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The synorogenic basins of central Cuba formed in a collision-related system. A tectono-stratigraphic analysis of these basins allows us to distinguish different structural styles along the Central Cuban Orogenic Belt. We recognize three distinct structural domains: (1) the Escambray Metamorphic Complex, (2) the Axial Zone, and (3) the Northern Deformation Belt. The structural evolution of the Escambray Metamorphic Complex includes a latest Cretaceous compressional phase followed by a Palaeogene extensional phase. Contraction created an antiformal stack in a subduction environment, and extension produced exhumation in an intra-arc setting. The Axial Zone was strongly deformed and shortened from the latest Cretaceous to Eocene. Compression occurred in an initial phase and subsequent transpressive deformation took place in the middle Eocene. The Northern Deformation Belt consists of a thin-skinned thrust fault system formed during the Palaeocene to middle Eocene; folding and faulting occurred in a piggyback sequence with tectonic transport towards the NNE. In the Central Cuban Orogenic Belt, some major SW–NE structures are coeval with the Cuban NW–SE striking folds and thrusts, and form tectonic corridors and/or transfer faults that facilitated strain-partitioning regime attending the collision. The shortening direction rotated clockwise during deformation from SSW–NNE to WSW–ENE. The synchronicity of compression in the north with extension in the south is consistent with the opening of the Yucatan Basin; the evolution from compression–extension to transpression is in keeping with the increase in obliquity in the collision between the Caribbean and North American plates.

Keywords: Cuban orogen; structural and tectonic evolution

Introduction

The regional structure of Cuba comprises an orogenic belt that originated during the Cretaceous to Palaeogene convergence between the Caribbean and North American plates (Figure 1). In western and central Cuba, these convergent processes included (1) Aptian–early Campanian subduction of the proto-Caribbean oceanic lithosphere and development of the Caribbean Volcanic Arc; (2) subduction and accretion of the Caribeana terrane, cessation of volcanic activity, and deposition of a syntectonic cover on the extinct arc during the late Campanian–Maastrichtian; and (3) Palaeocene–Eocene frontal-oblique collision between the Caribbean and North American plates and origin of large, intervening synorogenic basins (Figure 1B). Since the Oligocene, postorogenic sedimentation has prevailed throughout Cuba.

As a result of the subduction–accretion of Caribeana beneath the Caribbean Volcanic Arc, igneous activity ceased in western and central Cuba during the late Campanian (Iturralde-Vinent and García-Casco 2007; García-Casco *et al*. 2008). The latest Cretaceous subduction–accretion process is recorded in the metamorphism and structure of a suite of metamorphic complexes equivalent to the Caribeana terrane (Somin and Millán 1981; Millán 1997; Schneider *et al*. 2004; García-Casco *et al*. 2006, 2008; Stanek *et al*. 2006; Figure 1A). Subsequently, from Palaeocene to Eocene time, the Caribbean Plate collided with the southern margin of the North American Plate. Both the latest Cretaceous subduction–accretion and the Palaeogene collision are reflected in the structural evolution and sedimentary infill of the Cuban basins (Figure 1C).

This article seeks to improve our understanding of the accretion and collision that occurred in central Cuba. Our study is based on a tectono-stratigraphic analysis of the central Cuban synorogenic basins, using data from seismic sections, boreholes, and surface geology. We incorporate and synthesize some earlier ideas, and also provide new criteria for structural reconstruction of the Central Cuban Orogenic Belt.

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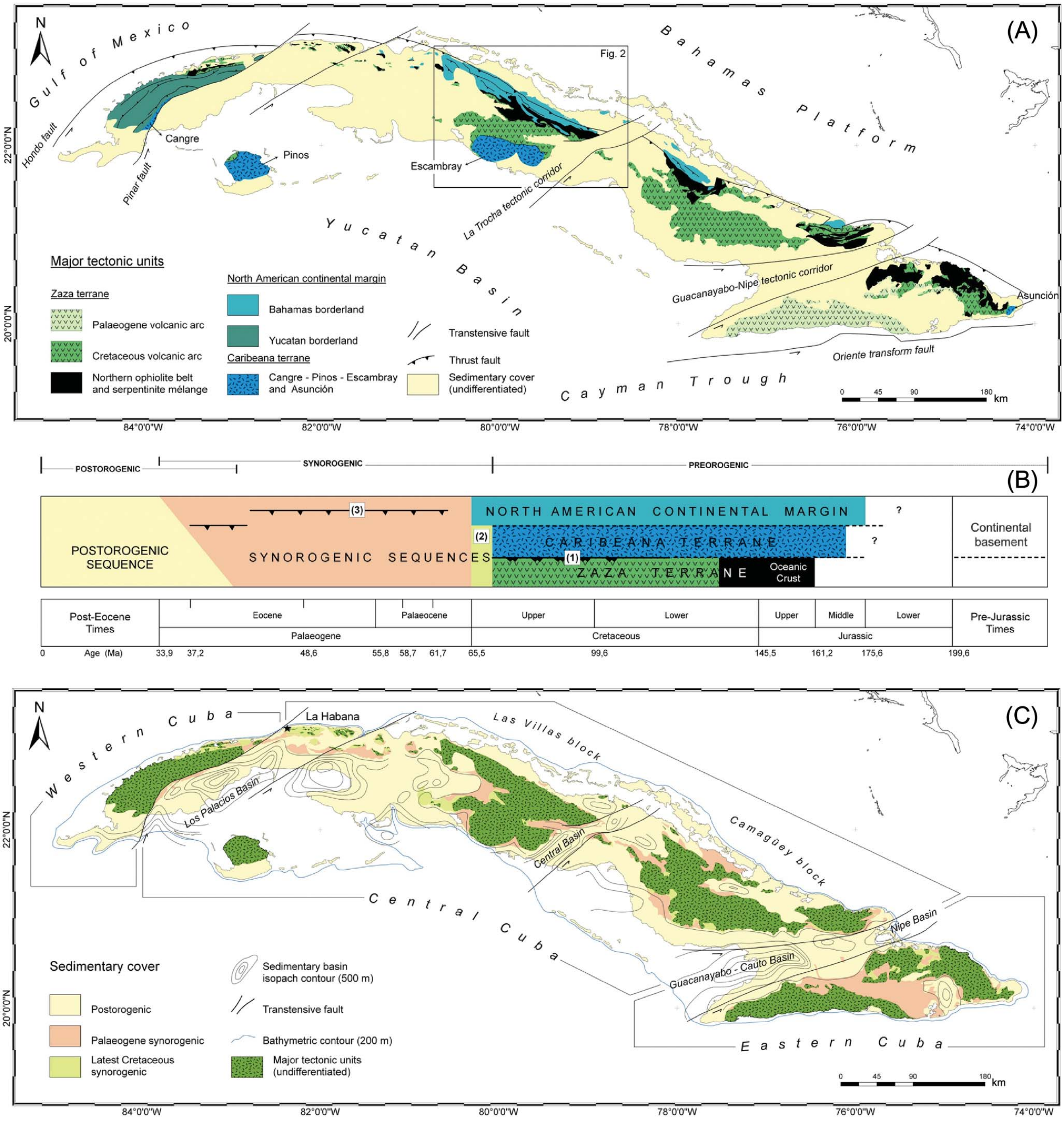

Figure 1. Geological sketch of the Cuban orogen: (A) Map showing the major tectonic units and structures modified from Pushcharovsky (1988); (B) evolutionary chart indicating the age of the major tectonic events in western and central Cuba – (1) subduction of the proto-Caribbean oceanic lithosphere, (2) subduction–accretion of the Caribeana terrane, and (3) collision between the Caribbean and North American plates, ages after Gradstein *et al.* (2004); and (C) map showing the location of the major Cuban basins, isopach contour is modified from Rosencrantz and Pardo (1993).

Central Cuban Orogenic Belt

The Cuban orogen results from the accretion and collision between three major tectonic units (Figure 1A): (1) the North American continental margin, which includes the Bahamas and Yucatan borderlands (Meyerhoff and Hatten 1968, 1974; Pszczolkowski 1986, 1999; Pszczolkowski and Myczynski 2003, 2010; Saura *et al*. 2008); (2) the Zaza terrane, which formed part of the Caribbean Plate and

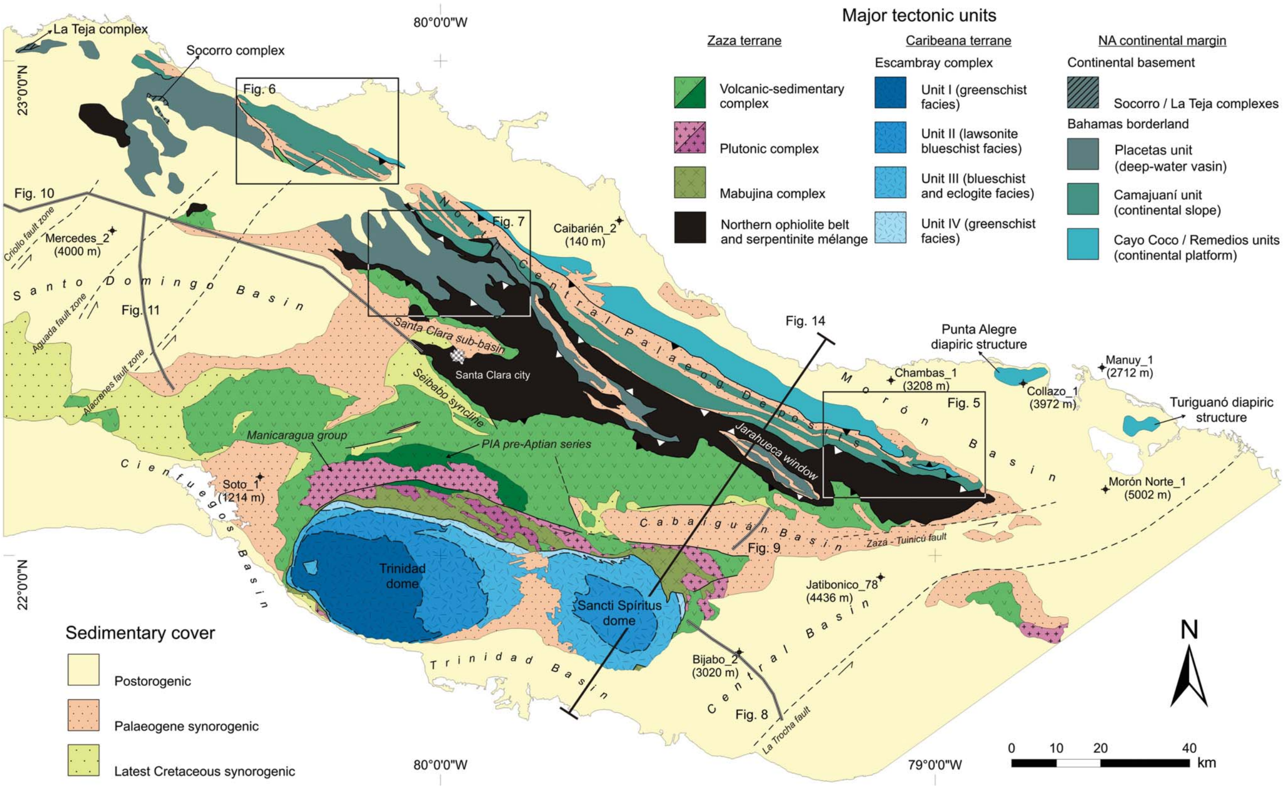

Figure 2. Geological sketch of the Las Villas block showing the location of available boreholes and the elements mentioned in text. The map is modified from García-Delgado *et al.* (1998) and the structural arrangement of the Escambray complex is based on Millán (1997).

embraces a portion of the Caribbean Volcanic Arc and its associated oceanic crust (Hatten *et al*. 1958; Rosencrantz and Pardo 1993; Draper and Barros 1994); and (3) the Caribeana terrane, which was defined by García-Casco *et al.* (2008) as a conceptual palaeogeographic domain characterized by Mesozoic sedimentary rocks of the proto-Caribbean with features similar to those of the North American margin.

The Las Villas block offers the most complete cross-section of the Central Cuban Orogenic Belt. This block is limited to the east by the La Trocha fault and to the west by the Criollo, Aguada, and Alacranes fault zones (Figure 2). These structures are included in a major fault system with a SW–NE strike and left-lateral motion and bound tectonic corridors that have been used to divide the Cuban orogen into structural blocks (Rosencrantz 1990; Rosencrantz and Pardo 1993; Draper and Barros 1994; Rojas-Agramonte *et al*. 2006). The La Trocha can be interpreted as a transfer fault that cuts the Central Cuban Orogenic Belt forming the La Trocha corridor and separating the Las Villas from the Camagüey block to the east. On the other hand, the Criollo, Aguada, and Alacranes fault zones probably acted as tear faults related to the northeastward overthrust of the Zaza terrane. According to Rosencrantz (1990, 1996) and Pindell *et al.* (2005), the origin of these faults could be associated with the opening of the Yucatan Basin during the latest Cretaceous.

North American continental margin

The southern continental margin of the North American Plate began to develop in the Middle-Late Jurassic, after the rifting of western Pangaea (Pindell and Dewey 1982; Iturralde-Vinent 2006; Pindell *et al*. 2006), giving rise to the Yucatan and Bahamas borderlands. The former is only present in western Cuba whereas the latter crops out in the northern part of central Cuba (Figure 1).

The continental basement crops out in the Socorro and La Teja complexes (Figure 2) and is formed by marbles and metasiliciclastic rocks dated as Neoproterozoic, 910–945 Ma (K/Ar ages) by Somin and Millán (1981) and 903.5 ± 7.1 Ma ($^{40}Ar/^{39}Ar$ ages) by Renne *et al.* (1989). These rocks are intruded by Jurassic granitoids of 139–150 ± 6 Ma (K/Ar ages) and 172.4 Ma (U/Pb zircon data) after Somin and Millán (1981) and Renne *et al.* (1989). Cover rocks (Pszczolkowski 1986; Pushcharovsky 1988; Pszczolkowski and Myczynski 2003) include syn-rift and post-rift sequences. Sandstones and shales belonging to the syn-rift sequence have only been

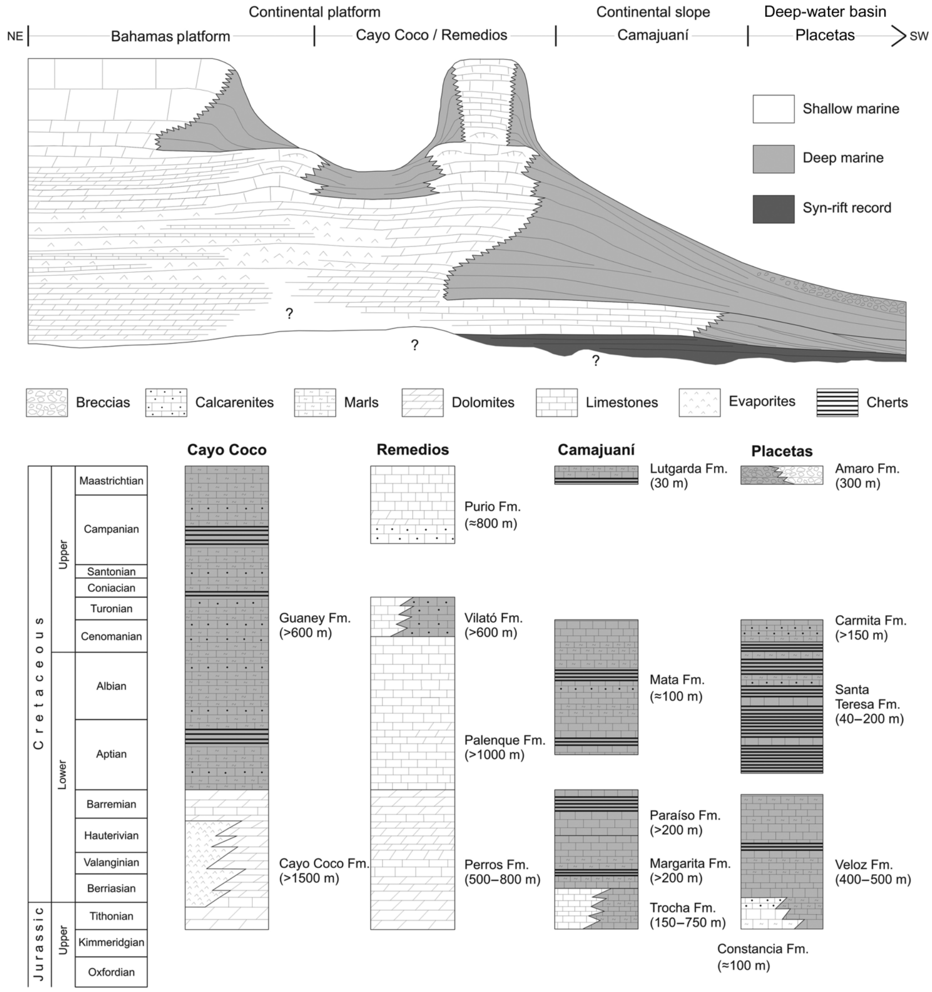

Figure 3. Synthetic palaeogeographic NE–SW cross-section of the Bahamas borderland (vertical scale exaggerated) and lithostratigraphic columns of the post-rift sections of the Cayo Coco, Remedios, Camajuaní, and Placetas units. Thicknesses and lithologies of the lithostratigraphic units are compiled from Ducloz and Vuagnat (1962), Meyerhoff and Hatten (1968, 1974), Díaz-Otero *et al.* (1997), Furrazola-Bermúdez and Gil-González (1997) and Pszczolkowski and Myczynski (2003).

identified as fragments in breccias of the Turiguanó and Punta Alegre diapirs (Figure 2), which are constituted by Upper Jurassic evaporites (Meyerhoff and Hatten 1968). The Tithonian to upper Maastrichtian sedimentary record has been interpreted as a typical progradational post-rift sequence fringing the continent (Figure 3). Some palaeogeographic units were identified by Hatten *et al.* (1958), Ducloz and Vuagnat (1962), and Pardo (1975) in this post-rift sequence. From northeast to southwest, the units are Cayo Coco, Remedios, Camajuaní, and Placetas (Díaz-Otero *et al*. 1997; Furrazola-Bermúdez and Gil-González 1997; Iturralde-Vinent 1997, 1998; Figures 2 and 3). The Cayo Coco and Remedios units, which are made up of evaporites and carbonate rocks, may be regarded as representatives of the continental platform whereas the Camajuaní and Placetas units, which are composed of calcareous and siliceous rocks, are the typical deposits of continental slope and deep-water domains. The stratigraphy of these units is summarized in Figure 3 and their structural features are discussed below.

Zaza terrane

The Zaza terrane in the Las Villas block thrusted northeastward onto the Bahamas borderland (Hatten *et al*. 1958; Pardo 1975; Draper and Barros 1994; Iturralde-Vinent 1997). From north to south, it is constituted by (a) the northern ophiolite belt, (b) a volcanic-sedimentary complex, (c) a plutonic complex, and (d) the Mabujina complex (Figure 2). The volcanic-sedimentary and plutonic complexes belong to the Caribbean Volcanic Arc, which resulted from the subduction of the proto-Caribbean oceanic lithosphere under the Caribbean Plate. The origin and structural features of the northern ophiolite belt and the

Mabujina complex continue to generate controversy (Millán 1996a, b; Blein *et al*. 2003; Cobiella-Reguera 2005, 2009; García-Casco *et al*. 2006; Stanek *et al*. 2009).

The northern ophiolite belt consists of a serpentinite mélange that includes peridotites, harzburgites, other elements of the ophiolite suite (Fonseca *et al*. 1985; Iturralde-Vinent 1996a; Lewis *et al*. 2006), and exotic blocks. These blocks consist of high-pressure metamorphic and plutonic rocks that originated in a suprasubduction environment (Somin and Millán 1981; Millán 1996a; García-Casco *et al*. 2006). Available K/Ar ages from these metamorphic rocks range from 130 Ma to 60 Ma, but cluster around 110 ± 10 Ma, suggesting an Early Cretaceous age for the subduction (Somin and Millán 1981; Somin *et al*. 1992; Iturralde-Vinent *et al*. 1996). Moreover, chert layers intercalated in basaltic lavas provide microfossils, such as radiolarians of Late Jurassic to Middle Cretaceous age (Llanes-Castro *et al*. 1998). The thickness of the serpentinite mélange has been estimated at about 1.5 km on the basis of geophysical data (Bush and Sherbacova 1986). According to García-Casco *et al.* (2008), the serpentinite mélange of central Cuba belongs to the forearc zone of the Caribbean Volcanic Arc.

The volcanic-sedimentary complex is a marine-deposited multiepisodic sequence and includes rocks belonging to (1) the Primitive Island Arc and (2) the Caribbean Volcanic Arc (Iturralde-Vinent 1996b; Díaz de Villalvilla 1997; Blein *et al*. 2003; Proenza *et al*. 2006). The Primitive Island Arc pre-Aptian series (dark green in Figure 2) crop out close to the Escambray complex and consist of volcanic rocks with intercalations of volcano-sedimentary and sedimentary rocks, whereas the Aptian to lower Campanian series (light green in Figure 2) crop out northward of the former series and are mainly composed of volcano-sedimentary and sedimentary rocks belonging to the Caribbean Volcanic Arc (Linares *et al*. 1985; Pushcharovsky 1988; García-Delgado *et al*. 1998; Figure 2). In the Jatibonico_78 borehole (Figure 2), the volcanic-sedimentary complex, which is over 3000 m thick, lies over ophiolitic rocks.

The plutonic complex is composed of two main textural types of granitoids (Sukar-Sastroputro and Pérez-Rodríguez 1997; Stanek *et al*. 2009): (1) the partially foliated granitoids and the gneisses intruding into the Mabujina complex (dark pink in Figure 2) and (2) the undeformed granitoids of the Manicaragua group (light pink in Figure 2) intruding into both the volcanic-sedimentary and Mabujina complexes. Using U/Pb radiometric data on zircons, Stanek *et al.* (2009) suggest an early magmatism from 132 Ma to 90 Ma, followed by ductile deformation at 90–88 Ma and the intrusion of the Manicaragua granitoids between 87 Ma and 80 Ma.

The Mabujina complex consists of high-relation T/P amphibolites, commonly schistose and banded, with collations of gneiss and hornblendites. According to the Cuban database (see review by Iturralde-Vinent *et al*. 1996), the age of the Mabujina complex ranges from 69 million years to 95 ± 2 million years (K/Ar ages). The age is refined by Grafe *et al.* (2001), who placed the minimum age of metamorphism at 80–88 million years (Rb/Sr ages) and the age of the onset of subsequent cooling at around 73 million years ($^{40}Ar/^{39}Ar$ ages). The cooling occurred at a rate of 14°C/million years. The Mabujina complex is usually interpreted as the deepest exposed component of the Caribbean Volcanic Arc and its oceanic basement (Somin and Millán 1981; Millán 1996b). However, using geochemical data, Blein *et al.* (2003) suggest that the Mabujina complex could form part of a different and older volcanic arc.

Caribeana terrane

The Caribeana terrane in the Las Villas block comprises only the Escambray complex, which crops out in a tectonic window below the Zaza terrane forming two structural domes: the Trinidad dome to the west and the Sancti Spíritus dome to the east (Figures 1 and 2). The rocks of the Escambray complex comprise monotonous metacarbonates and quartz-mica schists with tectonic slivers of metagabbro, greenschist, and serpentinite (Somin and Millán 1981; Millán and Somin 1985; Stanek *et al*. 2006). Occasionally, Upper Jurassic ammonites and Cretaceous radiolarians have been preserved within the metasedimentary rocks (Millán and Myczynski 1978; Millán and Somin 1981), suggesting that the protoliths were sedimentary rocks of a marine platform. It has been proposed that this platform was separated from the Bahamas and Yucatan borderlands (García-Casco *et al*. 2008). The metamorphosed basic and ultrabasic rocks of the Escambray complex are considered to be fragments of a subducted oceanic lithosphere, suggesting that the Escambray originated from accretionary complex to subduction channel environments (Millán 1997; Iturralde-Vinent 1998; Stanek *et al*. 2006; García-Casco *et al*. 2008).

The Escambray complex was structured as follows: (1) it consists of an antiformal stack comprising several structural units with a complex deformation and metamorphic history; (2) it contains some structural units that include high-pressure metamorphic rocks; and (3) its metamorphism is inverted, which is evidenced by the fact that the upper structural units contain metamorphic rocks of higher grade than those of the lower units (Millán 1997; Stanek *et al*. 2006; García-Casco *et al*. 2008; Figure 2).

Geochronological data (Schneider *et al*. 2004; García-Casco *et al*. 2006, 2008; Stanek *et al*. 2006) suggest that the subduction-related metamorphic peak occurred shortly before 70 Ma during the latest Campanian (García-Casco *et al*. 2008). Exhumation developed from 70 Ma and high-pressure metamorphic rocks reached the erosional surface

45 Ma as corroborated by the pebbles in the Eocene conglomerate of the Meyer Formation in the Trinidad Basin (Kantchev 1978). According to García-Casco *et al.* (2008), retrograde metamorphism followed a cold *P–T* path during exhumation, suggesting that exhumation occurred while subduction was still active. By contrast, Stanek *et al.* (2009) reported a *P–T* path corresponding to a near-isothermal decompression. Exhumation was coeval with the formation of the extensional Yucatan Basin (Pindell *et al*. 2005). The Escambray complex is thought to be a metamorphic core complex (Pindell *et al*. 2005; García-Casco *et al*. 2008). In summary, it is a result of the subduction–accretion of the Caribeana terrane under the Cretaceous volcanic arc and is assumed to be an antiformal stack that subsequently evolved as a metamorphic core complex.

Synorogenic basins

During the late Campanian to Maastrichtian, a synorogenic sequence coeval with the subduction–accretion of the Caribeana terrane was deposited onto the extinct arc. This latest Cretaceous synorogenic sequence generally overlies the Zaza terrane with an angular unconformity (Pushcharovsky 1988; Iturralde-Vinent 1994, 1998; U_K in Figure 4). From the late Campanian to the early Maastrichtian, detritic sediments were derived from the erosion of the Cretaceous volcanic arc, whereas the upper Maastrichtian sediments are essentially carbonates of a marine platform punctuated by reefs (Iturralde-Vinent 1995; Rojas-Consuegra and Núñez-Cambra 1997; Tada *et al*. 2003; Figure 4 and Table 1).

In the earliest Palaeocene, several synorogenic basins began to develop as a result of the collision of the Caribbean Volcanic Arc with the Bahamas borderland (Figures 2 and 4). These Tertiary basins cover the orogen, displaying varied relations and positions with respect to it. Their infills record a sudden deepening and the evolution from an arc-related to a collision-related setting. The basal unconformity of these basins is located on or near the *K–T* boundary (U_P in Figure 4) with the result that the latest Cretaceous synorogenic sequence may be regarded as part of the substratum. Nevertheless, the Palaeocene and latest Cretaceous sequences are concordant in the Santa Clara and Cienfuegos basins.

The sedimentary record of the Tertiary basins is summarized in Figure 4 and Tables 2 and 3. This comprises two sequences: (1) a lower synorogenic sequence, Palaeocene to middle or late Eocene in age; and (2) an upper postorogenic sequence, late Eocene to Quaternary in age. Both sequences are separated by unconformities: U_{E1} in the western and southern basins and U_{E2} in the eastern basins. The synorogenic sequence comprises olistostromic and flyschoid deposits in the deeper marine domains, whereas in the shallow-marine areas deposition was varied but dominated by clastic-carbonate deposits locally interstratified with coarse-grained detritic sediments (see Table 2 for a description of the Palaeogene synorogenic units). The postorogenic sequence presented a local character in each basin that evolved independently until the latest Oligocene. This sequence covers larger areas during the Miocene and displays gradual variations in facies and thicknesses. The most recent sedimentation period occurred during the late Pliocene to Quaternary and is separated from the Miocene successions by a hiatus embracing different time spans – depending on each basin. The postorogenic sequence is formed mainly by marly-calcareous and clastic-carbonate (partially terrigenous) series, which were initially deposited in shallow-marine environments and later in transitional to continental conditions (see Table 3 for a description of the postorogenic units).

North-central Palaeogene deposits

The Palaeocene to lower Eocene synorogenic sequence of north-central Cuba is considered part of a deformed foredeep basin (Iturralde-Vinent *et al*. 2008). These deposits unconformably overlie the Bahamas borderland units and are coeval with the deformation of this borderland. They constitute a shallowing-upward sequence and display a marked lateral variation in facies and thicknesses, thinning northeastward. The lower part appears intensively deformed and has an olistostromic character indicative of tectonic instability. These deposits include, from SE to NW, the Vega Alta, Vega, and Grande formations (Figure 4 and Table 2).

Figure 5 shows the structure of the Remedios unit in the Mayajigua area, which crops out in a tectonic window below the Camajuaní unit. The post-rift sequence of the Remedios unit includes the Purio, Vilató, Palenque, and Perros formations (Figure 3) and exceeds 3000 m in thickness. The Remedios series grade northeastward into the Cayo Coco series, which have been drilled by many deep on- and offshore boreholes in north-central Cuba. The Remedios unit is probably detached on the Jurassic evaporites that crop out in the Punta Alegre and Turiguanó diapirs (see Figure 2 for location), which can be interpreted as allochthonous salt sheet structures (see review by Hudec and Jackson 2006). The Grande Fm. is involved in the structure of the Remedios unit, indicating that this structure is younger than the Grande Fm. Thrust faults in the Camajuaní unit dip towards the SSW and the basal detachment is folded due to folding and thrusting in the Remedios unit, which is located below. This observation demonstrates that thrust faults in the Remedios and the Camajuaní units propagated in a piggyback sequence. An allochthonous sheet of serpentinite mélange (Zaza terrane) is thrusted onto the Camajuaní unit, cutting the structure of the latter unit and strongly suggesting that emplacement of the Zaza terrane occurred out-of-sequence.

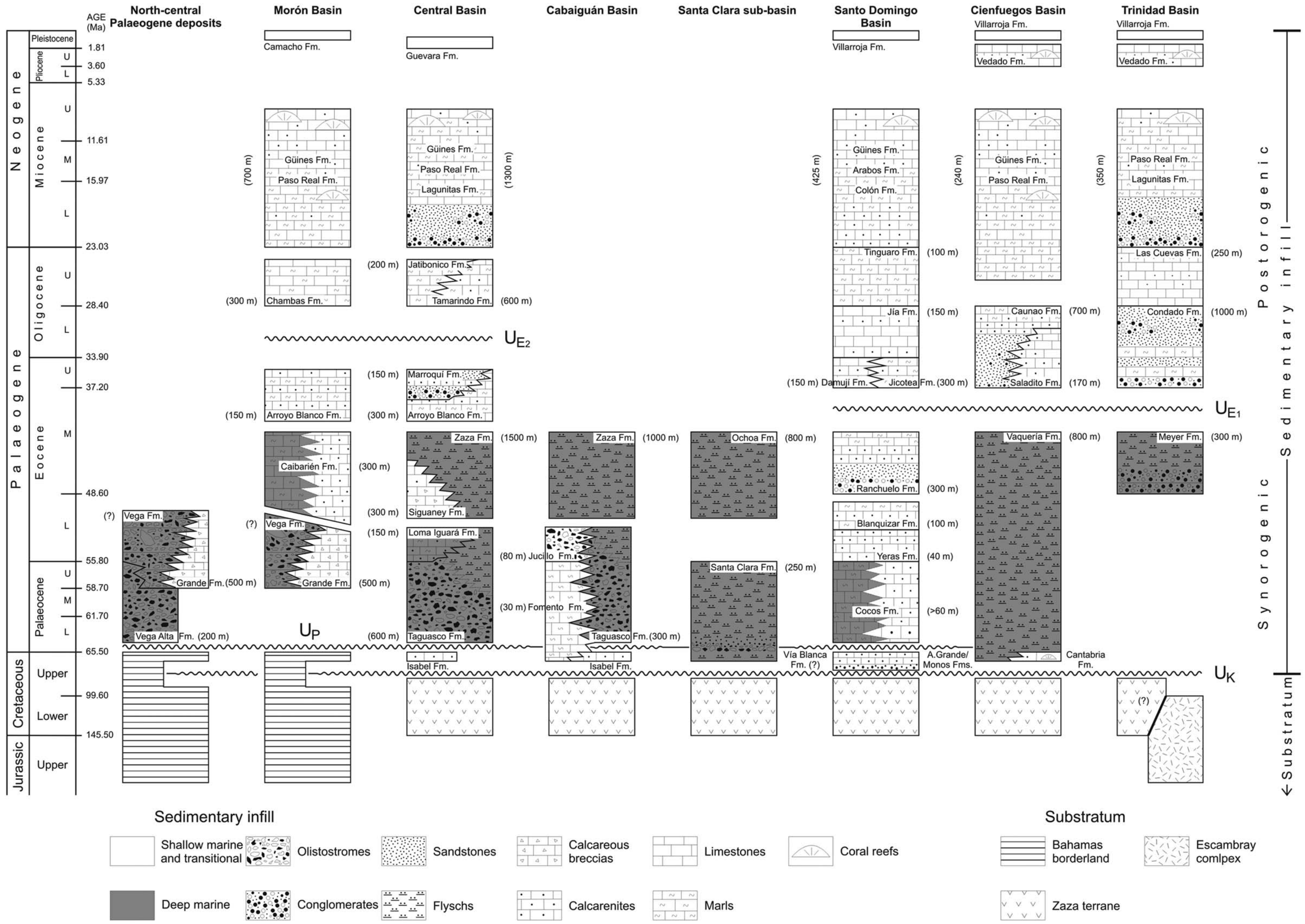

Figure 4. Synthetic lithostratigraphic columns of the sedimentary basins of central Cuba (Las Villas block) and major unconformities: U_K, basal unconformity of the latest Cretaceous synorogenic sequence; U_P, basal unconformity of the Palaeogene synorogenic sequence; and U_E, synorogenic–postorogenic unconformity. Thicknesses and lithologies of the lithostratigraphic units are compiled from Kantchev (1978), Belmustakov *et al.* (1981), Kartashov *et al.* (1981), Franco and Delgado-Damas (1997), García-Delgado and Torres-Silva (1997), Peñalver-Hernández *et al.* (1997), Rojas-Consuegra and Núñez-Cambra (1997), and Iturralde-Vinent *et al.* (2008), ages after Gradstein *et al.* (2004). See Figure 2 for location of basins and Tables 1, 2, and 3 for descriptions of lithostratigraphic units.

Table 1. Main features of the latest Cretaceous synorogenic units of central Cuba (Las Villas block).

Formation author(s)[a]	Thickness (m)	Lithologies	Fossil record	Depositional environment	Stratigraphic range
Arroyo Grande S. Gil *in*: Linares *et al.* (1985)	100–150	Calcareous series composed of marly and detritic limestones, calcarenites, biocalcarenites, and marls	Foraminifera	Continental shelf to shelf margin	Upper Maastrichtian
Cantabria I. Kantchev *in*: Kantchev (1978)	≈120	Calcareous series constituted by limestones, calcarenites, and biocalcarenites	Foraminifera and rudists	Continental shelf with local reefs	Upper Maastrichtian
Carlota K. Bandt *in*: Bandt (1958)	≈160	Calcareous series composed of calcarenites and biocalcarenites	Foraminifera, rudist, and molluscs	Continental shelf (reef)	Upper Maastrichtian
Cotorro H. Wassall and P. Truitt *in*: Brönnimann and Pardo (1954)	600–700	Siliciclastic series constituted by sandstones, conglomerates, and siltstones to mudstones. limestones, and marls	Foraminifera, ammonites, and rudists	Continental shelf to slope	Campanian to lower Maastrichtian
Isabel P. Truitt and G. Pardo *in*: Truitt and Pardo (1953)	100–150	Calcareous series composed of biocalcarenites, calcarenites, limestones, and marls	Foraminifera	Continental shelf to shelf margin	Upper Maastrichtian
Monos P. Truitt *in*: Brönnimann and Pardo (1954)	≈300	Siliciclastic series constituted by polymictic conglomerates and sandstones at base grading to calcarenites, limestones, and marls at top	Foraminifera	Continental shelf to shelf margin	Upper Campanian to lower Maastrichtian
Vía Blanca P. Brönnimann and D. Rigassi *in*: Brönnimann and Rigassi (1963)	500–800	Siliciclastic to turbiditic series composed of interbedded mudstones to siltstones, polymictic sandstones and conglomerates, calcarenites, marls, and limestones.	Foraminifera	Continental slope	Upper Campanian to lower Maastrichtian

Note: [a]Authors are taken from unpublished reports of the Stratigraphic Commission of the Institute of Geology and Palaeontology of Cuba. See also revisions by Kantchev (1978) and Rojas-Consuegra and Núñez-Cambra (1997).

Table 2. Main features of the Palaeogene synorogenic units of central Cuba (Las Villas block).

Formation author(s)[a]	Thickness (m)	Lithologies	Fossil record	Depositional environment	Stratigraphic range
Arroyo Blanco K. Bandt *in*: Bandt (1958)	150–300	Terrigenous and clastic-carbonate series composed of polymictic sandstones and conglomerates, calcarenites, biocalcarenites, limestones, and marls	Foraminifera	Continental shelf to shelf margin	Middle to upper Eocene
Blanquizar N. Popov *in*: Kantchev (1978)	100	Clastic-carbonate series constituted by marls, calcarenites, and biocalcarenites	Foraminifera	Continental shelf	Lower Eocene
Caibarién P. Ortega *in*: Ortega and Ros (1931)	300	Clastic-carbonate series composed of detritic, biodetritic, and marly limestones; marls, calcareous breccias and conglomerates, and polymictic sandstones	Foraminifera	Deep- to shallow-marine (?)	Lower to middle Eocene
Cocos N. Popov *in*: Kantchev (1978)	≥60	Clastic-carbonate (partially turbiditic) series constituted by marls, micritic limestones, and calcarenites	Mainly planktonic foraminifera	Deep- to shallow-marine (?)	Palaeocene
Fomento P. Truitt and G. Pardo *in*: Truitt and Pardo (1953)	20–30	Calcareous series composed of marls and marly limestones	Foraminifera	Mainly shallow-marine (shelf margin)	Upper Maastrichtian to Palaeocene
Grande G. Pardo *in*: Brönnimann and Pardo (1954)	500(?)	Clastic-carbonate series constituted by massive beds of calcareous breccias and breccio-conglomerates, intercalated with layers of biogenic limestones and detritic, micritic, and marly limestones	Foraminifera	Mainly shallow-marine	Upper Palaeocene to lower Eocene
Jucillo P. Truitt and G. Pardo *in*: Truitt and Pardo (1953)	80	Olistostromic series composed of breccias containing fragments of diabase, porphyry, andesite, flint, and subordinated limestones and sandstones	Unreported	Probably shallow-marine	Lower Eocene
Loma Iguará C.W. Hatten *in*: Hatten *et al.* (1958)	120–150	Clastic-carbonate series constituted by alternating beds of polymictic sandstones, calcarenites, limestones, marls, shales, and flints	Planktonic foraminifera and radiolaria	Deep-marine	Lower Eocene
Marroquí M.T. Kozary and P. Brönnimann *in*: Kozary and Brönnimann (1955)	300	Terrigenous series composed of polymictic sandstones and conglomerates, limestones, and marls	Mainly benthic foraminifera	Continental shelf	Upper Eocene
Meyer N. Popov *in*: Kantchev (1978)	300	Conglomeratic to turbiditic series constituted by thick stratified coarse-grained breccias and conglomerates grading upwards to a carbonate-turbiditic succession; the breccia and conglomerate clasts are from metamorphic rocks	Foraminifera	Mainly deep-marine (?)	Middle Eocene
Ochoa N. Popov *in*: Kantchev (1978)	800	Turbiditic series composed of thinly interbedded marls, shales, and sandstones	Foraminifera	Deep-marine (middle bathyal)	Lower to middle Eocene
Ranchuelo N. Popov *in*: Kantchev (1978)	300	Terrigenous and clastic-carbonate series constituted by thick fining-upwards succession made up of polymictic conglomerates and breccias at base grading to sandstones, marls, and limestones at top	Foraminifera	Continental shelf	Middle Eocene
Santa Clara P. Truitt *in*: Brönnimann and Pardo (1954)	250	Turbiditic series composed of breccias at base, while at top comprises microconglomerates to coarse-grained sandstones	Planktonic and small benthic foraminifera	Deep-marine (bathyal)	Upper Maastrichtian to Palaeocene

(*Continued*)

Table 2. (Continued)

Formation author(s)[a]	Thickness (m)	Lithologies	Fossil record	Depositional environment	Stratigraphic range
Siguaney P. Brönnimann and J.R. Macaulay *in*: Brönnimann and Macaulay (1955)	150–300	Clastic-carbonate series constituted by calcareous breccias, detritic, marly limestones, marls, polymictic sandstones, and conglomerates	Foraminifera	Continental shelf	Lower to middle Eocene
Taguasco P. Truitt *in*: Brönnimann and Pardo (1954)	300–600	Olistostromic to turbiditic series composed of polymictic conglomerates and breccias at base, grading upwards to a flyschoid sequence; the conglomerates and breccias are clast-supported and composed of andesite, granitoid, tuff, basalt, chert, sandstone, and limestone clasts	Planktonic foraminifera, and radiolaria	Mainly deep-marine	Palaeocene to lower Eocene
Vaquería N. Popov and I. Kantchev *in*: Kantchev (1978)	≈800	Turbiditic series (at least partially) composed of a thick succession of interstratified marl, limestone, and calcarenite beds	Foraminifera, radiolarian, and ostracod	Deep- to shallow-marine (shelf margin and slope?)	Upper Maastrichtian to middle Eocene (?)
Vega Alta L. Dodekova and V. Zlatarski *in*: Kantchev (1978)	≥200	Olistostromic series made up of sandy shales, sandstones, conglomerates, and breccias; the conglomerates and sandstones contain clasts of serpentinite, volcanic, and some metamorphic rocks; the breccias contain fragments of limestone and flint	Mainly planktonic foraminifera	Deep-marine (bathyal)	Palaeocene
Vega G. Pardo *in*: Brönnimann and Pardo (1954)	Estimated at several hundreds of metres	Olistostromic series made up of calcirudites including large olistoliths; the calcirudites contain clasts of limestone, dolostone, flint, and a few fragments of serpentinite and gabbros, and are interstratified with polymictic conglomerates, sandstones, and marls; the olistoliths are composed of Mesozoic rocks attributed to the Camajuaní unit	Foraminifera	Shelf slope to deep-marine	Upper Palaeocene to lower Eocene
Yeras N. Popov *in*: Kantchev (1978)	≈40	Clastic-carbonate series composed of biogenic and detritic limestones	Foraminifera	Continental shelf	Lower Eocene
Zaza A.A. Thiadens *in*: Thiadens (1937)	1000–1500	Turbiditic series constituted by interbedded polymictic sandstones and conglomerates, calcarenites, marls, and some limestones	Foraminifera	Shelf slope to deep-marine	Lower to middle Eocene

Note: [a]Authors are taken from unpublished reports of the Stratigraphic Commission of the Institute of Geology and Palaeontology of Cuba. See also revisions by Kantchev (1978), Belmustakov *et al.* (1981), García-Delgado and Torres-Silva (1997), Alegret *et al.* (2005), and Iturralde-Vinent *et al.* (2008).

Table 3. Main features of the postorogenic units of central Cuba (Las Villas block).

Formation author(s)[a]	Thickness (m)	Lithologies	Fossil record	Depositional environment	Stratigraphic range
Arabos M.A. Iturralde-Vinent *in*: Iturralde-Vinent (1966)	Up to120	Marly and calcareous series constituted by calcareous mudstones, marly limestones, and marls	Foraminifera, bivalve, and echinoids	Transitional (tidal flat and lagoon)	Lower to middle Miocene
Camacho I.P. Kartashov *in*: Kartashov *et al.* (1976)	Up to 3	Terrigenous series composed of siltstones and mudstones containing gypsum crystals	Unreported	Transitional (partially restricted)	Upper Pleistocene
Caunao N. Popov and I. Kantchev *in*: Kantchev (1978)	700	Terrigenous to clastic-carbonate series constituted by polymictic sandstones and conglomerates, calcarenites, biocalcarenites, and limestones	Mainly benthic foraminifera	Continental shelf	Upper Eocene to lower Oligocene
Chambas P. Truitt *in*: Brönnimann and Pardo (1954)	300	Calcareous series composed of limestones, biocalcarenites, and marls	Benthic foraminifera and molluscs	Continental shelf to shelf margin	Upper Oligocene
Colón J. Brödermann *in*: Brödermann (1945)	Up to 80	Clastic-carbonate series constituted by biocalcarenites and calcarenites, limestones, polymictic sandstones, marls, and calcareous mudstones	Foraminifera, ostracods, bivalves, echinoids, and corals	Continental shelf with local reefs	Upper Oligocene to lower Miocene
Condado N. Popov *in*: Kantchev (1978)	1000	Terrigenous series composed of conglomerates, sandstones, mudstones, and limestones; terrigenous input from Escambray complex	Mainly benthic foraminifera	Continental shelf	Upper Eocene to lower Oligocene
Damují N. Popov *in*: Kantchev (1978)	150	Calcareous series composed of limestones and biocalcarenites	Foraminifera	Continental shelf	Upper Eocene
Guevara I.P. Kartashov *in*: Kartashov *et al.* (1976)	Up to 50	Terrigenous series constituted by *claystones* and sandstones containing pisolithic, ferritic nodules, and hardpan fragments	Unreported	Littoral zone to continental (?)	Lower to middle Pleistocene
Güines A. Humboldt *in*: Humboldt (1826)	From 50 to over 1500	Clastic-carbonate to calcareous series composed of biocalcarenites, calcarenites, limestones, dolomites, and coral reefs; dolomitization is secondary	Foraminifera, ostracods, molluscs, and echinoids	Continental shelf (including reefs)	Miocene
Jatibonico H. Wassall and P. Brönnimann *in*: Brönnimann (1955)	200	Marly and calcareous series composed of marls, polymictic sandstones, and conglomerates, calcarenites, and coral reefs	Foraminifera, ostracods, echinoids, and molluscs	Continental shelf to shelf margin	Upper Oligocene
Jía N. Popov *in*: Kantchev (1978)	150	Calcareous series constituted by limestones, calcarenites, marls, and mudstones	Benthic foraminifera	Continental shelf	Lower Oligocene
Jicotea J.P. Bermúdez *in*: Bermúdez (1950)	300	Marly and calcareous series composed of marls and mudstones, polymictic sandstones, and conglomerates, calcarenites, and biocalcarenites	Foraminifera	Continental shelf to shelf margin	Upper Eocene

(*Continued*)

Table 3. (Continued)

Formation author(s)[a]	Thickness (m)	Lithologies	Fossil record	Depositional environment	Stratigraphic range
Lagunitas N. Popov and E. Kojumdjieva *in*: Kantchev (1978)	Up to 70	Terrigenous series constituted by polymictic sandstones and conglomerates, and mudstone; clastic material is composed of quartz, metamorphic rocks, volcanic, and limestones	Foraminifera, ostracods, echinoids, and molluscs	Continental shelf to transitional (beach to lagoon)	Upper Oligocene to lower Miocene
Las Cuevas N. Popov *in*: Kantchev (1978)	250	Calcareous series composed of limestones, calcarenites, and biocalcarenites, mudstones and marls, with intercalations of polymictic sandstones and conglomerates	Benthic foraminifera and corals	Continental shelf with local reefs	Upper Oligocene
Paso Real J.P. Bermúdez *in*: Bermúdez (1950)	From 30 to over 1600	Marly and calcareous series dominated by limestone and marl alternations; marly limestones, calcarenites, biocalcarenites, and coral reefs; some interbedded sandstones, mudstones to siltstones with pyrite, gypsum, halite, and lignite	Foraminifera, ostracods, echinoids, molluscs, and corals	Transitional (tidal flat and lagoon)	Upper Oligocene to upper Miocene
Saladito N. Popov *in*: Kantchev (1978)	170	Clastic-carbonate series composed of sandstones, calcarenites, and biocalcarenites	Mainly benthic foraminifera	Continental shelf	Upper Eocene to lower Oligocene
Tamarindo C.W. Hatten *in*: Hatten *et al.* (1958)	600	Calcareous and clastic-carbonate series constituted by limestones, biocalcarenites, calcarenites, marls, and mudstones	Foraminifera, molluscs, and echinoids	Continental shelf	Upper Oligocene
Tinguaro R.H. Palmer *in*: Palmer (1945)	100	Marly and calcareous series composed of marls and marly limestones	Foraminifera	Continental shelf to shelf margin	Upper Oligocene
Vedado P. Brönnimann and D. Rigassi *in*: Brönnimann and Rigassi (1963)	Up to 100	Calcareous series composed of coral reefs, biocalcarenites, and calcarenites	Foraminifera, corals, molluscs, ostracods, and echinoids	Continental shelf (reef)	Upper Pliocene to lower Pleistocene
Villaroja I.P. Kartashov *in*: Kartashov *et al.* (1976)	Up to 40	Terrigenous series constituted by mudstones to siltstones and sandstones with gravel intercalations; containing ferritic nodules and hardpan fragments	Redeposited	Littoral zone to continental (?)	Middle Pleistocene

Note: [a]Authors are taken from unpublished reports of the Stratigraphic Commission of the Institute of Geology and Palaeontology of Cuba. See also revisions by Kantchev (1978), Milián *et al.* (1979), Belmustakov *et al.* (1981), Kartashov *et al.* (1981), Franco and Delgado-Damas (1997), García-Delgado and Torres-Silva (1997), and Peñalver-Hernández *et al.* (1997).

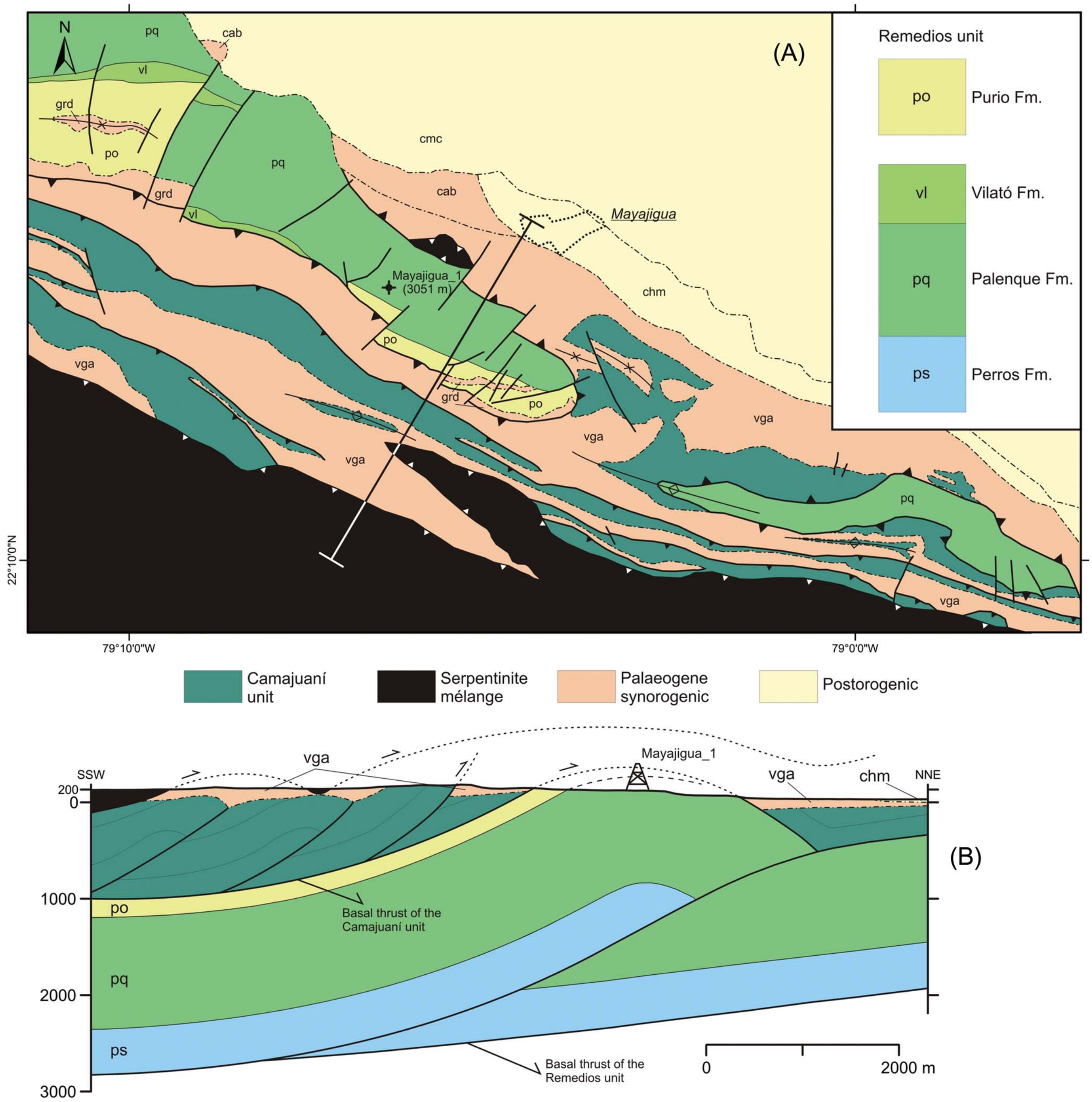

Figure 5. Structural map (A) and cross-section (B) of the Remedios unit structure at Mayajigua. The map is based on García-Delgado *et al.* (1998). Note: vga, Vega Fm.; grd, Grande Fm.; cab, Caibarién Fm.; chm, Chambas Fm.; and cmc, Camacho Fm. See details of the lithostratigraphic units in Figures 3 and 4, and Tables 2 and 3.

Figure 6 shows the thin-skinned imbricate thrust system of the Camajuaní unit in the Quemado de Güines area. The post-rift sequence of this unit includes the Trocha, Margarita, Paraíso, Mata, and Lutgarda formations (Figure 3) and is roughly 1200 m thick. These formations are unconformably covered by the upper Palaeocene to lower Eocene synorogenic Vega Fm. In the cross-section the post-rift series is more complete in the south whereas towards the north only the Trocha and Margarita formations are present. Thrust faults in this area dip SSW with the dip angle increasing southwestward. This could be related to a backward tilting to the southwest of the southern part of the section caused by the underlying structure of the Remedios unit. The Camajuaní unit is detached at the base of the Trocha Fm. The upper Palaeocene to lower Eocene Vega Fm. is both involved in and covers the

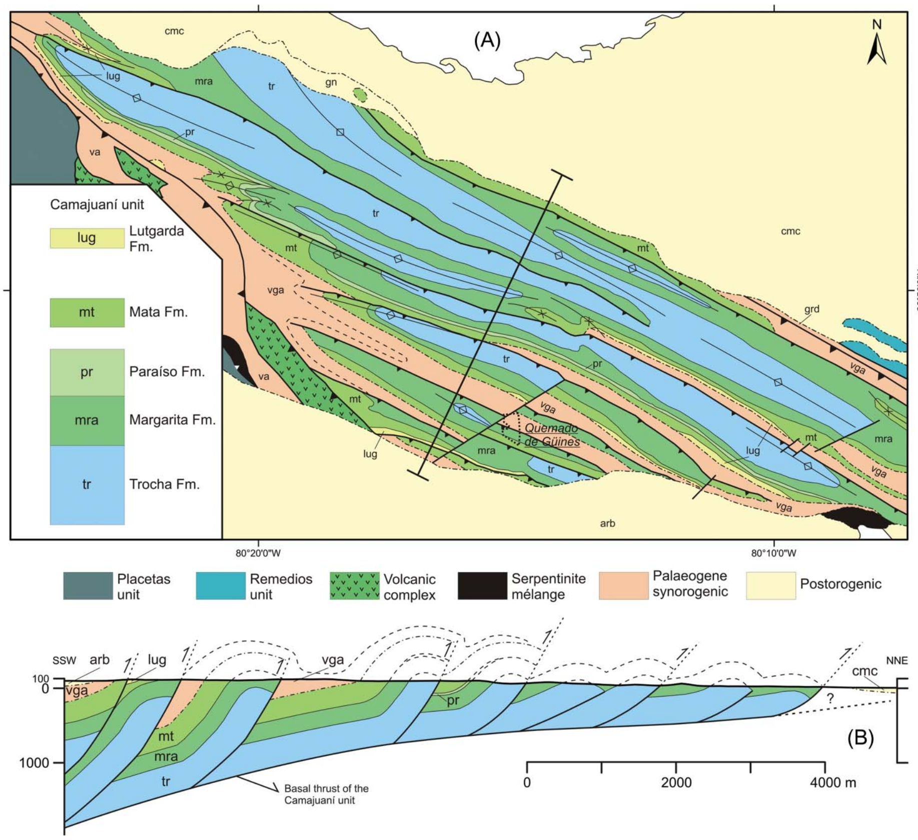

Figure 6. Structural map (A) and cross-section (B) of the Camajuaní unit structure at Quemado de Güines. The map is based on García-Delgado *et al.* (1998). Note: va, Vega Alta Fm.; vga, Vega Fm.; arb, Arabos Fm.; gn, Güines; and cmc, Camacho Fm. See details of the lithostratigraphic units in Figures 3 and 4, and Tables 2 and 3.

thrust fault system, indicating that it is syntectonic with the Camajuaní imbricate.

Figure 7 shows the structure of the Placetas unit in the Mata area, which is interpreted as an imbricate thrust system that resembles a duplex structure. The post-rift sequence of the Placetas unit includes the Constancia, Veloz, Santa Teresa, Carmita, and Amaro formations (Figure 3) and is over 1000 m thick. It is unconformably covered by the Palaeocene Vega Alta Fm. (Iturralde-Vinent *et al*. 2008). The basal detachment in the Placetas unit is situated at the base of the Constancia and Veloz formations and is presumably connected to that in the Camajuaní unit. It has been interpreted as being sub-horizontal, dipping slightly towards the SW, where it is rooted. The thrust faults of the Placetas imbricate dip southwestward. The Palaeocene Vega Alta Fm. is both involved in and covers the thrust fault system, indicating that it is syntectonic with the Placetas imbricate. The allochthonous Zaza terrane cuts thrust faults and folds of the Placetas unit, strongly suggesting that its emplacement occurred out-of-sequence. The syntectonic Vega Alta Fm. is present in the footwall of the basal thrust fault of the Zaza terrane, suggesting that the out-of-sequence thrust is subsequent (or synchronous) to its deposition. In this area, the Camajuaní unit is locally backthrusted onto the Zaza terrane and the Placetas unit with the typical geometry of a passive backthrust resulting from the emplacement of the Zaza terrane. The backthrust fault was synclinally folded after emplacement.

Morón Basin

The Morón Basin extends northeastward of the north-central Palaeogene deposits (Figure 2), onto the Remedios and Cayo Coco units. The basin covers an area exceeding 1200 km^2 on- and offshore, with a longitudinal axis striking NW–SE, which is parallel to the main trend of the Central Cuban Orogenic Belt. The depocentre of the basin is located in the southeast. As in the foregoing north-central Palaeogene deposits, the upper Maastrichtian Lutgarda and Amaro formations are included in the Bahamas units and are not regarded as a synorogenic sequence (Figure 3). Some boreholes have been drilled in the Morón Basin (Figure 2) with a maximum recorded thickness in the Morón Norte_1 (1766 m). Tertiary sedimentary infill may be divided into two major sequences: a lower synorogenic and an upper postorogenic (Figure 4 and Tables 2 and 3), which are separated by an unconformity (U_{E2}).

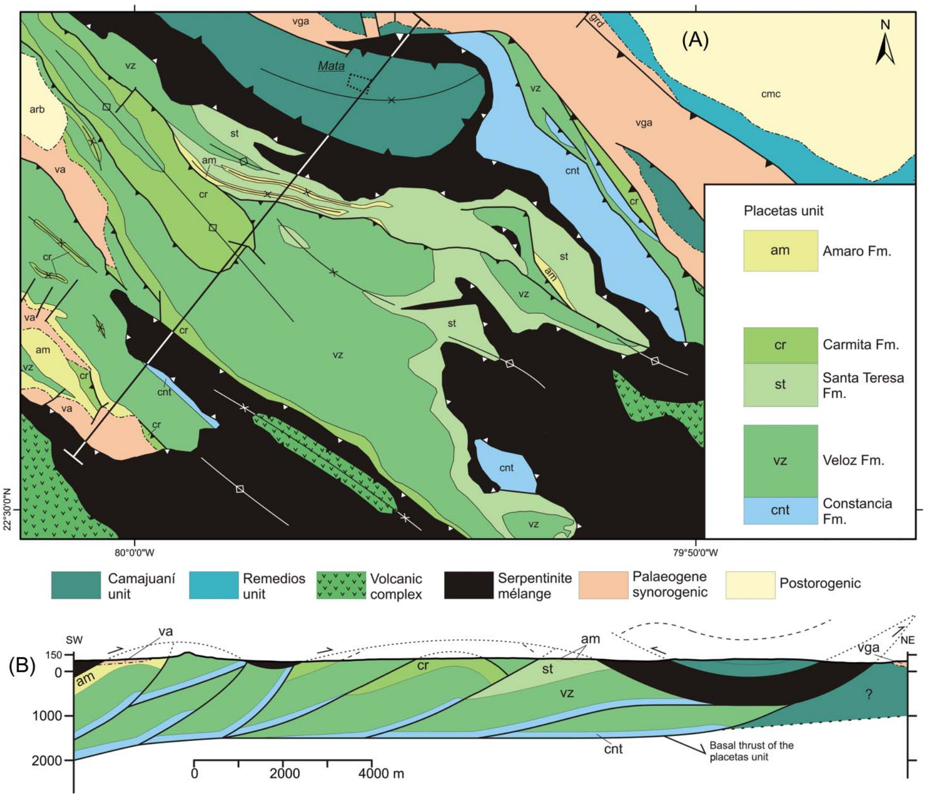

Figure 7. Structural map (A) and cross-section (B) of the Placetas unit structure at Mata. The map is based on García-Delgado *et al.* (1998). Note: va, Vega Alta Fm.; vga, Vega Fm.; cmc, Camacho Fm; arb, Arabos Fm.. See details of the lithostratigraphic units in Figures 3 and 4, and Tables 2 and 3.

The synorogenic sediments in the Morón Basin are not as thick as those in the other basins of central Cuba. The maximum thickness is around 1000 m in the Morón Norte_1 and Collazo_1 boreholes. The postorogenic sediments are widely distributed, with thicknesses wedging northwestward from over 700 m in the Morón Norte_1 borehole to less than 5 m in the Caibarién_2 borehole. Broadly speaking, the synorogenic sequence is constituted by olistostromic to clastic-carbonate series of deep- to shallow-marine environments, whereas marly-calcareous and clastic-carbonate series of shallow-marine environments predominate in the postorogenic sequence.

The Morón Basin corresponds to the northeastward prolongation of the north-central Palaeogene deposits. The substratum of the basin has been reached by a number of boreholes (e.g. Collazo_1, Manuy_1, and Morón Norte_1) that corroborate the presence of thrust faults that placed the Jurassic and Cretaceous series onto the synorogenic deposits. The structure of the substratum is interpreted as the continuation of that illustrated in Figure 5 (see also Meyerhoff and Hatten 1968). Confidential seismic data from Cubapetróleo support this interpretation and suggest that the thrust faults were involved in the origin of the Turiguanó and Punta Alegre diapirs.

Central Basin

The Central Basin, which extends west and southwest of the Las Villas block (Figure 2), occupies an area exceeding 2000 km^2 with a longitudinal axis striking SW–NE that is oblique to the main trend of the Central Cuban Orogenic Belt. This basin developed on the Zaza terrane. The latest Cretaceous synorogenic sequence in the Central Basin is constituted by the Isabel Fm. (Figure 4 and Table 1), which is a several hundred metre calcareous to clastic-carbonate succession deposited in a shallow-marine environment. Tertiary sedimentary infill may exceed 3000 m in thickness and includes a lower synorogenic and an upper postorogenic sequence separated by an unconformity (U_{E2}). The Palaeogene synorogenic sequence includes deposits related to tectonic instability at the base (olistostromic and turbiditic), grading upward to clastic-carbonate series of shallow-marine environments. The postorogenic sequence is mainly composed of marly and calcareous series, with some terrigenous inputs (Figure 4 and Tables 2 and 3).

The Central Basin is structurally related to the La Trocha fault. A cross-section of the southern part of the basin reveals a half-graben geometry associated with a normal displacement in the La Trocha fault (Figure 8). This

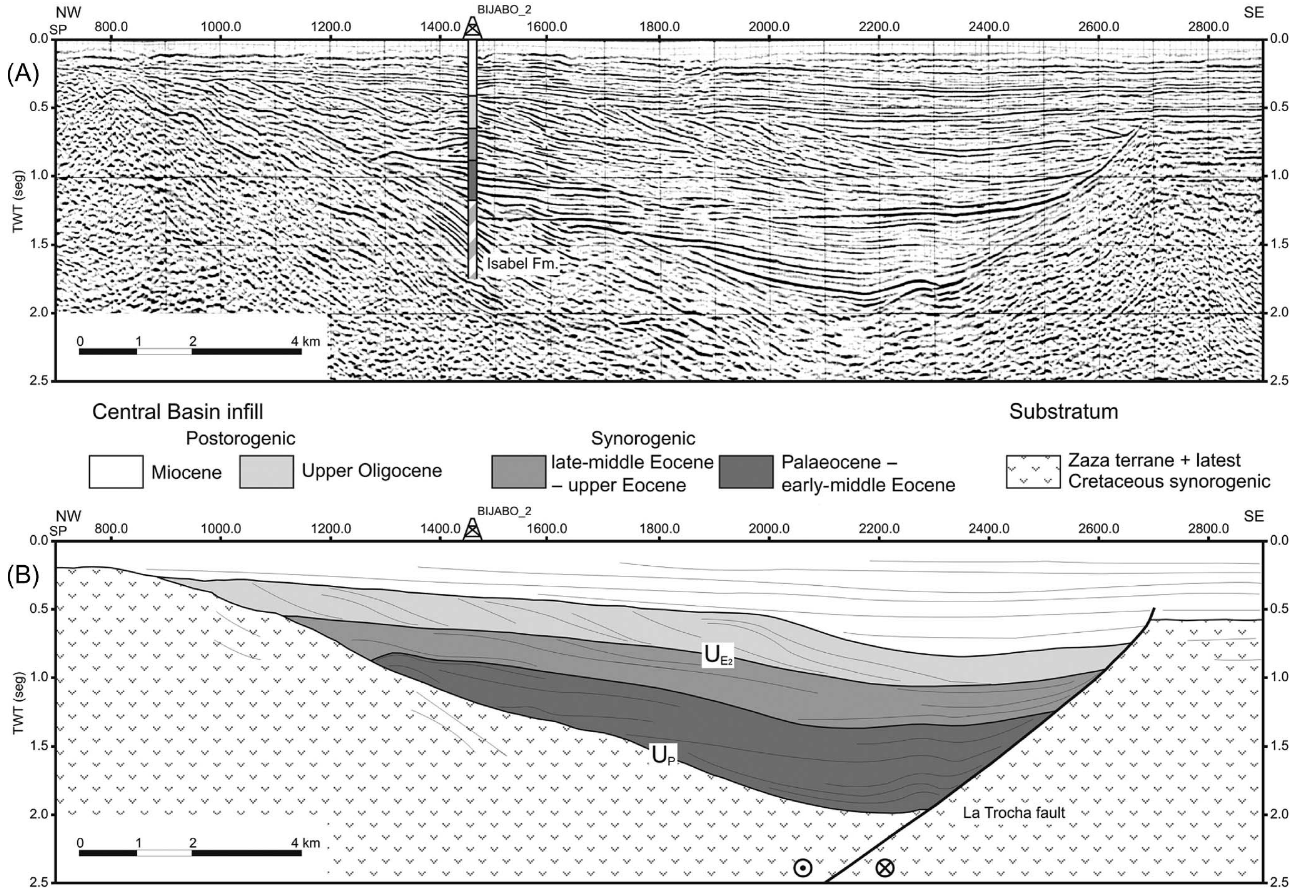

Figure 8. NW–SE seismic section (A) and line drawing (B) of the Central Basin showing a half-graben geometry associated with the La Trocha fault. U_P, basal unconformity of the Palaeogene synorogenic sequence, and U_{E2}, synorogenic–postorogenic unconformity.

interpretation is based on the Bijabo_2 borehole and shows that the La Trocha fault cuts the latest Cretaceous synorogenic sequence (i.e. the Isabel Fm.), indicating that the age of the fault displacement is post-Maastrichtian. Moreover, fault activity occurred from the Palaeocene to early-middle Eocene as corroborated by the growth strata of this age, and it probably continued until the late Eocene as suggested by a similar rate of continuous subsidence. Reflectors of the synorogenic interval (Figure 8A) present high reflectivity and a lateral change of seismic facies, which is consistent with a transition from olistostromic facies in the northwestern slope to flysch facies in the central areas. The synorogenic sequence is slightly deformed by some synsedimentary folds that gradually attenuate upwards. The middle to upper Eocene deposits show a slightly prograding southeastward geometry and are overlain (U_{E2}) by the upper Oligocene sequence, which displays a clear progradational geometry in the same direction. Miocene strata seal all the structures of the basin.

The structure of the Central Basin varies considerably along the SW–NE strike. The Jatibonico_78 borehole supports the existence of a structural high. Northeastward of this borehole lies another depocentre bounded to the NNW by the Zaza-Tuinicú fault (Figure 2). Today this part of the basin is raised and the sedimentary infill is not as thick as in the southwestern part of the basin (Cruz-Orosa *et al*. 2007). The structure of this area strongly suggests that compressional stress was due to the thrust character of the Zaza-Tuinicú fault.

Cabaiguán Basin

The Cabaiguán Basin extends westward from the Central Basin and onto the volcanic-sedimentary complex of the Zaza terrane (Figure 2). The basin currently occupies an area of 300 km^2, with a longitudinal axis striking E–W. The latest Cretaceous synorogenic sequence is equivalent to those in the Central Basin, but, towards the west, the Isabel Fm. grades into the Fomento Fm. (Figure 4 and Tables 1 and 2). The Tertiary sedimentary infill is constituted only by the Palaeogene synorogenic sediments that exceed 1500 m in thickness in the eastern part of the basin, becoming thinner towards the west. The Palaeogene synorogenic sequence consists of olistostromic and turbiditic

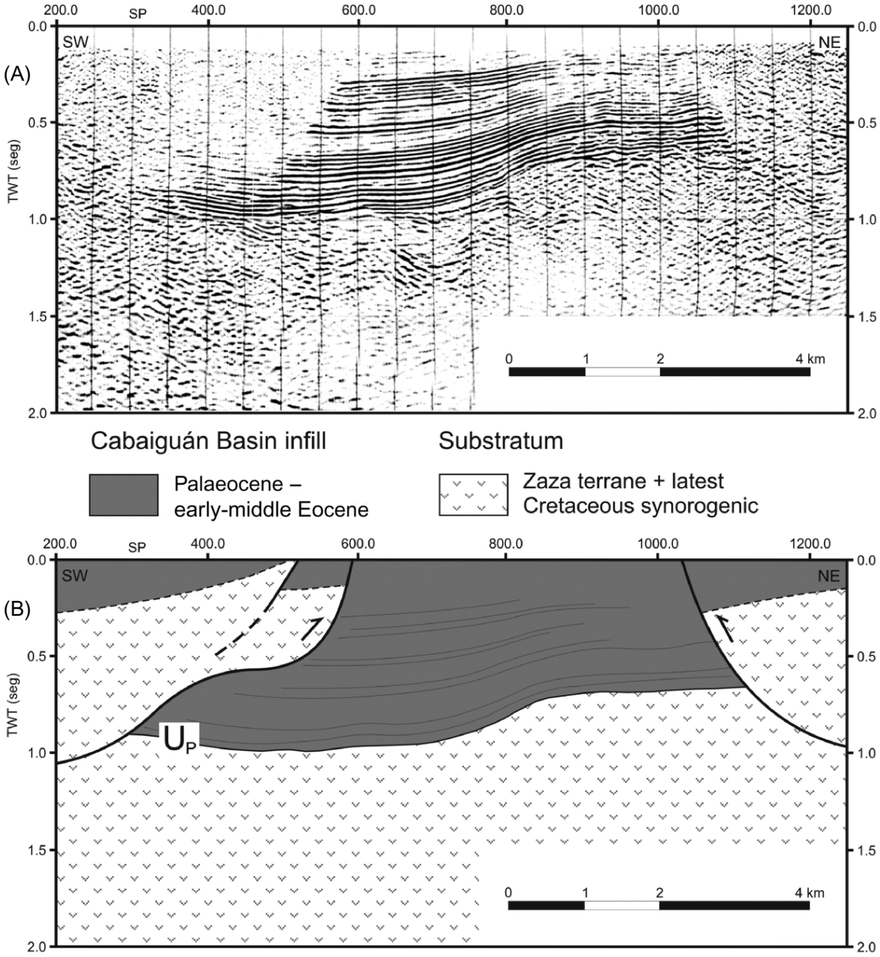

Figure 9. SW–NE seismic section (A) and line drawing (B) of the Cabaiguán Basin showing thrust faults as a main structural feature. U_P, basal unconformity of the Palaeogene synorogenic sequence.

to clastic-carbonate series of deep- to shallow-marine environments, reflecting a major E–W change in sedimentation.

The boundary between the Cabaiguán and Central basins is not clearly defined, but is probably affected by faults. The Cabaiguán Basin is limited to the west by a SSE–NNW fault (Pushcharovsky 1988; García-Delgado *et al*. 1998) and to the south by an E–W fault (Figure 2). SW–NE seismic sections (e.g. Figure 9) show thrust faults and folds affecting the Palaeocene to early-middle Eocene beds, strongly suggesting that shortening and deformation of the Cabaiguán Basin was younger than early-middle Eocene and that this basin developed over a larger area than it occupies today.

Santo Domingo suite of basins

The Santo Domingo Basin and its eastward prolongation, the Santa Clara sub-basin, lie westward of the Las Villas block (Figure 2) occupying an area exceeding 2500 km^2. This suite of basins is mainly developed on the Zaza terrane and can be structurally subdivided into three parts: the Santa Clara sub-basin, the eastern branch, and the western branch of the Santo Domingo Basin. The latest Cretaceous synorogenic sequence is well represented in the Santa Clara sub-basin by the Santa Clara Fm., in the eastern branch of the Santo Domingo Basin by the Monos and Arroyo Grande formations, and in the western branch by the two latter lithostratigraphic units probably grading westward into the Vía Blanca Fm. (Figure 4 and Table 1 and 2). These formations consist of siliciclastic, turbiditic, and clastic-carbonate series and display a shallowing-upward trend. In the Mercedes_2 borehole, the Tertiary sedimentary infill is 1600 m thick and thins progressively eastward. It is constituted by two sequences: a synorogenic and a postorogenic separated by an unconformity (U_{E1}). The Palaeogene synorogenic sequence in the Santo Domingo Basin consists of a clastic-carbonate series (partially turbiditic) with a shallowing-upward trend from deep- to shallow-marine environments, whereas it is formed only by turbiditic series of a deep-marine environment in the Santa Clara sub-basin.

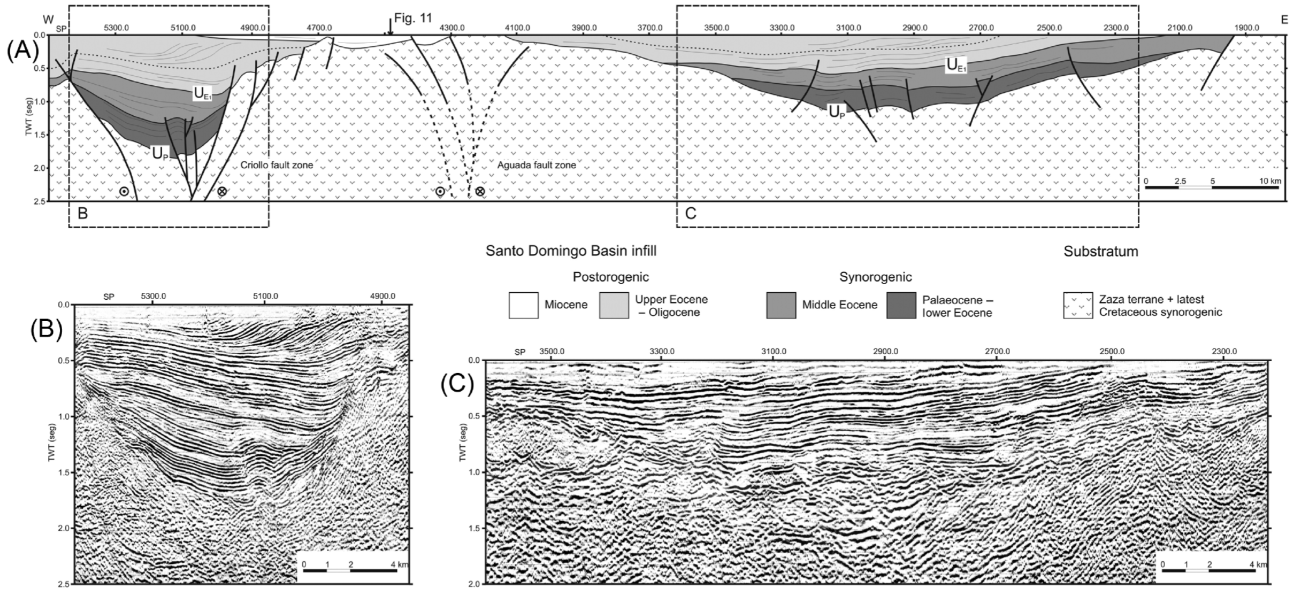

Figure 10. E–W line drawing (A) and seismic sections of the Santo Domingo Basin showing two depocentres located to the west (B) and east (C), respectively. The depocentre (B) is linked to the Criollo fault zone whereas the depocentre (C) is related to the ESE–WNW structures of the substratum. U_P, basal unconformity of the Palaeogene synorogenic sequence, and U_{E1}, synorogenic–postorogenic unconformity.

The postorogenic sequence is absent in the Santa Clara sub-basin whereas it is composed of marly-calcareous and clastic-carbonate series of shallow-marine environments in the Santo Domingo Basin (Figure 4 and Tables 2 and 3).

Seismic lines of Figures 10 and 11 show the basal unconformity (U_P) of the Santo Domingo Basin that is located at the boundary between strong and continuous reflectors and the acoustic basement. This unconformity corresponds to the *K–T* boundary based on the interpretation of the Mercedes_2 borehole.

Figure 10 shows two depocentres located to the west (Figure 10B) and east (Figure 10C), respectively. They are separated by a structural high, which is interpreted as a positive flower structure related to the Aguada left-lateral fault zone. The western depocentre has a sedimentary infill corresponding to 1.7 s of TWT (two-way traveltime) and shows a negative flower structure related to the Criollo fault zone. Syntectonic sediments associated with the faults at both margins of the depocentre suggest that an intense deformation occurred during the Palaeocene and the early Eocene. Deformation during the middle Eocene is indicated by the presence of a growth fold, which is attenuated towards the top of the sequence (U_{E1}), indicating a decline in tectonic activity. Postorogenic deposits that present westward progradational geometry filled the accommodation space after deformation. Residual activity occurred in the eastern fault during the postorogenic sedimentation. The eastern depocentre has a sedimentary infill corresponding to 1.1 s of TWT and does not present such a marked tectonic control. The main subsidence occurred from the Palaeocene to the early Eocene before diminishing during the middle Eocene. The upper Eocene to Oligocene progradational sequence is less pronounced than in the western depocentre. The eastern part of the basin is tilted to the west as shown in the seismic section. The influence of the Alacranes left-lateral fault zone on the Santo Domingo Basin is, however, not so evident.

The depocentre in the seismic section of Figure 11 has a sedimentary infill corresponding to 1.3 s of TWT. This depocentre is located between the Aguada and Alacranes fault zones and extends in an ESE–WNW direction, sub-parallel to the regional structures of the Central Cuban Orogenic Belt. In addition, the Santa Clara sub-basin is also sub-parallel to the regional structures and is located in a piggyback position on the Zaza terrane. This observation suggests that both the thrusting in the substratum and the displacement of the left-lateral fault zones controlled the genesis and evolution of the Santo Domingo suite of basins.

Broadly speaking, the structure of the Santo Domingo suite is complex. It probably comprises a number of contemporary sub-basins in which subsidence was controlled by a range of specific causes. The western branch represents a subsiding area primarily associated with the left-lateral strike–slip Criollo fault zone, whereas the eastern branch and the Santa Clara sub-basin are more closely associated with the Central Cuban Orogenic Belt structures.

Cienfuegos Basin

The Cienfuegos Basin is located southward of the Santo Domingo Basin and westward of the Trinidad dome

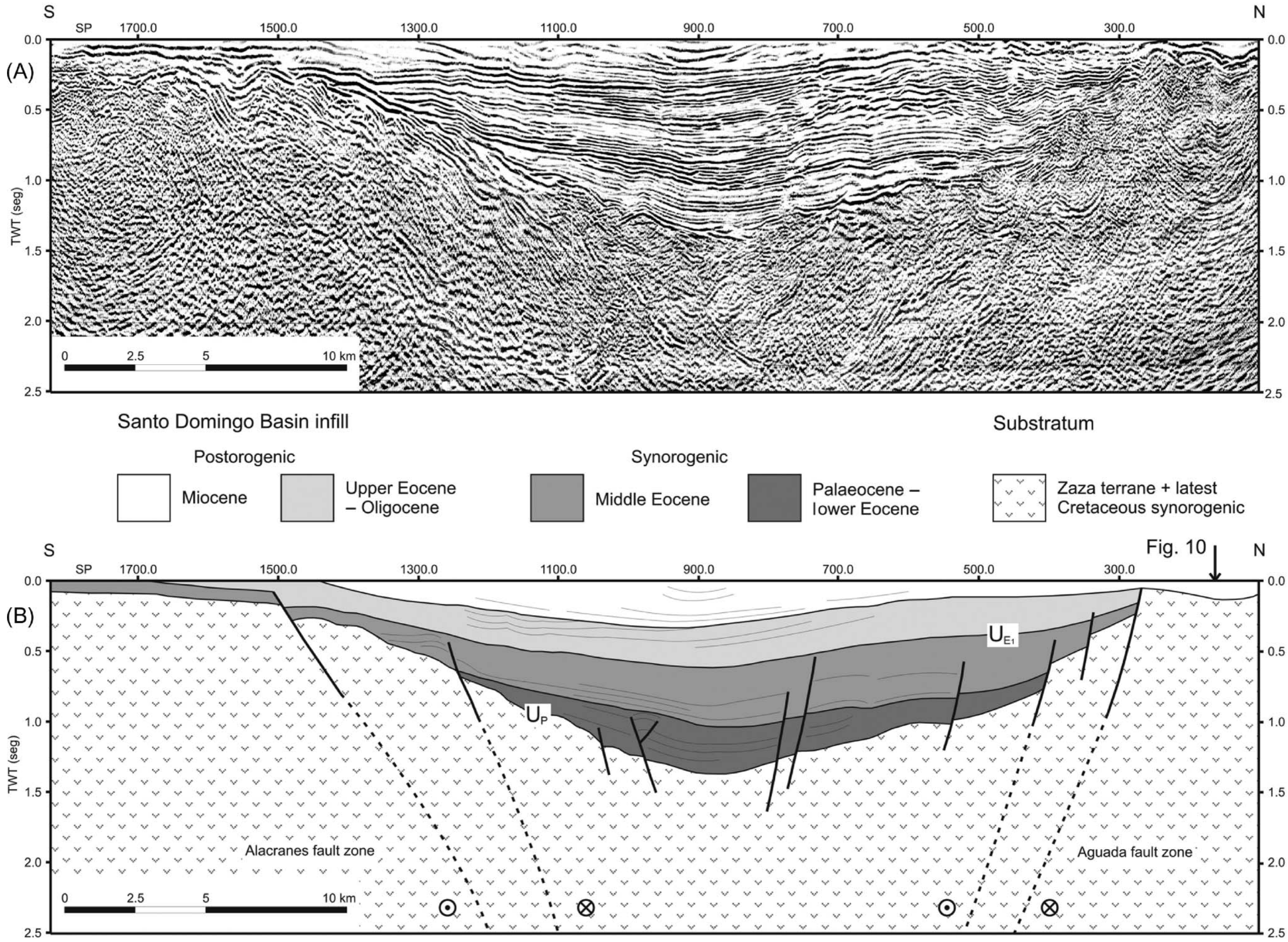

Figure 11. N–S seismic section (A) and line drawing (B) of the Santo Domingo Basin showing a depocentre striking ESE–WNW. U_P, basal unconformity of the Palaeogene synorogenic sequence, and U_{E1}, synorogenic-postorogenic unconformity.

(Figure 2). It occupies an onshore area exceeding 700 km^2 on the Zaza terrane, but probably also extended offshore. The latest Cretaceous synorogenic sequence in this basin is constituted by the upper Maastrichtian Cantabria Fm., which grades laterally into the Vaquería Fm., reflecting a change from a calcareous series of shallow-marine to a turbiditic series of deep-marine environments (Figure 4 and Table 1 and 2). Only a few boreholes have been drilled in this basin and the deepest, the Soto_1, reached a depth of 1214 m. According to subsurface and surface data, the Tertiary sedimentary infill is over 1000 m thick. The Palaeogene synorogenic sequence consists of turbiditic to clastic-carbonate series of deep- to shallow-marine environments, whereas the postorogenic sequence is mainly composed of clastic to marly carbonate series of shallow-marine environments (Figure 4 and Tables 2 and 3).

The structure of the Cienfuegos Basin is poorly documented. The basin displays a triangular shape in map view, with a SW–NE-trending syncline structure tilted towards the southwest. The eastern flank dips 10–35° towards the west whereas the northern flank dips around 10° southward. The surface data suggest that the eastern flank was passive, whereas the northern flank was tectonically active (Pushcharovsky 1988; García-Delgado *et al*. 1998).

Trinidad Basin

The Trinidad Basin extends southward of the Escambray complex, between the Sancti Spíritus and Trinidad domes (Figure 2). It occupies an onshore area of over 500 km^2 on metamorphic rocks of the Escambray, but probably extends offshore onto the Zaza terrane. The latest Cretaceous synorogenic sequence is unknown, and the Tertiary sedimentary infill has been estimated to be more than 1000 m thick according to surface data (Kantchev 1978). The Palaeogene synorogenic sedimentation began in middle Eocene times and resulted in the conglomeratic to turbiditic series of the Meyer Fm., whereas the postorogenic sequence consists of marly limestones and sandstones of shallow-marine environments (Figure 4 and Tables 2 and 3).

Few studies have been undertaken on the Trinidad Basin and little is known about its structure. Its sedimentary infill unconformably overlies the Escambray complex, becoming thicker southward. Broadly speaking, it comprises a pseudo-monocline sequence with beds dipping 10–35° southward.

Discussion

Tectonic classification of the synorogenic basins

The sedimentary basins of central Cuba constitute a collision-related system. During the latest Cretaceous (late Campanian to Maastrichtian), basins developed in forearc and intra-arc zones, and the synorogenic sedimentation records the cessation of volcanic activity and the arc erosion. A strong deepening process was recorded during the Palaeocene, and a foreland system began to develop northward of the orogen.

Given stratigraphic and structural features of the central Cuban synorogenic basins (see above and Tables 1, 2, and 3) as well as their relationships with the orogenic belt (Figures 2 and 4), two main groups of basins can be distinguished (Table 4). One group includes basins genetically related to the major strike–slip fault zones, and the other group includes basins associated with the orogenic belt structures. The latter group is subdivided into (a) a foreland basin system, (b) a forearc to piggyback basin, and (c) an intra-arc to intermontane basin.

The group related to the strike–slip faults includes the Central Basin and the western branch of the Santo Domingo Basin (Table 4). It is thought that these basins had developed from the earliest Palaeocene because the major faults cut the latest Cretaceous synorogenic sequences. Both basins are located at the ends of the Las Villas block onto the Zaza terrane. The Central Basin is related to the La Trocha and Zaza-Tuinicú faults, which form part of the La Trocha tectonic corridor (Figures 2 and 12). Similarly, the western branch of the Santo Domingo Basin appears to be linked to the Criollo fault zone.

The foreland basin system includes the north-central Palaeogene deposits and the Morón Basin (Table 4). The north-central Palaeogene deposits unconformably overlie the Bahamas units. They are coeval with the deformation of the Bahamas borderland and appear partially involved in the orogenic belt, displaying a complex geometry. According to Iturralde-Vinent *et al.* (2008), these deposits form part of a Palaeogene foredeep basin. These authors also suggest that, during foredeep sedimentation, deformation advanced northeastward, driving a migration of basin depocentres in this direction. The Morón Basin is asymmetrical in cross-section and its substratum (Remedios/Cayo Coco units) was probably affected by thrust sheets involving salt. This basin strikes NW–SE, which is sub-parallel to the substratum structures. It is reasonable to assume that the Morón Basin represents part of the Palaeogene foreland basin given its relation to and position in the fold-and-thrust belt and given the similarity of its basal sedimentary infill to that of the north-central Palaeogene deposits (i.e. the Vega and Grande Fms., Figure 4).

The forearc to piggyback basin follows an evolutionary trend from a latest Cretaceous forearc basin, which during the Palaeocene was incorporated and broken up onto the orogen as piggyback basins. This suite of basins comprises the eastern branch of the Santo Domingo Basin, the Santa Clara sub-basin, and the Cabaiguán Basin (Table 4). They share the following features: they are located in the Axial Zone of the Central Cuban Orogenic Belt (the Axial Zone is described in detail below); they have a similar strike, ESE–WNW in the case of the eastern branch of the Santo Domingo and Santa Clara basins, and E–W in the Cabaiguán Basin; and the sedimentary infill of the Santa Clara and eastern Cabaiguán basins is similar, composed solely of the synorogenic sequence that includes deep-marine turbiditic series.

The intra-arc to intermontane suite of basins includes the Cienfuegos and Trinidad basins (Table 4). These constitute an evolutionary trend from a latest Cretaceous intra-arc basin to Palaeogene intermontane basins. The origin of these basins was probably related to the onset of the formation of the Yucatan Basin (Rosencrantz 1990, 1996), which in turn was influenced by an extensional low-angle detachment in the Caribbean Volcanic Arc (Pindell *et al*. 2005; García-Casco *et al*. 2008). In the absence of data, it seems likely that both basins extend offshore.

Structural evolution of the Central Cuban Orogenic Belt

Three structural domains can be differentiated in the structural arrangement of the Las Villas block of the Central Cuban Orogenic Belt (Figure 12): (1) the Escambray Metamorphic Complex, (2) the Axial Zone, and (3) the Northern Deformation Belt.

Escambray Metamorphic Complex

This structural domain is characterized by a metamorphic complex (Escambray) that crops out in a tectonic window below the Zaza terrane and has been exhumed in an intra-arc setting (García-Casco *et al*. 2008; Figures 2 and 12). The Escambray constitutes part of an accretionary complex containing subduction-related metamorphic and platform-related metasedimentary rocks. According to Millán (1997) and Stanek *et al.* (2006), the Escambray complex is an antiformal stack that shows an inverted metamorphism and includes high-pressure metamorphic rocks and major folds resulting from a SW–NE shortening. The northern boundary of the Escambray complex is a high-angle extensional fault. This interpretation is based on the Güinía de Miranda structure (Figure 12B), where a NNE-dipping high-angle extensional fault cuts the detachment of the tectonic window.

Table 4. Main features and tectonic classification of the central Cuban synorogenic basins (Las Villas block).

	Structural relations	Geometry and structural features	Dimensions	Thickness of Cretaceous infill	Latest Cretaceous synorogenic sequence	Thickness of Tertiary infill	Palaeogene synorogenic sequence	Postorogenic sequence
Related to the major strike-slip faults								
Central Basin	Unconformably overlie the Zaza terrane	Complex, related to the La Trocha tectonic corridor	>2000 km^2, SW–NE strike	Locally up to 800 m	Shallow-marine calcareous and clastic-carbonate series	Over 3000 m	Deep- to shallow-marine olistostromic and turbiditic to clastic-carbonate series	Shallow-marine marly-calcareous and terrigenous series
Santo Domingo Basin (western branch)	The latest Cretaceous and Palaeogene synorogenic sequences are discordant with each other	Related to the Criollo fault zone	>500 km^2, SW–NE strike	100–400 m	Shallow-marine terrigenous-siliciclastic to clastic-carbonate series	Over 1600 m	Deep- to shallow-marine clastic-carbonate series (partially turbiditic)	Shallow-marine marly-calcareous and clastic-carbonate series
Foreland basin system								
Morón Basin	Unconformably overlies the Remedios and Cayo Coco units	Transversely asymmetric, probably controlled by the substratum thrust faults	>1200 km^2 on- and offshore, NW–SE strike	None: the upper Maastrichtian Amaro and Lutgarda formations are considered part of the post-rift sequence of the Bahamas borderland (?)		Over 1700 m	Deep- to shallow-marine olistostromic to clastic-carbonate series	Shallow-marine marly-calcareous and clastic-carbonate series
North-central Palaeogene deposits	Unconformably overlies the Placetas, Camajuaní, and Remedios units	Very complex, syntectonics with the structure of the Bahamas units	Highly deformed, NW–SE strike			Several hundred metres	None	
Cabaiguán Basin	Unconformably overlie the Zaza terrane	Current limits are controlled by thrust faults involving substratum	>300 km^2, E–W strike	Locally up to 500 m	Shallow-marine calcareous and clastic-carbonate series	Up to 1500 m	Deep- to shallow-marine olistostromic and turbiditic to clastic-carbonate series	None

(*Continued*)

Table 4. (Continued)

	Structural relations	Geometry and structural features	Dimensions	Thickness of Cretaceous infill	Latest Cretaceous synorogenic sequence	Thickness of Tertiary infill	Palaeogene synorogenic sequence	Postorogenic sequence
Forearc to piggyback Basin								
Santa Clara sub-basin	The latest Cretaceous and Palaeogene synorogenic sequences are both discordant and concordant with each other	Related to the substratum structure	$\approx$60 km^2, ESE–WNW strike	Few tens metres	Deep-marine turbiditic series	Estimated at 1000	Deep-marine turbiditic series	
Santo Domingo Basin (eastern branch)			$\approx$2000 km^2, ESE–WNW strike	Over 500 m	Shallow-marine terrigenous-siliciclastic to clastic-carbonate series	Up to 1000 m	Deep- to shallow-marine clastic-carbonate series	Shallow-marine marly-calcareous and clastic-carbonate series
Intra-arc to intermontane basin								
Cienfuegos Basin	Unconformably overlies the Zaza terrane. The latest Cretaceous and Palaeogene synorogenic sequences are concordant	Adapted to the substratum geometries	$>$700 km^2 onshore and extends offshore	Some tens of metres	Shallow- to deep-marine clastic-carbonate to turbiditic series	Over 1000 m	Deep- to shallow-marine turbiditic to clastic-carbonate series (?)	Shallow-marine clastic-carbonate (partially terrigenous) to marly-calcareous series
Trinidad Basin	Nonconformity with the Escambray complex	South-dipping monoclinal sequences	$>$500 km^2 onshore and extends offshore	Unreported		Roughly estimated at 1000 m	Deep- to shallow-marine breccio-conglomerate to turbiditic series	Shallow-marine marly-calcareous and terrigenous series

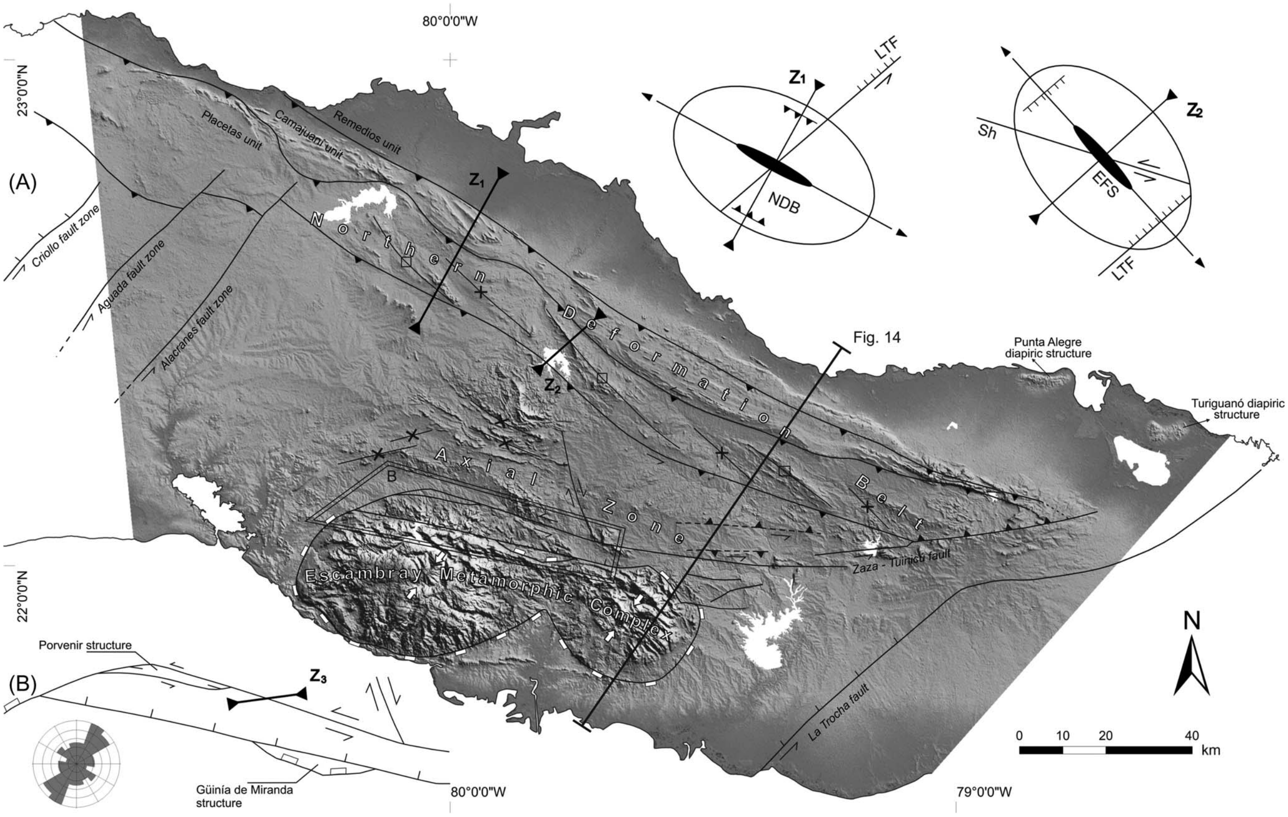

Figure 12. (A) Subcrop structural map of the Central Cuban Orogenic Belt with shaded relief. The location of some elements discussed in text is indicated. (B) detail of the structure at the northern edge of the Escambray Metamorphic Complex domain. Foliation data collected in the Sancti Spíritus dome are represented in rose plot. Note: EFS, 'en echelon' folds system in the Suture Zone; LTF, La Trocha fault; NDB, fold-and-thrust belt involving the Bahamas units; and Sh, shear in the Suture Zone. See also Figure 2 for comparison with the surface geology.

In order to better understand the evolution of the Escambray complex, the following considerations should be borne in mind:

(1) *P–T–t* paths (Schneider *et al*. 2004; García-Casco *et al*. 2006, 2008; Stanek *et al*. 2006) show a clockwise loop and demonstrate that metamorphic peak occurred shortly before 70 Ma at a pressure between 15 and 23 kbar, considering that the Escambray complex was subducted to different depths. Subsequently, a decompressional process is recorded during the exhumation that started around 70 Ma ago (Figure 13).
(2) The Escambray complex has an inverted metamorphic sequence (Millán 1997; Stanek *et al*. 2006; García-Casco *et al*. 2008; Figure 2 and 14), showing greenschist facies below of epidote-blueschist and eclogite facies. This feature suggests that the end of the compressive antiformal stack imbrication occurred after the metamorphic peak (Figure 13).
(3) Stanek *et al.* (2006) suggest various stages of deformation with a ductile–brittle trend (Figure 13), for example, the contact between the Mabujina complex and the upper unit of the Escambray consists of a mylonitic shear zone overprinted by a brittle normal fault.
(4) A significant metamorphic omission is recorded among the high-pressure metamorphic rocks of the Escambray complex and the cover rocks, especially with the non-metamorphic rocks of the volcanic-sedimentary complex (Figure 2). This strongly suggests that a major extension occurred. Probably, this extension is responsible for at least part of the exhumation (Figure 13).

Metamorphic core complexes (MCC) are domic exposures of deep-crustal metamorphic rocks structurally located below mylonitic shear zones and surrounded by non-metamorphic rocks. Deformation in the MCC shows a ductile–brittle evolution. Metamorphism in the MCC includes an initial high-pressure and a late high T/P ratio stage, following a clockwise loop. The origin of MCC is

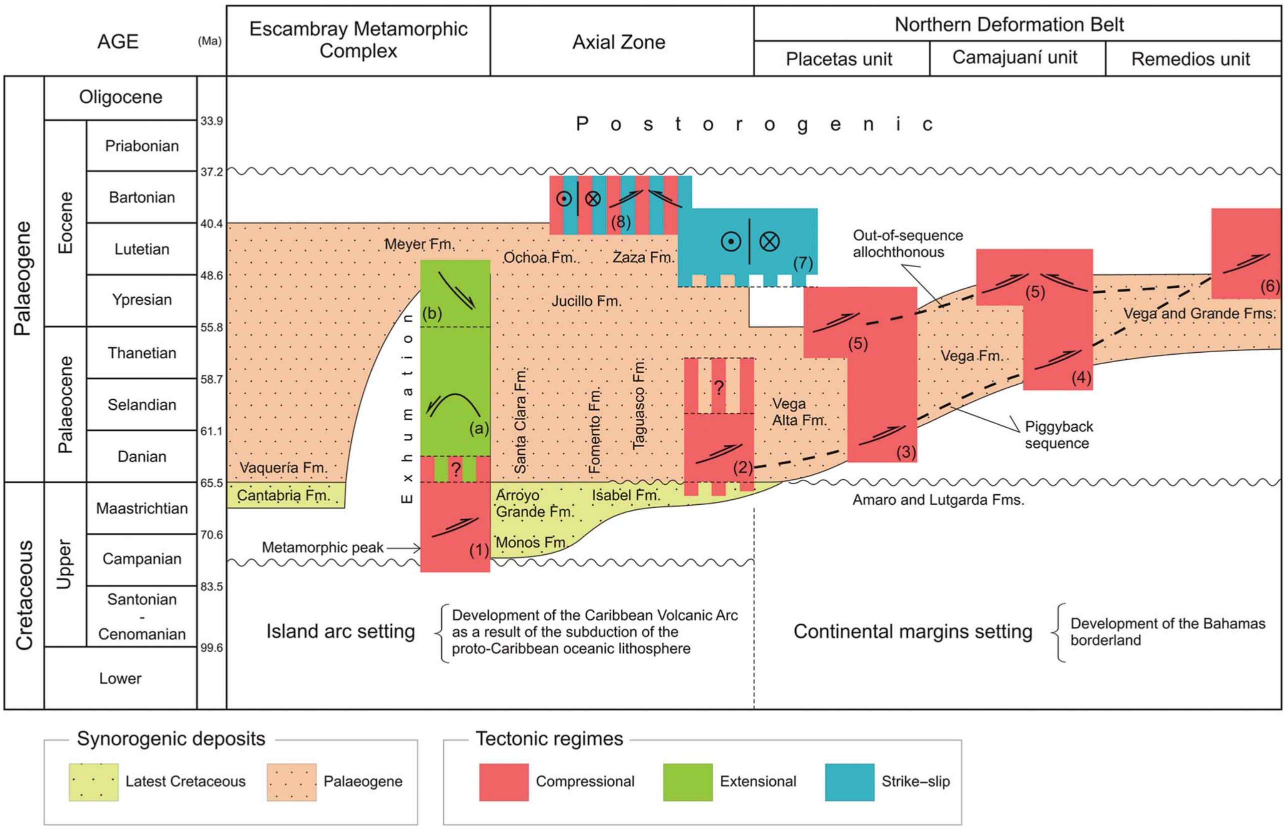

Figure 13. Timing chart showing the main deformation phases in the Central Cuban Orogenic Belt. Compressional–transpressional phases are (1) subduction–accretion of the Caribeana terrane and start of the exhumation, (2) imbrication of the Zaza terrane, (3) Placetas imbrication, (4) Camajuaní imbrication, (5) out-of-sequence overthrust of the Zaza terrane onto the Bahamas units, (6) structuration of the Remedios unit, (7) development of the left-lateral shear in the Suture Zone, and (8) transpression in the Cabaiguán Basin. Extensional phases are (a) emplacement of the Escambray metamorphic core complex (ductile exhumation), and (b) brittle deformation in the Escambray complex. Ages after Gradstein *et al.* (2004).

controversial but according to the most accepted hypothesis it results from compressional thickening followed by extension (Coney 1980; Lister and Davis 1989; McGrew *et al*. 2000; Tirel *et al*. 2008). The above considerations (2), (3), and (4) are consistent with an MCC origin for the Escambray. Nevertheless, *P–T–t* paths mentioned in (1) are inconclusive. García-Casco *et al.* (2008) support a cold path during retrogression whereas Stanek *et al.* (2009) suggest a late isothermal decompression.

Exhumation of the Escambray complex started during compression and continued through the subsequent extension (Figure 13). Considerations (1) and (2) suggest that compression ceased after the metamorphic peak and after the initiation of exhumation. In considerations (3) and (4), it is clear that extension played a major role in the structural arrangement of the Escambray complex and that rock behaviour was brittle during the end of deformation. The available data do not allow us to constrain the transit from compression to extension.

In conclusion, the Escambray complex was subducted and metamorphosed from the Campanian, reaching the high-pressure metamorphic peak during the Maastrichtian, shortly before 70 Ma. Compression in a subduction environment produced imbrication of nappes and slices, resulting in the initiation of exhumation around 70 Ma. Exhumation continued during the subsequent extension until 43 Ma (Figure 13).

Axial Zone

The Axial Zone structural domain consists of a synclinorium where the allochthonous Zaza terrane crops out (Figure 14). Northeastward of the Axial Zone, the Zaza terrane (i.e. serpentinite mélange) is exposed as nappes and tectonic klippes over the Bahamas units, whereas towards the south the Mabujina complex is exposed and eroded as a result of the exhumation of the Escambray complex. Laterally, the Axial Zone is truncated by the La Trocha corridor to the southeast and by the Criollo, Aguada, and Alacranes fault zones to the northwest (Figures 2 and 12). The Axial Zone is strongly deformed and shortened, but its structure is poorly documented owing to the absence of key horizons that are useful as reference.

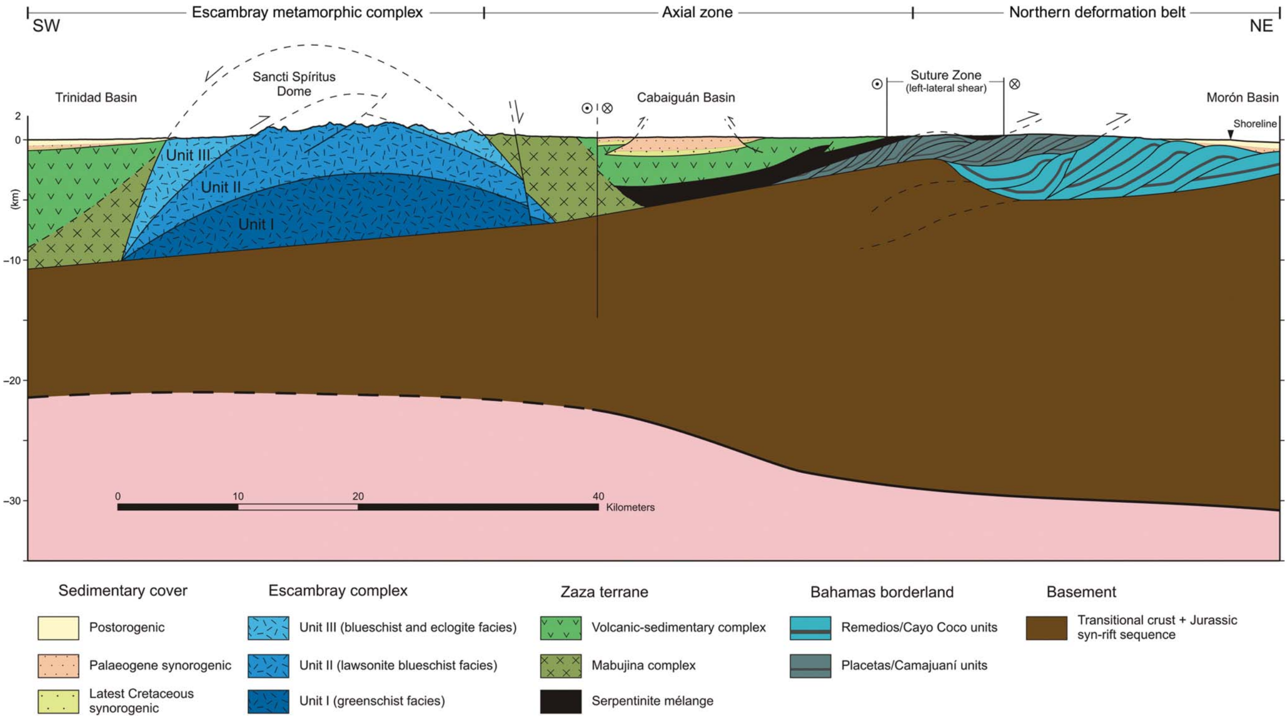

Figure 14. Upper crustal transect through the Las Villas block. Moho boundary is compiled from Otero *et al.* (1998) and Moreno-Toiran (2003), and the structural arrangement of the Escambray complex is based on Millán (1997). See location in Figures 2 and 12.

The Seibabo syncline is the most significant structure in the central part of the Axial Zone (Figure 2). This structure is complex and includes faults and second-order folds (Tait *et al*. 2009). Its northern flank is steeply dipping to overturned, whereas the southern flank dips more gently, forming a monocline structure. The latest Cretaceous synorogenic sequence (i.e. Cotorro Fm., see Table 1) is folded together with the rocks of the volcanic-sedimentary complex, suggesting that the formation of the Seibabo syncline occurred after the early Maastrichtian (Figure 13).

In the eastern part of the Axial Zone the main structure is the E–W-oriented Cabaiguán Basin. Seismic sections through this basin (e.g. Figure 9) show that the Palaeocene to middle Eocene synorogenic sequence is folded and thrusted, suggesting that the deformation in this basin and, therefore, in the Axial Zone remained active until after the early-middle Eocene (Figure 13). The E–W fault at the southern boundary of the Cabaiguán Basin is the eastward prolongation of the fault located between the Mabujina complex and the Cretaceous volcanic arc. At the western end of this fault is the Porvenir structure, which can be interpreted as a pull-apart downthrown block, suggesting a left-lateral slip of the E–W fault (Pushcharovsky 1988; García-Delgado *et al*. 1998), which is consistent with a WSW–ENE shortening (Z_3 in Figure 12B). Given the parallelism of the Cabaiguán Basin with the E–W strike–slip fault, it is reasonable to assume that this basin was deformed by transpression, giving rise to thrust faults and folds inside the basin and a strike–slip fault along its southern boundary.

Northern Deformation Belt

The Northern Deformation Belt consists of a thin-skinned imbricate thrust system that involves the Bahamas units (Figures 2, 12 and 14). Towards the southeast, it forms part of the substratum of the Central Basin as demonstrated by the Morón Norte_1 borehole. However, it is probably broken and left-laterally displaced by the Zaza-Tuinicú and La Trocha faults. This belt extends to the northwest in the subsurface of north-central Cuba as evidenced by several boreholes in the Cuban heavy-oil belt, east of La Habana (Figure 1). Towards the southwest, the Northern Deformation Belt is overthrusted by the allochthonous Zaza terrane. Offshore to the north, thrust fault deformation is attenuated (Meyerhoff and Hatten 1968, 1974; Ball *et al*. 1985; Masaferro *et al*. 1999).

From the Palaeocene to middle Eocene, the shortening axis was in a SSW–NNE direction (Z_1 in Figure 12) as corroborated by the NW–SE strike of the thrust system that affected the north-central Palaeogene deposits. During this time span, the La Trocha fault and probably the Criollo, Aguada, and Alacranes fault zones, which strike sub-parallel to the shortening axis, acted as oblique left-lateral normal faults (Figures 8, 10, and 12). Both the NW–SE strike of the thrust system and transtensional major faults are consistent with the SSW–NNE shortening.

The Placetas unit is the southwestern unit of the Northern Deformation Belt (Figures 2 and 12). It is characterized by a marked polyphase deformation (van Hinsbergen *et al.* 2008). Although the structure of the Placetas unit resembles a duplex thrust system, it is really an imbricate system cut by the basal thrust fault of the Zaza terrane (Figures 7 and 13). This pattern supports the presence of a set of tectonic slivers of Placetas rocks deeply embedded within a strongly deformed serpentinite mélange forming part of the Zaza terrane (Iturralde-Vinent *et al.* 2008). Structuration in the Placetas unit probably started during the early Palaeocene coeval with the deposition of the Vega Alta Fm. (Figure 13). The emplacement of the allochthonous Zaza terrane on the Placetas unit occurred out-of-sequence between the late Palaeocene and the earliest Eocene (see above). The Placetas unit usually crops out in tectonic windows under the Zaza terrane. Both are involved in an oblique 'en echelon' fold system (Figures 2, 7, and 12). The geometry of this fold system suggests that the Placetas unit and its contact with the Axial Zone – Suture Zone between the Zaza terrane and the Bahamas borderland – were subjected to a left-lateral shear owing to the oblique Z_2 shortening (Figures 2, 12, and 14). This shear is younger than the out-of-sequence emplacement of the Zaza terrane and could be middle Eocene in age (Figure 13).

The Camajuaní unit is located southwest of the Remedios unit (Figures 2 and 12). Structuration occurred in the Camajuaní unit from the late Palaeocene to the early Eocene, coeval with the deposition of the Vega Fm. (Figures 5, 6 and 13). The subsequent out-of-sequence emplacement of the allochthonous Zaza terrane onto the Camajuaní unit could have occurred during the late-early Eocene. The Zaza terrane is usually thrusted over the Camajuaní unit (Figure 5), but locally the Camajuaní unit is backthrusted southeastward onto the Zaza terrane (Figure 7). This backthrust accounts for the reported strips of serpentinites that are present between the Placetas and Camajuaní units (Iturralde-Vinent *et al.* 2008; Figures 6 and 7). The passive backthrust is of the same age as the emplacement of the Zaza terrane onto the Camajuaní unit because it resulted from this emplacement (Figures 7 and 13).

Remedios is the northern unit of the Northern Deformation Belt (Figures 2 and 12). It is characterized by open folds and thrust faults that can be attributed to a single deformation phase (van Hinsbergen *et al.* 2008). Its structure is subsequent to the overthrust by the Camajuaní unit and originated between the early and middle Eocene during the latest deformation phase of the Northern Deformation Belt. The Zaza terrane is not thrusted directly over the Remedios unit because this latter unit was overthrusted by the Camajuaní unit before the emplacement of the Zaza terrane (Figure 5). Folds in the Remedios unit (e.g. the anticline in Figure 5) involve the Zaza basal thrust fault, indicating that the Zaza overthrust onto the Camajuaní unit is previous to thrusting and folding in the Remedios unit (Figure 13).

Shortening and extension across the Central Cuban Orogenic Belt

The foregoing structural analysis allows us to focus on the evolution of the deformation that occurred in the Central Cuban Orogenic Belt during the collision between the Caribbean and North American plates. Shortening varies in time from a SSW–NNE Z_1 to the oblique Z_2 direction and then Z_3 in a WSW–ENE direction (Figures 12 and 13). Z_1 is supported by the NW–SE strike of the Northern Deformation Belt and is consistent with a transtensional motion in the SW–NE transversal faults, whereas Z_2 is confirmed by 'en echelon' folds of the Suture Zone between the Zaza terrane and Bahamas borderland, and Z_3 is mainly attributed to late transpressional structures along the southern Axial Zone. Shortening structures are visible along all the Las Villas transect and extends from the latest Cretaceous to the middle Eocene, with the exception of the Escambray Metamorphic Complex, where extension occurred during the earliest Palaeocene (Figures 12, 13, and 14).

Deformation in the Escambray complex is difficult to evaluate because this complex is a metamorphic equivalent of the Caribeana terrane. The structural evolution of the Escambray includes compression followed by extension. Nappes and slices of subduction-related metamorphic rocks were imbricated, and the resulting antiformal stack was subsequently exhumed in an extensional setting. This evolution gave rise to a complex structure and, at present, the magnitude of its shortening and extension cannot be evaluated. Palaeomagnetic data provided by Tait *et al.* (2009) suggest a northeastward displacement of the Cretaceous volcanic arc of about 1000 km. This displacement supports the postulated subduction of the proto-Caribbean oceanic lithosphere under the Caribbean Plate and could be equivalent to the Late Cretaceous width of the proto-Caribbean domain. This quantification is in close agreement with earlier palaeogeographic and palaeotectonic models proposed by Pindell and Kennan (2001) and Iturralde-Vinent (2006). Caribeana would have occupied part of this proto-Caribbean domain, but its original dimension cannot easily be restored.

Nor is it easy to evaluate the shortening of the Axial Zone because its structure has not yet been fully unravelled. However, the structure of the Cabaiguán Basin, as imaged in the seismic section in Figure 9, suggests that the Cabaiguán is a piggyback basin that developed on the extinct Cretaceous volcanic arc with an estimated pre-deformation width of 20–30 km in SW–NE direction. This feature supports a shortening in the Cabaiguán Basin of more than 10 km. The shortening of the Axial Zone must be greater than that observed in the Cabaiguán Basin because the cross-section through this basin is only a part of the Axial Zone cross-section. In addition, the Zaza terrane was thrusted at least 25 km onto the Bahamas borderland (Figures 2, 5, 7, and 13).

In the Northern Deformation Belt, the estimated shortening of the Placetas unit is over 9 km (Figure 7), suggesting that the minimum original width of the Placetas deep-marine basin was 27 km. The estimated shortening of the Camajuaní unit is about 6 km (Figure 6), indicating that the minimum original width of the Camajuaní continental slope was 17 km. In the Mayajigua area (Figure 5), the Camajuaní unit was thrusted at least 10 km onto the Remedios unit. This displacement diminished westward. The shortening in the Remedios unit is not easy to quantify because of limited exposures to the north. According to borehole data and some structural evidence, the shortening diminishes northward (Meyerhoff and Hatten 1968, 1974; Ball *et al*. 1985; Masaferro *et al*. 1999).

In summary, these data suggest that the minimal structural shortening of the Northern Deformation Belt is at least 25 km excluding that in the Remedios/Cayo Coco units. The shortening in the Axial Zone is unknown but greater than 35 km. Finally, the shortening and extension in the Escambray Metamorphic Complex remains highly speculative.

Concluding remarks

The collision between the Caribbean and North American plates resulted in an orogenic belt and an associated set of synorogenic basins. A tectono-stratigraphic analysis of these basins allows us to refine the structural evolution of the orogen. In the case of the Las Villas block in central Cuba, the following conclusions may be drawn:

(1) The synorogenic basins of central Cuba constitute a collision-related system in which two groups can be distinguished: (1) basins related to the major strike–slip structures and (2) basins associated with the orogenic belt (contractional) structures. The latter group is subdivided into (1) a foreland basin system, (2) a forearc to piggyback basin, and (3) an intra-arc to intermontane basin. The Central Basin and the western branch of the Santo Domingo Basin are related to the La Trocha corridor and to the Criollo fault zone, respectively. The north-central Palaeogene deposits and the Morón Basin form part of a foreland basin system, and developed on the Northern Deformation Belt of the orogen. The eastern branch of the Santo Domingo Basin and the Santa Clara and Cabaiguán basins are located in the Axial Zone of the orogen and are considered to be parts of a former forearc basin, which was subsequently fragmented and incorporated into the Central Cuban Orogenic Belt as piggyback basins. The Cienfuegos and Trinidad basins developed under an extensional regime attributed to the opening of the Yucatan Basin and are representative of a former intra-arc basin that later evolved as intermontane basins.

(2) Major SW–NE to WSW–ENE left-lateral structures in the Las Villas block also show an important normal component (e.g. the La Trocha fault and the Criollo fault zone). These structures are coeval with the Cuban NW–SE striking folds and thrusts, and form part of the major tectonic corridors and/or transfer faults that facilitated a strain-partitioning regime during collision between the North American and Caribbean plates.

(3) In the Northern Deformation Belt, a thin-skinned thrust fault system formed from the Palaeocene to the middle Eocene. Deformation occurred in a piggyback sequence with tectonic transport towards the NNE. Odd features and geometries resulted from the evolution of the thrust system. For instance, the polyphase deformation in the Placetas unit reflect imbrication followed by the out-of-sequence overthrust of the Zaza terrane, and by the left-lateral shear in the Suture Zone that gave rise to a set of 'en echelon' folds. Moreover, the presence of some strips of serpentinites between the Placetas and Camajuaní units is corroborated by a local backthrust of the Camajuaní onto the Zaza terrane and Placetas unit. The occurrence of the Remedios unit in tectonic windows and the single-phase deformation of this unit strongly suggest that the imbrication of the Remedios unit was younger in the Northern Deformation Belt.

(4) The Axial Zone was strongly deformed and shortened from the latest Cretaceous to the Eocene. It is difficult to assess the time of onset and cessation of the compression, which was probably active in the early Palaeocene. Subsequent transpressive deformation occurred in the middle Eocene and was recorded in the Cabaiguán Basin.

(5) The Escambray Metamorphic Complex resulted from strong deformation. Compression during the latest Cretaceous produced imbrication, which gave rise to inverted metamorphism. Extension permitted the emplacement of the metamorphic core complex producing structures that evolved from ductile to brittle during the Palaeocene and early Eocene. Both tectonic regimes contributed to exhumation of the Escambray unit.

(6) Different structural styles may be distinguished along the Central Cuban Orogenic Belt. This transect comprises an imbricated thrust system that affected the North American continental margin; it

was overthrusted by a strongly deformed volcanic arc and involved the emplacement of a metamorphic core complex. Deformation was active from the late Campanian to the middle Eocene. During this time span, compression migrated northeastward. Extension occurred during the Palaeocene and the early Eocene in the southern structural domain of the regional transect and was coeval with compression to the north. Strike–slip affected most of the Central Cuban Orogenic Belt during the middle Eocene, except for the northernmost area where compression remained active.

(7) The shortening direction rotated clockwise during deformation. SSW–NNE shortening (Z_1) prevailed from the late Campanian to the early Eocene. During the middle Eocene, shortening turned first to the SW–NE (Z_2) and later to the WSW–ENE (Z_3) directions. Z_1 generated the NW–SE striking fold-and-thrust belt, the transtensional SW–NE faults, and the related basins; Z_2 was responsible for the left-lateral shear in the Suture Zone; and Z_3 produced the left-lateral transpression in the E–W Cabaiguán Basin and the Axial Zone. We estimate a partial shortening of the Central Cuban Orogenic Belt of at least 60 km.

(8) The synchronicity of compression in the north and extension in the south is consistent with the opening of the Yucatan Basin on the south, during collision. The proto-Caribbean slab rollback probably played a key role as suggested by Pindell *et al.* (2005). Moreover, the evolution from compression–extension to transpression is in keeping with the increase in obliquity in the collision between the North American and Caribbean plates.

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References

Alegret, L., Arenillas, I., Arz, J.A., Díaz, C., Grajales-Nishimura, J.M., Meléndez, A., Molina, E., Rojas, E., and Soria, A.R., 2005, Cretaceous-paleogene boundary deposits at Loma Capiro, central Cuba: Evidence for the Chicxulub impact: Geology, v. 33, p. 721–724.

Ball, M.M., Martin, R.G., Bock, W.D., Sylvester, R.E., Bowles, R.M., Taylor, D.E., Coward, L., Dodd, J.E., and Gilbert, L., 1985, Seismic structure and stratigraphy of northern edge of Bahaman-Cuban collision zone: AAPG Bulletin, v. 69, p. 1275–1294.

Bandt, K., 1958, Geology of the Jatibonico area, Las Villas and Camagüey provinces: La Habana, Cuba, Archivo del Servicio Geológico Nacional, unpublished report.

Belmustakov, E., Dimitriva, E., Ganev, M., Haydutov, I., Kostadinov, I., Ianev, S., Ianeva, J., Kojumdjieva, E., Koshujarova, E., Popov, N., Shopov, V., Tcholakov, P., Tchounev, D., Tzankov, T., Cabrera, R., Diaz, C., Iturralde, M., and Roque, F., 1981, Geología del territorio Ciego – Camagüey – Las Tunas. Resultado de las investigaciones y levantamiento geológico a escala 1:250 000: La Habana, Cuba, Archivo del Servicio Geológico Nacional, unpublished report.

Bermúdez, P.J., 1950, Contribución al estudio del Cenozoico Cubano: Memorias de la Sociedad Cubana de Historia Natural, v. 19, p. 205–375.

Blein, O., Guillot, S., Lapierre, H., Mercier-de-Lepinay, B., Lardeaux, J.M., Millán, G., Campos, M., and García, A., 2003, Geochemistry of the Mabujina complex, central Cuba: Implications on the Cuban Cretaceous arc rocks: Journal of Geology, v. 111, p. 89–101.

Brödermann, J., 1945, Breve reseña geológica de la Isla de Cuba: Revista de la Sociedad Cubana de Ingeniería, v. 42, p. 110–149.

Brönnimann, P., 1955, Reporte paleontológico de muestras de superficie y de pozos: La Habana, Cuba, Archivo del Instituto de Hidroeconomía, Ministerio de la Construcción, unpublished report.

Brönnimann, P., and Macaulay, R.J., 1955, Annotations to correlation chart of the Fomento-Jatibonico areas and catalogue of formations: La Habana, Cuba, Archivo del Servicio Geológico Nacional, unpublished report.

Brönnimann, P., and Pardo, G., 1954, Annotations to the correlation chart and catalogue of formations (Las Villas province): La Habana, Cuba, Archivo del Servicio Geológico Nacional, unpublished report.

Brönnimann, P., and Rigassi, D., 1963, Contribution to the geology and paleontology of the area of the city of La Habana, Cuba and its surroundings: Eclogae Geologicae Helvetiae, v. 56, p. 193–430.

Bush, V.A., and Sherbacova, I.N., 1986, New data on the deep tectonics of Cuba: Geotectonics, v. 3, 24–43.

Cobiella-Reguera, J.L., 2005, Emplacement of Cuban ophiolites: Geologica Acta, v. 3, p. 273–294.

Cobiella-Reguera, J.L., 2009, Emplacement of the northern ophiolites of Cuba and the Campanian-Eocene geological history of the northwestern Caribbean-SE Gulf of Mexico region, *in* James, K.H., Lorente, M.A., and Pindell, J.L., eds., The origin and evolution of the Caribbean Plate: Geological Society, London, Special Publications v. 328, p. 315–338.

Coney, P.J., 1980, Cordilleran metamorphic core complexes: An overview, *in* Crittenden, M.D., Coney, P.J., and Davis, G.H., eds., Cordilleran metamorphic core complexes: Geological Society of America Memoir, v. 153, p. 7–34.

Cruz-Orosa, I., Blanco-Moreno, J.A., and Vázquez-Taset, Y.M., 2007, Análisis estructural a escala regional de la zona de fallas La Trocha: Minería y Geología, v. 23, p. 1–24.

Díaz de Villalvilla, L., 1997, Caracterización geológica de las formaciones volcánicas y volcano-sedimentarias en Cuba central. provincias Cienfuegos, Villa Clara, Sancti Spíritus, *in* Furrazola-Bermúdez, G., and Núñez-Cambra, K., eds., Estudios sobre Geología de Cuba: La Habana, Cuba, Centro Nacional de Información Geológica, p. 325–344 (published March 1998).

Díaz-Otero, C., Furrazola-Bermúdez, G., and Iturralde-Vinent, M.A., 1997, Estratigrafía de la zona de Remedios, *in* Furrazola-Bermúdez, G., and Núñez-Cambra, K., eds., Estudios sobre Geología de Cuba: La Habana, Cuba, Centro Nacional de Información Geológica, p. 221–242 (published March 1998).

Draper, G., and Barros, A., 1994, Chapter 4: Cuba, *in* Donovan, S.K., and Jackson, T.A., eds., Caribbean geology: An introduction: Kingston, Jamaica, University of the West Indies Publishers' Association, p. 65–86.

Ducloz, C., and Vuagnat, V., 1962, A propose de l'age des serpentinites de Cuba: Archives des Sciences, Socièté de Physique et d'Histoire Naturelle, Geneve, v. 15, p. 309–332.

Fonseca, E., Zelepugin, V.N., and Heredia, M., 1985, Structure of the ophiolite association of Cuba: Geotectonic, v. 19, 321–329.

Franco, G.L., and Delgado-Damas, R., 1997, Sistema Neógeno, *in* Furrazola-Bermúdez, G., and Núñez-Cambra, K., eds., Estudios sobre Geología de Cuba: La Habana, Cuba, Centro Nacional de Información Geológica, p. 141–164 (published March 1998).

Furrazola-Bermúdez, G., and Gil-González, S., 1997, Notas sobre la estratigrafía de las zonas Placetas y Camajuaní en Cuba Central, *in* Furrazola-Bermúdez, G., and Núñez-Cambra, K., eds., Estudios sobre Geología de Cuba: La Habana, Cuba, Centro Nacional de Información Geológica, p. 215–220 (published March 1998).

García-Casco, A., Iturralde-Vinent, M.A., and Pindell, J.L., 2008, Latest Cretaceous collision/accretion between the Caribbean Plate and Caribeana: Origin of metamorphic terranes in the Greater Antilles: International Geology Review, v. 50, p. 781–809.

García-Casco, A., Torres-Roldán, R.L., Iturralde-Vinent, M.A., Millán, G., Núñez, K., Lázaro, C., and Rodríguez-Vega, A., 2006, High pressure metamorphism of ophiolites in Cuba: Geologica Acta, v. 4, p. 63–88.

García-Delgado, D., Delgado-Damas, R., Millán, G., Díaz de Villalvilla, L., Sukar-Sastroputro, K., Llanes, I., Bernal, L., Rojas-Agramonte, Y., Pérez-Pérez, C., Díaz-Otero, C., Furrazola-Bermúdez, G., Peñalver, L., García-Cádiz, I., Pardo, M., Suárez, V., and Duani, E., 1998, Mapa Geológico de Cuba Central (Provincias Cienfuegos, Villa Clara y Sancti Spíritus) a escala 1:100 000: Memorias del III Congreso Cubano de Geología, v. I, p. 263–266.

García-Delgado, D., and Torres-Silva, A., 1997, Sistema Paleógeno, *in* Furrazola-Bermúdez, G., and Núñez-Cambra, K., eds., Estudios sobre Geología de Cuba: La Habana, Cuba, Centro Nacional de Información Geológica, p. 115–140 (published March 1998).

Gradstein, F.M., Ogg, J.G., Smith, A.G., Agterberg, F.P., Bleeker, W., Cooper, R.A., Davydov, V., Gibbard, P., Hinnov, L.A., House, M.R., Lourens, L., Luterbacher, H.P., McArthur, J., Melchin, M.J., Robb, L.J., Shergold, J., Villeneuve, M., Wardlaw, B.R., Ali, J., Brinkhuis, H., Hilgen, F.J., Hooker, J., Howarth, R.J., Knoll, A.H., Laskar, J., Monechi, S., Plumb, K.A., Powell, J., Raffi, I., Röhl, U., Sadler, P., Sanfilippo, A., Schmitz, B., Shackleton, N.J., Shields, G.A., Strauss, H., Van Dam, J., van Kolfschoten, T., Veizer, J., and Wilson, D., 2004, A geologic time scale 2004: Cambridge, Cambridge University Press, 589 p.

Grafe, F., Stanek, K.P., Baumann, A., Maresch, W.V., Hames, W.E., Grevel, C., and Millán, G., 2001, Rb-Sr and 40Ar/39Ar mineral ages of granitoid intrusives in the Mabujina Unit, Central Cuba: Thermal exhumation history of the Escambray massif: Journal of Geology, v. 109, p. 615–631.

Hatten, C.W., Schooler, O.E., Giedt, N., and Meyerhoff, A.A., 1958, Geology of central Cuba, eastern Las Villas and western Camagüey provinces: La Habana, Cuba, Archivo del Servicio Geológico Nacional, unpublished report.

Hudec, M.R., and Jackson, M.P., 2006, Advance of allochthonous salt sheets in passive margins and orogens: AAPG Bulletin, v. 90, p. 1535–1564.

Humboldt, A., 1826, Voyage aux regions equinoxiales du Nouveau Continent fait in 1799, 1800, 1801, 1802, 1803 et 1804: Gide, Paris, v. 2, p. 229–231.

Iturralde-Vinent, M.A., 1966, Comentarios a la obra Geología de Cuba del Instituto Cubano de Recursos Minerales: Revista Tecnológica, v. 4, p. 18–21.

Iturralde-Vinent, M.A., 1994, Cuban geology: A new plate tectonic synthesis: Journal of Petroleum Geology, v. 17, p. 39–70.

Iturralde-Vinent, M.A., 1995, Cuencas sedimentarias del Paleoceno-Eoceno de Cuba: Boletín Sociedad Venezolana de Geología, v. 20, p. 75–80.

Iturralde-Vinent, M.A., 1996a, Geología de las Ofiolitas de Cuba, *in* Iturralde-Vinent, M.A., ed., Cuban ophiolites and volcanic arcs. Special Contribution no. 1 to IGCP Project 364: Miami, FL, p. 83–120.

Iturralde-Vinent, M.A., 1996b, Cuba: el arco de islas volcánicas del Cretácico, *in* Iturralde-Vinent, M.A., ed., Cuban ophiolites and volcanic arcs. Special Contribution no. 1 to IGCP Project 364: Miami, FL, p. 179–189.

Iturralde-Vinent, M.A., 1997, Introducción a la geología de Cuba, *in* Furrazola-Bermúdez, G., and Núñez-Cambra, K., eds., Estudios sobre Geología de Cuba: La Habana, Cuba, Instituto de Geología y Paleontología, p. 35–68 (published March 1998).

Iturralde-Vinent, M.A., 1998, Sinopsis de la constitución geológica de Cuba: Acta Geológica Hispánica, v. 33, p. 9–56.

Iturralde-Vinent, M.A., 2006, Meso-Cenozoic Caribbean paleogeography: Implications for the historical biogeography of the region: International Geology Review, v. 48, p. 791–827.

Iturralde-Vinent, M.A., Díaz-Otero, C., García-Casco, A., and van Hinsbergen, D.J.J., 2008, Palaeogene foredeep basin deposits of north-central Cuba: A record of arc-continent collision between the Caribbean and North American plates: International Geology Review, v. 50, p. 863–884.

Iturralde-Vinent, M.A., and García-Casco, A., 2007. Caribeana, a possible solution to a long-standing puzzle: The Caribbean latest cretaceous tectonic events. Memorias Segunda Convención Cubana de Ciencias de la Tierra: Geociencias 2007 [CD-ROM ISBN 978-959-7117-16-2].

Iturralde-Vinent, M.A., Millán, G., Korpas, L., Nagy, E., and Pajón, J., 1996, Geological interpretation of the Cuban K-Ar database, *in* Iturralde-Vinent, M.A., ed., Cuban ophiolites and volcanic arcs. Special Contribution no. 1 to IGCP Project 364: Miami, FL, p. 48–69.

Kantchev, I., ed., 1978, Informe geológico de la provincia Las Villas – Resultados de las investigaciones geológicas a escala 1:250 000 durante el período 1969–1975: La Habana, Cuba, Archivo del Servicio Geológico Nacional, unpublished report.

Kartashov, I.P., Cherniajowski, A., and Peñalver, L.L., 1981, El Antropógeno de Cuba (in Russian): Moscow, Nauka, 147 p.

Kartashov, I.P., Mayo, N.A., Cherniajowski, A., and Peñalver, L.L., 1976, Descripción de algunas formaciones geológicas del Sistema Cuaternario de Cuba reconocidas recientemente: Serie Geológica, v. 26, p. 1–6.

Kozary, M.T., and Brönnimann, P., 1955, Geological Memorandum MK-4. Geology of the Ciego de Avila-Tamarindo, Camaguey: La Habana, Cuba, Archivo del Servicio Geológico Nacional, unpublished report.

Lewis, J.F., Draper, G., Proenza, J.A., Espaillat, J., and Jiménez, J., 2006, Ophiolite-related ultramafic rocks (Serpentinites) in the Caribbean region: A review of their occurrence, composition, origin, emplacement and Ni-Laterite soil formation: Geologica Acta, v. 4, p. 237–263.

Linares, E., Osadchy, P., Dovbnia, A., Gil, S., García, D., García, L., Zuazo, A., Gonzalez, R., Bella, V., Brito, A., Bush, W., Cabrera, M., Capote, C., Cobiella, J.L., Diaz de Villalvilla, L., Eguipko, O., Evdokimov, Y., Fonseca, E., Furrazola, G., Hernández, J., Judoley, C.M., Kondakov, L., Markovskiy, A., Norman, A., Perez, M., Peñalver, L., Tijomirov, I., Trofimov, V., Vtulochkin, A., Vergara, F., Zagoskin, A., and Zelepuguin, V., 1985, Mapa geológico de la República de Cuba, escala 1:500 000 (5 sheets): La Habana, Cuba/Moscow, USSR: Academy of Sciences of Cuba/USSR Academy of Sciences.

Lister, G.S., and Davis, G.A., 1989, The origin of metamorphic core complexes and detachment faults formed during Tertiary continental extension in the northern Colorado River region, U.S.A: Journal of Structural Geology, v. 11, p. 65–94. doi:10.1016/0191–8141(89)90036–9.

Llanes-Castro, A., García-Delgado, D., and Meyerhoff, D., 1998, Hallazgo de fauna jurásica (Tithoniano) en ofiolitas de Cuba central. Memorias II Geología y Minería, 98: La Habana, Centro Nacional de Información Geológica, p. 241–244.

Masaferro, J.L., Poblet, J., Bulnes, M., Eberli, G.P., Dixon, T.H., and McClay, K., 1999, Palaeogene–Neogene/present day (?) growth folding in the Bahamian foreland of the Cuban fold and thrust belt: Journal of the Geological Society, v. 156, p. 617–631.

McGrew, A.J., Peters, M.T., and Wright, J.E., 2000, Thermobarometric constraints on the tectonothermal evolution of the East Humboldt Range metamorphic core complex, Nevada: Geological Society of America Memoir, v. 112, p. 45–60.

Meyerhoff, A.A., and Hatten, C.W., 1968, Diapiric structure in central Cuba: AAPG Memoir, v. 8, p. 315–357.

Meyerhoff, A.A., and Hatten, C.W., 1974, Bahamas salient of North America: Tectonic framework, stratigraphy and petroleum potential: AAPG Bulletin, v. 58, p. 1201–1239.

Milián, E., Fernández, J., Blanco, S., and Fernández, G., 1979, Microfauna y algunas consideraciones bioestratigráficas de la formación Jatibonico: La Minería en Cuba, v. 5, p. 25–31.

Millán, G., 1996a, Metamorfitas de la Asociación Ofiolítica de Cuba, *in* Iturralde-Vinent, M.A., ed., Cuban ophiolites and volcanic arcs. Special Contribution no. 1 to IGCP Project 364: Miami, FL, p. 48–69.

Millán, G., 1996b, Geología del Complejo Mabujina, *in* Iturralde-Vinent, M.A., ed., Cuban ophiolites and volcanic arcs. Special Contribution no. 1 to IGCP Project 364: Miami, FL, p. 48–69.

Millán, G., 1997, Geología del macizo metamórfico Escambray, *in* Furrazola-Bermúdez, G., and Núñez-Cambra, K., eds., Estudios sobre Geología de Cuba: La Habana, Cuba, Instituto de Geología y Paleontología, p. 271–288 (published March 1998).

Millán, G., and Myczynski, R., 1978, Fauna Jurásica y consideraciones sobre la edad de las secuencias metamórficas del Escambray: Academia de Ciencias de Cuba, Informe Científico Técnico, v. 80, p. 1–14.

Millán, G., and Somin, M.L., 1981, Litología, Estratigrafía, tectónica y metamorfismo del Macizo del Escambray: La Habana, Academia de Ciencias de Cuba, 104 p.

Millán, G., and Somin, M.L., 1985, Contribución al conocimiento geológico de las metamorfitas del Escambray y del Purial: La Habana, Academia de Ciencias de Cuba, 74 p.

Moreno-Toiran, B., 2003, The crustal structure of Cuba derived from receiver functions analysis: Journal of Seismology, v. 7, p. 359–375.

Ortega, F., and Ros, P., 1931, Informe geológico presentado al gobierno provincial de Santa Clara sobre el registro petrolero “Carco”, denunciado por la compañía petrolera CARCO en la provincia de Santa Clara: La Habana, Cuba, Archivo del Servicio Geológico Nacional, unpublished report.

Otero, R., Prol, J.L., Tenreyro, R., and Arriaza, G.L., 1998, Características de la corteza terrestre de Cuba y su plataforma marina: Minería y Geología, v. 15, p. 31–35.

Palmer, R.H., 1945, Outline of the geology of Cuba: Journal of Geology, v. 53, p. 1–34.

Pardo, G., 1975, Geology of Cuba, *in* Nairn A.E.M., and Stehli, F.G., eds., The ocean basins and margins, Volume 3, The Gulf of Mexico and the Caribbean: New York, Plenum, p. 553–615.

Peñalver-Hernández, L.L., Lavandero-Illera, R., and Barriento-Duarte, A., 1997, Sistema Cuaternario, *in* Furrazola-Bermúdez, G., and Núñez-Cambra, K., eds., Estudios sobre Geología de Cuba: La Habana, Cuba, Instituto de Geología y Paleontología, p. 165–178 (published March 1998).

Pindell, J.L., and Dewey, J.F., 1982, Permo-Triassic reconstruction of western Pangea and the evolution of the Gulf of Mexico/Caribbean region: Tectonics, v. 1, p. 179–211.

Pindell, J.L., and Kennan, L., 2001, Kinematic evolution of the Gulf of Mexico and Caribbean, *in* Fillon, R., Rosen, N., Weimer, P., Lowrie, A., Pettingill, H., Phair, R., Roberts, H., and van Hoorn, B., eds., Transactions of the Gulf Coast Section Society of Economic Paleontologists and Mineralogists (GCSSEPM), 21st Annual Bob F. Perkins Research Conference: Petroleum Systems of Deep-Water Basins, Houston, TX, p. 193–220.

Pindell, J.L., Kennan, L., Maresch, W.V., Stanek, K.P., and Draper, G., 2006, Foundations of Gulf of Mexico and Caribbean evolution: Eight controversies resolved: Geologica Acta, v. 4, p. 303–341.

Pindell, J.L., Kennan, L., Maresch, W.V., Stanek, K.P., Draper, G., and Higgs, R., 2005, Platekinematics and crustal dynamics of circum-Caribbean arc-continent interactions: Tectonic controls on basin development in Proto-Caribbean margins, *in* Avé-Lallemant, H.G., and Sisson, V.B., eds., Caribbean-South American plate interactions, Venezuela, Geological Society of America, Special Paper, v. 394, p. 7–52.

Proenza, J.A., Díaz-Martínez, R., Iriondo, A., Marchesi, C., Melgarejo, J.C., Gervilla, F., Garrido, C.J., Rodríguez-Vega, A., Lozano-Santacruz, R., and Blanco-Moreno, J.A., 2006, Primitive Cretaceous island-arc volcanic rocks in eastern Cuba: The Téneme Formation: Geologica Acta, v. 4, p. 103–121.

Pszczolkowski, A., 1986, Secuencia estratigráfica de Placetas en el área limítrofe de las provincias de Matanzas y Villa Clara (Cuba): Bulletin of the Polish Academy of Sciences, v. 34, p. 67–79.

Pszczolkowski, A., 1999, The exposed passive margin of North America in western Cuba, *in* Mann, P., ed., Caribbean basins: Sedimentary basins of the world, Volume 4: Amsterdam, The Netherlands, Elsevier Science B.V., p. 93–121.

Pszczolkowski, A., and Myczynski, R., 2003, Stratigraphic constraints on the Late Jurassic–Cretaceous paleotectonic interpretations of the placetas belt in Cuba, *in* Bartolini, C., Buffler, R.T., and Blickwede, J., eds., The circum-Gulf of Mexico and the Caribbean: Hydrocarbon habitats, basin

formation, and plate tectonics: AAPG Memoir, v. 79, p. 545–581.
Pszczolkowski, A., and Myczynski, R., 2010, Tithonian–early Valanginian evolution of deposition along the proto-Caribbean margin of North America recorded in Guaniguanico successions (western Cuba): Journal of South American Earth Sciences, v. 29, p. 225–253.
Pushcharovsky, Yu., ed., 1988, Geologic map of the republic of Cuba: La Habana, Cuba/Moscow, USSR, Academy of Sciences of Cuba/USSR Academy of Sciences, scale 1:250 000, 40 sheets.
Renne, P.R., Mattinson, J.M., Hatten, C.W., Somin, M., Onstott, T.C., Millfin, G., and Linares, E., 1989, 40Ar/39Ar and U-Pb evidence for Late Proterozoic (Grenville-age) continental crust in north-central Cuba and regional tectonic implications: Precambrian Research, v. 42, p. 325–341.
Rojas-Agramonte, Y., Neubauer, F., Bojar, A.V., Hejl, E., Handler, R., and García-Delgado, D.E., 2006, Geology, age and tectonic evolution of the Sierra Maestra Mountains, southeastern Cuba: Geologica Acta, v. 4, p. 123–150.
Rojas-Consuegra, R., and Núñez-Cambra, K., 1997, Características de la cobertura Campaniano-Maastrichtiana del arco volcánico extinto, *in* Furrazola-Bermúdez, G., and Núñez-Cambra, K., eds., Estudios sobre Geología de Cuba: La Habana, Cuba, Instituto de Geología y Paleontología, p. 417–422 (published March 1998).
Rosencrantz, E., 1990, Structure and tectonics of the Yucatan Basin, Caribbean Sea, as determined from seismic reflection studies: Tectonics, v. 9, p. 1037–1059.
Rosencrantz, E., 1996, Substratum structure and tectonics in the Yucatan basin, *in* Iturralde-Vinent, M.A., ed., Cuban ophiolites and volcanic arcs. Special Contribution no. 1 to IGCP Project 364: Miami, FL, p. 36–47.
Rosencrantz, E., and Pardo, G., 1993, An overview of the Cuban Orogen, with an assessment of hydrocarbons potential: Austin, TX, University of Texas Institute for Geophysics, Technical Report No. 130, 47 p.
Saura, E., Vergés, J., Brown, D., Lukito, P., Soriano, S., Torrescusa, S., García, R., Sánchez, J.R., Sosa, C., and Tenreyro, R., 2008, Structural and tectonic evolution of western Cuba fold and thrust belt: Tectonics, v. 27, TC4002. doi:10.1029/2007TC002237.
Schneider, J., Bosch, D., Monie, P., Guillot, S., García-Casco, A., Lardeaux, J.M., Torres-Roldán, R.L., and Millán, G., 2004, Origin and evolution of the Escambray Massif (central Cuba): An example of HP/LT rocks exhumed during intraoceanic subduction: Journal of Metamorphic Geology, v. 22, p. 227–247.
Somin, M.L., Arakelyants, M.M., and Kolesnikov, E.M., 1992, Age and tectonic significance of highpressure metamorphic rocks in Cuba: International Geology Review, v. 34, p. 105–118.
Somin, M.L., and Millán, G., 1981, Geology of the metamorphic complexes of Cuba (in Russian): Moscow, Nauka, 218 p.
Stanek, K.P., Maresch, W.V., Grafe, F., Grevel, Ch., and Baumann, A., 2006, Structure, tectonics and metamorphic development of the Sancti Spíritus Dome (eastern Escambray massif, Central Cuba): Geologica Acta, v. 4, p. 151–170.
Stanek, K.P., Maresch, W.V., and Pindell, J.L., 2009, The geotectonic story of the northwestern branch of the Caribbean Arc: Implications from structural and geochronological data of Cuba, *in* James, K.H., Lorente, M.A., and Pindell, J.L., eds., The origin and evolution of the Caribbean plate: Geological Society, London, Special Publications, v. 328, p . 361–398.
Sukar-Sastroputro, K., and Pérez-Rodríguez, M., 1997, Granitoides del Arco Volcánico Cretácico de la Región Central de Cuba, *in* Furrazola-Bermúdez, G., and Núñez-Cambra, K., eds., Estudios sobre Geología de Cuba: La Habana, Cuba, Instituto de Geología y Paleontología, p. 371–386 (published March 1998).
Tada, R., Iturralde-Vinent, M.A., Matsui, T., Tajika, E., Oji, T., Goto, K., Nakano, Y., Takayama, H., Yamamoto, S., Kiyokawa, S., Toyoda, K., García, D., Díaz, C., and Rojas, R., 2003, K/T boundary deposits in the paleo-western Caribbean basin, *in* Bartolini, C., Buffler, R.T. and Blickwede, J., eds., The circum-Gulf of Mexico and the Caribbean: Hydrocarbon habitats, basin formation, and plate tectonics: AAPG Memoir, v. 79, p. 582–604.
Tait, J., Rojas-Agramonte, Y., García-Delgado, D., Kröner, A., and Pérez-Aragón, R., 2009, Palaeomagnetism of the central Cuban Cretaceous Arc sequences and geodynamic implications: Tectonophysics, v. 470, p. 284–297.
Thiadens, A.A., 1937, Geology of the southern part of the province Santa Clara (Las Villas) Cuba: Geographische en Geologische Mededeelingen, v. 2, no. 12, p. 1–69.
Tirel, C., Brun, J.-P., and Burov, E., 2008, Dynamics and structural development of metamorphic core complexes: Journal of Geophysical Research, v. 113, B04403. doi:10.1029/2005JB003694.
Truitt, P., and Pardo, G., 1953, Geologic Memorandum PT-21. Geology of Santa Clara-Calabazar-Camajuaní-Placetas area: La Habana, Cuba, Archivo del Servicio Geológico Nacional, unpublished report.
Van Hinsbergen, D.J.J., Iturralde-Vinent, M.A., Van Geffen, P.W.G., García-Casco, A., and Van Benthem, S., 2008, Structure of the accretionary prism, and the evolution of the Paleogene northern Caribbean subduction zone in the region of Camagey, Cuba: Journal of Structural Geology, v. 31, p. 1130–1144.