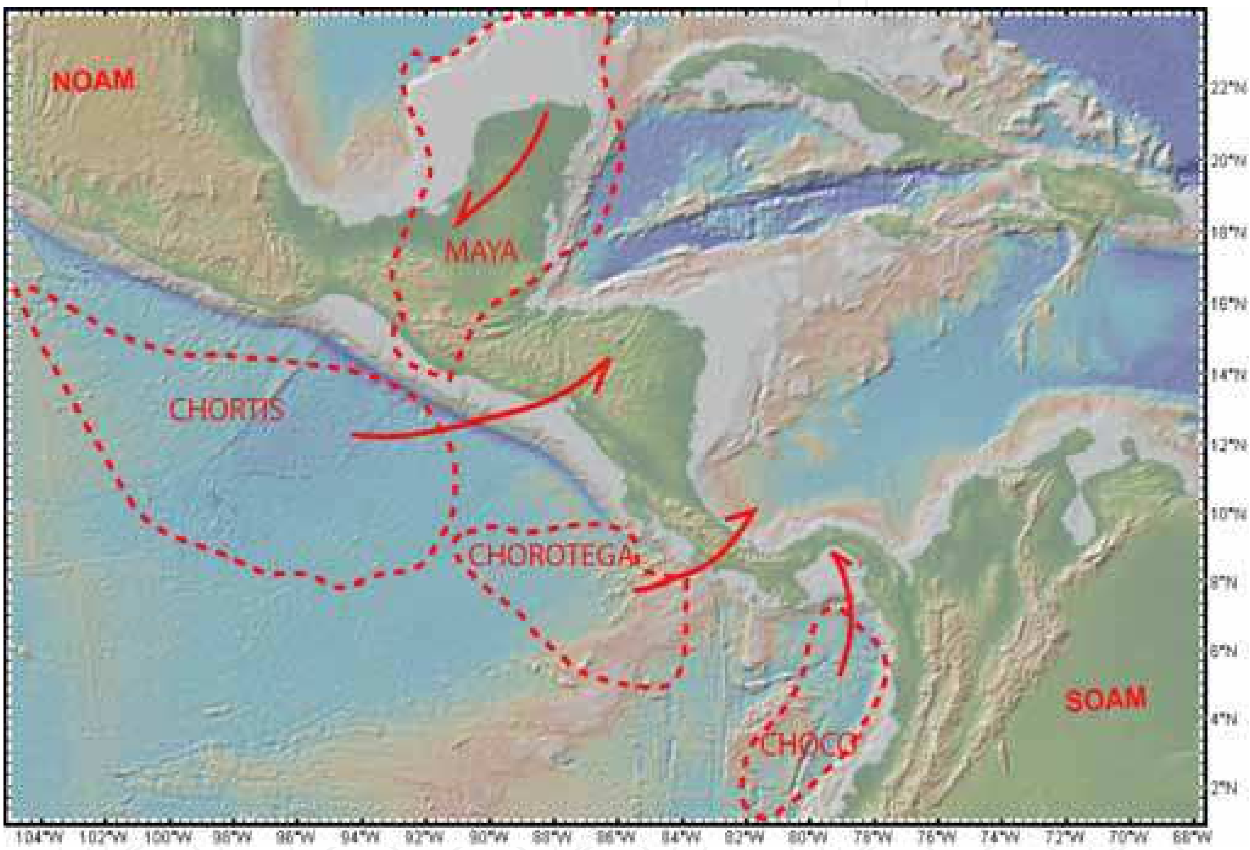


Fig. 16. Western boundaries of Caribbean

During the collisional events the main structural elements (terranes) of the present-day Caribbean were essentially established in the Paleocene onwards. Fore-or back-arc and piggy-back basins, on the deforming plate borders, were filled by clastic sediments and volcanoclastics. On the northern and southern continental margins, thrust belt-foredeep couples began to develop, involving previously deformed terranes along north- or south-verging fronts (Sepur Basin in Mexico-Guatemala; Foreland Basin in Cuba; Piemontine Basin in Venezuela).
The main controversy related to the collisional event are focused on the architecture of the deformed marginal belts, restoring then in a regional correlation way, especially through a detailed reconstruction of the deformation fronts evolution.

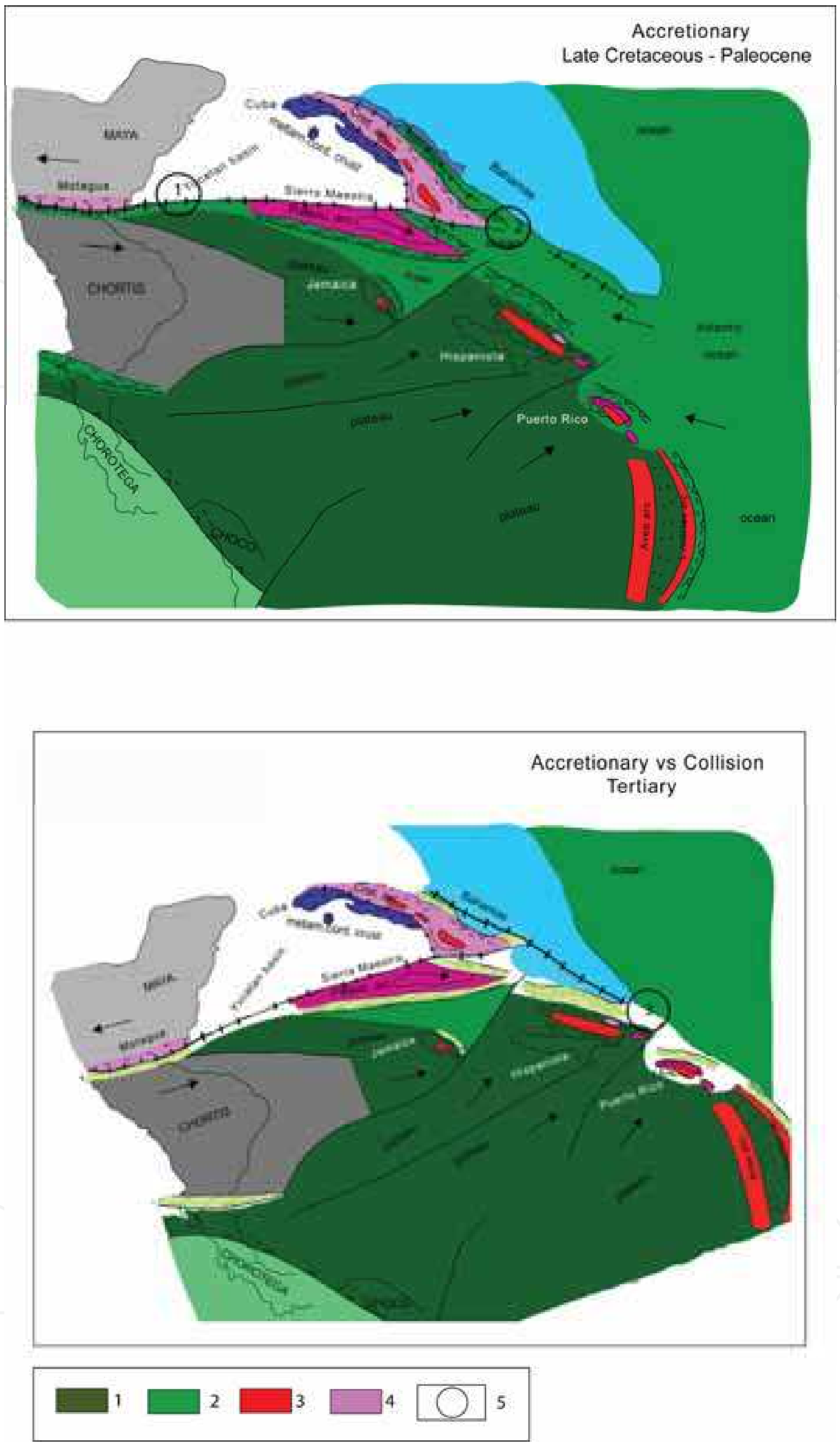
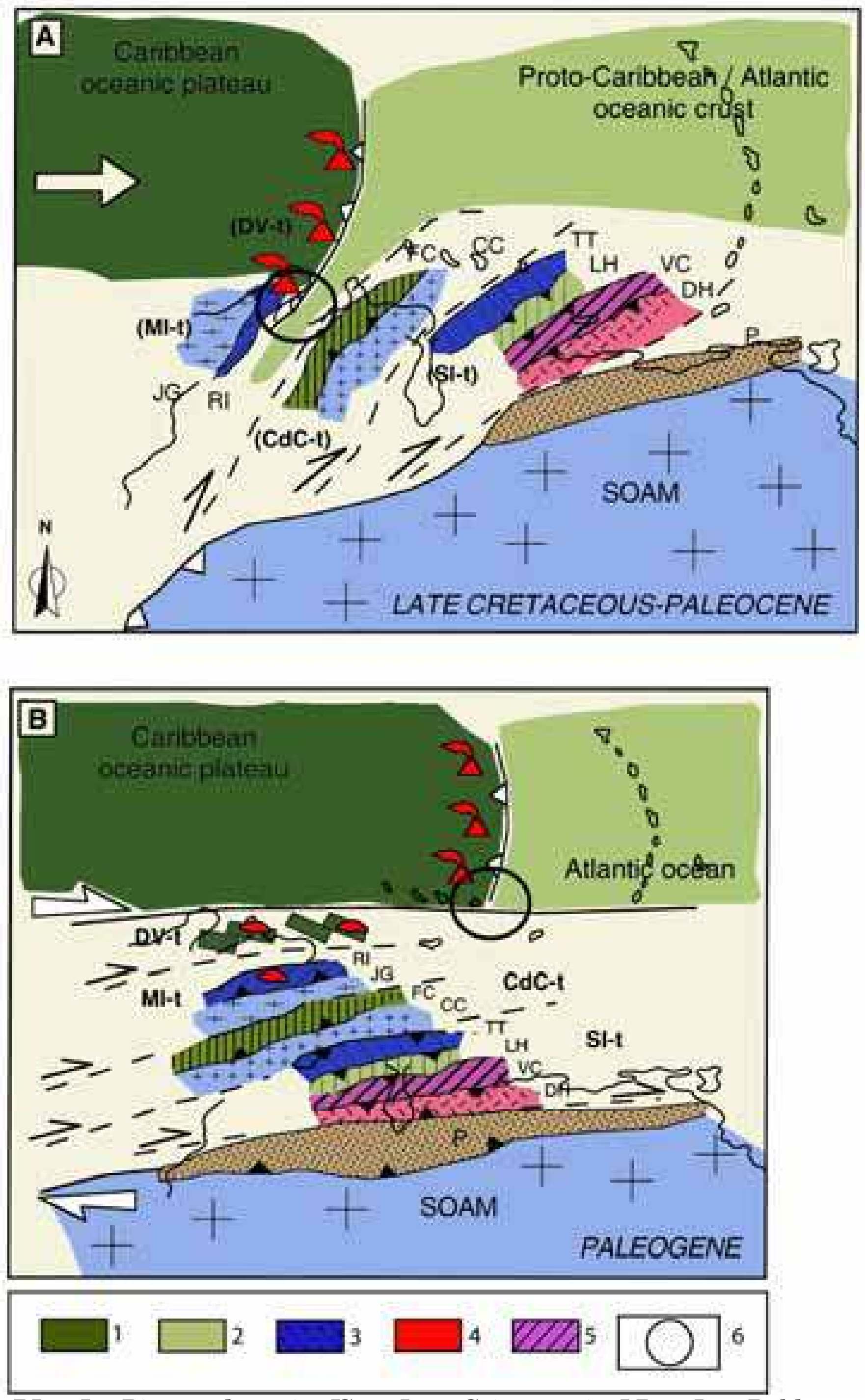


Fig. 17. Sketches illustrating the northern Caribbean plate margin reconstruction in (upper) the Late Cretaceous– Paleocene, and during (lower) the Tertiary. The diachronic tonalitic magmatic arc generally rests on both the older arc systems and the oceanic plateau, contemporaneously to the progressive north-eastward migration of the accretionary wedge front, followed from the west by suture zones related to triple junctions.
Numbers in legend: 1: Caribbean Oceanic plateau. 2: Accretionary wedge front.
3: Diachronic tonalitic magmatism arc. 4: Older arc systems. 5: Triple-junctions



Abbreviations: RI = La Rinconada unit; JG = Juan Griego unit; LR = Los Robles unit; FC = Franja Costera group; CC = Cordillera de la Costa group; TT = Caucagua–El Tinaco unit; LH = Loma de Hierro unit; VC = Villa de Cura unit; DH = Dos Hermanas unit; P = Piemontine Nappe; SOAM = South American plate.

Fig. 18. Sketches illustrating the southern Caribbean plate margin reconstruction in the (A) Late Cretaceous– Paleocene, and during (B) the Paleogene.
Numbers in legend: 1: Caribbean Oceanic plateau. 2: Proto-Caribbean-Atlantic oceanic crust. 3: Rifted continental margins. 4: Tonalitic magmatism arc. 5: Older arc systems. 6: Triple-junctions

5. Conclusion

At the moment, even if the acquired facts can be considered enough for an evolution outline, a lot of different order problems remain open or insufficiently explained, so that the related models seem to be far too speculative (Giunta & Oliveri, 2009).

However, we tried to resolve some of these problems; taking into account different possibilities based on the results of the discussions until today:

1. The original location of the proto-Caribbean oceanic realm; maybe by-pass between Atlantic and Pacific, as westward prosecution of the Tethyan ocean;
2. The Early Cretaceous paleogeography and morphology of the continental margins of NOAM, SOAM and minor blocks, as rifted continental margins close to the oceanic realm;
3. The number and location of magmatic arc events, maybe related to both 1^ eo-Caribbean (mid-Cretaceous), involving thin oceanic crust, and 2^ eo-Caribbean (Late Cretaceous), involving oceanic crust below the plateau;
4. The polarity of the Cretaceous subduction slabs, and possibility of subduction polarity reversal, can be resolved following two models, (i) Eastward in the 1^ eo-Caribb. and westward in the 2^ eo-Caribb., with flip of subduction polarity; or (ii) Westward in both the 1^ and 2^ eo-Caribb. phases;
5. The locations of and relationships between simultaneous intraoceanic and subcontinental subduction zones (1^ eo-Caribbean phase), could be resolved through different subduction sectors connected by free-boundaries;
6. The different characteristics of Supra Subduction Zones and volcanic arcs related to 1^ eo-Caribbean stage, including back-arcs or trapped crusts, and to 2^ eo-Caribbean stage in particularly in northern and southern margins;
7. The onset and growth of the so-called Great Volcanic Arc, if active since the Early-mid Cretaceous and coming from Pacific areas, or connected to the Late Cretaceous-Tertiary subduction (2° eo-Caribbean stage and collisional event), more and more bending eastward.
8. The progressive insertion in subduction of both rifted continental portions and suprasubduction complexes, probably induced by tectonic erosion related with strongly oblique subduction slabs;
9. The timing and characteristic of metamorphic deformation and exhumation: at the moment have been recognized differences of PT-t path in 1^ and 2^ eo-Caribbean phases even if associated with two ductile deformation related to the metamorphism and one or two related to exhumation, all in a strike-slip tectonic regime;
10. The evolution of the collisional belts (Late Cretaceous-Tertiary), almost resolved with two triple points of junction progressively shifting eastward, and increasing the strike-slip tectonics.
11. The relationships between Caribbean Plate and northern ending of the Andes, at the moment almost unknown, i.e. due to the different significance of the Romeral belt of Colombia (plateau or SSZ ?).

A number of these open-problems will be discussed in this paper, taking into account the recent researches and models, proposed in a multi-disciplinary point of view, in the aim to improve the knowledge of the Caribbean Plate tectonics.

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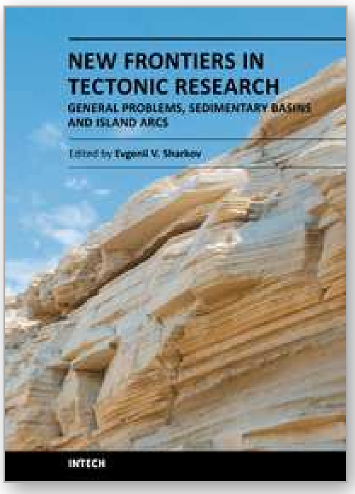

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This book is devoted to different aspects of tectonic research. Syntheses of recent and earlier works, combined with new results and interpretations, are presented in this book for diverse tectonic settings. Most of the chapters include up-to-date material of detailed geological investigations, often combined with geophysical data, which can help understand more clearly the essence of mechanisms of different tectonic processes. Some chapters are dedicated to general problems of tectonics. Another block of chapters is devoted to sedimentary basins and special attention in this book is given to tectonic processes on active plate margins.

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