Latest Cretaceous collision/accretion between the Caribbean Plate and Caribeana: Origin of metamorphic terranes in the Greater Antilles

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Abstract

Metasedimentary complexes dispersed all along the northwestern branch of the Caribbean orogenic belt between Yucatán and Virgin Islands provide evidence for a major tectonic event of latest Cretaceous (Late Campanian – Early Paleocene) age that played a key role in the evolution of the Caribbean realm. During the northeastward Cretaceous drift of the Caribbean Plate from the Pacific, the leading edge of the plate encountered a sedimentary prism that extended southeastward into the Proto-Caribbean realm from the southeastern edge of the Maya Block. Latest Cretaceous subduction of this Mesozoic sedimentary suite, dubbed here “Caribeana”, formed metamorphic complexes (i.e., East Yucatán, Cangre, Pinos, Escambray, Guayabal, Asunción, Samaná, and Puerto Rico Trench terranes). This latest Cretaceous subduction/accretion event triggered the interruption or attenuation of the activity of the Cretaceous volcanic arc and the tectonic emplacement of ophiolites and subduction channel complexes along the leading edge of the Caribbean Plate. Flat subduction of the Proto-Caribbean ensued during the Maastrichtian-Eocene in the western segment of the leading edge of the Caribbean plate, while normal-angle subduction and volcanic arc magmatism continued during the same time span in the eastern segment. The metamorphic complexes evolved differently since the Maastrichtian. As a consequence of the development of the Yucatan basin in the western part of the orogenic belt, the Pinos, Escambray, and probably the Guayabal terranes were exhumed in an intra-arc environment, while East Yucatan(?), Cangre, Asunción Samaná and Puerto Rico Trench terranes were exhumed in a fore-arc setting.

Introduction

TECTONIC UNITS OCCUR onshore and offshore Yucatan Peninsula, Cuba, Dominican Republic, Puerto Rico and the Virgin Islands that are composed of Jurassic-Cretaceous siliciclastic and carbonate sedimentary protoliths deposited in variable environments within the Proto-Caribbean ocean basin and/or its margins. The rocks were tectonically emplaced in the northern Caribbean orogenic belt during the latest Cretaceous to Eocene. Some of these units are not metamorphosed and formed in the original borderlands of the Bahamas (i.e., Placetas, Camajuaní, Remedios and Cayo Coco belts of northern central Cuba) and the Maya Block (Los Órganos and Rosario belts of western Cuba). However, other allochthonous terranes made of similar shallow to deeper marine sedimentary successions were metamorphosed to high-to-intermediate pressure and low-to-medium temperature conditions typical of subduction zones during the latest Cretaceous (e.g., Escambray and Samaná terranes of Cuba and Hispaniola, respectively). Explaining such a contrast in the metamorphism of sedimentary piles deposited in the Proto-Caribbean realm and accreted to the Antilles Arc is fundamental to understanding the plate tectonic evolution of the region.

Although the debate continues regarding the origin and evolution of the Caribbean realm (Iturralde-Vinent and Lidiak, 2006; Pindell et al., 2006), magmatic, metamorphic, sedimentary and tectonic events allow the plate tectonic evolution of the Caribbean to be constrained as follows (cf. Pindell et al., 2005): 1) Jurassic-latest Cretaceous development of the Proto-Caribbean oceanic basin between North and South American plates as a result of the break-up of Pangea and sea floor spreading, 2) Aptian initiation of southwest-dipping subduction of the Proto-Caribbean oceanic lithosphere below the Pacific Plate lithosphere that would become the Caribbean Plate, 3) latest Cretaceous-Present diachronous collision of the leading edge of the Caribbean Plate with the continental margins of North and South America, 4) Maastrichtian-Middle Eocene fragmentation of the northwestern Caribbean Plate and Late Eocene suturing of Cuba with the Bahamas; and 5) Eocene to Recent relative
eastward drift of the Caribbean Plate between the Americas. Here we review present evidence and demonstrate that a latest Cretaceous collision/accretion event represents a major transitory step in the evolution of the region that has never been recognized for all its implications. We will show that this event was triggered by the subduction and collision/accretion of a major submarine but buoyant feature of the Proto-Caribbean that we have dubbed “Caribeana” (Iturralde-Vinent and García-Casco, 2007).

Latest Cretaceous – Early Paleocene paleotectonic/paleogeographic setting of the Caribbean realm

It has long been known that collision of Caribbean lithosphere with the North American Plate took place during the latest Cretaceous in central Guatemala (southern Maya block). Some authors (e.g., Anderson et al., 1985; Donnelly et al., 1990) consider that this collision occurred between the Chortis and Maya blocks, but the oceanic nature of the obducted forearc rocks in the suture zone (e.g., El Tambor and Santa Cruz complexes) has caused others to consider that the collision occurred between an intra-oceanic arc and the Maya Block (Pindell and Dewey, 1982; Rosenfeld, 1993). Indeed, if we accept offset values of ~1000 km on the Cayman Trough (Mann and Burke, 1984; Rosencrantz, 1990), then the Chortis Block restores well to the west of the Maya Block for Cretaceous times, and therefore was probably not involved in the collision. The timing of this Caribbean Plate-Maya Block collision is dated by the Maastrichtian age of overthrusted ophiolite-rich olistostromes of the Sepur Fm. (Rosenfeld, 1993), and by the Campanian-Maastrichtian acceleration of foreland basin subsidence history in northern Guatemala (Pindell et al., 1988). In addition, in the Rabinal-Salamá area of central Guatemala, kinematic and age data are consistent with latest Cretaceous-Paleocene uplift and exhumation of the Chuacús Complex and obduction of the Baja Verapaz Ophiolite onto Paleozoic basement rocks of the Mayan margin (Ortega-Obregon et al., in press). Further, in the serpentinite mélange north of the Motagua Fault Zone, phengite Ar/Ar ages of 77–65 Ma from HP blocks record subduction related to Maastrichtian collision of an oceanic terrane with the Maya block (Harlow et al. 2004). A similar picture arises in Ecuador and Colombia (e.g., Escalante, 1990). Collision between 75–65 Ma of the Upper Cretaceous Caribbean plateau and arc with the NW South American plate margin caused cessation of subduction-related magmatism, deformation, and synchronous accelerated surface uplift and exhumation (e.g., McCourt et al., 1984; Vallejo et al., 2006).

Based on these and other evidences for latest Cretaceous tectonic interaction between the northeastern and southeastern extremities of the Caribbean Plate with the southern Maya Block and northwestern South America, respectively, current paleotectonic and paleogeographic models for the Caribbean realm locate the Caribbean volcanic arc at a position similar to the present-day Central American Arc between the Americas (e.g., Pindell et al., 1988; Pindell, 1994; Mann, 1999; Pindell et al., 2005). Consequently, these models do not show a scenario of general collision during the latest Cretaceous in the intra-oceanic parts of the Caribbean’s Antillean Arc. However, a latest Cretaceous orogenic event in the Caribbean realm has been suggested by some authors (e.g., Khudoley and Meyerhoff, 1971; Iturralde-Vinent, 1998; Iturralde-Vinent et al., 2006). Evidence provided below allows reconciling these contrasting ideas. We propose a major collision/accretion event of latest Cretaceous – early Paleocene age affecting the entire leading edge of the Caribbean Plate, including intra-oceanic arc locations in the Antilles as far east as the Virgin Islands. To accommodate this event into current paleotectonic and paleogeographic models, a hypothetical sedimentary basin (Caribeana) located between the Americas within the Proto-Caribbean Basin must be defined.

Definition of Caribeana

Joyce (1983, 1991), referring to marbles in the Samaná subduction complex of northern Dominican Republic, suggested that a carbonate bank of indeterminate provenance subducted during the Latest Cretaceous. Montgomery and Pessagno (1999), referring to a Campanian or Maastrichtian limestone boulder associated with the San Juan subduction complex (Dominican Republic), suggested that the Antillean Arc “…apparently encountered and subducted part of a carbonate platform (too early to be Bahamas platform?) during the latest Cretaceous.”. These seed of insight is the scenario we propose here on a regional scale for the construction of the concept of Caribeana, although the ages for HP metamorphism of Caribanen terranes preclude the Bahamas as the site of Caribeana. Before full evidence is presented, we shall define Caribeana.

As defined here, Caribeana is a conceptual paleogeographic domain characterized by Mesozoic sedimentary piles that occupied a portion of the Proto-Caribbean oceanic domain. The nature of these sedimentary piles is similar to that of sedimentary piles formed in the margins of North America (e.g., R Caribbean and Bahamas borderlands). Thus, we envisage Caribeana as a NW-SE elongated submarine promontory with oceanic to stretched continental basement, projecting off the southeastern edge of the Maya block, very similar in shape to the Bahamas submarine promontory off Florida (Fig. 1A). However,
in contrast to those of the Bahamas, Caribeanan sedimentary piles were metamorphosed in a subduction environment during latest Cretaceous – earliest Tertiary times (Fig. 1B). The metasedimentary complexes were later fragmented into several terranes and dispersed along the northern segment of the circum-Caribbean orogenic belt over more than 2500 km (Fig. 2). Most of the descriptions which follow are based on published material, and the assessment of various problems important for the clarification of our proposal is presented in parallel.

Fig.1. Paleogeographic sketches of the Caribbean region for mid- and latest-Cretaceous times (based on Iturralde-Vinent, 2006), showing the inferred position of Caribeanan (denoted by Cangre, Escambray and Samaná terranes) relative to the Mayan and Bahamian borderlands and the Greater Antilles arc. In B) Caribeanan is in the course of subduction. The trace of cross-sections of Fig. 8 is shown in B).
Fragments of Caribeana

Fragments of Caribeana are identified as metasedimentary rock complexes occurring onshore and offshore along the northern branch of the Caribbean orogenic belt (Fig. 3). The onshore fragments occur in Cuba and Hispaniola; from west to east, these include the Cangre, Pinos, Escambray, and Asunción terranes in Cuba, and the Samaná terrane in Hispaniola. There is also geophysical evidence for a concealed terrane in southern Camagüey province (central Cuba), termed here the Guayabal suspect terrane. Furthermore, marine geophysical research and samples dredged from different locations have also proved the existence of metasedimentary complexes offshore eastern Yucatan peninsula, termed here the East Yucatan terrane, and offshore eastern Dominican Republic, northern Puerto Rico and the northeastern Virgin Islands, collectively termed here Puerto Rico Trench terrane.

The term “terrane” has been used with variable meaning in the Caribbean realm (see Iturralde-Vinent and Lidiak, 2006). Here it is applied to describe fragments of Caribeana because the fragments represent distinct tectonostratigraphic elements bounded by faults and characterized by a geologic history which differs from that of neighboring rocks (Howell, 1985). However, differences in composition can be recognized within these terranes. For example, the Cangre, Pinos, and Asunción terranes are made of coherent metamorphic complexes. This is not the case for the Escambray, Samaná, and Puerto Rico Trench terranes, which are made of mixtures of Caribeana metasedimentary rocks and of oceanic (volcanic arc, forearc, trench, and mid-ocean) complexes. To describe these, we use the term “composite terranes” to embrace the different histories of the various elements prior to their amalgamation during the latest Cretaceous – Tertiary, after which they shared the same geologic history. Terranes identified by geophysical evidence only (Guayabal terrane) are termed here “suspect terrane”.

The Mesozoic (meta)sedimentary piles of Caribeana may have been deposited on top of stretched continental and/or oceanic basement. Continental basement rocks have not been described in Caribeana complexes. However, fragments of Proterozoic (Grenvillean) continental basement rocks crop out in the Socorro and La Teja complexes within the the Placetas belt of Cuba, as boulders within the San...
Adrián and other gypsum diapir, and as pebbles within arkosic conglomerates of the (Upper Jurassic-Lower Cretaceous) Constancia Formation (Meyerhoff and Hatten, 1968; Pardo, 1975; Somin and Millán, 1981; Pszczolkowski, 1986a; Pszczolkowski and Myczynski, 2003; Renne et al., 1989). Furthermore, gneiss pebbles of ca. 400 Ma old (zircon Pb-Pb; Millán and Somin, 1985b) and/or 250-220 Ma old (zircon U-Pb SHRIMP-II; Somin et al., 2006) occur in the Eocene El Guayabo conglomerate of the Pinar del Río region of Western Cuba. The source region of these rocks is unknown and has been identified with pre-Jurassic basement rocks (Somin and Millán, 1981) of unknown location but, as far as zircon rims from these pebbles have 72±1 Ma (Somin et al., 2006), they may represent the (stretched) continental basement of Caribeana (see below).

Fig.3. Caribeanan terranes (ruled). Ophiolitic bodies delineate the Caribbean-North America suture.
In the following paragraphs the occurrences of Caribeanan complexes are described from west to east.

**East Yucatan terrane**

Dredge hauls offshore Yucatan Peninsula and western Cuba recovered metasedimentary rocks (Pyle et al., 1973, and references therein). Basically, the topographic and structural elements offshore Yucatan between Cozumel and western Cuba include a 40 km wide sediment filled trough, a ridge of similar width, and a steep slope extending down to the Yucatan abyssal plain (Rosencreantz, 1990). Pyle et al. (1973) dredged metamorphic rocks at site 955, but they cite other sites in the area where similar rocks were dredged by the U.S. Geological Survey in 1971, and Eastward cruise E-31 F-71 (B.C. Heezen, Chief Scientist) in 1972 (Fig. 3A). All these samples are considered by Pyle et al. (1973) to represent a significant component of the rocks in the basement of the ridge, suggesting the presence of a metamorphic terrane in this region. This terrane is termed here East Yucatan terrane.

The dredged metasediments include slightly metamorphosed shale, siltstone and quartzite. Pyle et al. (1973) recognized similarities with the Jurassic San Cayetano Fm. of western Cuba. The rocks are cataclastic, and show low grade metamorphism with development of chlorite. Whole rock K-Ar determinations in these rocks yielded 33, 38 and 63-68 Ma, but Pyle et al. (1973) considered that the greatest age, although still minimal, is likely to be the most nearly correct. This led these authors to correlate these rocks with metasediments of the Pinos terrane with 73-78 Ma K-Ar ages (Meyerhoff et al., 1969; Khudoley and Meyerhoff, 1971).

**Cangre terrane**

Millán (1972) defined the Cangre “belt” of Sierra de los Organos (western Cuba) as a strip of metamorphosed sedimentary and intercalated mafic igneous rocks adjacent to the Pinar Fault (Fig. 3A). Along with the non-metamorphic Sierra de los Organos and northern Sierra del Rosario belts (Fig. 4), the Cangre Belt has been grouped in the Guaniguanico terrane of western Cuba (Iturralde-Vinent, 1994; Pszczolkowski, 1999). However, the Cangre belt is renamed here as a terrane to emphasize its distinct geologic history relative to its neighboring non-metamorphic belts of the Guaniguanico terrane.

The Cangre terrane has been subdivided into three tectonic thrust sheets: the larger Pino Solo and the smaller Mestanza and Cerro de Cabras thrust sheets (Piotrowska, 1975, 1981; Fig. 4). All three units are located on top of the non-metamorphic San Cayetano Fm. which belongs to the Alturas de Pizarras del Sur thrust sheet of the Sierra de los Organos belt, and the Pino Solo and Cerro Cabras units override the Mestanza thrust sheet. The general attitude of foliation is SW-NE and dipping to the SE. The protolithic stratigraphy of this terrane is similar to the Jurassic section of the Los Organos belt (Fig. 5A). The Pino Solo unit is formed mostly by the Arroyo Cangre Fm. (Piotrowski, 1987), with predominantly siliciclastic metasediments and intercalated (mostly at the base) metacarbonate and metamafic igneous rocks. The sedimentary age of this formation is unknown but general stratigraphic analogies suggest correlation with the pre-middle Oxfordian (Lower? to Upper Jurassic) San Cayetano Fm. (Hatten, 1957; Rigasi-Studer, 1963; Pszczolkowski, 1978, 1999; Fig. 5A). However, Piotrowski (1987), while accepting this age correlation, considers that the amount of metacarbonates mostly at the base of the formation along with the mafic material (meta-gabros, -basalts, and -tuffs) prevents direct correlation of this unit with the San Cayetano Fm. In our view, these aspects suggest a more marine (distal) position of the Arroyo Cangre Fm. with respect to the San Cayetano Fm. The Pino Solo unit locally contains metacarbonates and shales which have been correlated with the Late Jurassic to Early Cretaceous Jagua and Guasasa fms. of the Los Órganos belt (Pszczolkowski, 1978, 1999; Piotrowski, 1987). The Cerro de Cabras unit is made of the Arroyo Cangre Fm., while the Mestanza unit has a sedimentary section that correlates with the San Cayetano, Jagua and Guasasa Fms. (Pszczolkowski, 1978; Piotrowski, 1987). Pszczolkowski (1985, 1999) identified the Paleocene-Lower Eocene Ancón and Manacas Fms. in the Mestanza unit. Piotrowski (1987), Piotrowska (1987), and Millán (1997a) indicate gradual transitions between the Arroyo Cangre Fm. and Jagua and Guasasa Fms. in the Mestanza unit.

The metamorphic grade in the Cangre terrane is low (to very low, in the Mestanza unit). The metamorphic assemblages of metasediments (phylmites and impure metapsammites) and metabasites of the Arroyo Cangre Fm. are made of combinations of quartz, phengite, albite and chlorite, and of hornblende, glaucoephane, actinolite, (clino)zoisite, epidote, albite, pumpellyite, chlorite, quartz and phengite, respectively (Somin and Millán, 1981; Millán, 1988; Cruz-Gámez et al., 2007). The metabasites commonly show refl ex magmatic clinopyroxene and plagioclase and the metasiliciclastics contain detrital mica, which attest to incomplete recrystallization during low grade metamorphism. High pressure, low temperature conditions typical of subduction are attested to by glaucoephane-bearing assemblages in the Arroyo Cangre metabasites. Cruz-Gámez et al. (2003, 2007) suggested temperatures of 450 °C and pressures of 6 kbar based on the composition of amphibole. Rocks of the Pino Solo and Cerro de Cabras units have clearly been subducted, pointing to a paleogeographic-paleotectonic position that is distinct from the tectonic units of the Guaniguanico terrane, which lack evidence of subduction in units bearing similar (non-metamorphic) lithologies both in the Sierra
The age of subduction of the Pino Solo and Cerro Cabras units is uncertain. Somin et al. (1992) reported a K/Ar WR date of 113 ± 5 Ma in a phyllite of the Pino Solo unit. Rather than a metamorphic age, this figure is best explained as a mixture of ages of detrital and metamorphic ages, as demonstrated by the existence of Paleozoic and older micas in the contemporaneous San Cayetano Fm. (cf. Hutson et al., 1998). On the other hand, Pszczolkowski (1985, 1999) suggest post-early Eocene metamorphism based on the identification of the Ancón and Manacas Fms. in the Mestanza unit. However, high-pressure metamorphism in these formations has not been demonstrated, and the recrystallization noted by Pszczolkowski (1985) may relate to Tertiary deformation and thrusting in the region. This suggests that Mestanza unit is not part of the Cangre belt, but more work is needed in the region to solve these problems.

The metamorphic phyllites of the Cangre and the Pinos terranes (see below) are very similar. This makes lithostratigraphic correlation between these terranes plausible (Millán, 1997a). If this correlation proves certain, the latest Cretaceous age of high pressure metamorphism in the Pinos Terrane (see below) probably pertains to the Cangre terrane as well, and rules out the Paleocene-Eocene collision of the Guaniguanico terrane, and allows considering the Cangre terrane as allochthonous with respect to the Guaniguanico terrane.

**Pinos terrane**

The Pinos terrane crops out on the Island of Youth (formerly Island of Pines), located to the southwest of Cuba (Fig. 3A). The terrane tectonically underlies Cretaceous volcanic arc rocks of Sabana Grande Fm. (Fig. 6A). This tectonic arrangement is similar to that of the Escambray terrane (see below). However, the Pinos terrane does not show such a complex tectonic structure as the Escambray and the metasedimentary sections are not amalgamated with subducted oceanic material. Millán (1981, 1997b) subdivided the Pinos terrane into several fault-bounded synforms and antiforms formed by a number of folded tectonic slivers. Four main phases of deformation have been identified. The main phase D2 is syn-metamorphic and developed a NW-trending stretching lineation. Garcia-Casco et al. (2001) considered D2 related to exhumation in an extensional setting.

The major lithological features of the Pinos terrane include (Kuman and Gavilán, 1965; Millán, 1981, 1997b; Somin and Millán, 1981; Pardo and Moya, 1988; Pardo, 1990; Babushkin et al., 1990) graphite-bearing siliciclastic and carbonate metasediments with occasional metabasite intercalations (i.e. Daguilla...
amphibolites; Figs. 5A and 6A). Some sections (Cañada and Agua Santa Fms.) are dominated by siliciclastic rocks bearing similarities with the Jurassic San Cayetano Fm. of the Guaniguanico terrane. The depositional ages of these sections are not known, but fossils found in marble members of the Playa Bibijagua Fm. overlying the siliciclastic sections suggest a Mesozoic age and a possible correlation with the Upper Jurassic-Cretaceous section of the Guaniguanico terrane (Fig. 5A). The Daguilla amphibolites, on the other hand, correlate with the basaltic magmatism in the passive margin of San Cayetano and related formations of the Guaniguanico terrane (Iturralde-Vinent, 1988; Millán, 1997a). Based on these correlations Millán
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Fig. 6. A) Geologic map of the Isle of Pines with indications of formations and reconstructed stratigraphy (after Millán, 1997b). B) Geologic-Tectonic map of the Escambray terrane and Mabujina complex (after Millán, 1997c) with indication of major tectonic units, serpentinite mélanges and amphibolite and eclogite bodies within unit III.

Metamorphism in the Pinos terrane spans low to high grade conditions. Low-grade phyllites are similar to those of the Cangre terrane, bearing chlorite, phengite, albite, and quartz. Maximum Si contents of 6.95 Si atoms per 22 oxygen in pre-D2 phengite (García-Casco, unpublished data) indicate formation at a minimum pressure of ca. 11 kbar (at 400 °C; Fig. 5B).

These conditions translate into an apparent gradient of 36 °C/kbar (11 °C/km) typical of subduction-related environments. In the medium grade metapelites and high grade migmatitic metapelites pre-D2 garnet+kyanite-bearing assemblage developed at pressures of > 12 kbar at 600-650 °C and 700-750 °C, respectively (García-Casco et al., 2001, García-Casco et
al., 2003, and unpublished data; Fig. 5B). This characterizes pre-D2 metamorphism as of relatively high pressure, though maximum apparent gradients of 54 and 62.5 °C/kbar (16 and 19 °C/km), respectively, suggest a heating event after subduction. In these rocks, sillimanite defines the main foliation S2, and andalusite formed after D2. Metamorphic and structural relations indicate intense near-isothermal decompression during D2, from > 12 kbar down to ca. 3 kbar (Fig. 5B) likely caused by tectonic extension (García-Casco et al., 2001).

The tectonic interpretation of the heating event of medium and high-grade rocks is not straightforward. However, it compares well with the thermal evolution of subduction-related metamorphic core-complexes such as those of the Aegean (Jansen and Schuiling, 1976; Avigad, 1998; Ring and Layer, 2003; van Hinsbergen et al., 2005). In these complexes, subduction-related high-pressure low-temperature metamorphism was followed by (Barrovian-type) medium-pressure medium-to-high temperature metamorphism caused by extension during the retreat of the Hellenic subduction zone. This thermal evolution was caused by asthenospheric flow associated with subduction-zone retreat, which increased the geothermal gradient in the region being extended. Exhumation of hot footwall material along large-scale normal-fault detachments took place while the hanging wall material was barely heated. This mechanism explains the amalagamation of unheated low grade phylmites and heated medium-high grade rocks of the Pinos terrane.

K/Ar ages from metamorphic rocks of the Pinos terrane range from 78±4 to 49.3±3.8 Ma (see Iturralde-Vinent et al., 1996, for review). Late-Neogene subvolcanic rocks postdating metamorphism yield K/Ar ages of 68-60 Ma (Buguelski et al., 1985). Unpublished Ar/Ar data from micas and amphibole by P. Monié give 72-50 Ma. The Ar/Ar ages of phengite from low-grade phylmites give ca. 72 Ma, suggesting (pre-D2) high-pressure metamorphism during the latest Cretaceous. The Ar/Ar ages of biotite and muscovite from medium and high grade metapelites give consistent 68 ± 2 Ma. This age is interpreted as a cooling age and indicates latest Cretaceous exhumation due to extension shortly after subduction (Figs. 4B and C; García-Casco et al., 2001). The D2 NW-SE extension and exhumation of the Pinos terrane probably pertains to Late Maastrichtian-Paleocene opening of the Yucatan Basin and core-complex formation (Pindell and Barrett, 1990; García-Casco et al., 2001; Draper, 2001; Pindell et al., 2005).

Escambray composite terrane

The Escambray terrane is located to the south in central Cuba (Fig. 3). It crops out as two domes named Trinidad to the West and Sancti Spiritus to the East forming a tectonic window below the Mabujina complex, which represents the deepest exposed section of the Cretaceous volcanic arc and its oceanic basement in Cuba (Somin and Millán, 1976, 1981; Dublan and Alvarez, 1986; Millán, 1996b, and references therein). The footwall of the Escambray terrane is unknown. The Escambray terrane can be interpreted as an accretionary complex containing subduction-related metamorphic oceanic and platform-like sedimentary rocks that were tectonically assembled in the subduction environment (Millán, 1997c; Iturralde-Vinent, 1998; Stanek et al., 2006). The composite terrane started exhumation in the latest Cretaceous and reached the Earth’s surface by 45 Ma as documented by pebbles of high-pressure rocks in Eocene conglomerate deposits (Kantchev, 1978).

Millán (1997c) identified four major tectonic units named (bottom to top) I, II, III and IV, which are subdivided into smaller tectonic units and slivers (Fig. 6B). Stanek et al. (2006) have recently offered a different structural arrangement of the Sancti Spiritus dome. These authors identified the Pitajones, Gavilanes and Yayabo tectonic units. The Pitajones roughly corresponds with unit II, and Gavilanes and Yayabo with unit III of Millán (1997c). Unit III (or Gavilanes) is interpreted as a mega-melange made of rocks of a subducted passive margin and fragments of subducted oceanic lithosphere (Millán, 1997c; Stanek et al., 2006). Subducted oceanic rocks form strips of serpentinite mélanges which contain blocks of MORB-derived eclogite and blueschist (Somin and Millán, 1981; Millán 1997c, Schneider et al., 2004; García-Casco et al., 2006; Stanek et al., 2006). Similar strips of oceanic serpentinite mélanges are also present in unit II and I. Massive garnet-epidote amphibolite amphibolites (Yayabo unit) present in the Sancti Spiritus dome may represent mid oceanic (Millán, 1997c) or fore-arc (Stanek et al., 2006) material. This Yayabo unit was considered by Millán (1997c) to form part of his major unit III, though Stanek et al. (2006) consider it a different unit.

The metamorphic structure is inverted, with greenschist facies in the lowermost unit I, greenschist and lawsonite blueschist facies in intermediate unit II, and epidote-blueschist and eclogite facies in the upper unit III (Millán, 1997c; Fig. 6B). The uppermost unit IV (greenschist-blueschist facies) diverges from this pattern as a probable effect of the tectonic emplacement of the arc-related Mabujina complex on top of the Escambray (Millán, 1997c; Stanek et al., 2006). Variable P-T conditions of units I to III indicate subduction to variable depths. Tectonic amalgamation took place during subduction and exhumation. A number of tectonic phases have been described, though the general vergence of main structures indicates top to the NE transport, probably related to exhumation rather than to burial during subduction (Stanek et al., 2006).

A number of lithostratigraphic formations have been identified. The dominant rock assemblages are
graphite-bearing siliciclastics, carbonates (limestone, dolostone, carbonate-pelites) and local mafic rock intercalations. The protolithic stratigraphy of these tectonic units has been correlated with the Jurassic-Cretaceous sections of the non-metamorphic Guaniguano terrane in western Cuba (Millán and Myczynski, 1978; Millán and Somin, 1981; Millán, 1997a, 1997c; Fig. 5A). This correlation has been the basis for relating the origin of this complex to the passive margin of the Maya block (Iturralde-Vinent, 1994, 1998, 2006; Pszczolkowski, 1999). However, Somin and Millán (1976) and Stanek et al. (2006) suggested a Bahamas platform origin, Pushcharovski (1988) and Pushcharovski et al. (1989) suggested a South American origin, and Pindell and Kennan (2001) and Pindell et al. (2005, 2006), trying to acknowledge Albian ages of HP rocks (see below), suggested an origin from along the eastern margin of the Chortis block, which may have been near the Cuban portion of the Antillean trench at that time. 

Most geochronological data from different rock types in the Escambray terrane obtained using different methods cluster at 72-65 Ma (Iturralde-Vinent et al., 1996; Millán, 1996a, 1997c; Schneider et al., 2004; García-Casco et al., 2006; Stanek et al., 2006; Stanek and Maresch 2007, and references therein; Fig. 5C). Schneider et al. (2004) and García-Casco et al. (2006) noted that a ca. 70 Ma exhumation age for eclogites from serpentinite melanges and associated metasediments of unit III corresponds with near peak subduction-related metamorphic conditions, and suggested that the onset of terrane-trench collision took place shortly before 70 Ma. This is in agreement with recent Lu-Hf age data of Stanek and Maresch (2007). Cold P-T paths during retrogression characterize eclogites from unit III (Schneider et al., 2004; García-Casco et al., 2006; Stanek et al., 2006; Fig. 6B). These paths are typical of exhumation while subduction is still active, and indicate that subduction did not fully arrest during terrane-trench collision/accretion.

Pre-latest Cretaceous ages have been determined in oceanic mafic rocks of the Escambray. Eclogite samples from unit III have yielded 100, 102, and 105 Ma based on U-Pb zircon dating (Hatten et al., 1988, 1989; Fig. 4B). Also, a 90±5 Ma 40Ar/39Ar age of pegmatoid hornblende from an eclogite block has been determined by P. Renne (unpublished, cited in Draper and Nagle, 1991). The description of the outcrops by Millán (1996a, 1997c, and personal communication, 2007) suggests that the dated rocks represent exotic blocks within strips of serpentinite mélanges. Pindell et al. (2005) and Stanek et al. (2006) used these ages to constrain the subduction history of the Escambray terrane. However, in our view these blocks represent the subducted Proto-Caribbean oceanic basement that was incorporated into the subduction channel above the Proto-Caribbean slab during the Early Cretaceous, and were amalgamated with the metasedimentary piles of the Escambray during the latest Cretaceous when Caribeana was deeply buried into the subduction zone. Therefore, although these older ages attest to the Aptian-Albian age of the initial subduction zone, they do not constrain the subduction history of the continental margin-and platform-like sedimentary piles of the Escambray terrane.

**Guayabal suspect terrane**

Geophysical data led Pardo (1991, 1996) and Pardo et al. (1990) to propose that a longitudinal belt of low gravity values and a smooth magnetic field where negative values dominate in the southern flank of Cuba was a chain of “isostatic domes” covered by volcanic arc rocks. This belt encompasses the Pinos and Escambray terranes and a concealed dome structure south of Camaguey near the towns of Santa Cruz del Sur and Guayabal, west of the Cauto basin (Figs. 2 and 3A). The “isostatic domes” conforming this belt are best described as core-complexes. Following this interpretation, we consider the Guayabal dome is a concealed “suspect terrane” which represents a fragment of Caribeana similar to the Escambray and Pinos terranes.

**Asunción terrane**

The Asunción terrane is a metasedimentary complex located in easternmost Cuba (Figs. 2 and 3B). Millán and Somin (1985a and b) correlated this terrane with the Escambray terrane. It is made of two lithologic units outcropping as N-S elongated strips (Somin and Millán, 1972; Cobiella et al., 1977, 1984; Gyarmati, 1983; Millán and Somin, 1985a and b; Millán et al., 1985; 1997a; Fig. 7A). The Chafarina Fm. forms the eastern strip made mainly of calcitic and dolomitic marbles, commonly bearing graphite (black marbles), with occasional micaceous material. Based on lithology, sedimentary facies, and paleontological data, the Chafarina Fm. has been correlated with the Upper Jurassic and Cretaceous calcareous sections of the Guaniguano terrane (Millán et al., 1985; Millán, 1997a) and with the isochronous sections of the Remedios-Camajuaní belts of the Bahamas borderland (Iturralde-Vinent, 1998). The Sierra Verde Fm. forms the western strip made of impure quartzites and phyllites rich in graphite, with some intercalations of metabasalts, grey marbles, and metaradialrites. Locally preserved radiolaria and benthic foraminifera in the marbles of the Sierra Verde Fm. define its depositional age between the Tithonian and the Lower Cretaceous (Millán et al., 1985; Millán and Somin, 1985a and b). Millán (1997a) suggests that the protolith of the Sierra Verde Fm. should be younger than that of the Chafarina Fm.
The internal structure of the Asunción terrane is uncertain. Cobiella et al. (1984) indicate that both formations are in fact distinct tectonic units, with the

Chafarina unit on top of the Sierra Verde unit. The major tectonic displacements in the region are NW directed thrusts (Cobiella et al., 1984; Quintas, 1987, 1988; Nuñez Cambra et al., 2004). These directions are mostly related to the emplacement of the Moa-Baracoa ophiolitic body during the latest Cretaceous and early Danian (Iturralde-Vinent et al., 2006). Cobiella et al. (1984) indicate that the Asunción terrane overrides the Cretaceous volcanic arc suite (i.e., Purial complex) and the Güira de Jauco amphibolites. Our field observations suggest, instead, that the Asunción complex is the lowest tectonic unit in the region. The Moa-Baracoa ophiolitic thrust sheet overrides the Purial (meta)volcanic arc complex, while the syntectonic foredeep-related Maastrichtian-lower Danian olistostromal Picota Fm. occupies an intermediate discontinuous tectonic position below the Moa-Baracoa ophiolite thrust sheet (Iturralde-Vinent, et al. 2006; Fig. 7A). The major tectonic event (thrusting) in the region

is of latest Maastrichtian to early Danian in age (Iturralde-Vinent, et al. 2006).

The metamorphic assemblages of the phyllites and the metabasaltic rocks of the Sierra Verde Fm. contain lawsonite and glaucophane (Millán, 1997a), indicating subduction-related HP/LT metamorphism. Detailed petrologic analysis, P-T estimations, and geochronologic determinations are lacking, but a pre-early Danian metamorphic age is suggested by Iturralde-Vinent et al. (2006) based on stratigraphic arguments. This is consistent with the age of metamorphism of the Purial metavolcanic arc complex. This Campanian and older volcanic arc complex is metamorphosed to similar blueschist facies conditions (Boiteau et al., 1972; Cobiella et al., 1977; Somin and Millán, 1981; Millán et al., 1985) and its metamorphic cooling age has been dated as latest Cretaceous (75 ± 5 Ma, K-Ar whole-rock, Somin et al., 1992; and 75-72 Ma based on stratigraphic-paleontological arguments, Iturralde-Vinent et al., 2006). These data point to a latest Cretaceous timing for
subduction of the Asunción terrane, similar to the other sedimentary piles described so far.

Samaná composite terrane

The Samaná composite terrane is located in the Samaná Peninsula, northeastern Hispaniola (Figs. 2 and 3A). It faces the left-lateral, south-dipping strike-slip Puerto Rico trench to the north, and is bounded by the higher-angle left lateral Septentrional Fault Zone to the south (Fig. 7B). The complex is considered a syn-subduction accretionary complex developed during the Upper Cretaceous to Middle Eocene (Joyce, 1983; 1991; Mann et al., 1991; Gonçalves et al., 2000). It is one of the several pre-Late Eocene basement complexes of the island, but these complexes do not outcrop in the Peninsula so that their respective structural relations are unknown.

Three main geologic bodies are distinguished (Joyce, 1991): El Rincón marble, Santa Bárbara schists, and Majagual marble (Fig. 7B). The internal structure of the Santa Bárbara schists consists of an imbricate stack of discrete thrust sheets with top-to-NNE sense of shear developed during D2, the phase of exhumation in the accretionary complex (Joyce, 1991; Gonçalves et al., 2000; Escuder-Viruete and Pérez-Estaún, 2006). Joyce (1991) considered the higher grade (eclogitic) Punta Balandra zone of the Santa Bárbara schists as a discrete metamorphic zone that graded through a transitional lawsonite-actinolite-glaucophane-bearing schist (zone II) to the lower grade lawsonite-albite-bearing schists (zone I). Gonçalves et al. (2000), however, suggested that the Punta Balandra zone is a discrete thrust sheet overriding the lower grade schists (Fig. 7B). The structural relations among the Santa Bárbara – Punta Balandra stack of thrusts and the Majagual and Rincón marbles are less certain. Gonçalves et al. (2000) suggest that the contact with the Rincón marbles would also be interpreted as a thrust structure, which make these marbles the lowermost tectonic element of the complex, while Escuder-Viruete and Pérez-Estaún (2006) show the Majagual marbles overriding the Santa Bárbara unit (Fig. 7B).

The tectonic units of the Samaná composite terrane are characterized by different proportions of the same types of rock, i.e. metamorphosed pelitic, carbonate and mafic rocks, and with common transitional rock types (Joyce, 1991). Mafic rocks have oceanic geochemical signatures (Joyce, 1991; Escuder-Viruete and Pérez-Estaún, 2006), and volcanic-arc components have been distinguished in metasedimentary trench deposits (Perfit and McCulloch, 1982; Perfit et al., 1982; Joyce, 1991). The metapelitic rocks are meta-mudstone, -wacke, -chert and -arenites, while the metacarbonates are metacalcilutites and dolomitized interbedded metacalcarenites and metacalcilutites (Joyce, 1991). The presence of oolitic metadolomites and the abundance of carbonates are considered by Joyce (1991) as indicating tectonic intercalation of carbonate banks developed on seamounts or aseismic ridges with their underlying ocean floor rocks and with trench sediments during subduction.

The age of the protoliths is not known. A single Campanian or Maastrichtian fossil age from the Majagual marble is available ( Weaver et al., 1976). Joyce (1991) suggests a generalized Late Cretaceous depositional age, though he does not exclude Tertiary material. Subduction and accretionary prism formation spanning the Late Cretaceous to Middle Eocene (Mann et al., 1991) constrains the subducted material to pre-Middle Eocene in age. Cretaceous ages for the sediments of the Santa Bárbara and Punta Balandra units are expected for they are considered oceanic sediments and the subducted mafic oceanic crust was probably of Cretaceous age (Joyce, 1991; Escuder-Viruete et al., 2004; Escuder-Viruete and Pérez-Estaún, 2006). Based on the available timing constraints, we hypothesize that the carbonate banks of Joyce (1991) and perhaps also some of the other types of metasediment in Samaná formed part of Caribeana.

Isotopic Sm-Nd, K-Ar and Ar/Ar age data from the Samaná composite terrane indicate a long history of subduction and exhumation. Most of these data (if not all) pertain to rocks of probable oceanic origin, making most of the comments that follow not applicable to processes affecting Caribeana. Two very imprecise Sm-Nd ages of 84±22 and 86±47 Ma are reported by Perfit and McCulloch (1982) and Escuder-Viruete et al. (2004). A similarly imprecise glaucophane K-Ar age of > 100 Ma was reported by Joyce and Aronson (1987). These data have been considered indicative of Late Cretaceous metamorphism of oceanic material (Joyce, 1991; Gonçalves et al., 2000; Escuder-Viruete and Pérez-Estaún, 2006). We stress that these pre-latest Cretaceous ages do not constrain the subduction history of the sedimentary piles of the El Rincon and Majagual marbles.

Additional K-Ar and Ar/Ar ages reported from oceanic rocks of the complex range from 48.9 to 24.7 Ma (Joyce and Aronson, 1987; Catlos and Sorensen, 2003; Escuder-Viruete et al., 2004). These ages are considered as cooling ages related to uplift during the Eocene to Oligocene oblique collision with the Bahamas bank and ensuing left-lateral transpressional motion of the Puerto Rico trench fault zone. It merits mention, however, that Catlos and Sorensen (2003) emphasize that Ar/Ar ages of phengites of eclogitic blocks from the Punta Balandra unit indicate 25 million years of residence time within the subduction environment. Because the rock studied by these authors started exhumation at 600 ± 60 °C (at minimum pressure of 9.6-9.9 ± 0.1 kbar) and the Ar/Ar isotopic clock in phengites does not record ages at temperatures higher than 400-450 °C, such residence time must be considered a minimum estimate. Taking into account the Sm-Nd, K-Ar and...
The rocks recovered include marbles, calc-schist, mica schist and greenschist (Perfit et al., 1980). They are dominantly, but not exclusively, of island arc derivation (semipelitic sediments, graywackes, marls, island-arc volcanics and/or volcaniclastics and carbonates) amalgamated in an accretionary wedge. Some magnesian schists and serpentinites document the incorporation of oceanic material into the accretionary prism during subduction. Although no eclogite and glaucophane schist was recovered, some samples contain sodic amphibole (crossite) and needles of glaucophane indicating HP/LT metamorphism. Estimated conditions of metamorphism for samples are 400°C and 550°C at 3 to 7 kbar, and K-Ar ages of a mica-epidote schist and muscovite from a greenschist are 63±3 Ma and 66±6 Ma, respectively (Perfit et al., 1980), suggesting latest Cretaceous–earliest Tertiary metamorphism.

Metamorphism and exhumation of the Puerto Rico Trench terrane during the latest Cretaceous - early Tertiary is interpreted here as evidence for a latest Cretaceous subduction-collision event. Thus, the marbles recovered, at least at sites close to the Samaná Peninsula, are interpreted as fragments of Caribeana, while much of the metasedimentary rock recovered represents subducted fragments of the trench material derived from the Caribbean Plate.

**Expression of the latest Cretaceous collision/accretion of Caribeana in the upper Caribbean plate**

Further evidence for a major latest Cretaceous–earliest Tertiary collision/accretion event is found within rock complexes from the leading edge of the Caribbean Plate. The main evidence is the Late Campanian termination of magmatic activity in the west-central Cuban portion of the Antillean volcanic arc, and the concomitant occurrence of deformation, uplift and erosion of the arc’s Cretaceous volcanic and ophiolitic rocks. Latest Campanian-Maastrichtian sedimentary rocks generally overlie with angular unconformity the deformed Late Campanian and older volcanic-plutonic island arc suites (Pushcharovski, 1988; Pushcharovski et al., 1989; Iturralde-Vinent 1994, 1998). In central Cuba, latest Campanian through Danian sedimentary rocks overlying the Cretaceous arc suites yield fine-grained clastics derived from erosion of ophiolites and Cretaceous volcanic-plutonic arc rocks (Bronnimann and Rigassi, 1963; Albeir and Iturralde-Vinent, 1985; Iturralde-Vinent, 1976, 1977; 1995, 1998; Tada et al., 2003). Ar/Ar data from granitoids indicate cooling and uplift during 75-70 Ma (e.g., Hall et al., 2004). These data indicate that the activity of the volcanic arc in central and western Cuba ended by the Campanian and was not renewed any more. In Eastern Cuba, ophiolite emplacement took place during the
latest Cretaceous and was synchronous with deposition of olistostromes (La Picota Fm) associated with thrust tectonics and exhumation of ophiolites, volcanic arc rocks and metamorphic complexes (Iturralde-Vinent et al., 2006). These authors noted that this scenario closely correlates with the geological history of El Petén region of Guatemala. In eastern Cuba the activity of the volcanic arc was interrupted in the latest Campanian (Iturralde-Vinent et al., 2006), but resumed during the Paleocene (Iturralde-Vinent, 1976, 1977, 1994, 1998) perhaps as a result of continued southwestward subduction of the Proto-Caribbean (Pindell and Barrett, 1990) or of the onset of northeastward subduction of the Caribbean Plate (e.g., Iturralde-Vinent, 1994; Sigurdson et al., 1997; Rojas-Agramonte et al., 2006; Pindell et al., 2006).

In Hispaniola, the Cretaceous Tireo Fm (volcanic arc) shows interruption of the volcanic activity during the mid-late Campanian. Non-volcanic Late Campanian–Maastrichtian sediments (Trois Rivière Fm) cover the volcanics (Lewis et al., 1991), and latest Maastrichtian–Paleocene sediments include coarse grained and poorly sorted red terrestrial conglomerates (Don Juán Fm), which record the interruption of magmatic activity, and uplift and erosion of the volcanic arc. The Late Maastrichtian–Paleocene lower half of the Imbert Fm. yields conglomerates and olistostromal rocks containing ophiolite-derived material (Pindell and Draper, 1991) similar to La Picota Fm of eastern Cuba (Iturralde-Vinent and MacPhee, 1999). All these rocks and relationships support the idea of a tectonic phase as identified by Bowin (1966) and outlined by Mann et al. (1991, “phase 4” therein) and Draper et al. (1994) affecting the island arc terrane of Hispaniola. Mann et al. (1991) pointed to a possible mid-late Campanian flipping of subduction as the cause of this tectonic event, but Late Campanian to Paleocene collision and accretion of Caribeana would have had a similar tectono-sedimentary expression in the arc. Arc-related plutonic bodies with Maastrichtian–Eocene K-Ar cooling ages (Kesler et al., 1991) formed due to residual or renewed volcanic arc activity probably related to that occurring in eastern Cuba (Pindell et al., 2006).

In Puerto Rico, an important tectonic event and interruption of magmatic arc activity are identified during the latest Cretaceous–earliest Tertiary by means of an erosional hiatus embracing the Late Maastrichtian through Danian, which relates to uplift and erosion of the Cretaceous arc (Jolly et al., 1998). The activity of the Cretaceous volcanic arc was arrested at ca. 75 Ma in the Central Volcanic Province, and renewed in the Latest Danian (ca. 60 Ma). The Western and Northeastern Volcanic provinces of Puerto Rico show similar relations, although the initial interruption of volcanic activity is identified as taking place in the latest Maastrichtian (ca. 65 Ma). Further to the east, a Late Cretaceous arc disruption event is recorded in St. Croix (Larue, 1994).

In Jamaica, the volcanic arc section displays an interruption of the volcanic activity along with uplift, thrust tectonics, and a latest Campanian-early Maastrichtian hiatus, followed by deposition of Late Maastrichtian limestones and clastic rocks (Mitchell, 2006), and ophiolite obduction took place during the Maastrichtian (Mitchell et al., 1982). Furthermore, Maastrichtian to Paleocene coarse grained sedimentary rocks (Bowden Pen and Moore Town Fms) have been compared to the Sepur Fm of Guatemala (Robinson, 1994).

The intensity of the latest Cretaceous collision/accretion event was sufficiently great that it was manifested by intense vertical movements affecting the oceanic interior of the Caribbean Plate. For example, Mauffret et al. (2001) indicated that Late Campanian uplift and prominent Maastrichtian (71–65 Ma) erosion took place in the northern part of the offshore Beata Ridge, south of Hispaniola. In the Sierra Bahoruco of southernmost Dominican Republic, the oldest strata resting on Cretaceous basaltic basement and its terrigenous elastic intercalations (probable Dumisseaux Complex) are shallow-water limestones of Paleocene age (dated by E. Robinson for J. Pindell, pers. comm., 1983) recording a return to submarine deposition in the Beata Ridge region (Pindell, 1985b).

**Discussion**

**Timing of subduction of Caribeana**

All the evidence given above clearly point to a major latest Cretaceous – earliest Paleocene tectonic event all along the leading edge of the Caribbean Plate which can be related to the concomitant metamorphic events of the sedimentary piles of Caribeana. This conclusion is particularly evident for the case of low grade rocks (e.g., East Yucatán, Pinos, Puerto Rico Trench terranes), which K-Ar and Ar-Ar ages should not be interpreted as recording cooling during exhumation but to pertain to peak metamorphic conditions (even if care should be exercised in interpreting K-Ar whole-rock and mineral data). The same interpretation applies to the ca. 70 Ma Lu-Hf ages of eclogites from the Escambray terrane (Stanek and Maresch, 2007), which likely represent subducted oceanic basement of Caribeana, and to the 72±1 Ma of zircon rims with low to very low Th/U ratio (0.002-0.005) from gneiss pebbles from the Eocene El Guayabo conglomerate of the Pinar del Río region of Western Cuba (Somin et al., 2006), which likely represent subducted continental basement of Caribeana. In these pebbles, muscovite coexisting with zircon yield K-Ar ages of 71 ± 3 and 70.5 ± 1.4 Ma (determined by M. M. Arakeliants and R. E. Denison, respectively; cited in Somin et al., 2006) suggesting low-grade or
relatively fast exhumation, as in the Pinos and Escambray terranes (see above and Fig. 5). Thus, these data indicate that both basement and Mesozoic cover rocks in the region underwent a latest Cretaceous – earliest Paleocene tectonometamorphic event. Only in cases of slow exhumation of medium grade rocks (e.g., Samaná) there is no direct K-Ar and/or Ar/Ar geochronologic evidence for latest Cretaceous subduction.

Timing of the Caribbean Plate collision with the Bahamas

In order to establish the correct plate tectonic implications of the metamorphic terranes discussed above, it is essential to first clear up a dilemma concerning the timing of collision between the leading edge of Caribbean Plate and the Bahamas Platform. Some authors have used the Late Campanian termination of arc magmatism in central Cuba to infer Late Cretaceous collision (e.g., Pardo, 1975). Other explanation for the termination of arc magmatism is flattening of the subduction angle, which would have the same apparent effect in onshore Cuba (arc axis would shift to the south, offshore; Pindell et al., 2005). Stanek et al. (2006) presumed that the Late Cretaceous accretion of the Pitajones unit into the Escambray Complex must have pertained to the arc’s collision with the Bahamas Platform. Likewise, Joyce (1983) considered the marbles of the Samaná terrane in Hispaniola as possibly Bahamian, and Iturralde-Vinent (1994, 1998) suggested that the Asunción terrane in Cuba represents a metamorphic equivalent of the Bahamas platform.

However, several arguments clearly show that Caribbean Plate-Bahamas collision was Paleogene (Iturralde-Vinent 1994, 1998 and references therein). First, the stratigraphic belts of the southern Bahamas borderland were not deformed until the Paleocene-early Upper Eocene, which is also the time of primary olistostromal deposition, shallowing of paleo-water depths from abyssal to shelfal conditions normally associated with arc-continent collision, and northward thrusting of ophiolite thrust sheets over foreland sediments as young as early Upper Eocene (Meyerhoff and Hatten, 1968; Khudoley and Meyerhoff, 1971; Iturralde-Vinent, 1994, 1998; Iturralde-Vinent et al., submitted). Second, to the east in Hispaniola, similar arguments have been used to show collision occurred in the Late Paleocene-Middle Eocene (Nagle, 1974; Pindell et al., 1988; 2005; Pindell and Draper, 1991; Dolan et al., 1998; De Zoeten and Mann 1999). Third, the so called “Maastrichtian carbonate megaturbidites” in Cuba (Cacarajícara, Peñalver, and presumably Amaro Fms, sensu Puscharovski et al., 1989) in fact represent the K/T boundary impact event (Pszczolkowski, 1986b; Iturralde-Vinent, 1992; Takayama et al., 2000; Kiyokawa et al., 2002; Tada et al., 2002, 2003) and cannot be used to date the Cuba-Bahamas collision. Fourth, Bahamian foreland underwent forebulge formation and ensuing subsidence in the Paleocene-Early Eocene (Iturralde-Vinent, 1998), and subsidence rates underwent a four-fold acceleration which would only be expected if the collisional loading of the Bahamas was Paleogene, rather than Late Cretaceous (Paulus, 1972; Pindell 1985a). Given the overwhelming evidence that the Caribbean Plate-Bahamas collision was Late Paleocene-early Late Eocene, it is not valid to ascribe Late Cretaceous aspects of northern Caribbean metamorphic complexes and arc-related geology to collision with the Bahamas. In summary, the paleogeographic/paleotectonic position of the Escambray, Asunción and Samaná metasediments cannot be tied to the Bahamian borderlands.

Fragments of Caribeana vs fragments of the Maya borderlands

One concern here is distinguishing the original paleogeographic position of metamorphosed sedimentary piles relative to similar non-metamorphic sedimentary piles that formed part of the borderlands of the Maya Block, and possibly even the Chortis Block. As described above, different authors have demonstrated the general stratigraphic similarities of metamorphosed sediments in the Cangre, Pinos, Escambray and Asunción terranes with non-metamorphosed sedimentary rocks of the Guaniguanico terrane of western Cuba. Because the Guaniguanico terrane originated from the eastern margin of the Maya Block of the Proto-Caribbean Basin (Pszczolkowski 1978, 1999; Pindell, 1985a; Rosencrantz 1990, 1996; Iturralde-Vinent 1994, 1998), these stratigraphic similarities are in turn the basis for correlating the aforementioned metamorphosed terranes with the Maya borderland. However, the stratigraphic belts of the Guaniguanico terrane were not tectonically disturbed during the latest Cretaceous as were the terranes of Caribeana, but later during the Paleocene-early Late Eocene (Pszczolkowski 1978; Piotrowska, 1987; Gordon et al., 1997; Bralower and Iturralde-Vinent, 1997). This diachronity in margin deformation permits us to distinguish the paleogeographic position of Caribeana and the Guaniguanico terrane, and to suggest that Caribeana was approached by the Caribbean Plate earlier (Fig. 1A).

Plate tectonic model

Figures 1 and 8 illustrate the paleogeographic/paleotectonic model devised here for the Upper Cretaceous-Middle Eocene Caribbean evolution. The model is designed to be consistent with the stratigraphic, metamorphic, and tectonic aspects presented above. In particular, it takes into account two sets of metamorphic complexes: a) one including East Yucatán, Cangre, Asunción, Samaná, and Puerto Rico trench represents a frontal trench setting, while b)
another one including Pines, Escambray, and Guayabal (?) is associated with the opening of Yucatan intra-arc basin. The latter came to the surface by low angle normal detachment behind (south of) the arc-
forearc nappes, and can be characterized as core-complexes.

**Cretaceous pre-collision stage**

Southwestward subduction of the Proto-Caribbean lithosphere below the Caribbean Plate occurred until Late Campanian time (Pindell, 1994; Pindell et al., 2005; 2006). This subduction stage is recorded in the Escambray and Samaná terranes as eclogites and blueschists, commonly embedded in serpentinite mélanges. Pre-latest Campanian ages for high-pressure oceanic elements within these terranes suggest that Proto-Caribbean oceanic rocks subducted before latest Cretaceous times were stored in the subduction channel above the Proto-Caribbean slab until they were incorporated during the latest Cretaceous into the composite terranes of Caribeana (Fig. 8A).

Judging from Aptian-Albian ages of high pressure oceanic rocks around the Caribbean (e.g., Stockert et al., 1995; García-Casco et al., 2002; Krebs et al., 2007), the west-dipping subduction stage began in the Aptian-Albian (Pindell, 1994; Pindell et al., 2005; García-Casco et al., 2008). During this stage, Caribeana occupied a midway location within the Proto-Caribbean basin extending from the southern margin of the Maya block towards the southeast (Fig. 1A). In between Caribeana and the Bahamas, a northern branch of the Proto-Caribbean basin was filled with hemipelagic sediments such as those of the Placetas and Camajuaní and the Rosario belts of central and western Cuba, respectively (Figs. 1A and 8A).

**Latest Cretaceous-Danian: Subduction-accretion of Caribeana**

Subduction of Caribeana started in the Late Campanian (Figs. 1B and 8B). Different fragments of Caribeana reached variable depth, explaining the variability of recorded P-T conditions within and among terranes. In cases, amalgamation of rocks with contrasting metamorphic grade occurred during subduction of Caribeana, with emplacement of higher grade rocks on top of lower grade rocks and the development of inverted metamorphic gradients (e.g., Escambray, Samaná). Locally, slivers of the volcanic arc/forearc were subducted and metamorphosed, attesting to local tectonic complexities (e.g., Samaná and Puerto Rico Trench, Perfit et al., 1980, Perfit et al., 1982, Joyce, 1991; Purial Complex, eastern Cuba, García-Casco et al., 2006; Yayabo amphibolites, Escambray, Stanek et al., 2006). As a result of subduction of Caribeana, the activity of the Cretaceous volcanic arc was arrested all along the northern margin of the Caribbean Plate (Fig. 8B).

In eastern Cuba, Cretaceous volcanic arc rocks were overridden during the Maastrichtian-Danian by ophiolitic sheets of back-arc environment (Proenza et al., 2006; Marchesi et al., 2006) and synorogenic basins developed (i.e., La Picota and Mícaro Fms., Iturralde-Vinent et al., 2006; Fig. 8C inset). Ophiolite obduction and synorogenic basin development also occurred further to the west in Guatemala (Santa Cruz ophiolite and Sepur Fm.; Rosenfeld, 1993). However, the most important development during Maastrichtian time is the onset of formation of the Yucatán Basin (Rosenerantz, 1990, 1996) probably a consequence of a low angle intra-arc detachment (Pindell and Dewey, 1982; Pindell et al., 2005; Fig. 8C). Slab-flattening occurred in the western segment of the leading edge of Caribbean Plate as a response to, or concomitant with, collision, favoring onset of exhumation of footwall core-complexes (Pinos, Escambray, Guayabal?) shortly after subduction (Fig. 8C). However, parts of the subducted Pinos terrane experienced significant heating, forming medium-high grade rocks (García-Casco et al., 2001). We speculate that detachment of parts of the accretionary wedge due to normal faulting during basin development allowed heat transfer from the surrounding suprasubduction mantle to the detached subducted sedimentary pile (Fig. 8C). Further extension amalgamated these detached slices made of high-grade rocks with non heated low-grade phylites of the Pinos terrane and the non-subducted Sabana Grande Cretaceous volcanic arc rocks.

To the southeast of Cuba (Hispaniola-Puerto Rico-Virgin Islands) normal-angle subduction continued during the Maastrichtian, promoting arc magmatism (Fig. 8F). Intra-arc basin development did not occur, which prevented fast exhumation of the subducted Caribeanan terranes located in the subduction environment.

The Mayan and Bahamian borderlands of the Proto-Caribbean were, at this stage, tectonically “quiet”.

**Paleocene-Eocene: Flat subduction in Cuba and Yucatan basin development**

In central Cuba, N-NE tectonic emplacement of the arrested Cretaceous volcanic arc on top of probable forearc ophiolitic tectonic sheets (i.e., northern ophiolite belt) and synchronous thrusting of ophiolites on top of the Bahamian borderlands took place during the Paleocene-eariy Upper Eocene (Iturralde-Vinent, 1994, 1998; Iturralde-Vinent et al, submitted; Figs. 8D and E). During this stage, synorogenic basins dating the collision events developed in the Bahamian borderlands (Iturralde-Vinent, 1998) as the leading edge of the Caribbean Plate moved north. The first development of synorogenic basins took place during the Paleocene in the more distal sequence of the Bahamian borderlands (Placetas belt) which was deposited on top of the Proto-Caribbean (Fig. 8D). Synorogenic basins developed during the Eocene in more proximal environments (Camajuaní, Remedios and Cayo Coco belts; Fig. 8E). In western Cuba, the allochthonous arc and its accreted constituents began to converge with the northern
Proto-Caribbean margin during the Late Paleocene–Middle Eocene by means of northward thrusting of the allochthonous oceanic Cretaceous arc (Bahía Honda thrust sheet) and ophiolite (Cajálbana allochthon) along with the para-autochthonous Ganiguánico terrane onto the northeasternmost Maya margin (Pindell, 1985a; Bralower and Iturralde-Vinent, 1997).

Contemporaneous subduction complexes and/or volcanic arc suites do not occur in either region, suggesting that subduction of the Proto-Caribbean was atypical during the Paleocene–Eocene. As suggested by Pindell et al. (2005), we envisage a scenario of flat subduction of the Proto-Caribbean crust (Figs. 8D and E). This development explains cessation of volcanic arc activity in the Cuban fragment of the arc and the ensuing southward silt of volcanic arc activity, as documented by Early Danian-Early Eocene volcanic activity in the Cayman Rise/Ridge (Perfit and Heezen 1978; Sigurdsson et al. 2000, Lewis et al., 2005) and its eastern continuation in the Sierra Maestra Tertiary volcanics of eastern Cuba (Rojas-Agramonte et al., 2004 and references therein; Fig. 8D and E).

During this stage, fragments of Caribeana were finally exhumed. In this scenario the allochthonous arc-forearc system first completely overthrust the footwall trench system (Caribeana), allowing Caribeana to occupy a position adjacent to the developing Yucatán basin; later, the arc/forearc collided with and overthrust the Mayan-Bahamian borderlands and associated Paleocene-Eocene synorogenic basins (Fig 8D and E).

Paleocene-Eocene: Normal subduction in Hispaniola – Puerto Rico – Virgin Islands

Volcanic activity in the eastern part of the leading edge of the Caribbean Plate was interrupted during the Late Campanian due to the accretion of Caribeana into the subduction zone, but it was renewed in the late Danian (Figs. 8B and F). This renewed volcanic arc activity was fed either by a) continued normal-angle southwestward subduction of the Proto-Caribbean (e.g., Pindell and Barrett, 1990; Jolly et al., 2006), b) the onset of northeastward subduction of the Caribbean along the Muertos trench- Peralta-Ocoa of southern Hispaniola-Puerto Rico (Iturralde-Vinent, 1994, 1998; Sigurdsson et al., 1997; Rojas-Agramonte et al., 2006; Pindell et al., 2006), or c) both. Continued southwestward subduction is depicted in Fig. 8F, as suggested by recent geochemical evidence pointing to Atlantic pelagic sedimentary component in Tertiary volcanics of the region (Jolly et al., 2006).

Tertiary Caribbean Plate fragmentation

The distinct tectonic, magmatic, and geologic evolutions of the western and eastern regions of the leading edged of the Caribbean Plate during the Paleocene-Eocene were caused by the distinct styles of subduction (flat in the western part, normal-angle in the eastern part). These contrasting scenarios must relate to a plate tectonic reorganization and fragmentation stating in the Maastrichtian for which different models have been devised (cf. Mann et al., 1995; Iturralde-Vinent and MacPhee, 1999; Leroy et al., 2000; Pindell et al., 2005). During this stage, the Cuban portion of the arc drifted northeastward by low-angle subduction, and as much as 1000 km of Proto-Caribbean and Bahamian-Mayan borderlands were overthrust (cf. Pindell et al., 2005) until it was sutured to North America in the Late Eocene. The Hispaniola-Puerto Rico-Virgin Islands portion of the arc, on the other hand, drifted towards the northeast by normal subduction of the Proto-Caribbean until the leading edge of the Caribbean Plate finally collided with the Bahamas banks during the Eocene, followed by Oligocene and younger transcurrent displacement thereafter. During this process, as much as 1000 km of Proto-Caribbean and 100 km of Bahamian borderland crust was subducted beneath Hispaniola (Dolan et al., 1998; Pindell et al., 2005).

Conclusions

Onshore and offshore geological evidence all along the northwestern branch of the Caribbean orogenic belt indicates that the leading edge of the Caribbean Plate collided during the latest Cretaceous – earliest Tertiary with Caribeana. This Mesozoic terrane occupied a paleogeographic location within the Proto-Caribbean basin, was formed by sedimentary piles similar to those formed in the borderlands of the Bahamas and the Maya block, and was subducted during the latest Cretaceous. This subduction-collision event affected geologic bodies located as far East (relative to the Maya block) as the Virgin Islands, and precedes the West-to-East progressive (diachronic) Tertiary collision stage between the leading edge of the Caribbean Plate and the margins of the Maya block and the Bahamas.

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