Emplacement of the northern ophiolites of Cuba and the Campanian–Eocene geological history of the northwestern Caribbean–SE Gulf of Mexico region

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Abstract: The Mesozoic Proto-Caribbean Plate was consumed in the subduction zone of the Greater Antilles volcanic arc until the Campanian. At this time, volcanic arc magmatism ceased along Cuba. From Late Campanian to Danian, Cuba and its surroundings were a collision zone where the GAC accreted to the North American palaeomargin. In the Danian the almost east–west trending SE Cuba–Cayman Ridge–Hispaniola? volcanic arc was born. The related north dipping subduction zone acted as the SE North American plate boundary. From the Paleocene to Middle Eocene dense Caribbean lithosphere travelled northwards. The location, strike and subduction polarity of the assumed subduction zone are very different from those described by other models. Almost simultaneously the Cuban Orogeny developed in western and central Cuba. During the orogeny the northern ophiolite belt of Cuba and the Cretaceous volcanic rocks were thrust northwards tens of kilometres, onto the Mesozoic North American palaeomargin. In the Middle Eocene subduction stopped. Simultanously(?) a change in the regional stress field originated the near east–west trending sinistral Oriente fault zone, whose position and origin are probably tied to the weakened hot crust to the south of the Palaeogene volcanic arc axis.

At the present time Cuba belongs to the North American plate. Its SE part is located along the Oriente fault zone, one of the major tectonic elements separating the North American and Caribbean plates. It also belongs to the Greater Antilles islands. Despite present positions on different plates, Cuba, Hispaniola and Puerto Rico share some features pointing to a common pre Middle Eocene geological history. Insufficient use has been made of Cuban geological data to test Caribbean tectonic models and the present paper is an attempt to correct this trend.

An outstanding feature of the Cuban geology is the belt of Mesozoic ultramafic and associated rocks that occur as a discontinuous chain of upper Mesozoic ultramafic and mafic rocks, extending for more than 1000 km along the northern half of Cuban mainland. In recent years, several contributions have greatly increased the knowledge on the petrology and geochemistry of the Cuban and other Greater Antilles ophiolites and the spatially related Cretaceous volcanic arc magmatic rocks (Andó *et al.* 1996; Rodríguez *et al.* 1997, 2001; Proenza *et al.* 1999, 2006; Kerr *et al.* 1999; Lewis *et al.* 2006; García Casco *et al.* 2006, among others). The later tectonic emplacement has also been recently studied by Iturralde-Vinent (Iturralde-Vinent & Marphee 1996; Iturralde-Vinent *et al.* 2006), Lewis *et al.* (2006), Cobiella-Reguera (2000, 2002, 2005) and García-Casco *et al.* (2002, 2006), among others. This last event, together with the development of the Late Cretaceous and Early Palaeogene volcanic arcs, is important in unravelling the North American–Caribbean Plate boundary history.

The first part of the paper presents a brief discussion of the geology of the northern ophiolites. The data and conclusions are used in the second part for a discussion of evolution of the North America–Caribbean Plate boundary as indicated by Cuban data.

Tectonic setting of the northern ophiolites

In order to understand the emplacement of the northen ophiolites some general knowledge of the geology of Cuba, as it relates to the age and origin of these rocks, is neccesary. Two main structural levels can be distinguished in Cuba. The upper level comprises little-deformed Eocene–Quaternary cover. The lower level (sole), is a variably deformed sequence of older rocks (Iturralde-Vinent 1997; Cobiella-Reguera 2000). The sole has two main parts: (1) the pre-Cenozoic basement and (2) a lower Cenozoic folded belt built during the Early Cenozoic Cuban Orogeny. The pre-Cenozoic basement includes three different terranes (Fig. 1): a northern belt of ophiolites (NO), a Cretaceous volcanic arc terrane (KVAT) with its uppermost Cretaceous sedimentary cover and the southern metamorphic terranes (SMT). The SMT protoliths

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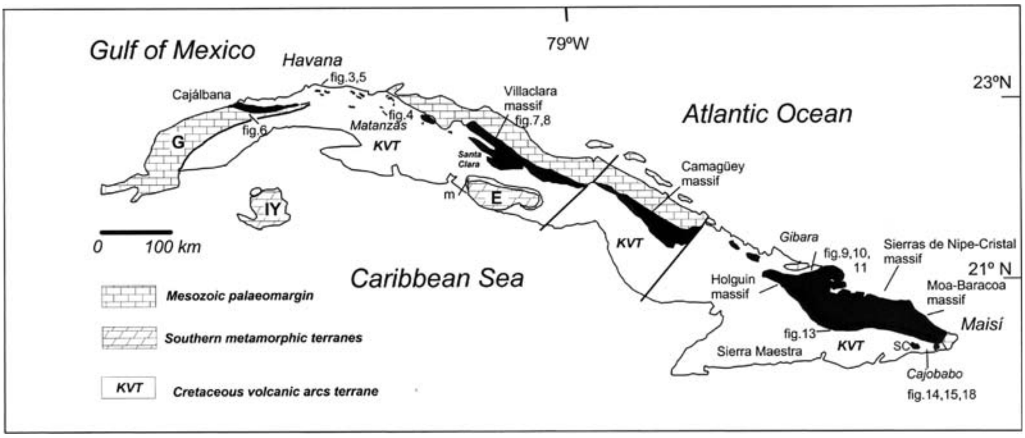

Fig. 1. Mesozoic domains of Cuba after stripping of the Cenozoic cover. G, Guaniguanico Highlands; IY, Isle of Youth; E, Escambray (Guamuhaya) Massif; m, Mabujina complex (metamafites, oceanic basement of the Cretaceous volcanic sequences). In black are ophiolitic massifs. SC, Sierra del Convento ophiolites. Modified after Cobiella-Reguera (2005).

are mainly Mesozoic (Jurassic) continental margin sections, very similar to coeval deposits in Guaniguanico mountains (Somin & Millan 1981; Cobiella-Reguera 2000). However, in central Cuba Escambray (Guamuhaya) mountains, Cretaceous(?) metavolcanic sequences also occur. The different Mesozoic terranes were initially accreted to the North American continental margin during the Cretaceous (Fig. 1; Cobiella-Reguera 1998, 2000, 2005), but the welding process ended in the Middle and Late Eocene (Iturralde-Vinent 1996*a*; Pszczolkowski 1999). The Northern Ophiolites and the Cretaceous volcanic arc terrane are allochthonous units, resting on the Mesozoic North American passive palaeomargin. The southern metamorphic terranes outcrop in two great tectonic windows below the volcanic terrane. The North American palaeomargin contains Jurassic and Cretaceous mainly marine sections. Precambrian (Grenvillian) rocks are present in small and poor outcrops in its southern fringe (Pszczolkowski & Myczynski 2003). Thin-skinned tectonics is well developed in the palaeomargin, particularly in western Cuba (Guaniguanico mountains) and in the well-stratified deep water sections in central Cuba and Camaguey.

Two different sedimentary, magmatic and tectonic scenarios existed from Danian to Middle Eocene (Fig. 2). West of the Camaguey lineament, the Late Paleocene–Middle (locally Late) Eocene Cuban orogeny developed. During this event the ophiolite massifs and the Cretaceous volcanic terrane are thrusted northward upon the foreland basin built upon the southern fringe of the North American palaeomargin (Pardo 1975). Olistostrome deposits are preserved between the thrust sheets. Small piggyback basins, filled with turbidites, are locally present on top of the KVAT sections. Eastward of Camaguey lineament orogenic deformations are absent or at least poorly recorded. Marine Danian–Middle Eocene volcanic arc rocks (Turquino arc) attain up to 6000 m in thickness in the Sierra Maestra mountains of SE Cuba and become thinner northward (Lewis & Straczek 1955; Khudoley & Meyerhoff 1971, fig. 2). Intrusive magmatic rocks are abundant in the Sierra Maestra, decreasing towards northern eastern Cuba. Volcanoclastic Middle and Late Eocene deposits attain almost 1000 m in thickness and rest conformably on the underlying lower Palaeogene volcano-sedimentary sequence. Deformations in the entire Paleocene–Eocene section increase southward.

Following (with minor modifications) Iturralde-Vinent's (1996*a*) classification, three types of ophiolites can be distinguished in Cuba: (1) the northern ophiolites; (2) the metamorphic basement of the Cretaceous volcanic arc terrane (Mabujina complex); and (3) tectonic slices in the Escambray Massif (part of the SMT), in central Cuba. The present paper deals only with the first group (see Iturralde-Vinent 1997; Cobiella-Reguera 2005, for additional information on Cuban ophiolites).

Over 90% of the oceanic lithosphere remains in Cuba occur in the northern ophiolites. It forms an almost continuous, strongly deformed chain of bodies, transported from the south over the continental margin (Kozary 1968; Meyerhoff & Hatten 1968; Iturralde-Vinent 1990; Echevarría-Rodríguez *et al.* 1991). Most of the NO is a huge mélange,

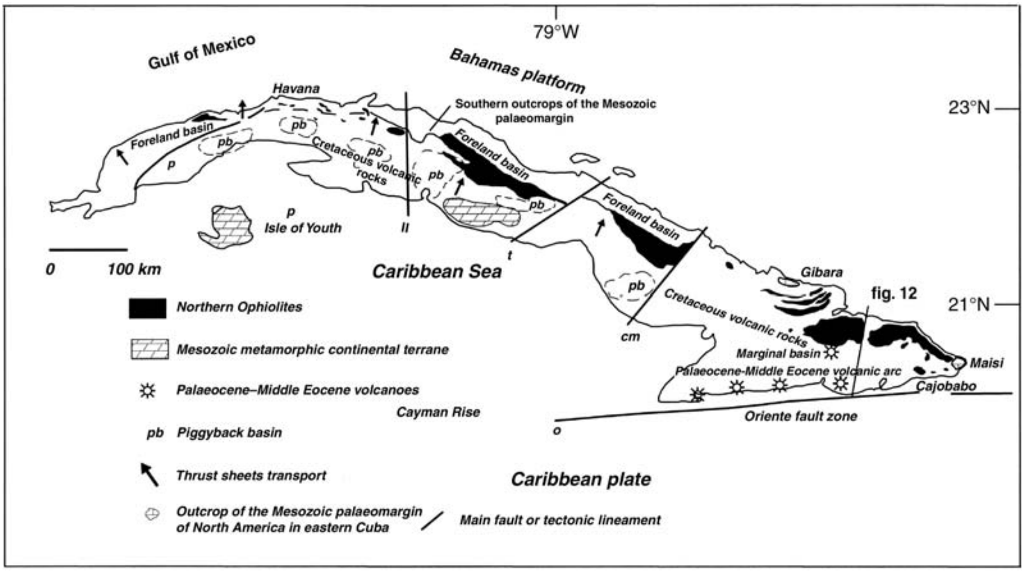

Fig. 2. Danian to Middle Eocene main tectonic elements of Cuba. p, Pinar fault; ll, Llabre lineament; t, La Trocha fault; cm, Camaguey lineament; o, Oriente fault.

extended *c*. 1000 km along the northern half of Cuba (Fig. 1). Blocks of mainly ophiolitic suite components float in a highly deformed serpentinitic matrix. The ophiolites show evidence of pervasive deformation and almost all the contacts are tectonic, with severely crushed bodies cut by tongues of brecciated or foliated serpentinites mm to metres thick (Knipper & Cabrera 1974). Despite internal deformation and mixing, the main members of the suite preserve their identities and in some places the original pretectonic relationships are recorded. Tectonized ultramafic rocks (serpentinites) and the rocks of the cumulative complex (ultramafites + gabbros) are the most common lithologies, while basalts and sedimentary rocks are poorly exposed (Kozary 1968; Knipper & Cabrera 1974; Fonseca *et al.* 1984; Cobiella-Reguera 1984; Iturralde-Vinent 1990, 1996*a*; and others). Biostratigraphic and radiometric data yield Upper Jurassic-Aptian and/or Albian ages (Iturralde-Vinent 1990, 1996*a*; Iturralde-Vinent *et al.* 1996; Andó *et al.* 1996; Millan 1997; Cobiella-Reguera 2005). Some proposed younger ages (Iturralde-Vinent *et al.* 2006; Proenza *et al.* 2006) seem to occur locally and require further research. Recent studies record distinct origins for the NO rocks. Mid Oceanic Ridge (MOR) magmatism has been reported by Beccaluva *et al.* (1996), Giunta *et al.* (2002), Andó *et al.* (1996) and García-Casco *et al.* (2002), while Kerr *et al.* (1999) and Andó *et al.* (1996) found island arc tholeiites and Proenza *et al.* (1999) detected suprasubduction signatures. According to Cobiella-Reguera (1998, 2000, 2005), Upper Jurassic–Neocomian ophiolites probably have a MOR origin, whereas those of Aptian–Albian age are related to a suprasubduction zone. The NO crops out in several regions, each with distinct characteristics. The areas are: (1) western Cuba; (2) central Cuba and Camaguey; (3) Holguin; (4) eastern Cuba; and (5) Cajobabo. Summary descriptions of these areas have appeared in recent years (Iturralde-Vinent 1996*a*, *b*; Cobiella-Reguera 2005; Lewis *et al.* 2006).

Western Cuba

Western Cuba ophiolitic bodies are represented by the following outcrop areas separated by Cenozoic rocks (from west to east, Fig. 1): Cajalbana–Bahia Honda, NW Havana, NE Havana province and northern Matanzas. These small massifs are located west of the Llabre lineament (defined as a strike–slip fault by Pszczolkowski 1983). In these areas the ophiolites occur as small bodies in tectonic mix with the Cretaceous volcanic arc rocks (volcano-ophiolitic mélange, Figs 3 & 4). Unconformably on the mélange rest strongly deformed upper Campanian, Maastrichtian and K/T boundary deposits (Piotrowska 1986*a*, *b*; Piotrowski 1986; Diaz-Otero *et al.* 2003). The mélange is probably lower Campanian in age (Cobiella-Reguera 2005). The oldest beds in the sedimentary cover containing clasts from the ophiolite suite are upper Campanian conglomerates

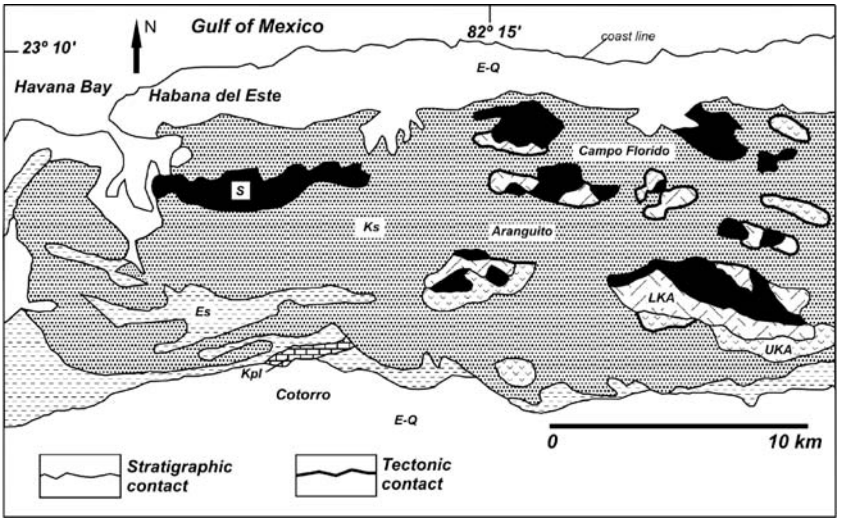

Fig. 3. Geological map of eastern Havana City and its surroundings (simplified and slightly modified after Pushcharovsky, 1988). See location in Figure 1. LKA, Lower Cretaceous volcanic arc rocks (Chirino Fm); UKA, Upper Cretaceous volcanic arc rocks (La Trampa Fm); Ks, upper Campanian, Maastrichtian and K–T boundary sedimentary deposits (Via Blanca and Penalver Formations); Es, Upper Paleocene–Lower Eocene sedimentary beds (Vibora Group and Capdevila Fm); Kpl (?), 'Placetas type' deep water beds; E–Q, upper Lower Eocene–Quaternary deposits. See location in Figure 1. After Cobiella-Reguera (2005).

Fig. 4. Outcrop of the volcano-ophiolitic mélange at Loma Esmeralda, Limonar, Matanzas province. Tectonic serpentinite breccia (**S**) in the background at the summit of the hill. Strongly weathered and deformed thin bedded tuffs (?) (**T**) in the foreground. Contacts are fault planes. See location in Figure 1. Photograph courtesy of Martin Meschede, Greifswald University, Germany. Latitude: 22° 59′ 00″, longitude: 82° 41′ 20″.

(Brönniman & Rigassi 1963; Albear-Fránquiz & Iturralde-Vinent 1985). In some places in northern Havana, upper Paleocene beds lie unconformably upon the uppermost Cretaceous and the K/T boundary beds, recording an Early Paleocene deformation event. A third tectonic event, the Cuban Orogeny, is represented by northward thrusted ophiolite and volcanic arc upon the North American Mesozoic palaeomargin (Meyerhoff & Hatten 1968; Echevarría-Rodríguez *et al.* 1991). The palaeomargin crops out only to the south of the Cajalbana-Bahia Honda area (Pszczolkowski & Albear 1982; Cobiella-Reguera 2005). In the east (northern Havana and Matanzas provinces) it lies at variable depths below the thrust pile. Thin skinned tectonics characterize the deep water Mesozoic palaeomargin beds and the overlying lower Palaeogene siliciclastic deposits (Bralower & Iturralde-Vinent 1997; Gordon *et al.* 1997; Fig. 5). Uppermost Paleocene and/or lowermost Lower Eocene chaotic deposits (olistostromes) with clasts from the ophiolites and the Mesozoic palaeomargin accumulated in front of each advancing sheet (Fig. 6, Manacas Fm). Immediatly after deposition these soft water-saturated marine sediments were over-ridden and mechanically mingled with the sheets, becoming a mélange. The lack of sorting and rounding in the olistostromes suggests very rapid erosion and deposition along submarine scarps. Lower Eocene beds rest unconformably on the thrust sheets (Fig. 5).

In the Cajalbana–Bahia Honda area the Mesozoic palaeomargin and the overlying Manacas Fm form a near east–west trending tectonic fenster in Sierra del Rosario, eastern Guaniguanico Cordillera, containing a north dipping thrust pile (Pushcharovsky 1988) several kilometres thick. To the north of Sierra del Rosario, the basal thrust plane of the overlying volcano-ophiolitic mélange has been found in deep wells near the Gulf of Mexico coast. Recent seismic data shows that the front of the Cuban thrust belt lies several kilometres to the north of the coastline (Moretti *et al.* 2003). As the ophiolites and the Cretaceous volcanic arc terrane were thrusted northward, the sum of Sierra del Rosario fenster width along a SSE–NNW line (16 km) plus the distance from the northern tectonic boundary of Sierra del Rosario to the coast (10–16 km) gives a minimum value for the tectonic displacement of the volcano-ophiolitic mélange (26–32 km) but more than 100 km seems

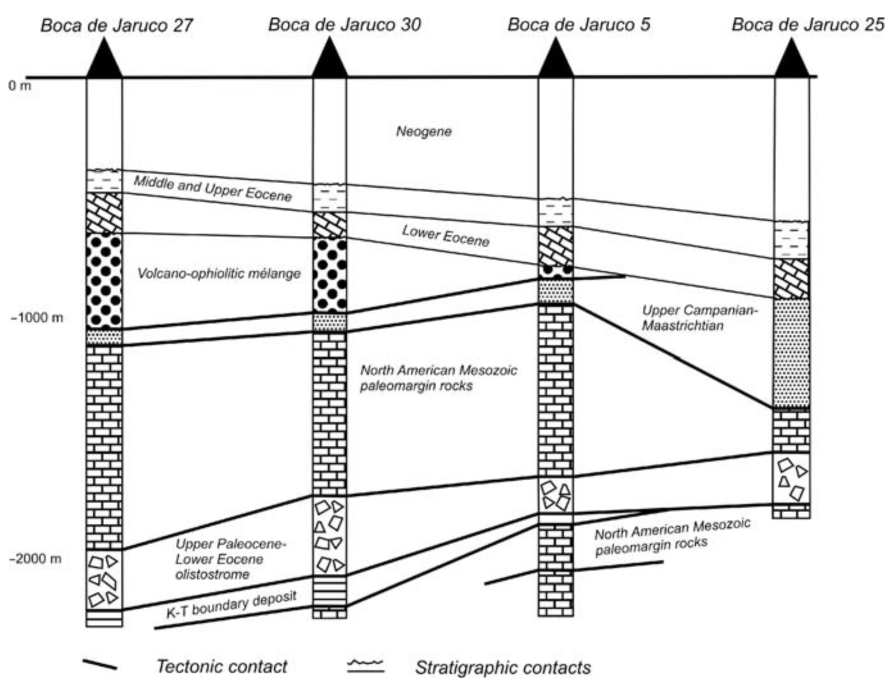

Fig. 5. Sketch correlation in the Boca de Jaruco oil field, located about 20 km to the east of Havana City. A Lower Eocene–Neogene cover rests unconformably on the Cuban orogeny thrust sheets. In this region, the Mesozoic North American palaeomargin rests at least several hundred metres below the Earth's surface and only crops out in small areas (see Fig. 3). The characteristic thin skinned tectonics of the NA palaeomargin is evident (after Furrazola-Bermudez *et al.* 1979, modified). See location in Figure 1.

Fig. 6. Outcrop of the Manacas Fm at Las Terrazas, Guaniguanico Cordillera (Fig. 1), western Cuba. The unit consists of chaotic submarine deposits (olistostromes), with a foliated, commonly serpentinite rich, silty or sandy matrix, surrounding strongly brecciated blocks of limestones (**bl**, foreground in the photograph), quartzose sandstone, cherts and other lithologies derived from the Mesozoic palaeomargin, and rocks of the ophiolitic suite. Foliation gently dips to the right in the photograph. Similar deposits are present along northern Cuba from the Guaniguanico Highlands to Camaguey (compare with Fig. 8). See location in Figure 1. Latitude: 22° 51′ 20″, longitude: 84° 04′ 06″.

possible. In the same way, in northern Havana and Matanzas province the minimum horizontal movement is between 15 and 25 km.

In deep wells of southern Havana and Matanzas provinces the volcano-ophiolitic mélange is absent and the Cretaceous arc volcanics lie in tectonic contact on top of ophiolitic (?) dolerites (García & Fernandez 1987; Cobiella-Reguera 2005).

Central Cuba and Camaguey

Between the Llabre and Camaguey tectonic lineaments (Fig. 2) the ophiolites form two huge bodies, the Villaclara and Camaguey massifs, resting on the Mesozoic North American palaeomargin. Cretaceous volcanic arc rocks are thrusted from the south upon the ophiolitic massifs (Knipper & Cabrera 1974; Meyerhoff & Hatten 1968; Pardo 1975; Iturralde-Vinent 1997).

In the Villaclara Massif the upper members of the ophiolite suite show the most complete development, particularly in the east. Radiolarites interbedded with basalts and dolerites yield Tithonian ages (Llanes Castro *et al.* 1998). Despite tectonic mixing along the contact with the Cretaceous volcanic terrane, mélanges similar to those in western Cuba are absent. Upper Maastrichtian–Paleocene beds (Santa Clara Fm) cover both lithologies and the oldest beds in the volcanic arc sedimentary cover are Maastrichtian (Fig. 7). As the youngest volcanics below the unconformity are lower Campanian (Pushcharovsky 1988), a tectonic event more or less coeval with the volcano-ophiolitic mélange formation of western Cuba is indicated. The Early Cenozoic Cuban Orogeny is recorded by deformed olistostromes and turbidites (Fig. 8, Vega Alta Fm, in Pushcharovsky 1988; the 'members' 5 and 6 of Las Villas belt in Pardo 1975). This unit resembles the western Cuba Manacas Fm, occurring as thin tectonic lenses, metres to several hundred of metres thick and hundred of metres to tens of kilometres long, within thin bedded deep water beds (the upper Mesozoic Placetas belt of the North American margin in northern central Cuba). In some places, klippen of the ophiolitic sheet lie upon the southernmost carbonate banks of the Bahamas platform (Remedios zone), showing that in north central Cuba, immediately after the thrusting, the ophiolite

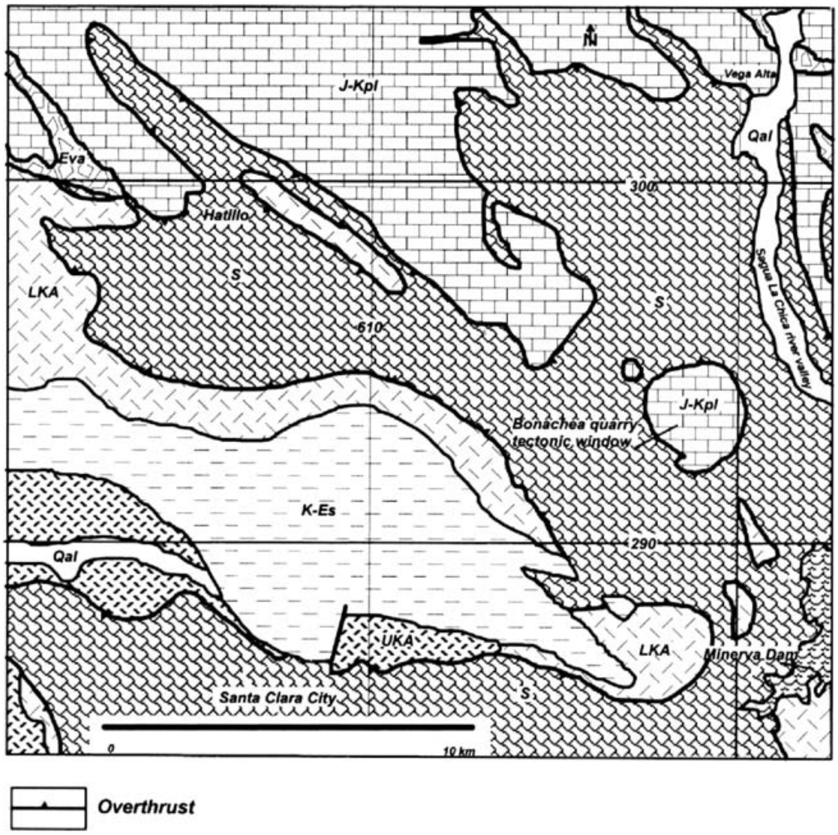

Fig. 7. Simplified geological map of Santa Clara city and its surroundings (local coordinates Cuba North), after Pushcharovsky (1988). The (upper?) Maastrichtian–Eocene gently deformed sedimentary cover rests unconformably on the ophiolitic and volcanic arc thrust sheets. Tectonic mixing between the ophiolites and the Cretaceous volcanic rocks, however present, is less marked than in western Cuba. J–Kpl, Deep water deposits of Placetas zone (Veloz, Santa Teresa, Carmita and Amaro formations); LKA, Lower Cretaceous volcanic arc rocks (Matagua Fm); UKA, Upper Cretaceous volcanic arc rocks (Brujas and Tasajeras formations); K–Es, upper? Maastrichtian–Middle Eocene sedimentary beds (Santa Clara and Ochoa formations); Qal, Quaternary alluvia. See Figure 3 for geological contact symbols. See location in Figure 1.

massifs covered not only the thrust pile belt of the well stratified southern facies of the palaeomargin (Placetas and Camajuani zones, Pszczolkowski 1983), but also reached the southern fringe of the platform. Based on this fact, a minimum of 30 km of horizontal movement can be envisaged for the northern ophiolites of central Cuba. Pszczolkowski (1983) estimated 50–70 km of northward transport for the Placetas belt rocks. Therefore, the horizontal travel of the ophiolite belt rocks, originally located southwads of the Placetas basin, should be much larger. Palaeontological constraints for the Vega Alta Fm are very limited (Kantchev *et al.* 1978). Together with regional stratigraphic data, they indicate deposition between the Paleocene and the Middle Eocene. However, the chaotic and inmature deposits clearly suggest a much shorter time interval for deposition. As in western Cuba, the nature of the Vega Alta olistostromes points to rapid erosion and sedimentation along submarine fault scarps.

The Camaguey Massif (Fig. 1) lies between the La Trocha fault (west) and the Camaguey lineament (east). Biostratigraphic data from the volcano-sedimentary member indicate an Aptian–Albian age, whereas a 160 ± 24 Ma K–Ar age was obtained from gabbroids. The massif is a gently south-dipping body resting on the Cretaceous Bahamian carbonate banks (Remedios zone). North of Camaguey city, a Lower Eocene chaotic deposit lies between the ophiolites and the Cretaceous volcanic arc cover (Iturralde-Vinent 1996*a*). As in central Cuba, the youngest volcanic arc rocks are Campanian in age. Upper Campanian and Maastrichtian sediments rest unconformably on

Fig. 8. Vega Alta Fm at Crucero Tarafa, *c*. 20 km NE of Santa Clara city. In this outcrop, small phacoidal blocks of harder rocks (mainly limestones) are surrounded by a fine grained wavy foliated matrix. See location in Figure 1. Photograph courtesy of Martin Meschede, Greifswald University, Germany.

the volcanic arc suite. The >20 km of tectonic overlap of the carbonate banks and their southern deep water facies (Placetas zone) by the Camaguey ophiolites records a second episode of the Cuban Orogeny in this region. The ophiolite emplacement is recorded by olistostromes (Iturralde-Vinent 1997; Quintas 1998; Pszczolkowski & Flores 1986) filling a Middle and/or Upper Eocene foreland basin. In Camaguey, the lowest olistostromes contain only clasts derived from the ophiolitic suite, while sedimentary rock clasts from the Mesozoic palaeomargin are predominant in the upper part (Quintas 1998). The Camaguey lineament represents the eastern limit of the orogeny; there are no Early Palaeogene foreland basin and thrust sheets further east.

Holguin ophiolites

In northern eastern Cuba, ophiolites outcrop in the Maniabon Highlands (NW Holguin province). In the north, the Holguin ophiolites form several gently convex to the SE anastomosing arcuate narrow strips of pervasively deformed serpentinites. South-dipping thrust faults separate the metaultramafic rocks from the intervening strongly deformed sedimentary (mainly greywackes) and volcanic rocks of the Iberia mélange (Fig. 9; Kozary 1968; Knipper & Cabrera 1974; Pushcharovski 1988). Some narrow, isolated, deep water limestone tectonic lenses (La Morena and Lindero members of 'Iberia Fm' of Jakus 1983), contain an Upper Cretaceous fauna. Further south the ophiolite suite outcrops become wider and continuous (Kozary 1968; Pushcharovsky 1988). This rock complex probably records a forearc accretionary prism (Andó *et al.* 1996). A second mélange in this region is made of serpentinite and gabbro clasts with more or less significant amounts of sedimentary and Cretaceous volcanic rock blocks (Yaguajay Fm). Probably the Yaguajay mélange originally was an olistostrome. The youngest blocks in this last type of mélange are Campanian–Maastrichtian biogenic massive limestones. Similar rocks rest on the serpentinites with tectonic contacts (Fig. 10). Outcrops of the carbonate Bahamas bank (Remedios zone) occur in a small area in Gibara and its western surroundings. The relationships between the North America palaeomargin and the ophiolites at the surface are unclear because of an intervening strip of lower Palaeogene sediments in between (Fig. 9). However, a tectonic contact is almost surely present. In cherts spatially related with basalts Andó *et al.* (1996) found Hauterivian–Barremian radiolaria. K–Ar radiometric ages in basalts and dolerites range from 126.3 ± 8.3 to

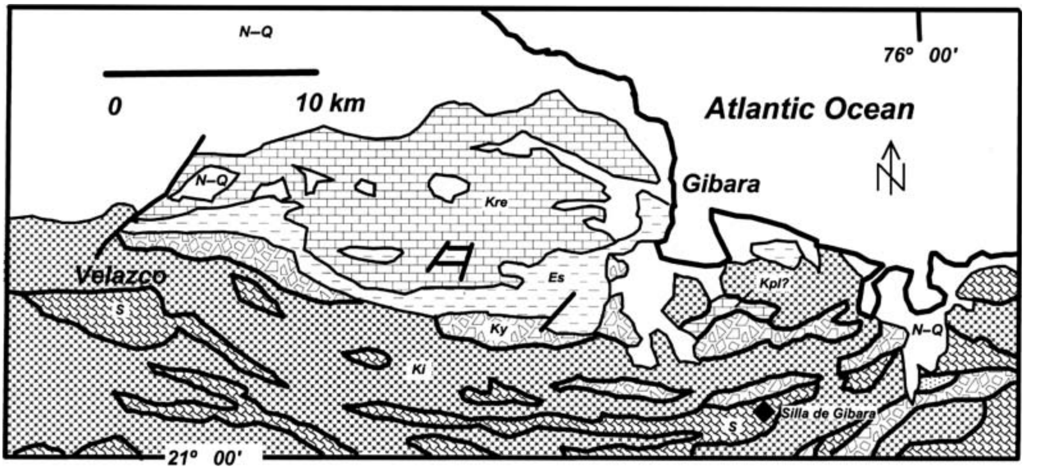

Fig. 9. Geological map of Gibara area, Maniabon Highlands, Holguin (slightly modified after Cobiella-Reguera 2005). Ki, Cretaceous Iberia Fm (mélange); S, ophiolitic rocks (mainly serpentinites); Ky, Maastrichtian olistostrome–mélange (Yaguajay Fm); Kpl, tectonic wedge of Placetas zone-like rocks (Cretaceous deep water sections); Kre, massive shallow water biogenic limestones (Remedios zone–southern fringe of Bahamas platform); Es, Paleocene–Middle Eocene deposits (Embarcadero and Vigia formations); N–Q, Neogene and Quaternary. See location in Fig. 1. See Figure 3 for geological contact symbols.

57.8 ± 5.4 Ma (Iturralde-Vinent *et al.* 1996). The oldest rocks lying with unconformity on the mélanges are upper Maastichtian turbidites (La Jiquima Fm, Gil Gonzalez *et al.* 2003) and Upper Paleocene breccias with some tuffaceous beds (Fig. 11, Haticos Fm) crop out on the southern massif rim. The sum of structural, radiometric and stratigraphic evidence points to Maastrichtian

Fig. 10. Typical landscape at Maniabon Highlands, Holguin. The low areas in the foreground contain mainly outcrops of the Iberia and Yaguajay mélanges. The plateau-like elevation in the cental background is known as Silla de Gibara (Fig. 9). Campanian–Maastrichtian massive south-dipping biogenic limestones (**T**, Tinajita Fm) crops out at its summit and the cliffs below, whereas serpentinites (**S**) are present in the lower, gentler slopes. The contacts between both lithologies are tectonic (Kozary 1968; Pushcharovsky 1988). See location in Figures 1 & 9. Looking from the north. Photograph courtesy of Martin Meschede, Greifswald University, Germany.

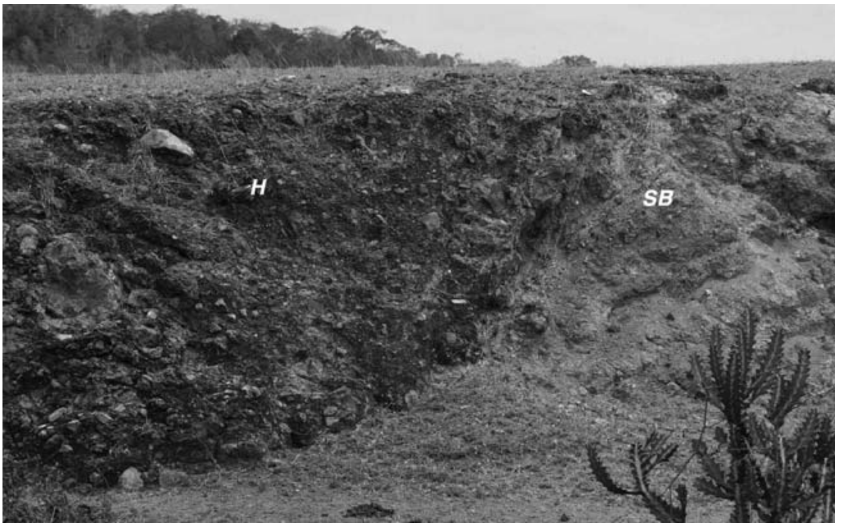

Fig. 11. Haticos Fm In the outcrop at Tacajo, Holguin province, beside the typical Haticos Fm breccia, rich in gabbro and dolerite clasts (**H**, left side of the photograph), a second type containing only serpentinite clasts (**SB**) is present. The contact between both units shows some shearing. A crude foliation appears in the serpentinitic breccia, but not in the first type. The breccias seem to be debris flow deposits of very local provenance. Outcrop height: *c*. 2 m. See location in Figure 1. Photograph courtesy of Martin Meschede, Greifswald University, Germany. Latitude: 20° 53′ 02″, longitude: 76° 03′ 30″.

(pre-Late Maastrichtian) emplacement for the Holguin ophiolitic rocks. It may have occurred in two phases, the first related to a Campanian accretionary prism, now probably vanished, and the second recorded by the Maastrichtian Yaguajay mélange.

Regional data suggest north-northwestward tectonic transport (Kozary 1968). Assuming that (1) all along this area the ophiolitic rocks rest with tectonic contact, (2) the tectonic transport was from south to north, at right angle with the the regional structural trend, and (3) at least the northern border of the ophiolitic mélange probably lies on the carbonate bank facies of the continental palaeomargin (Remedios zone), we can suppose that the northwards transport was no less than the width of the ophiolitic belt (22.5 km) and probably it was much larger.

Several authors claim strong Early Cenozoic deformation (Cuban orogeny) in the Holguin masif (Kozary 1968; Knipper & Cabrera 1974; Andó *et al.* 1996), but no definitive evidence for such deformation in the lower Cenozoic rocks has been shown. In fact, strong Paleocene–Eocene deformations in the Holguin Massif area were not reported by Nagy (1984), Brezsnyansky & Iturralde-Vinent (1978) and Cobiella-Reguera *et al.* (1984*b*). In contrast to massifs west of the Camaguey lineament, the characteristic lower Cenozoic olistostromes of the Cuban Orogeny, with the mix of ophiolitic and continental palaeomargin clasts, are absent.

Eastern Cuba ophiolites

At the surface the Holguin Massif is separated from the eastern Cuba massifs by Cenozoic deposits, but in depth the ophiolites probably form a single body (Figs 1 & 12; Knipper & Cabrera 1974; Cobiella-Reguera *et al.* 1984*b*). Two great ophiolite outcrops area are present: the Sierra de Nipe–Cristal and Moa–Baracoa massifs, separated by the Sagua de Tanamo River basin. The main feature distinguishing eastern Cuba ophiolites from the other massifs of the NO (except the Holguín area) is their tectonic superposition upon the KVAT (Knipper & Cabrera 1974; Cobiella-Reguera 1978; Iturralde-Vinent 1996*a*; Iturralde-Vinent *et al.* 2006). Only its eastern tip lies on the North American palaeomargin, together with KVAT metamorphic rocks (Cobiella-Reguera 2005; Iturralde-Vinent *et al.* 2006; García-Casco *et al.* 2006). Most of the eastern Cuba ophiolites are a huge, dismembered, almost flat tectonic prism, about 1 km in maximum thickness (Figs 12 & 13), thrusted several tens of kilometres (Knipper & Cabrera 1974; Cobiella-Reguera 1978) to the north (Nuñez Cambra *et al.* 2003). In some

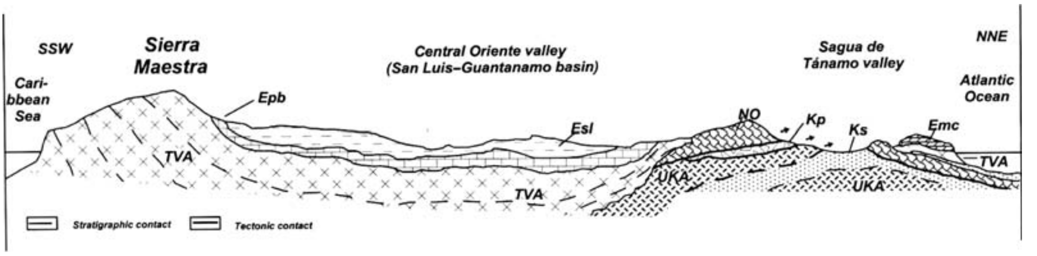

Fig. 12. Schematic geological profile from eastern Sierra Maestra to the northern coast of eastern Cuba, showing the NOB–Palaeogene volcanic arc–Middle–Late Eocene basin relationships. Without scale. Length of the section: 100 km. NO, Northern Ophiolite; UKA, Upper Cretaceous arc rocks (Santo Domingo Fm); Ks, Maastrichtian volcanoclastic deposits; Kp, Maastrichtian olistostromes (La Picota Fm); TVA, Danian–Middle Eocene Turquino volcanic arc rocks (El Cobre and Sabaneta formations); Epb, Middle Eocene carbonate horizon (Puerto Boniato and Charco Redondo formations); Esl, Volcanoclastic Middle and Late Eocene deposits (San Luis and Camarones formations). See Figure 2 for location.

Fig. 13. Sheared massive serpentinite (**S**) resting with almost horizontal contact upon chaotic breccia conglomerates (olistostromes) of La Picota Fm (**P**) at Sabanilla Mayari Arriba, Santiago de Cuba province. All the clasts belong to lithologies of the ophiolite suite. A crude foliation is present in the matrix. A diagenetic hematitic film stains matrix and clasts in many places in this and other outcrops of the unit. East to the right. See location in Figure 1. Photograph courtesy of Martin Meschede, Greifswald University, Germany. Latitude: 20° 24′ 02″, longitude: 76° 25′ 09″.

areas, tectonic deformations and mixing are not as pervasive as in other Cuban ophiolites. A wealth of new data on the primary structure, petrology and geochemistry of several areas belonging to the eastern Cuba ophiolites has been published in the last few years (Cobiella-Reguera 2005 and references therein; see also papers in *Geologica Acta* 1–2, 2006). They suggest that a mantle tectonite more than 5 km thick is exposed in the Sierra de Nipe–Cristal Massif, while the Moa–Baracoa Massif comprises mantle tectonites more than 2.2 km thick, capped by a thin crustal section of lower gabbros (300 m) and discordant volcanics (Quibiján Fm, Proenza *et al.* 2006). Recently, the last volcanic unit was described as part of the volcanic arc section (Iturralde-Vinent *et al.* 2006). Great blocks of high-presssure metamorphic rocks (mainly amphibolites, Somin & Millan 1981; García-Casco *et al.* 2006) are disseminated in both massifs. García-Casco *et al.* (2006) relate this pressure and strong synmetamorphic deformation to collision. K–Ar ages range between 72 ± 3 and 58 ± 4 Ma. The amphibolites belong to the eastern Cuba thrust pile (Cobiella-Reguera *et al.* 1984*a*, Cobiella-Reguera 2005; Iturralde-Vinent 1996*a*; Iturralde-Vinent *et al.* 2006; García-Casco *et al.* 2006) and so are pre-Maastrichtian in age. Maastrichtian shallow water biogenic limestones rest on the ophiolites (Cobiella-Reguera *et al.* 1984*a*; Iturralde-Vinent *et al.* 2006).

In many places, deformed olistostromes (with blocks of serpentinite, dolerite, gabbro, basalt and amphibolite, up to several hundred metres in diameter) of Maastrichtian age (La Picota Fm, Fig. 13; Cobiella-Reguera 1978), lie below the ophiolites. The olistostromes consist almost 100% of serpentinitic and gabbroic clasts. Clasts from the Cretaceous volcanic arc are minor components. Fine grained clastic beds yield Maastrichtian fossils. Some blocks of Maastrichtian shallow limestones with rudists are also present (Iturralde-Vinent *et al.* 2006), but clasts clearly derived from a Mesozoic continental palaeomargin are absent. The Holguin and eastern Cuba Maastrichtian beds are the only chaotic deposits related to the ophiolite emplacement lacking palaeomargin clasts. The oldest beds resting above La Picota Fm are uppermost Maastrichtian or lowermost Paleocene, with abundant serpentinite olistoliths (Iturralde-Vinent *et al.* 2006). Therefore, a Maastrichtian age for the ophiolite emplacement is indicated (Cobiella-Reguera *et al.* 1984*a*; Nuñez Cambra *et al.* 2003; Iturralde-Vinent *et al.* 2006). Regional geology and structural features recorded in the ophiolite massifs and other rocks indicate tectonic transport from south to north (Nuñez Cambra *et al.* 2003; Iturralde-Vinent *et al.* 2006). The massifs travelled no less than 30 km; probably no less than 60 km, if the Sierra del Convento klippe in southern Sierra del Purial (see Fig. 1) is included in the calculation. Emplacement was very rapid and gravity driven (Cobiella-Reguera 1974, 1978; Iturralde-Vinent *et al.* 2006). Subaerial relief on the moving ophiolite thrust is suggested by blocks of weathered serpentinite, derived from lateritic soils, and abundant rounded clasts of mafic rocks found in the olistostromes (Fig. 13).

No record of significant Cenozoic deformation is present in eastern Cuba ophiolitic massifs. Little-deformed Paleocene–Middle Eocene tuffs and sedimentary rocks, belonging to the Early Cenozoic volcanic arc developed in southeastern Cuba, rest upon the older rocks. In easternmost Cuba (Maisí area; Fig. 1) rocks of the Moa–Baracoa Massif lie in tectonic contact upon metamorphic rocks of Jurassic and Cretaceous age, probably a passive continental margin section (Pardo 1975; Somin & Millán 1981; Cobiella-Reguera *et al.* 1984*a*; Iturralde-Vinent 1997; Cobiella-Reguera 2000).

Cajobabo body (easternmost Cuba)

Near the mouth of Cajobabo river, in the Sierra del Purial, easternmost Cuba (Figs 1 & 14), a small serpentinite body rests on Middle–Upper Eocene submarine fan deposits of the San Luis Fm. This includes olistostromes with clasts of serpentine, gabbro, amphibolite and other members of the ophiolite suite, mixed with tuffs and andesite clasts from an Early Cenozoic volcanic arc (Cobiella-Reguera *et al.* 1977). The Early Cenozoic volcanics (El Cobre Fm) are thrust upon the Eocene turbidites and the Cretaceous metavolcanic rocks and lie with unconformity below Upper Miocene–Quaternary strata (Fig. 15, Iturralde-Vinent 1997; Cobiella-Reguera *et al.*1977, 1984*a*). The volcanic rocks are not recorded in the local pre-Middle Eocene section. Thrusting was probably a late Middle Eocene event, tied to the intense erosion of a nearby mountain chain. Despite its small size, the Cajobabo body is a key piece in northern Caribbean geology, because its emplacement seems to be related to the first recorded horizontal movements along the Oriente fault in the Caribbean–North American plate margin (Cobiella-Reguera *et al.* 1977, 1984*b*).

Some conclusions on the Northern Ophiolites

The NO probably are the obducted remains of NW Proto-Caribbean lithosphere (Pindell & Barrett 1990; Cobiella-Reguera 2005; Pindell 2006). The preceding paragraphs show a complex and varied NO emplacement story. Several facts strongly suggest that the NW Proto-Caribbean oceanic

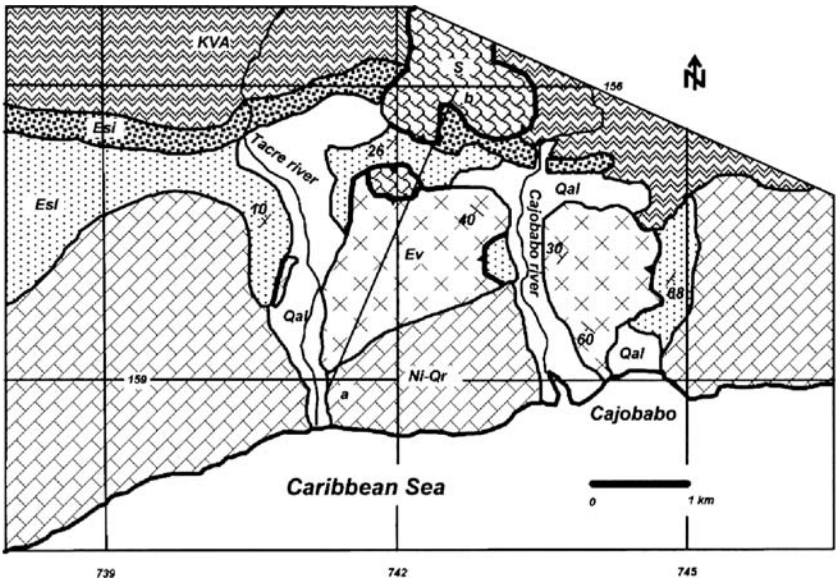

Fig. 14. Geological map of Cajobabo, Guantanamo province (modified after Cobiella-Reguera *et al.* 1977). Local coordinates (Cuba South). See location in Figure 1. KVA, Cretaceous metavolcanic rocks (Sierra del Purial Fm); Ev, Palaeogene volcanic arc rocks (El Cobre Fm Lower Eocene at this locality); Esi, Middle Eocene talus megabreccia; Esl, Middle Eocene (at this locality) volcanomictic deposits (San Luis Fm); Ni–Qr, Upper Miocene–Pliocene (Imias Fm) marine talus deposits and Quaternary fringing reefs limestones; S, serpentinites. Line a–b corresponds to the profile in Figure 15.

basin was closed before the end of the Cretaceous. Among them are:

1. The disappearance of the Late Cretaceous volcanic arc in Cuba (and possibly in Hispaniola) during Campanian time (Iturralde-Vinent 1997; Iturralde-Vinent & Macphee 1999; Draper & Barros 1994). Volcanism ceased for about 15 Ma and was only resumed in SE Cuba in the Early Paleocene (Cobiella-Reguera 1988). The more or less simultaneous break in volcanic activity in a *c.* 1000 km long belt should be tied to the more or less coeval arrival of the North American palaeomargin to the subduction zone.
2. The development of volcanomictic Campanian sediments above the North American Mesozoic palaeomargin in western Cuba (Pszczolkowski 1994, 1999). This could be possible only if the oceanic basin in between the Cretaceous volcanic arc and the NA margin disappeared (Cobiella-Reguera 2000, 2005, fig. 12).
3. The Campanian–Maastrichtian (and K–T boundary) sedimentary rocks unconformably rest on the ophiolites of western Cuba (Piotrowska 1986*a*, *b*; Pushcharovsky 1988).
4. The upper Maastrichtian–Paleocene sedimentary cover lies on top of the post Early Campanian serpentinite–volcanic tectonic mix in central Cuba (Kantchev *et al.* 1978; Pushcharovsky 1988).

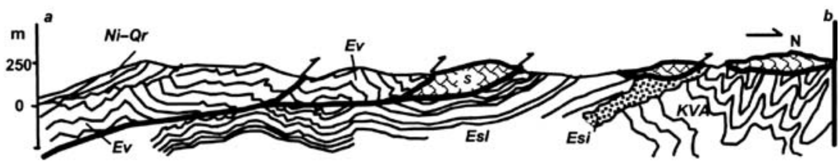

Fig. 15. Sketch structural profile along the a–b line in Figure 14 (slightly modified after Cobiella-Reguera 2005). Same vertical and horizontal scales. KVA, Cretaceous metavolcanic rocks (Sierra del Purial Fm); Ev, Palaeogene volcanic arc rocks (El Cobre Fm, Lower Eocene in this locality); Esi, Middle Eocene talus megabreccia (San Ignacio Fm); Esl, Middle Eocene (in this locality) volcanomictic deposits (San Luis Fm); Ni–Qr, Upper Miocene–Pliocene (Imias Fm) marine talus deposits and Quaternary fringing reefs limestones; S, serpentinites; N, North.

5. The conglomerates and breccias with serpentinite and gabbroid clasts in the upper Campanian beds of western Cuba (Via Blanca Fm, Iturralde-Vinent 1996*a*, *b*), and Maastrichtian (La Picota, Yaguajay, Micara and La Jiquima formations) of eastern Cuba (Jakus 1983; Gil *et al.* 2003). All these units belong to the Cretaceous volcanic terrane cover.

Furthermore, extraordinary K–T boundary deposits with similar characteristics in western and central Cuba rest on the volcanic arc as well as on the continental palaeomargin (Pszczolkowski 1986; Tada *et al.* 2003). This indicates that 65 Ma ago these units were not very separate, leaving very little or no space for the Proto-Caribbean basin at that time.

In several models on the origin of the Caribbean Plate, the NO is considered part of a great ophiolitic suture developed along the northern Caribbean, recording oblique and diachronous collision between the North American and Caribbean plates. However, the data described above show that in most of the cases, the present NO position is due to distinct events of later thrusting, 10–30 Ma after (i.e. Late Maastrichtian to Middle or Early Late Eocene) the Campanian collision. The small Cajobabo body was emplaced in (late?) Middle Eocene, not far away from the Oriente fault zone in SE Cuba. This age is a little younger than the Cayman Trough opening assumed by Leroy *et al.* (2000), supported on very different data.

The association of the ophiolite bodies with olistostromes and the general geological scenario shows that final NOB emplacement events were always violent, and probably, ephemeral events.

Campanian–Late Eocene tectonic history of Cuba and surroundings

The Proto-Caribbean Plate is a vanished oceanic plate developed between the two American continents and connected to the Atlantic realm. Its origin was related to the breakup of western Pangaea, begining in the Late Triassic (Iturralde-Vinent 2003) or Jurassic (Pindell & Barrett 1990; Marton & Buffler 1999). Radiolarites of Upper Jurassic age are preserved in Proto-Caribbean rocks in the Cuban ophiolite belt (Llanes-Castro *et al.* 1998), the Duarte complex in Hispaniola (Lewis *et al.* 2002), and in northern South America (Giunta *et al.* 2002, 2003). Separation of North America and Gondwana plates continued until the Early Cretaceous (Marton & Buffler 1999). The ammonite fauna in Upper Jurassic deposits of the North America palaeomargin in western and central Cuba points to an oceanic seaway open to the Tethys from the Oxfordian onward (Pszczolkowski & Myczynski 2003; Iturralde-Vinent 2003).

The begining of volcanic arc magmatism during the Early Cretaceous represents a first indication of subduction of Proto-Caribbean lithosphere. In Cuba, the oldest volcanic arc rocks are of Aptian age (Rojas *et al.* 1995). At the same stratigraphic position, rare tuff beds are intercalated within the successions of the North American palaeomargin in western Cuba, which supports the beginning of arc volcanism during Aptian time (Cobiella-Reguera 2000) and its not very distant location from the NA palaeomargin. In Hispaniola, a few fossil finds indicate a Neocomian–Aptian age for the early arc, although robust stratigraphic control on the age of the lower beds of the arc is absent. Kesler *et al.* (2005) reported Aptian and Albian radiometric ages (113.9–110.9 Ma) for PIA rocks in Hispaniola.

The Aptian–Albian volcanic arc was characterized by tholeiitic bimodal magmatism, with some boninitic affinities in Hispaniola and probably in Cuba (Diaz de Villalvilla 1997; Kerr *et al.* 1999; Cobiella-Reguera 2000; Lewis *et al.* 2002). Volcanic activity in Cuba and other parts of the Greater Antilles drastically diminished during the Late Albian–Cenomanian (Kantchev *et al.* 1978; Iturralde-Vinent 1997; Kesler 2005). In the Cenomanian–Campanian (locally Maastrichtian?) volcanic arc magmatism resumed with a prevailing calcalkalic character (Jolly *et al.* 1998; Lebrón & Perfit 1994; Iturralde-Vinent 1996) and with local tholeiitic manifestations in eastern Cuba (Proenza *et al.* 2006).

Campanian and Maastrichtian

For those models of Middle America evolution proposing a Cretaceous–Quaternary ‘Great Arc of the Caribbean’ (GAC) (Mann 1999) or Great Caribbean Arc (Pindell *et al.* 2006) related to a Pacific origin for the Caribbean Plate (e.g. Pindell & Barrett 1990; Mann 1999; Pindell *et al.* 2006), the Late Cretaceous was a time when the GAC moved to the NE, consuming Upper Jurassic–Lower Cretaceous Proto-Caribbean crust located between the arc and the North American palaeomargin. In these interpretations, the same movement continued in the Early Palaeogene until the arc collided with the North American palaeomargin, first in western Cuba (Paleocene), and thereafter in central and eastern Cuba in different times during the Eocene.

In the Kerr *et al.* (1999) and Iturralde-Vinent (1997) model, the Late Cretaceous volcanic arc travel in the NW Caribbean was in the same direction as in the Cretaceous–Quaternary GAC hypothesis, but the consumed oceanic lithosphere is from the Pacific plate, diving in an east or NE dipping

subduction zone. Campanian–Paleocene quiescense in volcanism is considered, but in the accompanying illustrations subduction without volcanism continued during Late Campanian and Maastrichtian (Kerr *et al.* 1999, fig. 12). The Cretaceous volcanic arc/North American palaeomargin collision was an Early Palaeogene event as in the GAC models. The emplacement from the south of the ophiolites and the volcanic arc terrane upon the North American palaeomargin cannot be explained by the author's proposed mechanism. According to the same authors, the Paleocene–Middle Eocene volcanic arc (Turquino) in SE Cuba is inherited from the Cretaceous subduction zone.

Data from Cuba reviewed here refutes all these models. One of the basic features of the GAC Late Cretaceous travel is its collision with southern Yucatán (Pindell *et al.* 2006) and the emplacement of the so-called southwestern terranes in Cuba. Iturralde-Vinent (1996*a*) brought together the Mesozoic sections of Escambray, Isla de la Juventud and Guaniguanico mountains in his 'Southwestern terrains'. In fact, Jurassic sections in the Guaniguanico Cordillera, Isle of Youth and Escambray mountains share many common features. According to Cobiella-Reguera (1996, 2000) they probably were deposited in the same basin, but their present respective location with regard to ophiolites and the Cretaceous volcanic arcs terrane is very different. Regional geology suggests that rocks in Escambray and Isla de la Juventud were always placed south from the Cretaceous volcanic arcs, while Upper Jurassic–Cretaceous sections belonging to the Guaniguanico Cordillera were the western continuation of the deep water Upper Jurassic and Cretaceous sections of the Mesozoic palaeomargin in northern central Cuba (Cobiella-Reguera 1996, 2000; Pszczolkowski & Myczynski 2003). Data from the SE Gulf of Mexico (Marton & Buffler 1994, 1999; Moretti *et al.* 2003) clearly show close stratigraphic relationships with the Mesozoic sedimentary sections in Guaniguanico Cordillera. Therefore, it seems difficult to consider the last region as a tectono-stratigraphic terrane (e.g. as envisaged by Iturralde-Vinent 1996*a*; Pszczolkowski 1999; and partially Pindell *et al.* 2006) since it does not represent crustal blocks exotic to its present tectonic setting.

Recently Pindell *et al.* (2006) considered the Escambray terrane as a 'tectonically-unroofed, deep level of the Great Arc's forearc where passive margin strata has been subducted and subcreted in the Aptian-Albian'. According to the same authors, the Southern Metamorphic terranes and Guaniguanico were torn from the eastern or southern Yucatán margin much later, during the Campanian and Maastrichtian, when the western leading edge of the Great Caribbean Arc slid along the Yucatán border. In central Cuba, the Escambray–Cretaceous volcanic arcs terrane tectonic contact is crossed by 88–80 Ma pegmatites (Stanek *et al.* 2000), showing that the terrane welding in central Cuba probably is a Cretaceous pre-Coniacian event. In that case, and supposing a SE Yucatán origin for the Escambray metamorphic rocks, at least some remains of middle Cretaceous high-pressure rocks or structures pointing to a pre-Coniacian tectonic event should be present in the southeastern Yucatán margin. However, no evidence for such events in SE Yucatán or northern Central America is reported in the geological literature (e.g. Donnelly *et al.* 1990; Morán-Zenteno 1994). Other authors also pointed out a Yucatán (Maya Block) origin for the Southern Metamorphic terranes and Guaniguanico (Iturralde-Vinent 1996*a*, *b*; Kerr *et al.* 1999; Schaffhausser *et al.* 2003), but correlation between the Cuban sections and SE Yucatán was not attempted, except by the last mentioned authors. According to Schaffhausser *et al.* (2003), the Lower Cretaceous 'Guaniguanico like' sections in western Belize were emplaced as thrust sheets between the Maastrichtian and the Eocene, several million years after Pindell *et al.* (2006) supposed travel and collision of the Great Caribbean Arc with SE Yucatán to have occurred. In the author's opinion, there is no conclusive tectonic or stratigraphic evidence allowing an original position of the Cuban southern metamorphic terranes at the Yucatán SE margin, which accords with Escambray as a Mesozoic poly-genetic unit (terrane) amalgamated into a subduction zone (e.g. García-Casco *et al.* 2006; Stanek *et al.* 2000).

Geological information from all of Cuba's territory shows that volcanic arc activity ended during the Campanian and did not resume until late in the Danian (and then only in SE Cuba; Pushcharovsky 1988; Cobiella-Reguera 1988; Iturralde-Vinent 1997). The end of volcanism in Cuba during the Early Campanian suggests that subduction stopped more or less simultaneously along *c*. 1000 km. Probably, the end of the arc was related to collision and underplating of the North American palaeomargin during the Campanian. Several lines of evidence suggest Campanian emplacement. Indirect evidence of the closing of the oceanic depression between the Late Cretaceous, volcanic arc and the North American Mesozoic palaeomargin occurs in the Campanian sedimentary rocks of western Cuba. Here, the Moreno Fm of the Cordillera de Guaniguanico contains clastic material derived from the KVAT (Pszczolkowski 1994, 1999). This shows that at least in the west there was no Late Campanian oceanic depression between the arc and the palaeomargin (Cobiella-Reguera 2000). A Campanian collision is also known in northern Central America where ophiolite emplacement is recorded by the

siliciclastic Campanian–Lower Cenozoic Sepur Fm (Donnelly *et al.* 1990; Pindell *et al.* 2006).

In western Cuba, the upper Campanian–Maastrichtian volcanomictic turbidites (Via Blanca Fm) lie on the ophiolites and the volcano-ophiolitic mélange as well as on the KVAT rocks (Pszczolkowski & Albear 1982; Pushcharovsky 1988; Piotrowska 1986*a*, *b*). This points to a Campanian? (pre-Via Blanca Fm) tectonic event in this area. Evidence of pre-Late Maastrichtian thrusting and tectonic mixing is present in central Cuba. After the initial Campanian collision, the extinguished Cretaceous volcanic arc was deformed and uplifted and terrigenous sediments, followed by some carbonates, accumulated in basins during the Late Campanian until the Late Maastrichtian (Diaz-Otero *et al.* 2003). Iturralde-Vinent (1997) considers Campanian–Maastrichtian depressions as piggy back basins, an interesting proposal that needs further consideration.

In Hispaniola also, volcanic quiescence occurred from the Late Campanian or Maastrichtian to the Early Palaeogene (Lewis & Draper 1990; Draper & Barros 1994, fig. 7.7). In Puerto Rico, a Late Maastrichtian–Danian pause in volcanism is recorded, whereas Maastrichtian volcanic rocks are limited to the western province of the island (Jolly *et al.* 1998, fig. 2). In conclusion, at the end of the Cretaceous–begining of the Palaeogene, there probably was no GAC in the NW Caribbean. From Late Maastrichtian to Early Paleocene tectonic unrest occurred in different places. A regional tectonic event in easternmost Cuba raised ophiolite massifs to the surface (Kozary 1968; Knipper & Cabrera 1974), thrusting them to the north during the (Late?) Maastrichtian (Cobiella-Reguera 2005; Iturralde-Vinent *et al.* 2006). Overlying Danian olistostromes and turbidites in the same area point to continued instability in the earliest Cenozoic. The unconformity between Maastrichtian (including K–T boundary deposits) and upper Paleocene sediments in the Havana area, and the poor distribution of upper Maastrichtian and Paleocene (Pardo 1975) beds in Cuba, suggest a period of general tectonic deformation at the Cretaceous–Paleocene transition.

Paleocene–Middle Eocene

In the Early Paleocene (Danian) the tectonic setting changed (Fig. 16). A new east–west trending submarine volcanic arc was born in SE Cuba (the Turquino–Cayman Ridge volcanic arc) on top of the Cretaceous volcanic terrane and its sedimentary cover. Several thousand metres of effusive and pyroclastic rocks, ranging from rhyolites to basalts, but mainly andesites, with marine sedimentary intercalations, crop out in the Sierra Maestra

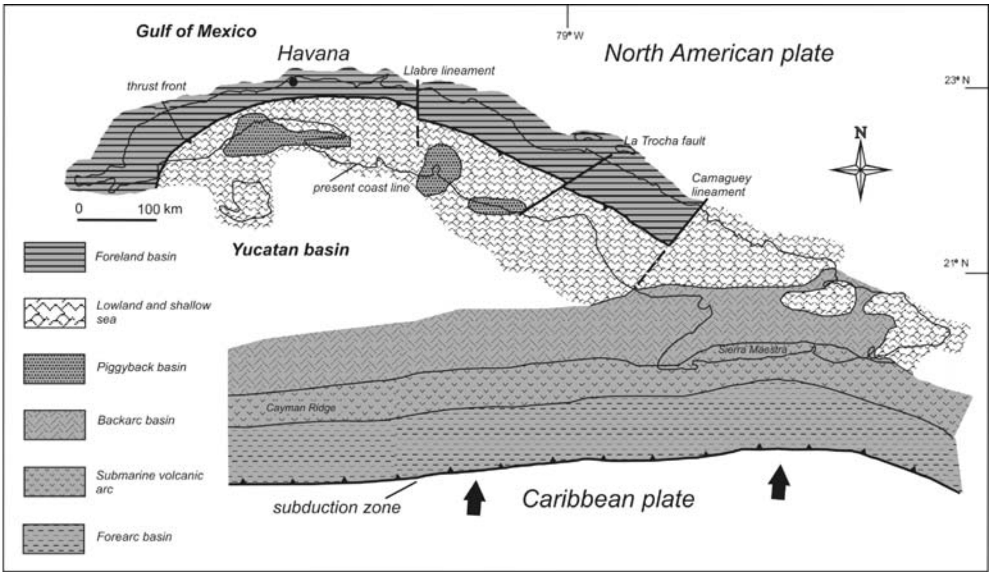

Fig. 16. Late Paleocene tectonic setting of Cuba and its surroundings. West of Camaguey lineament, the Cuban Orogeny was going on, with northwards moving thrust sheets carrying piggyback basins on top. In SE Cuba the Turquino–Cayman Ridge volcanic arc was active, with its north-dipping subduction zone acting as the boundary between the Caribbean and North American plates.

(Lewis & Straczek 1955; Khudoley & Meyerhoff 1971; Cobiella-Reguera 1988; Iturralde-Vinent 1996*a*, *b*). Its corresponding back arc basin, filled mainly with pyroclastic rocks, volcanogenic turbidites and sedimentary rocks, lay to the north (Fig. 16, Cobiella-Reguera 1988; Iturralde-Vinent 1996*b*, 1997). Intruding into the volcanic sequence in the Sierra Maestra are a large number of magmatic bodies with compositions ranging from granites to gabbro. According to Rojas-Agramonte *et al.* (2005), these are volcanic arc calcalkalic granites of intraoceanic origin. Pb–U analyses from zircons in the granitoids yielded ages from 60 Ma (Paleocene) to 48 Ma (Middle Eocene). This is very similar to the time span for the volcanic rocks of the arc. Westward, Paleocene–Eocene volcanic rocks were recorded in the Cayman Ridge and Nicaragua Plateau by Perfit & Heezen (1978, fig. 9a). According to Siggurdsson *et al.* (1997), an Early Palaeogene volcanic arc and a northern back arc and basin are present in the Cayman Ridge and Yucatán basin. According to this architecture, a north-dipping suduction zone should flank the Turquino–Cayman Ridge arc to the south (Fig. 17; Cobiella-Reguera 1988; Iturralde-Vinent 1996*b*; Siggurdsson *et al.* 1997) and dense oceanic Caribbean crust dived below the arc. Coeval Eocene volcanic arc rocks occur in the Northwestern Peninsula and the Montaignes Noires of Haiti (Butterlin 1960) and are also present in Sierra de Neiba and Seibo of the Dominican Republic (Lewis & Draper 1990; Draper & Barros 1994). If they originally were part of the Turquino–Cayman Ridge arc, then probably this structure was more than 1500 km long.

This geographic distribution of the main tectonic Early Cenozoic units is an extremely important fact in the Caribbean–North American plate boundary history. The subducted (Caribbean) oceanic crust must have moved with a strong northward component along the 1000–1500 km long subduction zone of the Turquino–Cayman Ridge arc (Fig. 16). This point was suggested by Siggurdsson *et al.* (1997), but has been largely overlooked. In many of the Caribbean evolution models, at this time (Danian–Middle Eocene) the Caribbean Plate is moving with a strong eastward component (compare Fig. 16 with Pindell *et al.* 2006, fig. 7). In the present interpretation, the lithosphere to the north of the Turquino–Cayman Ridge subduction zone was already accreted to the North American plate in the Paleocene, and the southeastern boundary of the North American plate was a north-dipping subduction zone from the Paleocene to the Middle Eocene.

From the Danian to the Middle Eocene, in western and central Cuba (west of the Camaguey lineament) a different tectonic environment existed. In these areas volcanic activity was absent and thrust sheets several kilometres thick, containing rocks of the ophiolite belt and the Cretaceous volcanic terrane, with small marine piggyback basins (Hatten *et al.* 1988; Cobiella-Reguera 1988, 2005; Iturralde-Vinent 1997), moved in a general northward direction toward the North American Mesozoic palaeomargin and the overlying southern

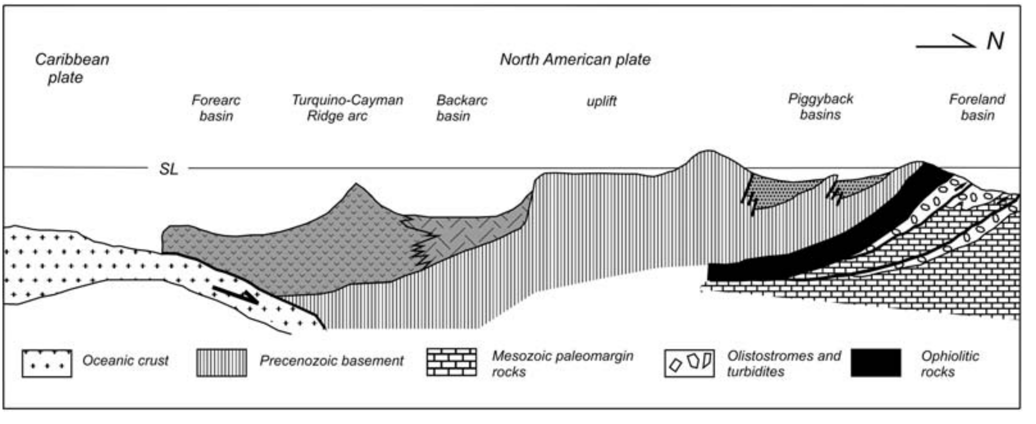

Fig. 17. Paleocene–Early Middle Eocene conceptual palaeotectonic cartoon profile during the Cuban orogeny (modified after Cobiella-Reguera 2005). The profile is located to the west of Camaguey lineament (see Fig. 16) and is about 300 km long. The subduction zone location is assumed from theoretical considerations and regional geology data (Figs 2 & 16, Cobiella-Reguera 1988; Siggurdsson *et al.* 1997), but no evidence of this structure or the subducted Caribbean lithosphere has been found. The sketch summarizes the proposed relationships between the Turquino–Cayman Ridge arc and the coeval piggyback and foreland basins.

fringe of the foreland basin, that also became involved in deformation (Figs 16 & 17, Cuban Orogeny). The crust north of the thrust belt was depressed below northward-moving nappes and a foreland basin developed from Late Paleocene to Middle (locally Late) Eocene. Subaerial relief was not particularly great, as coarse clastic deposits are rare (except the olistostromes). Rocks of the ophiolite belt were mainly exposed in submarine cliffs. Debris flows and other gravitational deposits moved to the seafloor to form the olistostromes and turbidites. During continued advance the nappes overrode, crushed and partly mingled with the olistostromes, creating mélanges (Cobiella-Reguera 1997). This tectonic event migrated eastwards. In western Cuba, thrusting occurred from Late Paleocene to early Early Eocene. East of the Llabre lineament (Fig. 2) thrusting occurred from Early to Middle Eocene, while east of La Trocha fault it was a late Middle Eocene–?Late Eocene event. Some authors (Brzesnyansky & Iturralde-Vinent 1978) extend this orogeny to Holguin in northern eastern Cuba, but no clear evidence of intense Paleocene or Eocene deformation is present there. In the GAC models, this diachronous orogenic Early Palaeogene event is interpreted as the Late Cretaceous–Early Palaeogene volcanic arc/North American palaeomargin oblique collision (Mann 1999; Pindell 2006). However, as explained earlier, volcanism in Cuba ceased from the Late Campanian to the Danian. The north-dipping subduction zone of the Turquino–Cayman Ridge arc, several hundred kilometres south of the Early Cenozoic deformed belt (Figs 17 & 18),

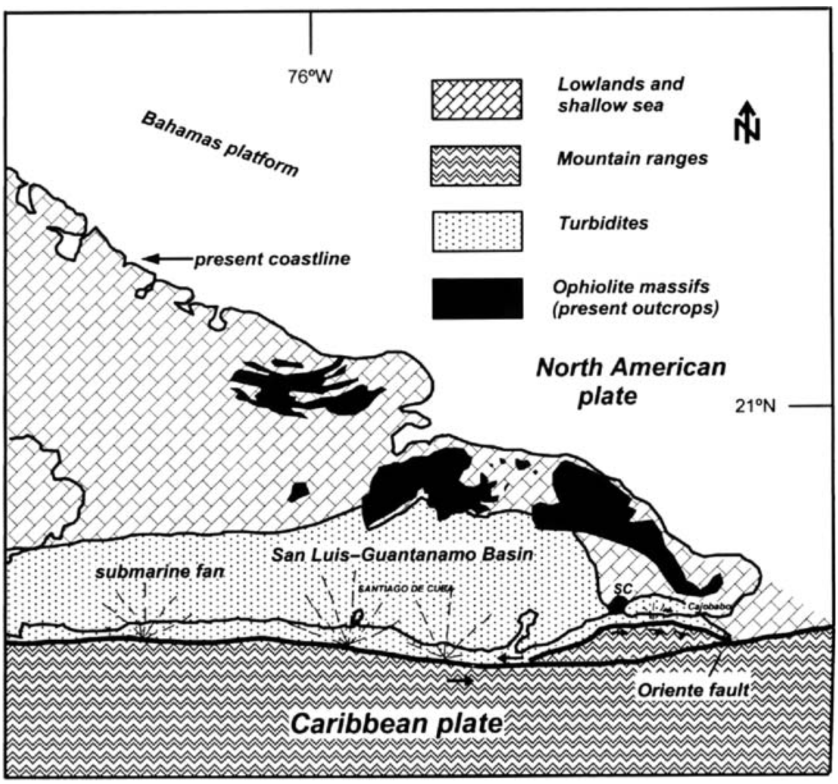

Fig. 18. Palaeogeographic reconstruction of eastern Cuba during late Middle Eocene and Late Eocene made with data from Keijzer (1945), Lewis & Straczek (1955), Bresznyansky & Iturralde-Vinent, M. (1978) and Cobiella-Reguera (1984). The southern highlands were named the Bartlett Land by Taber (1934). Probably their origin is tied to the compressive deformations present along the southern fringe of eastern Cuba, considered Oligocene in age by different authors (Rojas-Agramonte *et al.* 2006; Iturralde-Vinent 1997). However, the thick volcanoclastic Middle–Upper Eocene deposits of the San Luis-Guantanamo basin and the coeval emplacement of the Cajobabo tectonic sheet (Figs 14 & 15), together with the mild deformations in eastern Cuba Oligocene beds, points to a Middle–Late Eocene compressive event. SC, Sierra del Convento ophiolites.

cannot be invoked to explain the deformation of the latter.

Middle–Late Eocene

Early in the Middle Eocene, the Turquino–Cayman Rise volcanic arc became inactive (Cobiella-Reguera 1988; Rojas-Agramonte *et al.* 2004, 2005, 2006). In SE Cuba, several hundred metres of Middle–Upper Eocene terrigenous volcanomictic deposits (the San Luis, Camarones and related formations) crop out in the San Luis–Guantanamo basin, north of the Sierra Maestra (Keijzer 1945; Lewis & Straczek 1955; Khudoley & Meyerhoff 1971). Highlands with outcrops of the vanished Turquino–Cayman Rise arc (Fig. 18), located in the present Cayman Trough area, not far from the coastline, was the sediment source (Keijzer 1945; Cobiella-Reguera *et al.* 1984*a*, *b*). Erosion unroofed Early Cenozoic granitoid intrusives as their clasts occur in the conglomerates (Lewis & Straczek 1955; Rojas-Agramonte *et al.* 2004). The sediments conformably lie on top of the underlying Early Cenozoic volcanic arc section (Lewis & Straczek 1955). Compressive deformation also affected the Middle Eocene and older rocks in the Sierra Maestra and its northern foothills. The intensity of deformation increases southward towards the Oriente fault (Iturralde-Vinent 1997; Rojas-Agramonte *et al.* 2005, 2006). Iturralde-Vinent (1997) assigned an Oligocene age to this event. However, the thick upper Middle and Upper Eocene siliciclastic sections of the San Luis–Guantanamo basin probably are synorogenic deposits related to this tectonic phase. Compression was accompained by local thrusting in southeasternmost Cuba, where the small Cajobabo allochthon, with Lower Eocene volcanic arc rocks and serpentinite, lies upon Middle Eocene volcanomictic sediments, not far from the Caribbean coast. The sediment source area and the thrust 'roots' were located to the south of the present coastline (Cobiella-Reguera *et al.* 1977). Because there is no record of autocthonous Turquino volcanic arc rocks in eastermost Cuba, the last two facts could be interpreted as evidence of the first sinistral movement along the Oriente fault, probably in the Middle Eocene. This was an initial short-lived but intense displacement, provoking rapid uplift of the southern block and its relative eastward movement for several tens of kilometres, locating the Turquino volcanic arc sequences in front of the Cajobabo territory (Cobiella-Reguera *et al.* 1984*a*, *b*; Cobiella-Reguera 2005). Local thrusting at Cajobabo should be related to some nearby restraining bend along the fault (Fig. 18). The age of this episode is similar to initiation of Cayman spreading centre as determined by Leroy *et al.* (2000): 49 Ma (late Early Eocene, UNESCO & IUGS 2000; Early–Middle Eocene boundary in Witrock *et al.* 2003).

The position of the Oriente fault zone (Calais & de Lepinay 1991; Rojas-Agramonte *et al.* 2006) seems to be almost the same as the Turquino–Cayman Ridge volcanic axial zone trace, perhaps a little southward of the latter. However, if the Montaignes Noires of Haiti (Butterlin) and the Sierra de Neiva (Dominican Republic) Eocene sections represent the easternmost area of the Turquino arc, its strike probably turned to ESE (Fig. 16). The volcanic sections in northern Hispaniola, invoked by Pindell (2006) as part of the Palaeogene arc, resemble those of the northern marginal basin in eastern Cuba, including the pre-Cenozoic ophiolite rich basement. Therefore, the Oriente fault zone is, in some way, related to the Turquino–Cayman Ridge volcanic arc. It probably developed as a consequence of changes in the regional tectonic stress field at the begining of the Middle Eocene, focusing sinistral movement along a latitudinal weakened belt between the Turquino–Cayman Rise volcanic arc axis and its subduction zone.

Conclusions

A complicated Campanian–Eocene history is recorded in Cuba. It is fundamental to understanding of Middle America geological development and regional tectonic models.

During the Late Cretaceous the oceanic Proto-Caribbean Plate was consumed in the subduction zone of the Greater Antilles volcanic arc until the Campanian. At this time, volcanic arc magmatism ceased along Cuba (a *c.* 1000 km long belt) due to collision with the North American passive margin. The strike of the subduction zone must have been more or less orthogonal to descending lithosphere. From Late Campanian to Danian, Cuba and its surroundings were a poorly defined collision zone where the accretion of the Late Cretaceous arc to the North American palaeomargin occurred. The most outstanding example of this tectonic unrest was the obduction of NE Cuban ophiolites and their gravitational Maastrichtian emplacement. Volcanism was absent from the Late Campanian to the Danian in Cuba and, probably, in Hispaniola. Therefore, the presence of a postulated coeval and spatially continuous Great Arc of the Caribbean, critical to Pacific models of Caribbean evolution, is not supported by geological data from Cuba.

In the Mid- or Late Danian the almost east–west trending Turquino–Cayman Ridge–Hispaniola? volcanic arc was born upon the Cretaceous arc.

The related north-dipping subduction zone should act as the SE North American plate boundary and the Yucatán basin was its backarc basin. From the Paleocene to Middle Eocene dense Caribbean lithosphere was subducted. As suggested by Siggurdsson *et al.* (1997), the oceanic lithosphere traveled northwards towards the east–west subduction zone. The location, strike and subduction polarity of the Early Palaeogene subduction zone of this paper are very different from those described by GAC models.

Almost simultaneous with the magmatic event in SE Cuba, the Cuban Orogeny developed in western and central Cuba, west of the Camaguey lineament. The orogeny was diachronous, younging towards the east. During this event the northern ophiolite belt and the Cretaceous volcanic terrane were thrusted northward for at least tens of kilometres, onto the southern fringe of the Mesozoic North American palaeomargin and its overlying Early Cenozoic foreland basin. The preceding facts show that the present NOB position is not the original location of the North American–Proto-Caribbean Plate ophiolitic suture as has been interpreted in several models.

At the beginning of the Middle Eocene subduction stopped, perhaps due to the arrival of an oceanic plateau. Simultanously(?) a change in the regional stress field originated near the east–west trending sinistral Oriente fault zone, whose position and origin are probably tied to the weakened hot crust of the Palaeogene volcanic arc axis.

Recently James (2006) questioned several of the basic arguments of the Pacific origin models of Caribbean origin. The present paper shows many inconsistencies of the GAC (a fundamental element of the Pacific models) with the Cuban geological data and presents an alternative to the GAC hypothesis. The author is conscious that his hypothesis is in a rudimentary state and has several undeveloped questions. Among these are the unexplored relationships between the Palaeogene volcanic arc and neighbouring northern Central America structures (Maya and Chortís Blocks), or with structures bounded by the south the Late Cretaceous volcanic arc. The answers to these questions wait for new research dealing with the poorly known NW Caribbean Sea.

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