The geotectonic story of the northwestern branch of the Caribbean Arc: implications from structural and geochronological data of Cuba

K. P. STANEK[1]*, W. V. MARESCH[2] & J. L. PINDELL[3,4]

[1]*TU Bergakademie Freiberg, Institut für Geologie, D-09596 Freiberg, Germany*

[2]*Ruhr-Universität Bochum, Institut für Geologie, Mineralogie und Geophysik; D-44780 Bochum, Germany*

[3]*Tectonic Analysis Ltd, Chestnut House, Duncton, West Sussex GU28 0LH, UK*

[4]*Department of Earth Science, Rice University, Houston, Texas, USA*

**Corresponding author (e-mail: stanek@geo.tu-freiberg.de)*

Abstract: Within the last decade, modern petrological and geochronological methods in combination with detailed studies of the field geology have allowed the reconstruction of tectonic processes in the northwestern part of the Caribbean Plate. The development of an oceanic Proto-Yucatán Basin can be traced from the Late Jurassic to the Mid-Cretaceous. From the Mid-Cretaceous onward, an interaction of this basin with the Caribbean Arc can be observed. Geochronological data prove continuous magmatic activity and generation of HP mineral suites in the Caribbean Arc from the Aptian to the Campanian/Maastrichtian. Magmatism ceased at least in onshore central Cuba at about 75 Ma, probably as the southern edge of the continental Yucatán Block began to interact with the advancing arc system. Similarly, the youngest recorded ages for peak metamorphism of high-pressure metamorphic rocks in Cuba cluster at 70 Ma; rapid uplift/exhumation of these rocks occurred thereafter. After this latest Cretaceous interaction with the southern Yucatán Block, the northern Caribbean Arc was dismembered as it entered the Proto-Yucatán Basin region. Because of the continued NE-directed movement, Proto-Yucatán Basin sediments were accreted to the arc and now form the North Cuban fold and thrust belt. Parts of the island arc have been thrust onto the southern Bahamas Platform along the Eocene suture zone in Cuba. Between the arc's interaction with Yucatán and the Bahamas (*c.* 70 to *c.* 40 Ma), the Yucatán intra-arc basin opened by extreme extension and local seafloor accretion between the Cayman Ridge (still part of Caribbean Plate) and the Cuban frontal arc terranes, the latter of which were kinematically independent of the Caribbean. Although magmatism ceased in central Cuba by 75 Ma, traces of continuing Early Palaeogene arc magmatism have been identified in the Cayman Ridge, suggesting that magmatism may not have ceased in the arc as a whole, but merely shifted south relative to Cuba. If so, a shallowing of the subduction angle during the opening of the Yucatán Basin would be implied. Further, this short-lived (?) Cayman Ridge arc is on tectonic strike with the Palaeogene arc in the Sierra Maestra of Eastern Cuba, suggesting south-dipping subduction zone continuity between the two during the final stages of Cuba–Bahamas closure. After the Middle Eocene, the east–west opening of the Cayman Trough left the present Yucatán Basin and Cuba as part of the North American Plate. The subduction geometry, P–T–t paths of HP rocks in Cuban mélanges, the time of magmatic activity and preliminary palaeomagnetic data support the conclusion that the Great Antillean arc was initiated by intra-oceanic subduction at least 900 km SW of the Yucatán Peninsula in the ancient Pacific. As noted above, the Great Antillean Arc spanned some 70 Ma prior to its Eocene collision with the Bahamas. This is one of the primary arguments for a Pacific origin of the Caribbean lithosphere; there simply was not sufficient space between the Americas, as constrained by Atlantic opening kinematics, to initiate and build the Antillean (and other) arcs in the Caribbean with *in situ* models.

The origin of the Caribbean Plate: contrasting models

Previous interpretations of the geotectonic development of the Caribbean Plate have been based on different data sets and sometimes yielded contradictory results. However, modern analytical methods now allow the geodynamic processes and events involved in plate collisions to be understood on a three-dimensional scale down to deeper crustal and upper mantle levels. This is especially true for the northern and southern margins of the present Caribbean Plate, where petrological, geochronological and geophysical data are providing

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an increasingly robust basis for objective plate-tectonic interpretations. Most recently, the origin of this largely oceanic plate was discussed extensively in the Sigüenza workshop (Spain) in 2006, and was reduced to two principal models of Caribbean evolution: The 'Pacific-origin' or 'tectonic indenter model' on the one hand, and the 'intra-American' or '*in situ*-model' on the other. The tectonic indenter model invokes east–west displacement of an oceanic piece of Pacific crust into the gap between the westward-drifting (in the mantle reference frame) North and South American continental plates, beginning in the Early Cretaceous (Pindell & Dewey 1982; Pindell 1993; Pindell *et al.* 2005, 2006). Because of the relative motion, an island arc developed at the leading edge of the Pacific crustal fragment (the Caribbean Arc), subducting the 'Proto-Caribbean' (inter-American) oceanic crust between the Late Jurassic–Cretaceous passive margins of the American continents. Multiple plate boundary interactions occurred, such as collision and obduction of parts of the island arc, shifting of the magmatic axis, and lateral translation of fragments of American continental crust. However, the precise time and style of initiation of the subduction zone along the 'bow' of the Pacific/Caribbean Plate remain unclear. The *in situ* model also calls for the opening of space between the two American continents by rifting, but all tectonic features since the Late Jurassic are explained in terms of an inter-American Caribbean oceanic crust which later converged along all the American margins, forming island arc/subduction–zone complexes and collisional suture zones by uncoordinated movements of the Caribbean and American plates (Meschede & Frisch 1998; Giunta *et al.* 2006; James 2002, 2006). In order to acknowledge Caribbean arc histories which started in the Early Cretaceous, this involves active northern and southern Caribbean continental margins early in the Caribbean history rather than the predominantly passive ones acknowledged by the indenter model. The large Cenozoic strike–slip movements in the northern and southern Caribbean as recorded by the Cayman Trough (Rosencrantz *et al.* 1988; Leroy *et al.* 2000), the subduction histories of long-lived island arcs (Pindell & Barrett 1990), and the occurrence of Early Cretaceous island arc related magmatism are not satisfactorily explained by the *in situ* model. Further, the Aptian initiation of circum-Caribbean HP subduction zone metamorphism (Pindell *et al.* 2005) during a time of definite and rapid plate divergence between the Americas (extension) is difficult to reconcile with *in situ* Caribbean models.

For better understanding, the following terms will be used in this paper: all tectonic units that disappeared during the geodynamic evolution by subduction will be characterized by the prefix 'Proto', for example the oceanic crust between the American continental plates after rifting will be called 'Proto-Caribbean', and the subducted oceanic crust in the original triangle between the Yucatán and the Bahamas Blocks will be called 'Proto-Yucatán Basin'. A key area for deciphering the Late Mesozoic to Early Palaeogene geotectonic history of the Caribbean Plate is the triangular region in the northwestern Caribbean between the Yucatán Peninsula, the Cayman Trough and the southern Bahamas Platform (Cuba) (Fig. 1). After the initial opening of the Cayman Trough by an east-trending sinistral strike–slip system in the Eocene (Leroy *et al.* 2000), the Yucatán Basin, the Cayman Ridge and the Cuban terranes of the Caribbean Arc were left behind as part of North America and protected from further significant tectonic activity or magmatism (Fig. 1). The area can be subdivided into several crustal domains, although the data for the southern submerged domains are very poor. The northern shoulder of the Cayman Trough, the Cayman Ridge, shows evidence of Palaeogene arc magmatism (Sigurdson *et al.* 1997; Lewis *et al.* 2005). The Yucatán Basin consists of highly stretched arc (?) and local oceanic crust, as deduced from geophysical data (Rosencrantz 1990). In the western part of the Yucatán Basin, geothermal values have been interpreted as denoting Eocene oceanic crust, suggested to have formed in a pull-apart regime in the final stages of Cuba's migration toward the Bahamas. Along the eastern Yucatán margin, the Hondo Fault Zone separates Yucatán Block continental crust from the stretched arc/oceanic crust in the Yucatán Basin. At this fault zone, obducted bodies of low-grade metasediments (siltstone, shale, quartzite) probably correlate with the San Cayetano Formation of western Cuba (Dillon & Vedder 1973), suggesting a convergent stage between the arc and western Cuba with this continental margin, followed by transcurrence or transtension thereafter to form the current margin. In the NE, the Central Cuban Main Thrust, the western part of the North Caribbean Suture zone (NCSZ), extends along the length of the Cuban archipelago. Along this suture zone, parts of the North American palaeo-continental margin and the Cretaceous Caribbean (Great Antillean) island arc have been amalgamated, and provide a broad exposition of geology for reconstructing the geotectonic history of the northern Caribbean Plate. In the following we will present a short compilation of available stratigraphic, tectonic, geochronological and petrological data for the Yucatán 'triangle', with special emphasis on Cuba, and a geotectonic reconstruction that considers the three-dimensional nature of subduction zones.

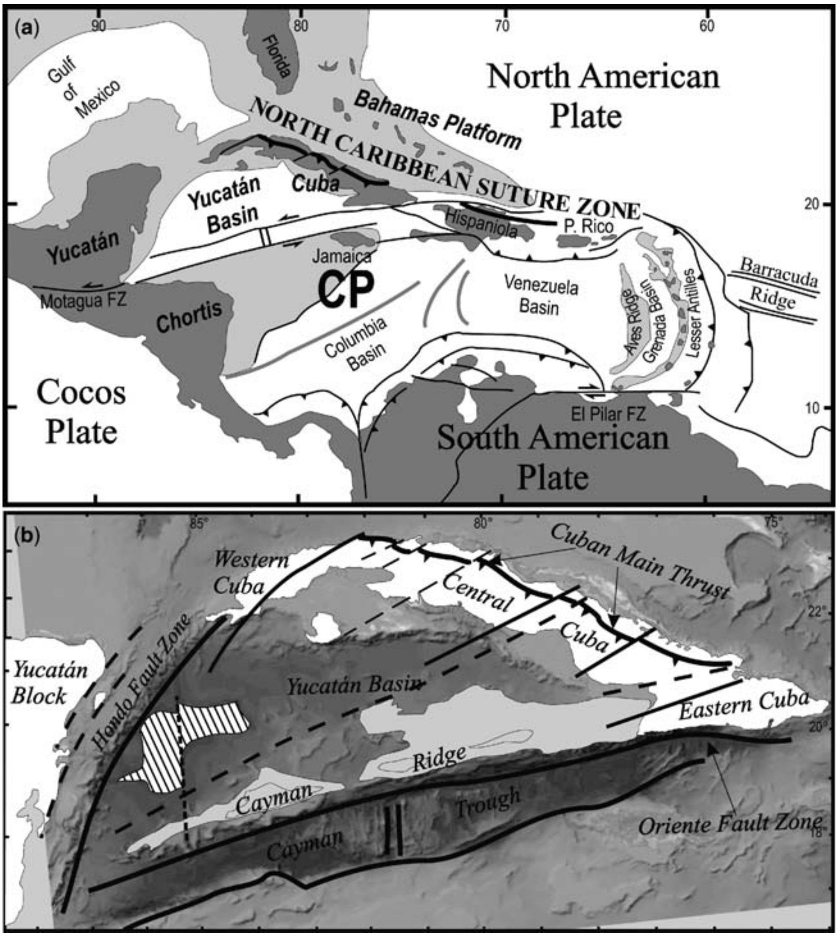

Fig. 1. Sketch map of the geotectonic framework of the Caribbean Plate (CP) (**a**) and the Yucatán Basin (**b**). The Yucatán Basin is bounded by the sinistral Hondo Fault Zone, the Cuban Main Thrust and the sinistral fault system of the northern Cayman Trough. The diagonal patterned area in the western part represents supposed Palaeogene oceanic crust (Rosencrantz 1990).

The geotectonic units of the Cuban part of the North Caribbean Suture Zone: nature and distribution of rocks

The Cuban mainland consists of three major geological regions that differ in structural style and lithological nature (Fig. 2). These areas are separated by regional faults and associated sedimentary basins: in the west the Pinar Fault with the Los Palacios Basin and in the east the Cauto Fault system and the related depression of the same name. Based on this tectonic subdivision of the Cuban mainland, the terms ‘western Cuba’, ‘central Cuba’ and ‘eastern Cuba’ are used for the regions west of the Pinar fault, the area between the Pinar fault and the Cauto Depression, and the area south of the Cauto Depression, respectively. For better understanding, the stratigraphic names mentioned in this paper are briefly explained in the Summary Lithostratigraphic Chart at the end of the text.

Northwest of the Pinar Fault Zone the West Cuban antiformal stack (the Guaniguanico terrane of Iturralde-Vinent 1994) comprises folded and thrusted sediments and intercalated volcanic rocks of the eastern continental margin of the Yucatán Block. The use of the term ‘terrane’ in the Caribbean geological literature has been discussed by Iturralde-Vinent & Lidiak (2006). In the present paper the term ‘terrane’ will be adapted from the cited authors with respect to regional units without semantic changes.

The central part of the Cuban mainland east of the Pinar Fault and west of the Cauto Depression can be subdivided on the basis of geological and

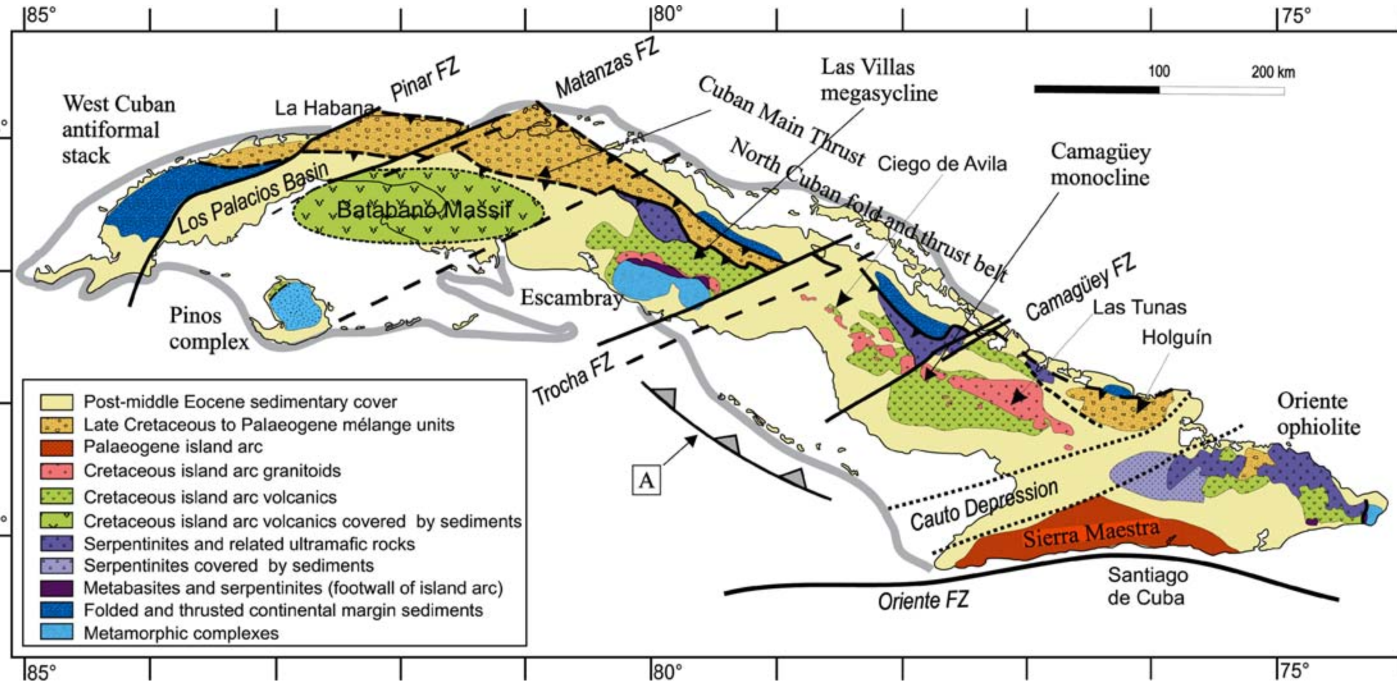

Fig. 2. Generalized geological map of Cuba compiled from the Geological Map of Cuba 1 : 500 000 (Perez Othon & Yarmoliuk 1985) showing the main tectonic units of Cuba. The Batabano Massif has been interpreted on the basis of gravimetric and magnetic data as part of the Cretaceous island arc covered by younger sediments (Pusharovski *et al.* 1989). The broad grey line limits the shelf area deeper than 2000 m. (A) indicates the low angle fault detected by Rosencrantz (1990).

geophysical data into three east–west trending belts. In the northern belt, sediments of the Bahamas carbonate platform, of a continental margin and adjoining deep sea basin have been thrust onto the southern edge of the Bahamas platform and are characterized by typical thin-skin tectonics. This North Cuban fold and thrust belt has been overthrust along the Cuban Main Thrust by a serpentinitic mélange. The serpentinic matrix of the mélange contains in different proportions all rock types of an oceanic crust including ultrabasic lithologies, gabbros as rare basalts and related sedimentary rocks (Kudělásek *et al.* 1984; Fonseca *et al.* 1984, 1988). The largest outcrops of serpentinites and gabbros have been mapped in eastern Cuba, but the size of the exposed mélange bodies decreases westward. The serpentinitic mélange has been interpreted as Alpine-type ophiolite suite by Knipper (1975). The occurrences of ultrabasic rocks have been assigned in two types (Kudělásek *et al.* 1984; Iturralde-Vinent 1994): the northern ophiolites comprise the serpentinitic mélange and the southern ophiolites consist of isolated serpentinitic tectonic slivers in nappe structure of the metamorphic complexes along the southern coast of Cuba. Parts of the Cretaceous Caribbean magmatic arc form the hanging-wall unit of the serpentinitic mélange. In central Cuba both units, mélange and island arc, were subsumed as so-called Zaza zone (Pardo 1975). South of the Cretaceous island-arc sequences, domes of metamorphic rocks like the Pinos complex (Isla de Juventud) and the Escambray complex form isolated, window-like outcrop areas. Together with the serpentinitic mélange, these metamorphic complexes provide a means of studying the subduction–accretionary complex of the Caribbean Arc. Southeast of the Cauto Depression, the Oriente Block consists of metamorphosed parts of the Caribbean Arc, overthrust by ultrabasic and gabbroic rocks of the Nipe–Cristal and Moa–Baracoa massifs and covered by Palaeogene island-arc related volcanic rocks of the Sierra Maestra. Different from central Cuba, the ultrabasic rocks in the easternmost Cuba have been interpreted as supra-subduction related ophiolite (Proenza *et al.* 1999).

In the following sections, we review these and other aspects of the geology of Cuba. As will be seen, several of the reviewed aspects are important for distinguishing the validity of the *in situ* and the Pacific origin models for Caribbean evolution.

The continental margin sequences: two types of continental margins

Sediments related to those continental margins formed before and during the opening of the oceanic basin between North and South America are exposed in the Guaniguanico terrane of western Cuba and along the northern edge of central Cuba. Both areas can be distinguished by the range of their stratigraphic profiles and the facies characteristics of their sediments (Fig. 3). The sedimentary sequences of western Cuba have been assigned to the margin off eastern Yucatán (Haczewski 1976; Pindell 1985; Hutson *et al.* 1998), those of central Cuba to the southern margin of the Bahamas platform (Pardo 1975; Lewis & Draper 1990; Iturralde-Vinent 1994; Draper & Barros 1994; Pszczółkowski 1999).

Western Cuba: the Yucatán type margin

In western Cuba (Guaniguanico terrane), the sediments can be subdivided into four tectonic units on the basis of their facies development and their present tectonic position (Fig. 4). The southern and lowermost tectonic unit comprises the folded sediments of the Sierra de los Organos, (including the Viñales tectonic window) followed to the north by the southern and northern Sierra del Rosario units and the Esperanza unit. At the top of the nappe stack, the island-arc related rocks of the Bahia Honda unit are exotic with respect to the continental margin development. The lowermost part of the stratigraphic record of Guaniguanico comprises the siliciclastic sediments of the San Cayetano Formation, the oldest known sediments of Cuba (see Fig. 3), which form part of the Sierra de los Organos (Pizarras del Norte y del Sur) and the southern Rosario units. The San Cayetano Formation was deposited along the rift-related continental basin between Yucatán and South America during the Lower to Middle Jurassic (Haczewski 1976; Pindell 1985). In the Oxfordian (160–155 Ma), marine carbonates and basic volcanic rocks (Jäger 1972; Pszczółkowski 1994; Cobiella 1996) occur in the stratigraphic succession. The basalts of the El Sabalo Formation show geochemical patterns of a rift-related magmatism (Kerr *et al.* 1999). This facies change to carbonate-dominated sediments and basaltic magmatism, which can be traced from the southwestern extent of the Esperanza unit to the northern Sierra del Rosario, is the first evidence of seafloor spreading in the region. The upper part of the stratigraphic profile reaches the Middle Cretaceous (Turonian, 90 Ma) and consists of marine carbonates and cherts (Santa Teresa Fm). From the Late Turonian to the Early Campanian (90–80 Ma) there is a hiatus in the stratigraphic profile of Guaniguanico (Iturralde-Vinent 1994). The Upper Cretaceous sediments show the influence of an approaching volcanic arc (Moreno Formation). Detailed descriptions of the biostratigraphy and sedimentology of

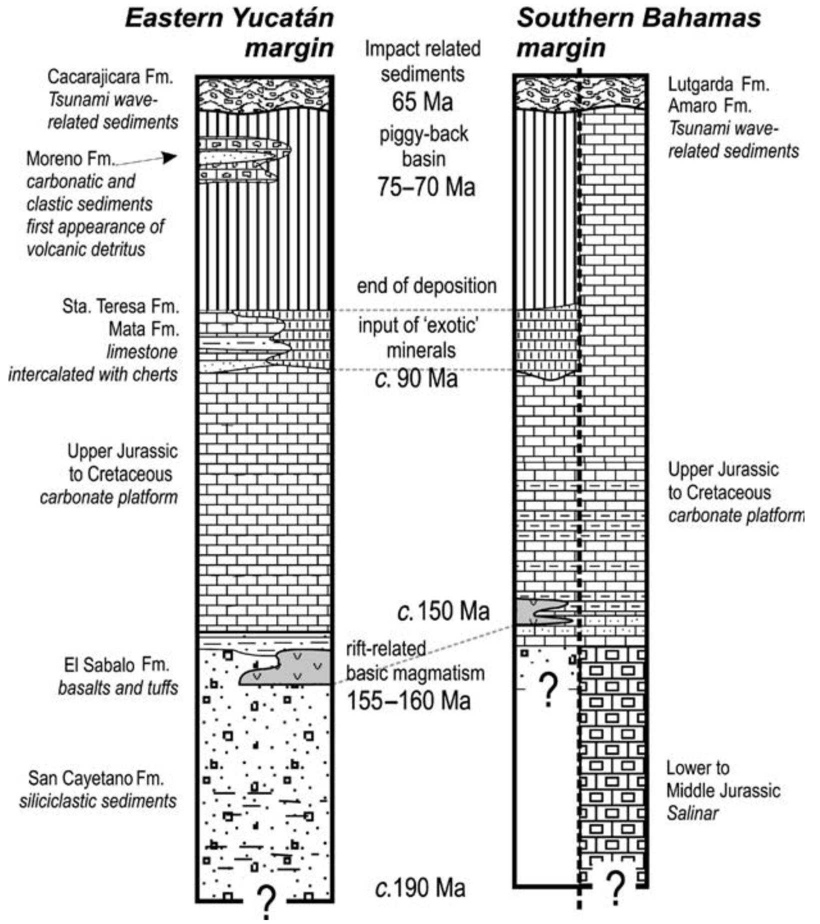

Fig. 3. Generalized stratigraphic profiles of the Yucatán-type continental margin sediments and the Bahamas-type sediments. At the Bahamas column, the right side represents the platform stratigraphic sequence, the left side the sedimentary sequence involved in the North Cuban fold and thrust belt. Note the similarities in both Yucatán-type sequences and the sequences on the left side of the Bahamas column. In both stratigraphic profiles, the Chicxulub impact related sediments cover disconformly the older sedimentary sequences (Pszczółkowski 1986*b*).

the eastern Yucatán continental margin have been summarized by Pszczółkowski (1999). No information is available on the basement and the detachment horizon of the nappe stack in western Cuba.

Central Cuba: the Bahamas-type margin

In central Cuba, the sediments of the North Cuban fold and thrust belt between Matanzas and Holguín (see Fig. 2) have been traditionally subdivided into several sedimentary belts, summarized and interpreted by Ducloz & Vuagnat (1962), Knipper & Cabrera (1974), Pardo (1975), Hatten *et al.* (1988) and Iturralde-Vinent (1994). The three northernmost stratigraphic-facies belts belong to the southern extent of the Bahamas carbonate platform (Cayo Coco, Canal Viejo de Bahamas and Remedios belts) which comprises Lower Jurassic to Upper Cretaceous evaporitic and carbonate deposits. Stratigraphic hiatuses only occur at the southern edge of the Bahamas platform in the Turonian and Coniacian (*c.* 90–85 Ma). Much more informative in the light of geotectonic reconstructions are the stratigraphic-facies belts which have been interpreted as the slope (Camajuani belt) and basin sediments (Placetas belt) south of the Bahamas platform, thrust onto its southern edge. The known stratigraphic record begins in both zones with Upper Jurassic (Kimmeridgian to Tithonian) deep- and shallow-water carbonate and terrigenous siliciclastic sediments (Pszczółkowski 1987; Iturralde-Vinent 1994) as

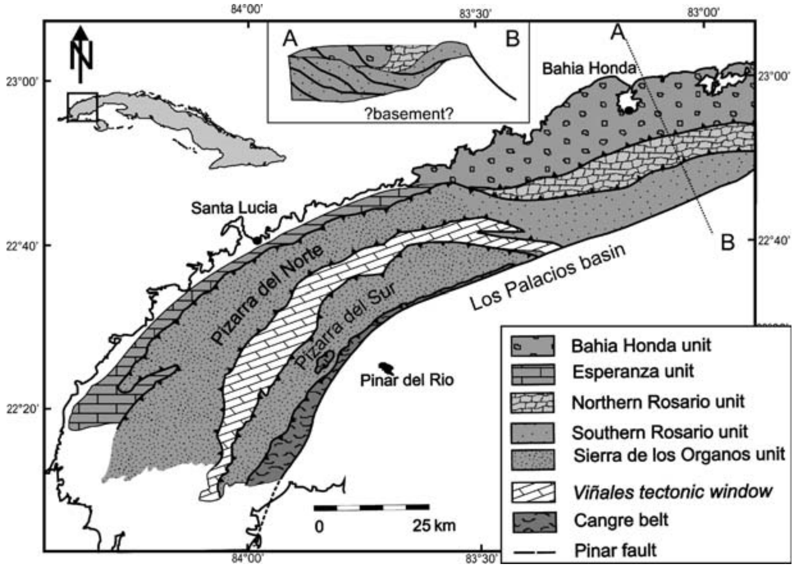

Fig. 4. Tectonic sketch map of the relationship of the thrust sheets in the West Cuban anticlinal stack (Guaniguanico terrane); adapted from Pszczółkowski (1999). The Viñales tectonic window consists of Upper Jurassic to Lower Cretaceous limestones of the Mogote Valley. The bore hole Mariel (Segura Soto *et al.* 1985) is located about 50 km west of Bahia Honda (not shown on the map).

well as rare basic volcanic rocks (Iturralde-Vinent & Morales Marí 1988). Despite the facies differences, the sedimentation in both zones ended in the Turonian (at about 90 Ma). In the Aptian to Cenomanian section of the stratigraphy (Mata Fm and Santa Teresa Fm), an alternating sequence of fine-grained limestones, cherts and bentonitic clays yields detrital minerals such as staurolite, glaucophane, zoisite, white mica and chlorite as well as fragments of K-rich volcanic and ultrabasic rocks (Linares & Smagoulov 1987). This input of 'exotic' minerals in the marine sedimentary rocks has not been investigated in western Cuba. The occurrence of these minerals indicates the erosion of a fore-arc or arc domain. This domain, with its bentonitic clays, could only have been deposited somewhere to the south of today's Cuba, because concurrent deposition of pure carbonate sequences has been described from the Bahamas Platform (Iturralde-Vinent 1998) and basinal DSDP site 540 in the Florida Straits (Schlager & Buffler 1984).

Tectonic environment of the continental margins

The different stratigraphic and facies sections in western and central Cuba (Fig. 3) allow the interpretation that the respective continental margins in which they formed originated in different geotectonic environments. The Sierra Guaniguanico, representing the east Yucatán margin, formed during the opening of the oceanic basin parallel to the Proto-Caribbean spreading ridge, which steps downward from the Esperanza belt through the Southern Rosario belt to the northern Rosario belt (Pindell 1985; Pszczółkowski 1999). In northern central Cuba, the section represents the southern Bahamas margin, formed under transform control associated with the opening of the Atlantic. Further, in some geotectonic models the south Bahamas margin is shown as developing diachronously from west to east by movement along a palaeo-Bahamas–Guayana transform fault (Pindell 1985; Iturralde-Vinent 1994; Stanek & Voigt 1994; Pindell & Kennan 2001; Pindell *et al.* 2006).

Apart from contrasts in sedimentation on these two palaeo-margins, there are also differences in magmatic activity. In the Guaniguanico Terrane, basic lavas and small subvolcanic intrusions have been observed in the Middle to Late Jurassic (*c.* 155–160 Ma) in all tectonic units (Cobiella 1996; Pszczółkowski 1999). From the southern Bahamas margin, basic volcanic rocks (150 Ma) are only known from the Sierra Camaján north of Camagüey (Iturralde-Vinent & Morales Marí 1988). But the rocks of the Sierra de Camaján have been assigned to the Placetas Belt (Iturralde-Vinent *et al.* 2000). This could suggest that the Sierra de Camaján and thus the whole Placetas do not belong geotectonically to the palaeo-Bahamian margin, but rather to the oceanic basin east of the

Yucatán Block. Until now, no rift-related magmatism has been detected along the southern margin of the Bahamas Platform.

Is there a continental basement?

Until now, there has been no drilled or otherwise exposed basement of the Bahamas platform around the Cuban archipelago. The presence of continental crust beneath central Cuba has been suggested by the interpretation of gravity data proposing a thinned continental basement below the southern edge of the Bahamas platform (Otero *et al.* 1998). The presence of a continental basement in this part of the Bahamas is supported by the occurrence of the Punta Alegre and other salt diapirs amidst the imbricated shallow-water Bahamian carbonates of the Cayo Coco zone of central Cuba and by the presence of probable Jurassic red beds drilled at the Great Isaac borehole, some 300 km north of central Cuba (Meyerhoff & Hatten 1974). In and near the arc-related parts of Cuba (Zaza zone of Pardo 1975), there are several field indications of slivers of a continental basement included in the thrust structure of the Cuban fold and thrust belt. As for western Cuba, basement remains unknown, but the lowest unit (San Cayetano Fm) derives from quartzose continental basement types with Precambrian and Lower Palaeozoic ages of detrital mica (Hutson *et al.* 1998) and zircon grain ages (Rojas-Agramonte *et al.* 2008).

From the above, a fixist view might suggest that the entire region is underlain by continental crust. However, it must be kept in mind that the Island of Cuba represents three distinct domains; two sedimentary provinces (West and Central Cuba) are separated from an overthrust arc terrane at an oceanic suture down the island's axis. Because all arc-related magmatism lies south of this suture, subduction was SW-dipping and the oceanic basin that closed originally lay between the Bahamas and the Cuban part of the Great Antillean arc. Because of the long history of arc magmatism (at least Aptian to Campanian/Maastrichtian, some 40 Ma), followed by several hundred kilometres of north–south tectonic shortening adjacent to the suture zone after the magmatism ended (Hempton & Barros 1993), the original palaeogeographic separation was necessarily significant (>1000 km). Thus, we should not expect any particular relationship between basement rocks of the allochthonous Cuban arc with those of the Bahamas (Central Cuba) or of the Yucatán (West Cuba) margins. This is borne out by the respective geologies as well: there is no mutual geological affinity between the Cuban arc and the Bahamas/Florida Straits DSDP sites until the Maastrichtian or possibly even the Palaeogene (i.e. first arrival of volcanogenic sands/arc-related tuffs in the latter).

In the Cuban arc terranes and adjacent thrust belt, local areas of metamorphic rocks have been reported since the 1950s (Fig. 5). Because of their uncertain nature at the time, a pre-Cretaceous age was commonly allocated to them. As geochronological work began, Precambrian and Jurassic ages were reported on metamorphic rocks and spatially related granites, respectively, from tectonic blocks involved in the folded and thrusted sequences of the Placetas belt of the Sierra Morena (Somin & Millán 1981; Renne *et al.* 1989). An Ar/Ar cooling

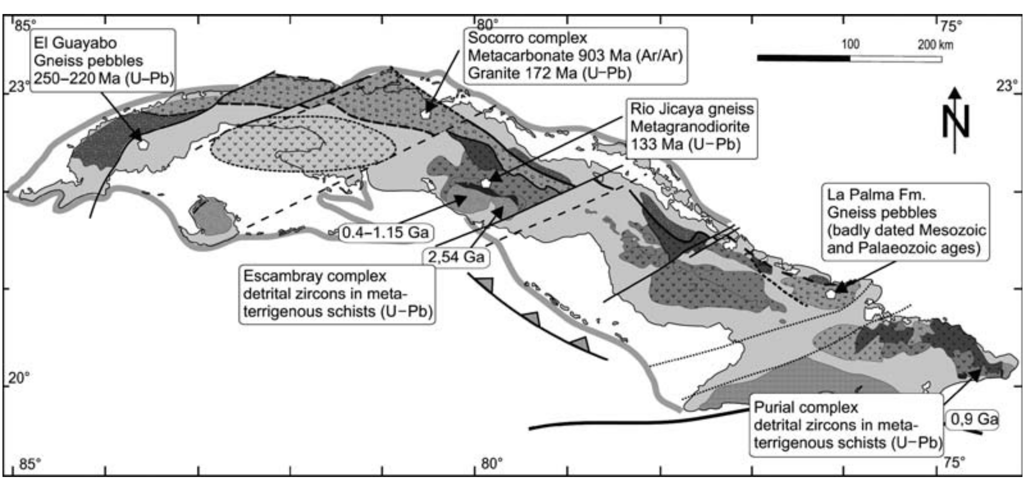

Fig. 5. Occurrences of metamorphic and magmatic rocks interpreted as 'basement' rocks of the continental margin and the Cretaceous island arc. The zircon data on metaterrigenous schists from the Escambray and the Purial complexes are given for comparison.

age of 903 Ma for biotite was reported from metacarbonate rock slivers of the so-called Socorro complex. The intrusive age of pink granites in the Rio Cañas valley (also included in the Placetas belt) was determined by U–Pb on zircon as 172 Ma (Renne *et al.* 1989). K–Ar data and the observation of weathering crusts above the granites have been interpreted as erosion along the southern Bahamas platform in the Upper Jurassic (140–150 Ma) (Somin & Millán 1981; Pszczółkowski 1986*a*). However, the tectonic position and the contacts with the hosting units of the Socorro complex and the granites are unknown due to the poor exposure. If the granites and the metamorphic rocks belong to the rock suite of the Placetas belt, then they are far-travelled from the south. If not, both the Socorro complex and the granites are slivers of the Bahamas basement tectonically involved in the fold and thrust belt during the thrusting of the island arc. Additional continental lithologies associated with the Placetas and Camajuaní belts are the felsic gneisses in tectonic mélanges north of Holguín (La Palma Formation); the geochronology of these rocks is not well constrained, but K–Ar determinations on mica suggest Palaeozoic to Early Mesozoic ages (Kosak *et al.* 1988). Of the above, the 903 Ma age is most interesting, as such ages are not otherwise known from Florida, the Bahamas or Yucatán, and suggest a highly allochthonous origin possibly as far as the Grenvillian terranes of SW Mexico or the Chortís Block.

To the south of the Cuban Main Thrust where the Cuban Cretaceous arc lavas and intrusives occur (Fig. 2), at least two additional areas of metamorphic rocks are found that had originally been thought to represent Cuban basement (see the geological map edited by Perez Othon & Yarmoliuk 1985). These are the Pinos complex (Millán 1975; Somin & Millán 1981; García-Casco *et al.* 2001) and the Escambray complex (Millán & Myscinski 1978; Somin & Millán 1981). Based on fossils and facies analysis, the protoliths of these metasedimentary and metavolcanic rocks are facies analogous to and coeval with the (Late Jurassic–Early Cretaceous) sedimentary sequences of the West Cuban antiformal nappe stack (Pinar del Rio) (Millán & Myczynski 1978; Piotrowska 1978; Pszczółkowski 1985). The similarities in the sedimentary facies and depositional ages of the metamorphic protoliths with the sedimentary sequences of western Cuba suggest a common palaeo-environment along the NW Proto-Caribbean basin or continental margin. Provenance analysis for the siliciclastic sediments of the Escambray by U–Pb data on detrital zircons gave 0.4–1.15 Ga and 2.45 Ga (Early Palaeozoic to Early Proterozoic) as the age of the sedimentary source (Rojas-Agramonte *et al.* 2008; Krebs *et al.* 2007). Ar/Ar data on detrital muscovite grains provide a Pan-African source area of 700–550 Ma for the sediments of West Cuba (Hutson *et al.* 1998), but recent SHRIMP U–Pb ages for zircons from the San Cayetano Fm sandstones of West Cuba range from 398–2479 Ma (Rojas-Agramonte *et al.* 2008), nearly identical to those from Escambray and further verifying the facies and chronological correlation. Of great importance is that the quartzose and zircon-bearing metasediments of the Escambray, and probably also of the Pinos complex (García-Casco, pers. comm. 2006) underwent HP metamorphism. Thus, they represent Jurassic–Early Cretaceous material that was subducted at the Cuban trench (Stanek *et al.* 2000), meaning that the sedimentary protoliths lay on the Proto-Caribbean seafloor and/or its margins ahead of the advancing arc. These metamorphic complexes do not represent the basement of the original Caribbean Arc, but rather were underplated to it (i.e. accreted to the base of the arc crust by subduction). García-Casco *et al.* (2008) make a strong case for these sediments having originally been located off the coast of southern Yucatán, forming a palaeogeographic element which they call 'Caribeana', where they were subcreted to the advancing Cuban arc in the Campanian–Maastrichtian.

It is important to realize that the metamorphic rocks noted above in the thrusted subduction zone mélanges of the Cuban suture are continuous beneath the synformal and monoclinal arc belt with the Pinos and Escambray metamorphics to the south. Both regions represent the same subduction channel, although the channel has been tectonically elevated in the south during the opening of the Yucatán Basin to expose a deeper level at Escambray and Pinos (Pindell *et al.* 2005). Support for this continuity lies in the Cangre Belt along the north flank of the Pinar Fault: there, additional outcrops of the Pinos- and Escambray-type metasediments structurally connect the Cuban Suture with the southern metamorphic rocks in an up-plunge position where the synformal arc terrane projects westward above the surface geology. In addition, pebbles of garnet-bearing gneiss and S-type granite are found in a Palaeogene conglomerate (El Tumbadero unit) in the Los Palacios Basin just south of the Pinar Fault (Somin *et al.* 2006). SHRIMP dating on zircons from these pebbles reveals a probable Late Triassic protolith age (220–250 Ma) and a metamorphic overprint at about 72 Ma, related to very fast exhumation/cooling determined by K–Ar dating (about 71 Ma). The source of the pebbles is likely to be slivers of Proto-Caribbean continental margin basement that were subducted along with the sediments discussed above. The best fit of geochronological characteristics of the pebbles with regional geology and evolution shows the El Tumbadero

unit at the southern edge of the Yucatán platform (Martens *et al.* 2007), similar to the position of Caribeana as proposed by García-Casco *et al.* (2008). These pebbles may provide the first indication of basement involvement in Caribeana.

In summary, the geology of the Cuban 'basement' is known only for a scattered collection of localities. The Great Bank of the Bahamas probably has a stretched continental foundation (Pindell 1985) against which Cuban arc and accretionary prism (Placetas Belt and Maastrichtian–Palaeogene flysch units) collided in the Palaeogene. Unless we accept a 903 Ma metamorphic age for the Bahamian basement, which appears contrary to the regional geology of the rest of the Florida/Bahamas, it is unlikely that any of the Bahamian basement has been caught up in the Cuban thrust belt as the arc approached. It appears that only the sedimentary cover of that basement (carbonates and salt diapirs of Cayo Coco zone) was picked up in the thrusting. As so often is the case, the salt horizon of the southern Bahamas probably served as the décollement for this imbrication. As for the Cuban arc itself, pre-Jurassic continental lithologies occur only as slivers or blocks, mainly in mélange units associated with subduction and subcretion, which could have entered the subduction channel by lateral transport from areas of continental crust along strike in the Early Cretaceous, such as the Chortís Block and southwestern Mexico (Pindell *et al.* 2005). Otherwise, the arc is entirely an intra-oceanic arc thrust onto the Bahamas. Subcreted metasediment serves as 'basement' along the southern flank of Cuba, which is a Maastrichtian–Paleocene rift flank of the Yucatán intra-arc basin whose detachment level cut into the Late Cretaceous subduction channel (Pindell *et al.* 1988, 2006). However, this rifting was situated so close to the Cuban Trench that the central Cuban terrane was thereafter narrower than any typical arc-trench gap, so any latest Cretaceous–Palaeogene arc magmatism probably lies in the southern offshore or Yucatán Basin floor (Pindell & Barrett 1990), and possibly the Cayman Ridge (Sigurdson *et al.* 1997; Lewis *et al.* 2005). This rifting and magmatic shift was apparently associated with the subcretion of the Caribeana sediment pile (García-Casco *et al.* 2008), which itself probably lay above stretched continental crust whose buoyancy caused subduction zone flattening that led to the southward shift in arc magmatism. Finally, the West Cuban thrust pile comprises sediments from the eastern Yucatán margin that were transpressed by the Cuban arc but not subducted as deeply as Pinos and especially Escambray. It is not known if any basement from that margin is incorporated at depth in the sinistral transpressive thrusting. The fact that sediments as old as the Middle Jurassic San Cayetano occur at the surface today suggests three possibilities: (1) that sediment imbrication is multi-fold, bringing old strata to shallow levels atop other imbrications; (2) that the West Cuban section was thrust onto a nearly autochthonous piece of thick, probably Yucatán, continental crust; or (3) one or more slices of Yucatán marginal basement is/are imbricated in the thrusting with the sediments; if the slice is thick enough, then a single thrust (with simple attendant structure) may suffice to have caused the high structural level.

Timing of thrusting and nappe stacking at the Yucatán and Bahamas platforms

In Central Cuba, northward shifting (migration?) of stratigraphic hiatuses can be observed in the sediments representing the Proto-Yucatán or Proto-Caribbean Basins (i.e. Placetas and Camajuaní Belts). In the southern basin and slope areas of the Proto-Yucatán Basin, deposition stopped at the end of the Turonian (*c.* 90 Ma). Erosional and weathering features have been described in the uppermost part of the basin sediments of the Placetas zone (Pardo 1975). In the Turonian until Campanian a northward-shifting uplift and emergence of the southern Placetas and Camajuaní zones and their involvement in the accretionary prism of the approaching Caribbean arc can be assumed from available stratigraphic data (see Iturralde-Vinent 1994, and citations therein). At this time the Caribbean arc was located near the tip of the southern Yucatán Block. The thrusting of the accretionary prism of the Caribbean arc onto the southern Bahamas platform ended in the Late Eocene, when foreland sediments (Senado Fm) were overthrust by ophiolite nappes (Iturralde-Vinent *et al.* 2000).

In western Cuba (see Fig. 4), the Rosario and the Sierra de los Organos units consist of several nappe sheets which have been thrust from south to north (Pardo 1975; Piotrowska 1987). The tectonically uppermost unit of the stack is represented by the fragments of ultrabasic rocks, gabbro and serpentinite (Sierra de Cajalbana) and the island-arc rocks of the Bahia Honda unit, which were thrust from the south over the continental margin and possibly deeper water sediments (Pszczółkowski & Albear 1982; Pszczółkowski 1994; Iturralde-Vinent 1994). Final thrusting of the island-arc-related rocks and their frontal piggy-back basins took place in the Late Paleocene to Early Eocene between 56 and 50 Ma (Bralower & Iturralde-Vinent 1997). Crucial for the interpretation of the provenance of the tectonic units is the timing of the clastic input of island-arc-derived detritus into the sediments (Pszczółkowski 1994). The first record is the volcanoclastic component of the

Campanian Moreno Formation (northern Rosario unit, *c*. 75–70 Ma). Fragments of subduction-related igneous rocks are also reported from the latest Maastrichtian Via Blanca Formation (Takayama *et al.* 2000). In the southern Rosario unit the carbonates of the Middle Paleocene Ancon Formation (*c*. 60 Ma) yield volcanoclastic detritus, whereas the input of such detritus in the Sierra de los Organos unit is delayed until the Upper Paleocene and Lower Eocene Manacas Formation (*c*. 55 Ma). Comparing the onset of arc-derived sedimentary influence with the indications for northward thrusting and stacking, an inverse position of these tectonic units due to thrusting is apparent (Pszczółkowski 1999; Saura *et al.* 2008). This can be explained by the formation of fault-bend-fold structures and a regional duplex. The duplex has been inverted with northern vergence due to the northward thrusting of the subduction–accretionary complex and the forearc of the Caribbean Arc. Parts of the foreland thrust belt were buried by higher nappes and/or island-arc units. The siliciclastic sediments of the San Cayetano Formation (Sierra de los Organos unit) underwent low-grade metamorphism with estimated pressures of 2 kbar, equivalent to a burial depth of 6–7 km (Hutson *et al.* 1998). Parts of the weak metamorphic overprint can be attributed to the stacking of thrusts. The age of this low-grade overprint is probably post-Maastrichtian–pre-Late Paleocene. The nappe of San Cayetano sediments was tectonically covered by the metamorphic unit of the Cangre belt probably in the Palaeogene. The metabasic rocks of the Cangre belt show indications of a HP metamorphic overprint (Somin & Millán 1981; García-Casco *et al.* 2002; Cruz *et al.* 2007) of uncertain age. On the basis of balanced cross-sections, the shortening by northward thrusting in western Cuba can be estimated from the nappe geometry to be a minimum of 150–200 km (Saura *et al.* 2008).

The Caribbean (Great Antillean) Arc: a record of movement between the Caribbean and North American plates

Island arc-related geological units of Cuba

Outcrops of the Cretaceous Caribbean (island) Arc extend along the Greater Antillean islands from western Cuba to at least Puerto Rico. In Cuba, Cretaceous island-arc-related rocks form a belt from the Pinar Fault through the entire length of the island, and form the largest outcrop of such units in the Caribbean. South of the Eocene suture (the Cuban Main Thrust of Knipper & Cabrera 1974) a 4–5 km thick nappe comprising a serpentinitic mélange with overlying island-arc rocks has overridden the southern edge of the Bahamas Platform (Fig. 2). The serpentinitic mélange contains dislocated slivers of all rock types typical of an ophiolitic profile; this was the reason for calling it the 'Northern Ophiolites' (Kudělásek *et al.* 1984; Iturralde-Vinent 1994). Parts of the thinned island arc are located on the top of the 'ophiolitic' thrust sheets. South of the Cretaceous island-arc units, domes like the Pinos complex (Isla de Juventud) and the Escambray complex form isolated outcrops of relatively high-grade metamorphic rocks (see Fig. 2). These metamorphic complexes and the serpentinitic mélange together represent the subduction–accretionary complex of the Caribbean Arc. In general, thrusting of the island arc onto the southern edge of the Bahamas platform led to incremental tectonic episodes of exhumation which now allow both the stratigraphic succession as well as the lateral extent of the igneous rocks to be studied. On the basis of the tectonic setting and the regional structure, the following key outcrop areas of Caribbean Arc-related rocks can be distinguished (Fig. 2):

- The Bahia Honda unit northwest of the Pinar fault (see Fig. 4), deposited in a forearc position, and now resting as an allochthonous sequence at the top of the West Cuban antiformal nappe stack.
- The mélange unit in the area of La Habana–Matanzas, consisting of completely dislocated island-arc sequences and carbonate rocks with continental margin provenance. South of the mélange zone, the Batabano Massif has been interpreted to be a part of the Cretaceous island arc covered by younger sediments on the base of gravimetric and magnetic data (Bush & Sherbakova 1986).
- The megasyncline of Cretaceous island-arc volcanic rocks in Las Villas, infolded above the metamorphic Escambray complex to the south and the ophiolitic mélange to the north.
- The monoclinal stack of island-arc intrusions and related volcano-sedimentary sequences in the area of Camagüey.
- The mélange-like unit surrounding Holguin.
- The metamorphosed Cretaceous island-arc volcanic sequences in Oriente, forming the footwall of the overthrust Oriente ophiolite.

Subduction related magmatism

In western Cuba, the Bahia Honda unit comprises Early to Mid-Cretaceous island-arc sequences and basic and ultrabasic rocks of oceanic crust provenance (Kerr *et al.* 1999). Tectonically, the unit is an allochthon (Fig. 4), resting on other tectonic units of the Yucatán continental margin (as seen at borehole Mariel 50 km east of the city of Bahia Honda; Segura Soto *et al.* 1985). The inverted

stratigraphic profile, the north-vergent tectonic style and the presence of the underlying continental margin (Straits of Florida) were the arguments for the interpretation of the Bahia Honda unit being the uppermost nappe of the West-Cuban antiformal stack (Pardo 1975; Stanek *et al.* 2000; Saura *et al.* 2008). The occurrence of large blocks of ultrabasic rocks (Cajalbana Massif) and tholeiitic basalts of the Encrucijada Formation (Fonseca *et al.* 1984) have been used as arguments for the interpretation of the Bahia Honda unit as a remnant of a back-arc basin (Iturralde-Vinent 1994, 1998). The tholeiitic basalts and the presence of boninitic volcanic rocks of suggested Early Cretaceous age have been tentatively related to an early primitive arc north of the later Caribbean Arc and a subsequent polarity reversal of the subduction (Kerr *et al.* 1999, 2003).

In central Cuba, the largest outcrop areas of the Caribbean Arc are located west and east of the Trocha Fault zone (see Fig. 2). In Las Villas to the west of the fault, the thickness of internally thrusted island arc units including the serpentinitic mélange (arc basement), calculated from seismic data, reaches up to 10 km (Pusharovski *et al.* 1989), which is unusually thin for a long-lived island arc. It seems that the original island arc has been dismembered tectonically and deeply eroded. In Las Villas, the volcanogenic parts of the Cretaceous arc have been folded into a several kilometre-wide megasyncline, comprising the nearly complete stratigraphic section of the Caribbean Arc. In contrast, east of the Trocha fault zone (Ciego de Avila–Camagüey–Las Tunas), Late Cretaceous erosion cut deep into the thrusted island arc sequence exposing the deep-seated and subvolcanic intrusions of the Cretaceous island arc. The alignment of the intrusive bodies clearly defines two magmatic belts, a wider one in the south with dominating alkaline and calc-alkaline granitoids and a northern belt with Na-rich bimodal intrusive bodies (Stanek & Cabrera 1992; Marí Morales 1997; Stanek *et al.* 2005).

In the Las Villas megasyncline, the pre-Albian part of the stratigraphic section starts with a sodium-rich bimodal series of plagio-rhyolites and basalts (Los Pasos Formation) outcropping in the southern fringe of the syncline (Fig. 6). The volcanic rocks show island-arc tholeiitic (IAT) geochemical characteristics. The upper part of the formation includes air fall tuffs, tuffites, marl and stratiform sulphide bodies (Dublan & Alvarez 1986). The age of the Los Pasos volcanic suite is still not constrained. After the extrusion of the Los Pasos lavas, the geochemical behaviour of the magmatism changed from IAT to calc-alkaline lavas (Diaz de Villalvilla 1997). In the southern part of the megasyncline the Matagua and Cabaiguan Formations consist of basaltic and andesitic lavas, related tuffs and volcanoclastic sediments. Both formations are overlain by the Provincial Formation. The Provincial Formation yields facies transitions from flyschoid to carbonate sediments. The age of the carbonates was constrained on the basis of a rich marine fauna to the Upper Albian and Lower Cenomanian (*c.* 105–98 Ma, Iturralde-Vinent 1996). In the Upper Cretaceous, volcanoclastic rocks and sediments dominate the stratigraphic section. In the lower part of the Late Cretaceous, differentiated calc-alkaline lavas are involved in the stratigraphic sequence (Perera Falcón *et al.* 1998), but subduction related magmatism ceased in Las Villas in the Campanian (Diaz de Villalvilla 1997). The lower part of the volcanic sequences and of related intrusions has been metamorphosed up to the amphibolite facies, forming the Mabujina unit (Somin & Millán 1981). The stratigraphic age of the Mabujina unit has been estimated from poorly preserved sporozoans and pollen as Jurassic–Cretaceous (Dublan & Alvarez 1986). Zircons from two plagiogranitic gneisses dated by the U–Pb method range between 110 Ma (Bibikova *et al.* 1988) and 133 Ma (Rojas-Agramonte *et al.* 2006*a*, *b*). This period probably spans the age of the initiation of the Caribbean Arc, judging from regional geology and Atlantic triggering mechanisms (Pindell 1993). On the basis of isotopic data, Blein *et al.* (2003) suggested that the amphibolites and gneissic granitoids of the Mabujina Unit are correlative with the Mexican Guerrero terrane, which may have been along-strike with the Great Antillean arc prior to the Albian.

A small belt of outcrops of subduction-related granitoids can be mapped along the northern limit of the Escambray Mountains. There are two textural types of granitoids. Undeformed granitoids form the so-called Manicaragua batholith intruding both the volcanic formations in the north as well the amphibolites and gneisses of the Mabujina unit in the south. U–Pb data on zircons (see Fig. 6) have been compiled from Hatten *et al.* (1988), Rojas-Agramonte *et al.* (2006*b*) and Stanek *et al.* (2005). This preliminary data set suggests: (1) an early stage of magmatism from 132 Ma into the 90s Ma; (2) a ductile deformation event at about 90–88 Ma, during which the parts of the subduction-related intrusive rocks have been transformed into gneisses; and (3) the intrusion of the Manicaragua type granitoids between 87 and 80 Ma. The dating of the intrusion of undeformed pegmatites and granitoids into the Mabujina unit (88–80 Ma) constrains the timing of the deformation event (Grafe *et al.* 2001; Rojas-Agramonte *et al.* 2006*b*). Most probably, the ductile deformation of the lower parts of the island arc should be related to the collision of the Caribbean arc with the southern margin of the

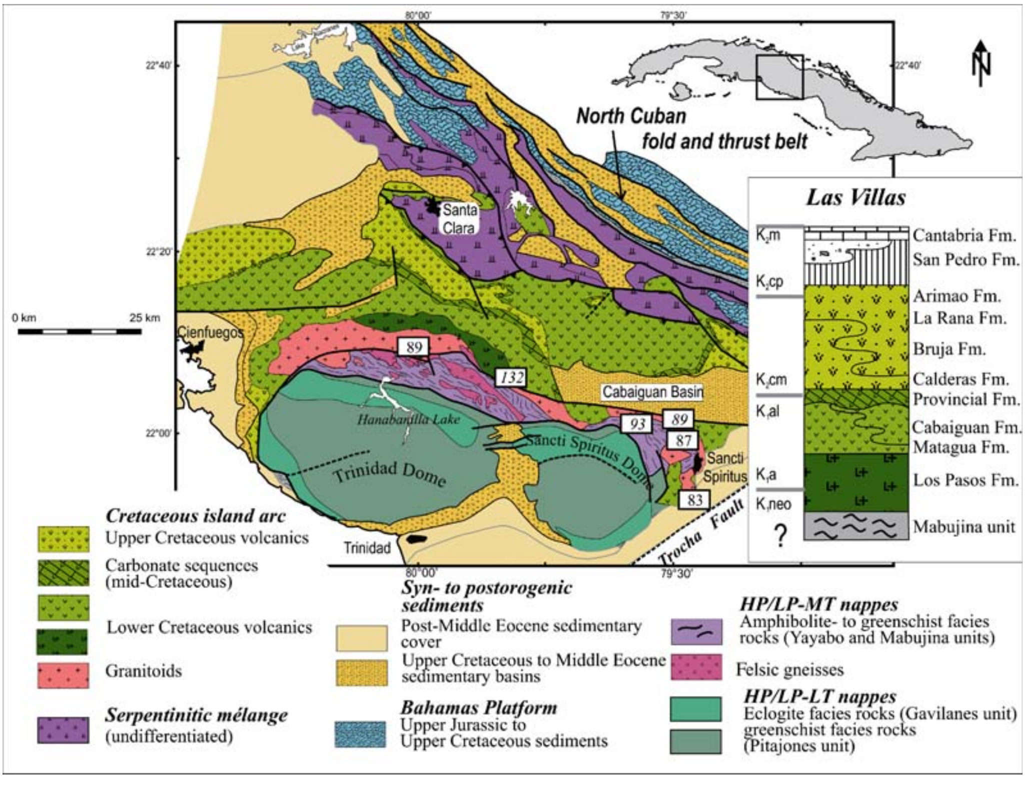

Fig. 6. Tectonic sketch map of western central Cuba (Las Villas), adapted from Kančev (1978) and Belmustakov *et al.* (1981). The North Cuban fold and thrust belt has been overridden by a serpentinitic mélange and Caribbean Arc-related volcanic formations. In the south, the Manicaragua batholith (undeformed granitoids) is in tectonic contact to the Mabujina unit with mostly gneissic granitoids. The numbers in the boxes refer to U–Pb ages on zircon of granitoids; numbers in italics are gneissoid rocks. In the southern backland of the Caribbean Arc, the Escambray metamorphic complex has been exposed since Palaeogene. A generalized stratigraphical section of the Caribbean Arc is given in the inlayer.

Yucatán Block (Pindell *et al.* 2006; Ratschbacher *et al.* 2009).

To the north, the Caribbean Arc-related volcanic sequences of Las Villas are underlain by a serpentinitic mélange including fragments of the entire ophiolite suite. Here the thickness of the mélange has been estimated on the basis of geophysical data as about 1.5 km (Bush & Sherbakova 1986). So far, the age of the ophiolitic fragments in central Cuba is not well constrained. Isolated findings of fossils in cherts intercalated in basaltic lavas span the Upper Jurassic (Llanes-Castro *et al.* 1998) to the Middle Cretaceous (Fonseca *et al.* 1984).

East of the Trocha fault, around Camagüey, erosion has removed the uppermost volcanic structures and revealed a monoclinal stack of igneous massifs. The thrust faults are hidden by Palaeogene basinal sediments (Iturralde-Vinent & Thieke 1987). The intrusive massifs form the magmatic axis of the Caribbean Arc (Fig. 7) and can be subdivided into two belts. The northern belt consists of bimodal intrusions of IAT affinity. The geochemical patterns are similar to those of the Los Pasos Formation, giving a reason to correlate the northern intrusive belt of Camagüey with the Los Pasos Formation in Las Villas (Stanek & Cabrera 1992). A single date on zircon (Stanek *et al.* 2005) suggests a Campanian age, similar to small stocks intruding the ophiolitic mélange of Las Villas (Rojas-Agramonte *et al.* 2006*b*). Thus, IAT type magmatism appears to occur not only in the lowermost part of the Caribbean Arc, but also in the forearc at later times.The southern belt near Camagüey consists of large alkaline (syenites and monzonites) and calc-alkaline differentiated intrusions. The broadly eroded sections of the plutons west of the Camagüey fault (Fig. 7) and the occurrence of hydrothermal alteration zones of the apical part of the intrusions

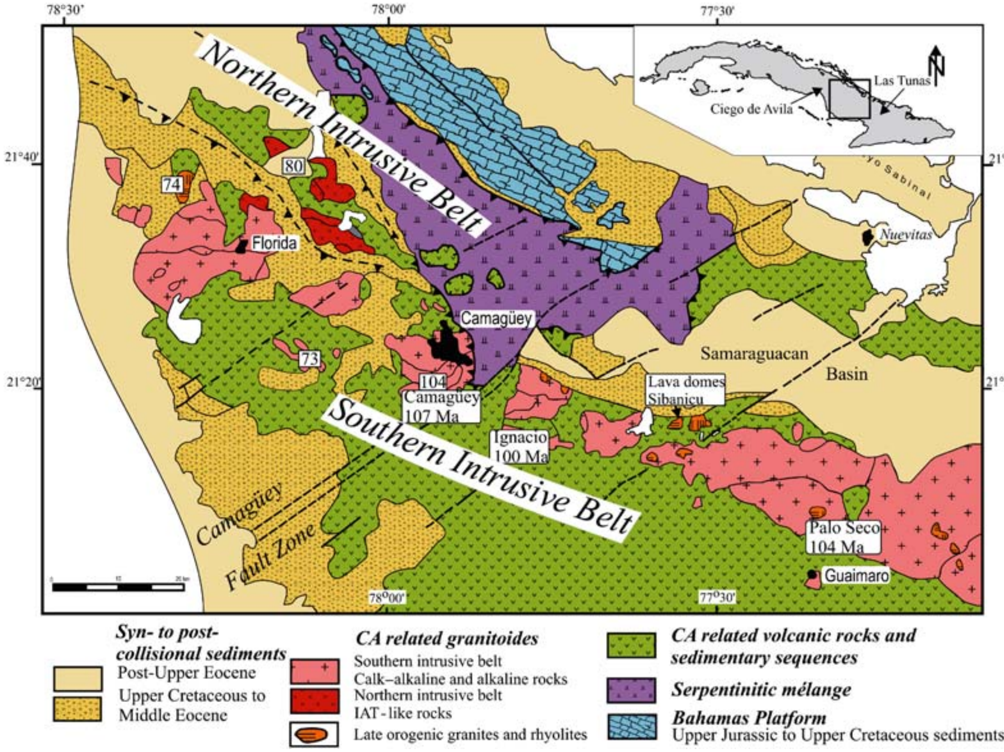

Fig. 7. Tectonic sketch map of eastern Central Cuba (Camagüey), adapted from Iturralde-Vinent & Thieke (1987). The sequences of the Caribbean Arc and the Camagüey batholith form a monoclinal structure; suggested thrust faults have been covered by Palaeogene sedimentary basins. The numbers in boxes refer to U–Pb ages on zircon of granitoids by Stanek *et al.* (2005) and Rojas-Agramonte *et al.* (2007).

east of the fault could be interpreted as east-side-down normal faulting along the Camagüey fault. U–Pb dating on zircon and titanite revealed that the alkaline rocks intruded the arc in the Albian (107–100 Ma), whereas most of the calc-alkaline intrusions yield ages between 95 and 75 Ma (Stanek *et al.* 2005; Rojas-Agramonte *et al.* 2006*b*). The last magmatic pulses in the Caribbean Arc have been reported from felsic lava domes in the area of Sibanicú (show on the map in Fig. 7), east of Camagüey (Hall *et al.* 2004). The Ar/Ar cooling age of about 75 Ma on rhyolites can be considered as the time of extrusion. Similar U–Pb ages on zircons of about 75–78 Ma were obtained from small intrusive stocks west of Camagüey (Stanek *et al.* 2005), but Ar/Ar 'ages' of about 75 Ma have also been obtained from igneous rocks intruded 25–35 Ma earlier (the alkaline rocks of the Camagüey, Ignacio and Palo Seco massifs shown on the map in Fig. 7). The similar Ar/Ar ages in both older intrusive and youngest extrusive rocks give the impression that the island arc was uplifted and cooled down through the 300 °C isograd in the Late Campanian (at about 75 Ma). The same age range of Ar/Ar cooling ages in the island arc was described in the area north of the Escambray Massif (Grafe *et al.* 2001).

Considering the results of the dating of zircons from the Los Ranchos Formation in Hispaniola between 118 and 110 Ma (Kesler *et al.* 2005; Escuder Viruete *et al.* 2006) and the similar stratigraphic position of the Los Pasos Formation in central Cuba, the initiation of Cretaceous arc magmatism in both countries is at least Early Aptian (>120 Ma). The magmatic activity in the onshore central Cuban part of the Caribbean Arc lasted about 45 Ma (to the Campanian/Maastrichtian). If we acknowledge that the arc axis shifted south at that time, then arc magmatism lasted into at least the Paleocene. This should not be surprising: in Hispaniola the arc persisted into the Eocene, which is also the time of arc collision with the Bahamas (Nagle 1974; Pindell & Draper 1991), recording some 70 million years of south-dipping subduction beneath the arc as it advanced between the Americas from the Pacific.

Over this time the subduction behaviour changed episodically, as reflected in the geochemical characteristics of the intrusive rocks of Camagüey through time (Stanek *et al.* 2005). The geochemical characteristics of the granitoids indicate a subduction origin of the igneous suites (see Fig. 8). The magmatism of the Caribbean Arc starts with island arc tholeiites (the Primitive Island Arc suite in the sense of Donnelly & Rodgers 1980), typical for early subduction of oceanic crust. Development of alkalic magmatism may relate to the onset of subduction of hot (young) oceanic crust, or to subduction of a seafloor spreading ridge. After cooling of the subduction zone, the magmatism continued in the Late Cretaceous with calc-alkaline intrusive compositions (see also Kerr *et al.* 2003). The final magmatic 'pulse' at about 75 Ma consists of only small felsic magmatic bodies which are timely related to the collision of the Caribbean Arc with the southern edge of the Yucatán block (Ratschbacher *et al.* 2009).

Uplift and erosion of the Caribbean Arc

In southern Central Cuba, a peneplain has formed revealing the emergent island arc formations at the

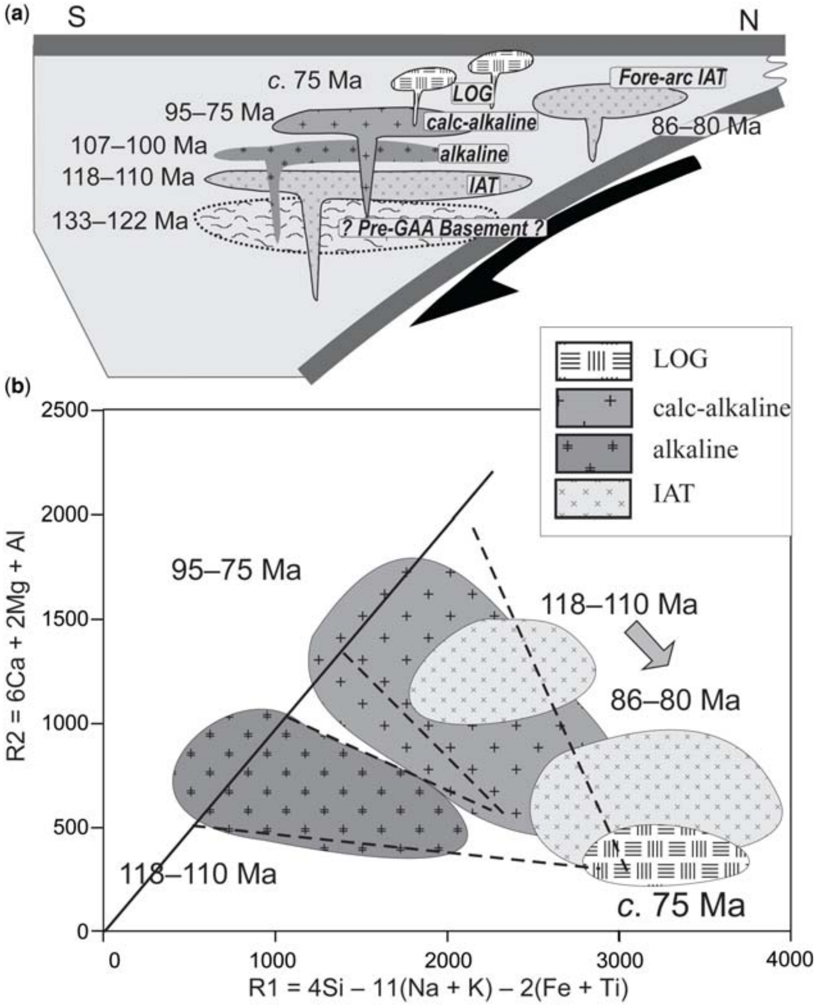

Fig. 8. (**a**) Suggested spatial succesion of the magmatic 'events' in Cuban part of the Caribbean Arc. (**b**) Geochemical evolution in time of the Cuban part of the Caribbean Arc, based on the relations of main elements (Batchelor & Bowden 1985). The magmatism of the Caribbean Arc starts with island arc tholeiits (IAT), shows an episode of alkali magmatism and continues with calc-alkaline composition. The final magmatic 'pulse' is related to small plugs of granitic composition in the field of 'Late Orogenic Granites' (LOG).

Middle Campanian through Early Maastrichtian level. A carbonate platform covering an interval of clastic, molassic sediments on this surface was deposited from the Early Maastrichtian (69.6 Ma) to the Late Maastrichtian (*c.* 67–65.5 Ma) (Pszczółkowski 2002). This platform was designated as the 'Proto-Cuban Maastrichtian Platform' (Iturralde-Vinent 1992). Similar Upper Cretaceous post-arc sediments have been mapped in the Camagüey area, differing only in some facies developments. As the Maastrichtian carbonate platform developed in central Cuba, the basement was intruded by rare basic to intermediate dykes. For example, samples from the Leila mine on the Isla de Juventud have given 68 Ma K–Ar ages; (E. Malinovski, pers. comm. 1988). This particular occurrence may pertain to the southward shift in the magmatic axis noted earlier. However, some young basaltic extrusions (51 Ma Ar/Ar age) are also known from Lavas La Mulata in NE Camagüey (Hall *et al.* 2004), which would not relate to a southward shift. These would instead lie within the deforming forearc (still supra-subduction) as it began collision with the Bahamas.

In central Cuba, the first indication of thrusting in the Caribbean Arc can be related to the onset of piggy-back basins. At the northern side of the Escambray metamorphic complex, the erosional detritus from the exhuming complex accumulated in the Cabaiguan Basin (Fig. 6). The sedimentation started in the Middle Paleocene (62–60 Ma) with olistostrome-like sediments including large blocks of Maastrichtian limestones which covered the Caribbean Arc rocks, as the Proto-Cuban Maastrichtian Platform had earlier. At its southern margin, the sediments of the Cabaiguan Basin were folded and rotated by the rising metamorphic complex in the Late Paleocene and Early Eocene. The first pebbles of HP metamorphic rocks of the Escambray complex appear in the Cabaiguan Basin only in the Eocene (*c.* 45 Ma). North of the Pinos complex to the west, pebbles of marbles, presumably derived from the Pinos complex, have been deposited in the Capdevila Formation (Lower Eocene) near Havana and in the Los Palacios Basin between the Isla de Juventud (isle of Pine) and the Pinar Fault. At the northern flank of the Cuban suture zone, the final thrusting of the ophiolitic units onto the southern Bahamas platform and foreland took place in the Middle Eocene (45–40 Ma), dated by the overriding of ultrabasic rocks onto the foreland olistostromes.

Caribbean Arc related rocks in eastern Cuba

In the easternmost part of eastern Cuba (Oriente) (Fig. 9), the Cretaceous volcano-sedimentary sequences of the Caribbean Arc are referred to as the Santo Domingo and Téneme Formations, as well as the metavolcanic rocks of the Purial Complex (Iturralde-Vinent *et al.* 2006). Here, the arc rocks are metamorphosed to various grades (Purial complex) and occur in a different tectonic position than in central Cuba (see Fig. 10). The blueschists and eclogite-facies rocks of the Sierra del Convento are overthrust by the Cretaceous volcanic arc sequences of the Purial complex, the Santo Domingo Formation and the Oriente ophiolite (Cobiella *et al.* 1984).

Until now, only a few data exist concerning the stratigraphy, structure and geochemical character of the volcanic rock sequences. Calc-alkaline as well as IAT and boninitic compositions have been reported from basic volcanic rocks (Proenza *et al.* 2006). Palaeontological data suggest Middle to Upper Cretaceous age of the volcano-sedimentary sequences (Iturralde-Vinent *et al.* 2006). Upper Cretaceous IAT-like volcanic rocks have been described, supporting the occurrence of a magmatic pulse of forearc related magmatism with IAT-like geochemical characteristics in the Late Cretaceous, which was also described in central Cuba (Rojas-Agramonte *et al.* 2006*b*; Stanek *et al.* 2005).

The volcano-sedimentary sequences have been overthrust by the Moa–Baracoa and the Nipe–Cristal ultrabasic massifs, considered as Oriente ophiolite by Fonseca *et al.* (1984), which thickness no oversteps 2 km (Knipper & Cabrera 1974). The mafic and ultramafic rocks of these massifs show characteristics of a supra-subduction related origin, such as those formed in an intra-arc basin (Proenza *et al.* 1999). The underlying Purial volcanic rock sequences underwent greenschist-facies up to blueschist- and amphibolite-facies metamorphism (Boiteau *et al.* 1972, Somin & Millán 1981; García-Casco *et al.* 2006).

The earliest possible time of metamorphism and thrusting (?) has been estimated as Campanian, based on poorly preserved Turonian–Campanian microfossils in marbles (Somin & Millán 1981; Millán & Somin 1985) and K–Ar ages of about 75 Ma on white mica of granitoid pegmatites (Somin *et al.* 1992). In some locations, the ultrabasic rocks are covered with unconformable stratigraphic contact by the Upper Maastrichtian Yaguaneque limestones (Cobiella *et al.* 1984; Iturralde *et al.* 2006). This stratigraphic relationship constrains the latest timing of thrusting, meaning that the thrusting of the Oriente ophiolite occurred coeval to the collision at the southern Yucatán margin and is probably related to this tectonic event.

The ultrabasic massifs of the Oriente ophiolite are surrounded by exotic breccias and very coarse-grained sediments (La Picota and Mícara

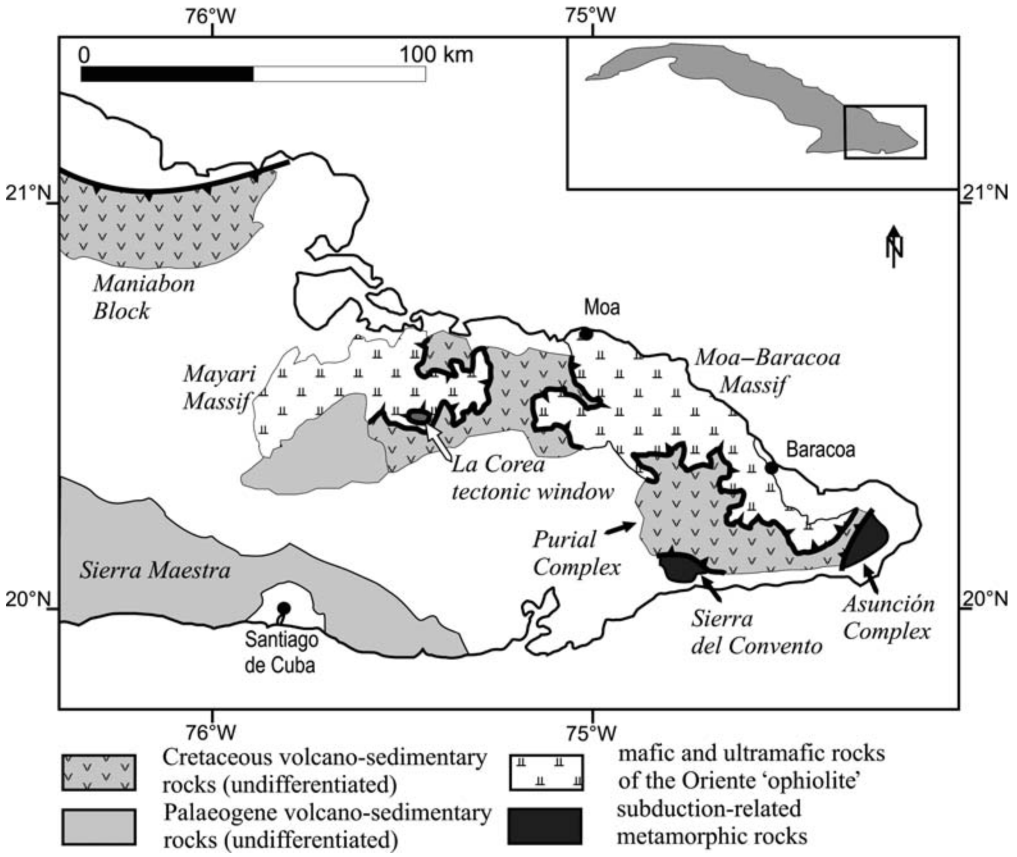

Fig. 9. Sketch of the geological units related to the Cretaceous–Palaeogene subduction in Eastern Cuba (Oriente). The heavy black lines indicate thrust faults. The Cretaceous volcano-sedimentary rocks comprise the Santo Domingo and Téneme Formations, and the metavolcanic rocks of the Purial Complex.

Formations) which contain Maastrichtian fossils (Cobiella *et al.* 1984; Iturralde *et al.* 2006). The La Picota and Mícara Formations are at the stratigraphic level of the Chicxulub impact. The structure of the sedimentary breccias and the large incorporated blocks of serpentinized ultramafic rocks and clastic sediments suggest that the La Picota and Micara Formations may have formed in response to tsunami waves caused by the meteoritic impact and are not the sedimentary fan derived from the thrusting of the ultrabasic massifs. The deposition of ultramafic debris together with littoral fossils suggests that the ultrabasic rocks had been exhumed up to the sea level at the K/T time.

Both the Oriente ophiolite and the underlying Purial meta-arc complex have been thrust onto the Asunción metamorphic complex to the east, which consists of metaterrigenous rocks of continental margin provenance, marbles and amphibolites (see Fig. 12c). Preliminary structural observations (field campaign 2006) in the serpentinites of the Oriente ophiolite and the Purial complex suggest an east- to southeast-directed thrusting of the nappe stack, disregarding possible subsequent larger block rotations.

In the southwestern part of Oriente, Cretaceous volcano-sedimentary sequences of the Caribbean Arc form the basement of Palaeogene volcanics and intrusions of Sierra Maestra. The Sierra Maestra arc rocks represent a short pulse of magmatism (Cazañas *et al.* 1998) that may or may not have been related to the primary SW-dipping subduction zone discussed thus far herein (see discussion in Pindell *et al.* 2006). The intrusions align parallel to the southern coastline of Cuba and have been dated between 60 and 48 Ma (Kysar *et al.* 1998; Rojas-Agramonte *et al.* 2004).

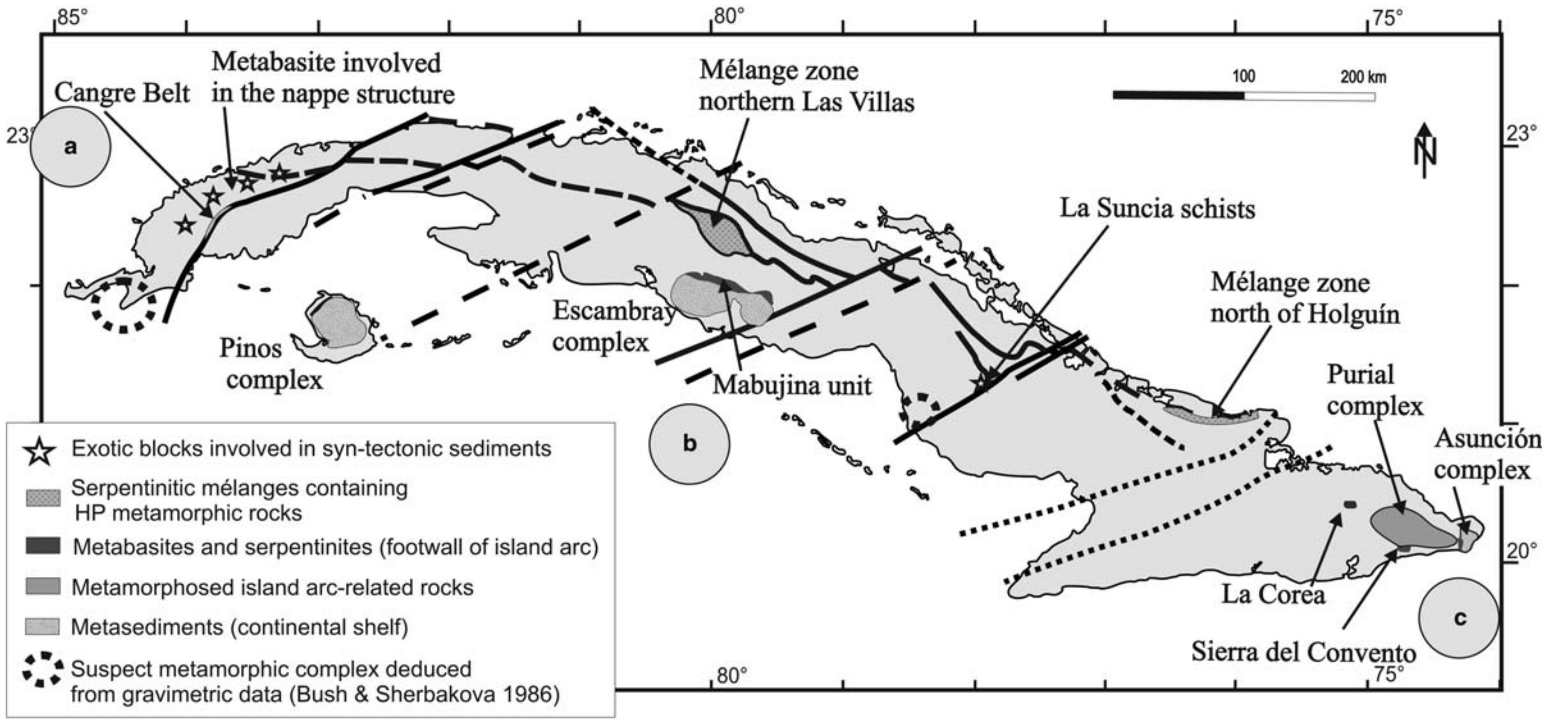

Fig. 10. Sketch map of the outcrops of subduction-related metamorphic rocks in Cuba and suspected complexes hidden by sediments. The letters in the circles indicate the position of the tectonic sections presented in Fig. 12.

Subduction–accretionary complex of the Cretaceous Caribbean arc in Cuba: *P–T* paths of the metamorphic units and their timing

Geotectonic and petrological background

Today, subduction zones are accepted as an integral part of modern geodynamic concepts. The basic architecture has been clarified, even if details remain to be worked out. The Caribbean Arc had an intra-oceanic character for much of its magmatic life along much of its length, so that this architecture is in fact a relatively simple example of a subduction zone; both of the converging lithospheres had a similar structure. During subduction, the rocks of the downgoing plate will undergo deformation and metamorphism. In the near-surface part of the subduction zone, off-scraping and accretion of sediments and even upper parts of the downgoing oceanic crust may create an accretionary prism. The thickness and extent of this submarine fold and thrust belt will depend on the volume and nature of sediments introduced the angle of subduction, and the velocity of plate convergence. The rocks of the down-going plate face progressive metamorphism and dehydration due to increasing pressure and temperature and dynamic deformation. High-pressure/low-temperature metamorphic suites (such as blueschists and eclogites that require lower than normal temperatures for a given pressure to form) dominate the depth range of 20–80 km along the slab, as isotherms are physically dragged deeper than normal due to the downgoing slab being colder than the surrounding mantle. These high-pressure/low-temperature (often abbreviated simply to HP/LT or HP) suites cannot form in the upper crust, as horizontal tectonic forces are not strong enough to cause the required pressures; sub-horizontal thrusting (and reduction of cumulative stress by tectonic escape) occurs long before diagnostic HP minerals (such as lawsonite, aragonite, jadeite, omphacite, glaucophane, barroisite) can form at such shallow levels. Only in active subduction zones will the normal geotherms be dragged downward so that the pressure–temperature conditions for HP metamorphism can be attained.

The fluids released from the downgoing slab as temperature and pressure increase will serpentinize the peridotites of the overlying mantle wedge (in the corner zone between the two plates), and when critical temperatures are reached, typically at 100–150 km depth, partial melting will trigger the formation of melts that will rise and feed the overlying volcanic arc paralleling the trench of the subduction zone (Gerya & Stöckhert 2006). This depth is independent of slab dip: if the slab dip is low angle ($<30°$), then the arc will lie farther from the trench than an arc above a steeper subduction zone. In examples of newly initiated subduction, there will be a discrete delay between subduction initiation and resultant volcanic arc activity, as time is required for the surface rocks to reach the required depths. A plate entering a 30°-dipping trench at 30 mm a^{-1} will need 5–8 Ma to initiate an overlying arc after some 160–250 km of subduction. Thus, significant palaeogeographic movements must occur before arc magmatism will be seen. Further, subduction must then continue at rates of 20 mm a^{-1} or more in order to allow enough water to reach the mantle wedge for arc magmatism to be continuous enough to dominate the geology of the arc, as opposed to a few sporadic eruptions here and there. In short, lateral migrations of many hundreds of kilometres are required to build arcs, and the greater the duration of arc magmatism, the greater the amount of required subduction. As noted above, the Great Antillean arc spanned some 70 Ma prior to its Eocene collision with the Bahamas. This is one of the primary arguments for a Pacific origin of the Caribbean lithosphere (Pindell 1990); there simply was not sufficient space between the Americas, as constrained by Atlantic opening kinematics, to initiate and build the Antillean (and other) arcs in the Caribbean with *in situ* models (Pindell *et al.* 1988).

Numerical models (e.g. Gerya & Stöckhert 2002; Gerya *et al.* 2002) have increasingly shown that the 'two-way' transport of material necessary in subduction zones (e.g. Hsu 1971; Cloos 1982; Cloos & Shreve 1988*a*, *b*; Shreve & Cloos 1986) is best explained by forced flow in a wedge-shaped subduction channel in which hydrated serpentinized peridotite from the overlying mantle wedge plays a critical role. With regard to the exhumation of HP metamorphic rocks in the Greater Antilles, two scenarios thus present themselves. One is the on-going return flow in the subduction channel towards the accretionary wedge, leading to a *subduction–accretionary complex* (SAC) in the fore-arc region. During final collision of the oceanic island arc with continental crust of North America, parts of the SAC will be thrust onto the continental margin, marking a suture zone typically characterized by serpentinite mélanges entraining blocks of HP metamorphic rocks (e.g. García-Casco *et al.* 2002, 2006; Krebs *et al.* 2008). The pressure–temperature–time (P–T–t) paths of these blocks provide critical information on subduction zone dynamics, and therefore also the physical parameters (e.g. convergence rate, subduction angle, lithosphere age) governing the subduction zone itself (e.g. Krebs *et al.* 2008). Nevertheless, there are also possibilities of 'short-circuiting' this two-way flow in the subduction channel. Rocks from deeper parts of the subduction channel, at or

near the thermal stability limits of serpentinite (i.e. where the serpentinite-based subduction channel is thin or non-existent), can be exhumed along 'backstop thrusts' in the hinterland of the suture zone (e.g. Schwartz *et al.* 2007).

Tectonic settings of subduction-related metamorphic rocks in Cuba

In the northern Caribbean, the SAC of the Caribbean Arc was disrupted during collisional interactions of the arc with the Yucatán Block and later with the Bahamas platform. As a result, subduction-related metamorphic rocks of the SAC were uplifted in the subduction channel very rapidly, and progressively appeared at the surface as metamorphic nappes and tectonic blocks in serpentinitic mélanges of the accretionary complex as well as exotic blocks in sedimentary foreland basins. The outcrops of subduction-related HP metamorphic rocks in Cuba are schematically summarized in Figure 10.

Two primary settings for HP rocks occur: (1) as coherent slabs or blocks in mélange along the Main Cuban Thrust, which can be called the suture zone; and (2) as extensionally unroofed metamorphic core complexes along the southern flank of Cuba (Draper 2001). The first setting was comprehensively described by Somin & Millán (1981), and is spatially related to the Late Cretaceous sole thrust and the Palaeogene suture. The serpentinitic mélanges contain tectonic blocks of HP metamorphic rocks, and are reported from northern Las Villas (Somin & Millán 1981; García-Casco *et al.* 2002), from the La Suncia schists east of Camagüey City, and also north of Holguín City (Szakmány *et al.* 1999). Metasedimentary and minor metaigneous rocks such as those in the Cangre belt in western Cuba or the Asunción complex in easternmost Cuba (see Fig. 12a & c) have also been mapped in a footwall position with respect to the suture (Somin & Millán 1981). The second setting includes the Pinos and Escambray complexes, which are dominated by metasedimentary sequences. The protoliths were derived from a continental margin setting and were each metamorphosed at different grades. The Pinos and Escambray metamorphic complexes are characterized by typical, slightly positive gravimetric anomalies, two more of which are also observed SW of Camagüey City on the western shoulder of the Camagüey Fault, and SW of the Pinar Fault, suggesting additional unexposed metamorphic complexes (Fig. 10; Bush & Sherbakowa 1986). Because the Pinos and Escambray complexes and the Camagüey anomaly are localized on the upthrown western shoulders of the NE-trending faults which cross-cut and post-date the thrust structures (Fig. 10), extension is likely to be involved in their exhumation.

In eastern Cuba, the blueschists and eclogite-facies rocks of the Sierra del Convento differ in that they are overthrust by arc sequences of the Purial complex and the Oriente ophiolite. García-Casco *et al.* (2007) and Lázaro & García-Casco (2008) have made a cogent case for suggesting that the amphibolites of the Sierra del Convento represent relatively hot subducted oceanic crust.

Pressure–temperature–time paths of metamorphic rocks

As indicated above, pressure–temperature–time paths of rocks involved in high-pressure metamorphism in subduction zones can provide valuable information on the petrological and thermal structure as well as on the dynamics of plate convergence and mass movement in such collision zones. In an early summary, Ernst (1988) discussed how the different prograde and mainly retrograde trajectories can be logically used to identify specific geodynamic scenarios. Thus P–T trajectories may show clockwise loops denoting essentially isothermal decompression. These can, for instance, be explained by rapid exhumation associated with cessation of active subduction. 'Hair-pin' type P–T paths with exhumation P–T trajectories essentially retracing burial trajectories can logically be related to exhumation during active subduction. However, recent numerical modelling (e.g. Gerya *et al.* 2002; Gerya & Stöckhert 2006; see also Krebs *et al.* 2008) has shown that these two situations are end-member scenarios. As the subduction zone evolves and matures, the serpentinized part of the overlying mantle wedge will widen and a funnel-shaped (downward-narrowing) subduction channel can evolve. Depending on the relationship of mass flow with respect to the local trend of the subduction zone isotherms, isothermal uplift paths are possible in active subduction zones. Counterclockwise paths with isobaric cooling segments are typical of mass trajectories in the early stages of subduction zones, before consistent return flow is established and strong cooling of the system is still underway. As the system matures, the P–T–t paths are constrained to increasingly higher P–T regimes.

Escambray complex. Along the Cuban suture zone, various different types of P–T–t paths can be distinguished (Fig. 11). The most comprehensive data set for constructing a complete P–T–t–d-path (d = deformation) exists for the metamorphic Escambray complex. Here five tectonic units (see Fig. 12b) have been stacked onto the southern margin of the Bahamas platform by top-to-north thrusting (Stanek *et al.* 2006). The protolith ages of the

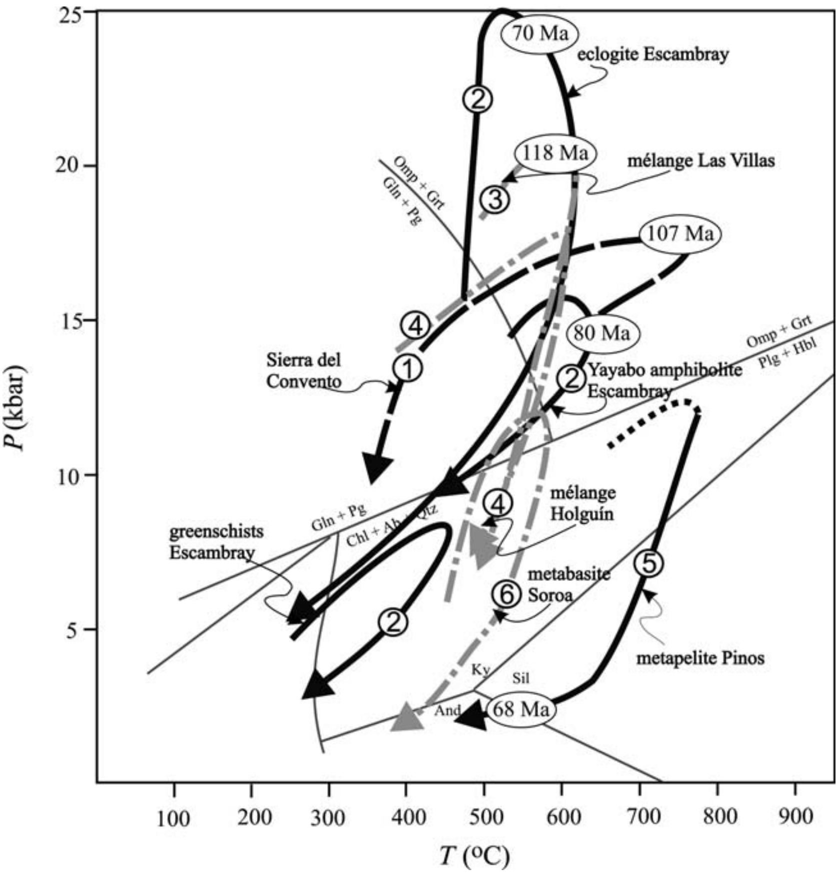

Fig. 11. Examples of metamorphic paths for Cuban SAC related rocks. The broken black line indicates initial subduction conditions, solid black lines metamorphic complexes of the hinterland, grey broken lines HP metamorphic rocks of the footwall mélange. The numbers in circles refer to (1) Sierra del Convento (García-Casco *et al.* 2006, 2007), (2) Escambray complex (Grevel 2000; Schneider *et al.* 2004; Grevel *et al.* 2006), (3) Mélange Las Villas (García-Casco *et al.* 2002), (4) Mélange Holguín (Szakmány *et al.* 1999; García-Casco *et al.* 2006), (5) Pinos complex (García-Casco *et al.* 2001), (6) metamorphic blocks in western Cuba (García-Casco *et al.* 2006). Petrological framework of the diagram from Bucher & Frey (2002).

lower Pitajones and Gavilanes nappes have been estimated as Upper Jurassic to Lower Cretaceous (see above). The protoliths of the uppermost three nappes consist of tholeiitic basalts (Yayabo unit), tholeiitic and IAT-like igneous sequences (Mabujina unit) and the low- to non-metamorphic island arc unit. Gneisses of the Mabujina unit and granitoids of the island arc have been dated between 132 and 80 Ma (Grafe *et al.* 2001; Rojas-Agramonte *et al.* 2006*a*, *b*; Stanek *et al.* 2005). The peak metamorphic conditions in the HP eclogites of the Gavilanes metamorphic unit reached 16–25 kbar at 580–630 °C (Grevel 2000; Schneider *et al.* 2004; Grevel *et al.* 2006; see Fig. 11). The P–T trajectories of these HP metamorphic rocks of the Gavilanes unit describe a near-isothermal decompression. Different geochronological methods have been applied to determine the timing of the corresponding peak metamorphic conditions, as well as the timing and velocity of exhumation of the metamorphic complex after the beginning of stacking (e.g. closure temperatures of Spear 1993). Earlier dating of zircons from the eclogites by the U–Pb method led to data that spread from about 245 (270–140) Ma (Somin *et al.* 2005), and about 170–106 Ma (Hatten *et al.* 1988; Grafe 2000; Krebs *et al.* 2007). The results near 106 Ma were obtained from rounded zircons thought to be metamorphic in origin, and thus were interpreted as an indicator for peak-metamorphic conditions (Hatten *et al.* 1988). There are no geological arguments to link the older, pre-Late Jurassic ages to subduction

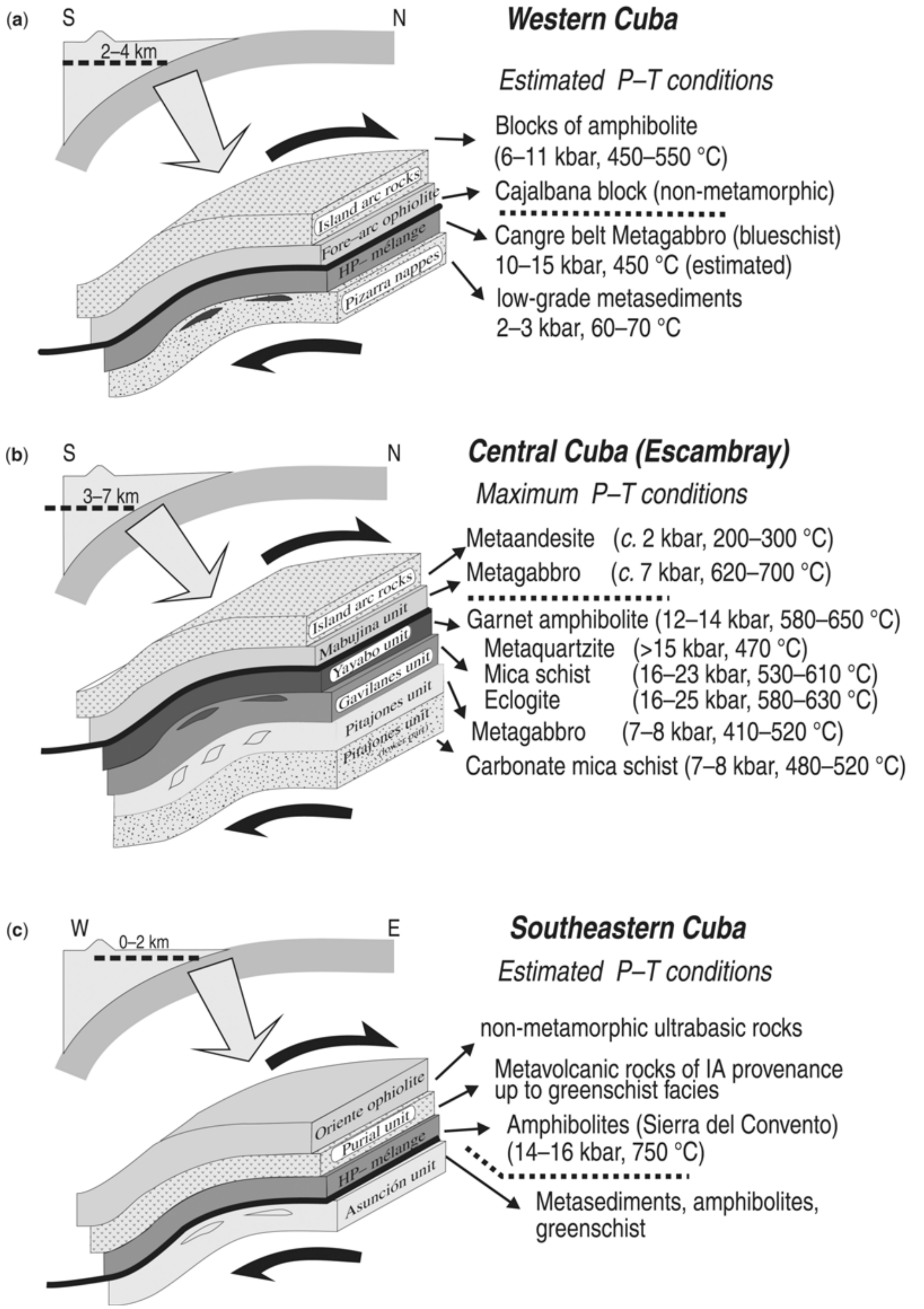

Fig. 12. Generalized nappe stacks of (**a**) western Cuba (García-Casco *et al.* 2006; Cruz *et al.* 2007), (**b**) Central Cuba (Escambray; Grevel 2000; Stanek *et al.* 2006) and (**c**) Eastern Cuba (Sierra del Convento; García-Casco *et al.* 2006).

processes of the Caribbean Arc in the area between the spreading American plates. More likely, the U–Pb data on zircons represent protolith ages of basic igneous rocks from the rifting and pre-rifting environment at the Mesozoic continental margin. Rb–Sr isochron and Ar/Ar data on eclogites suggest rapid exhumation after the HP metamorphism at about 70–68 Ma (Schneider *et al.* 2004). New Lu–Hf isochron data (Krebs *et al.* 2007) also constrain peak metamorphism to the Late Cretaceous, that is, of the eclogites of the Gavilanes unit to *c*. 70 Ma, and of the overlying Yayabo unit to *c*. 80 Ma. The 70 Ma Lu–Hf data on the eclogites substantiates the rapid exhumation at this time and corroborates that the 106 Ma U–Pb age represents the protolith. The trend to 'older' cooling ages in the higher tectonic units is also worthy of note in the Ar/Ar data set: *c*. 65 Ma in the lower metamorphic nappes, *c*. 73 Ma for the Mabujina nappe (Grafe *et al.* 2001), and about 75 Ma for the volcanic level of the island arc (Hall *et al.* 2004).

Pinos complex. The P–T paths of metapelites and metatrondhjemites of the Pinos complex have still not been completely reconstructed, but are clearly characterized by rapid near-isothermal uplift at unusually high temperatures (*c*. 700–750 °C; Fig. 11). Available Ar/Ar cooling ages indicate uplift of the metamorphic complex in the latest Cretaceous (68 Ma; García-Casco *et al.* 2001).

The P–T–t paths of the Escambray complex indicate rapid uplift at 70 Ma under conditions of on-going subduction (or at least non-decay of a subduction thermal regime). The Lu–Hf data on metamorphic garnets show that the prograde subduction path also was rapid (Krebs *et al.* 2007). In other words, we had a sharp 'yo-yo-type' subduction–exhumation path. The Pinos path appears incompatible with the ongoing subduction scenario, but not necessarily so. The numerical simulations of Gerya & Stöckhert (2006) for an active continental margin indicate what could happen, if a 'lid' (e.g. continental crust, thick sedimentary prism, or forearc) existed or was thrust over the subduction–accretionary complex and its underlying subduction zone channel. Exhumation paths with broad clockwise form, with isothermal paths at high T down to low P can result when exhumation occurs in the 'back-stop' position. This scenario could relate to the Great Antillean Arc colliding with a spur of continental crust (e.g. Caribeana or the southern Yucatán margin; see García-Casco *et al.* 2008), thickening northward.

Southeastern Cuba. In the Purial complex (Sierra del Convento, eastern Cuba), a distinctive counterclockwise path is indicated (Fig. 11). In fact, as suggested by García-Casco *et al.* (2007), the combination of still 'near-normal' geothermal gradients and particularly young, hot subducting crust led to partial melting of the amphibolites, with a subsequent blueschist overprint of these migmatites. This must be considered a rare if not unique example of preserved *in situ* evidence of partial melting of subducted oceanic crust. U–Pb age determination on zircons from the trondhjemitic melting products reveals an age of about 107 Ma (Hatten *et al.* 1988; García-Casco *et al.* 2007) and thus provides critical evidence for subduction initiation in this segment of the Caribbean Arc. A similar U–Pb age has been reported from tonalite-trondhjemites of the Corea mélange exposed in a tectonic window below the Mayarí ophiolite massif (Somin & Millán 1981; Blanco-Quintero *et al.* 2008). The P–T–t paths of the HP metamorphic rocks of the Sierra del Convento and the La Corea mélange represent the initial stage of subduction in this segment of the Caribbean Arc, about 10–15 Ma later than in northern Hispaniola (Krebs *et al.* 2007). However, beyond this detailed local data, there is no additional information concerning further ongoing south-dipping subduction through the Palaeogene. Preliminary K–Ar and Ar/Ar data on white mica and amphibole of the rocks of the Sierra del Convento Complex and the Corea mélange scatter between 85 and 75 Ma (Somin *et al.* 1992; García-Casco *et al.* 2007). These age data indicate a cooling of the metamorphic rocks in the middle crust which took place somewhat earlier than in central Cuba. The HP metamorphic blocks involved in the serpentinitic mélange of the Rio San Juan complex of northern Hispaniola, located in a tectonic position similar to that in eastern Cuba, demonstrate ongoing subduction from an Early Aptian–Albian stage through to the Eocene (Krebs *et al.* 2008).

Northern and western Cuba. The subduction-related metamorphic rocks of western Cuba, of northern Las Villas and of Holguín are situated in tectonic units near the Palaeogene Main Thust (Fig. 10). In western Cuba, HP metamorphic basic rocks occur in the Cangre Belt (Fig. 12a) and reach blueschist conditions (Millán 1972; Somin & Millán 1981; Cruz *et al.* 2007). Amphibolites occur as exotic blocks in a serpentinitic mélange at the top of the West Cuban anticlinal stack (Felicidades belt in the Bahia Honda unit) and as blocks and olistoliths in syntectonic sediments of the nappe structure (Somin & Millán 1981; García-Casco *et al.* 2006). In northern Las Villas exotic blocks of eclogite are included in the Northern Serpentinite Mélange (García-Casco *et al.* 2002, 2006). The serpentinite mélange forms the footwall mélange of the overthrust Cretaceous island arc. A similar tectonic environment has been mapped near the city of Holguin (Kosak *et al.* 1988; Szakmány *et al.* 1999;

García-Casco *et al.* 2002). The polymictic mélange of the La Palma Formation contains blocks of eclogite, metacarbonate and orthogneiss. The retrograde P–T paths of the HP metamorphic rocks included in the mélange of the Cuban Main thrust are quite similar (Fig. 11). The rocks reached different depths and have been uplifted with near-isothermal trajectories. The timing of HP metamorphism and of cooling (exhumation) differs significantly in the various complexes. In northern Las Villas, the data for HP metamorphism and subsequent cooling range from *c*. 118 to 103 Ma (García-Casco *et al.* 2002). In southern Las Villas, in the Escambray complex, the peak of HP metamorphism seems to be simultaneous in the whole complex: the 70 Ma old HP metamorphic overprint was followed by very rapid exhumation and cooling at 65 Ma. In the Pinos complex, Ar/Ar cooling ages indicate latest Cretaceous uplift (68 Ma; García-Casco *et al.* 2001). In western Cuba and in Holguín HP metamorphism and exhumation have not been constrained as yet. The available K–Ar data of the gneisses in Holguín show Middle Mesozoic to Middle Palaeozoic 'ages', which need further detailed geochronological work.

Based on the interpretation by Ernst (1988) of the various possible shapes of subduction-zone P–T paths, García-Casco *et al.* (2002) postulated an end of subduction at 120–100 Ma in West and Central Cuba. However, comparing the P–T–t paths of West and Central Cuba with the well-documented systematic P–T–t paths of the Rio San Juan mélanges in Hispaniola (Krebs *et al.* 2008) as well as the numerical models of Gerya *et al.* (2002) and Gerya & Stoeckhert (2006), the assumption of an end of subduction at this time no longer appears tenable. In any case, magmatism in the 'Cuban' arc requires subduction until at least 75 Ma. The interpretation of the P–T path of HP rocks occurring in the Cangre belt still remains problematic. The mélange occurrences of northern Central Cuba (Las Villas) speak for a mature subduction zone at 120–100 Ma (García-Casco *et al.* 2002). The path of the Soroa amphibolites in West Cuba extends to unusually low pressures (although still in the Barrovian regime), and mirrors the Pinos path, although at considerably lower temperatures.

Geotectonic model

To compile an internally consistent geotectonic model of the Cuban part of the North Caribbean suture zone (NCSZ), the structural units of the suture zone must be traced back in space and time to their original positions. This procedure gives a measure of the deficiencies in the available data sets and the reliability of existing models. Using the data of the autochthonous and parautochthonous terranes related to the passive continental margins presented above, and the allochthonous terrane of the Caribbean Arc, three tectonic regions with certain differences in thrust mechanics (western Cuba, central Cuba and eastern Cuba) can be observed along the suture in onshore Cuba. The geotectonic control points in the geological history of the terranes are the onset of sedimentation and magmatism respectively, the time and grade of metamorphism, and the first contact of the terranes and their mutual thrusting. The Caribbean literature is clear about: (1) the formation of passive continental margins between the rifting American continental plates from the Late Jurassic and into the Cretaceous; (2) the subduction-related origin of the Caribbean (Great Antillean) Arc; and (3) interaction of the Caribbean Arc with the continental crust of the Yucatán platform in the Late Cretaceous (80–70 Ma) and final thrusting onto the Bahamas platform in the (Early) Middle to Late Eocene (45–40 Ma). All the data outlined above imply an accumulation of sediments along the continental margins of the Yucatán and the Bahamas platforms and the Proto-Yucatán Basin, depending on the palaeogeographic position, from the Upper Middle Jurassic to the Middle Cretaceous or even to the final collision time in the Eocene (Fig. 13). The subduction-related magmatism at the northwestern part of the Caribbean arc reported from Cuban occurrences lasted, with a possible interruption in the Late Campanian–Maastrichtian, over some 70–80 Ma from Early Cretaceous to the Palaeogene. Today, all the terranes discussed above are found in tectonic juxtaposition; however, if we take a minimum of 20 mm a^{-1} convergence rate as a rule of thumb for the continuous generation of an arc, then we see that in excess of 1400 km of subduction and horizontal migration of the Cuban arc terranes toward the Bahamas is indicated for the development of the Cuban arc. This can only be accommodated in Pacific origin-type Caribbean models.

The post-collision structure of the northwestern branch of the North Caribbean suture zone in Cuba

In central Cuba, the WNW-trending Cuban Main thrust suggests a uniform Palaeogene collision belt somewhat offset by NE-trending faults across the thrust belt (Bush & Sherbakova 1986). The crustal thickness (depth to Moho) of the Cuban collision belt has been interpreted from receiver functions (Moreno Toiran 2003) and from gravity and seismic data (Bush & Sherbakova 1986; Otero

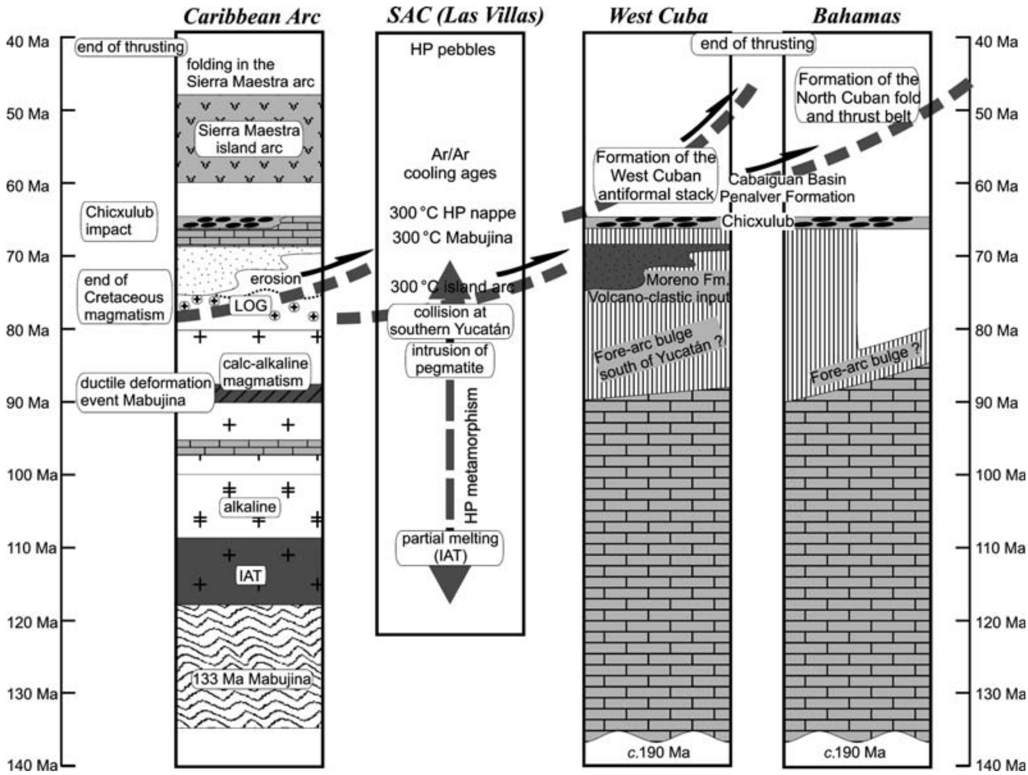

Fig. 13. Comparison of the geological–tectonic events recorded in the geotectonic terranes of the Cuban part of the North Caribbean Suture Zone.

et al. 1998; Fig. 14). According to the existing geophysical data, the crustal thickness gradually steps down from the collision belt (30 km for the Bahamas crust and foreland fold and thrust belt at the southern edge of the Bahamas platform), to the thrust and stacked arc crust (*c.* 20–30 km), the thin crust of the short-lived Sierra Maestra arc (<20 km) to the oceanic crust (<10 km) in the Yucatán Basin (Rosencrantz 1990; Fig. 14). The southeastern margin of the continental crust (Bahamas platform) has been identified east of Holguín by the interpretation of gravity data (Uchupi *et al.* 1971). The vergence of the folded and thrusted Bahamas-type sediments indicates a uniform tectonic transport top to the NE in the Late Paleocene through Middle Eocene. The structures in the overthrust Caribbean Arc sequences follow the northeastern direction of tectonic transport in the eastern part of Central Cuba. The thrust direction of the metamorphic complexes and the fold structures in the western part (Las Villas) show a certain anticlockwise rotation and trend to slightly more northerly directions, possibly due to rotation of the allochthon late in the collision.

In western Cuba, the fold-thrust structures of the sediments of the Guaniguanico terrane, the duplex formation and the overthrusting of the volcano-sedimentary sequences of the Bahia Honda unit indicate tectonic transport and stacking top to NNW (Piotrowska 1987; Saura *et al.* 2008) cross-cut by the Pinar Fault (Gordon *et al.* 1997). In eastern Cuba (Oriente), two major tectonic events with divergent directions of compression are observed. In the Late Cretaceous the ultrabasic rocks of the Sierra Cristal and Moa–Baracoa ophiolitic massifs were thrust onto the previously metamorphosed (HP/LT) Purial Caribbean Arc units. In contrast to central Cuba, the lower metamorphosed part of the island arc shows top to the ESE tectonic transport in the Late Cretaceous. During the Palaeogene, the compression changed to north–south, indicated by north-vergent folding of the Sierra Maestra Middle Eocene volcanic rocks.

The tectonic data suggest bending and segmentation of the Cuban suture zone, which is also supported by geophysical studies. Velocity models of seismic waves and the interpretation of data from receiver functions give more detailed information

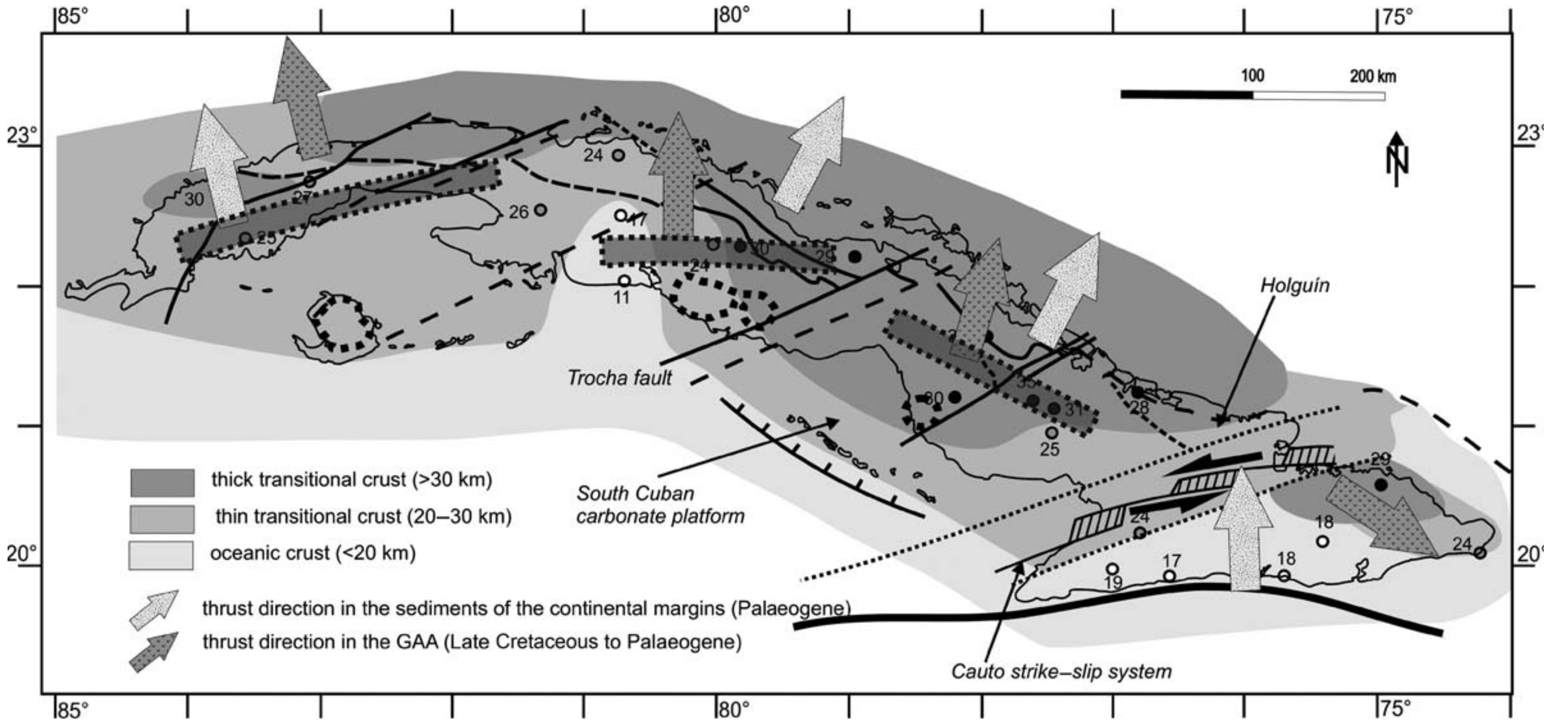

Fig. 14. Sketch map of the crustal thickness (depth to Moho) of the Cuban collision belt. Data compiled from Otero *et al.* (1998), and Moreno Toiran (2003). Grey bars indicate the palaeomagnetic trends (Renne *et al.* 1991; Chauvin *et al.* 1994; Pérez Lazo *et al.* 1994; Bazhenov *et al.* 1996). The Cauto strike–slip system is interpreted from Makarov (1986). The opening of the Cauto Fault Zone is suggested to taken place in the Late Eocene (Leroy *et al.* 2000). The directions of the tectonic transport have been compiled from tectonic field data (1985–2006).

of the crustal thickness (depth to Moho) of the Cuban mainland (Otero *et al.* 1998; Moreno Toiran 2003). The southeastern parts of Cuba (Oriente) consist of thin, probably arc-modified oceanic crust with a juxtaposed arc pile (Sierra Maestra Arc) above (Fig. 14). Only the easternmost part of Oriente shows an area of typically continental crustal thickness, possibly suggesting a piece of continental crust and sedimentary cover involved in subduction in the Late Cretaceous. Considering the amphibolite-facies metamorphic grade of the Asunción complex (Somin & Millán 1981) and its protoliths, this metamorphic suite does not fit logically into the general geology of the Oriente region. The complex may also have been entrained somewhere at the southeastern margin of Yucatán. After the Palaeogene collision, the complex was displaced by the Paleocene–Eocene Cauto fault system (Leroy *et al.* 2000). The Cauto Depression, as modelled from gravity data, could be interpreted as a sinistral strike–slip fault system with three extensional pull-apart basins (Makarov 1986; Fig. 14).

The eastern part of central Cuba has a thick homogenous crust (depth to Moho). In the southeastern offshore area, trending along the recent South Cuban carbonate platform (Fig. 14), a NE-dipping seismic reflector was interpreted as an inactive, NE-dipping (SW-vergent) thrust zone (Rosencrantz 1990). The fault plane is buried by presumed Upper Palaeogene and younger sediments. Relative to the NE-vergent accretionary suture zone of central Cuba, this thrust zone could be interpreted as a backstop thrust in the overall collision (Ellis *et al.* 1999), active during the Palaeogene collision of the Caribbean Arc with the Bahamas platform. The structure of the collision belt west of the Trocha fault appears more complicated, and most of the Caribbean Arc related rocks are hidden below younger sediments (Batabano Massif; Fig. 2). West of the Escambray Mountains a tongue of thin, possibly oceanic crust extends to the north, separating the central Cuban region from western Cuba. This segmentation of the overthrust island arc could explain the different trends and thrust directions in the regions described above. The nature of the thin crust in the collision belt west of the Escambray is still unclear.

The tectonic and geophysical indications of segmentation by faulting are also supported by palaeomagnetic data. Palaeomagnetic determinations from the Bahia Honda unit and the Guaniguanico terrane in western Cuba indicate an anticlockwise rotation of about 90°, and a remagnetization in the Late Cretaceous, which is suggested to be related to the beginning of deformation in this nappe stack (Bazhenov *et al.* 1996). Data from Upper Jurassic sediments gave palaeolatitudes of about 12°N, which place the sediments at the southern margin of the Yucatán Block (Pérez Lazo *et al.* 1994). Reconnaissance palaeomagnetic studies from central Cuba (Las Villas) also reveal a remagnetization in the Campanian and an anticlockwise rotation of about 43–37° (Renne *et al.* 1991; Chauvin *et al.* 1994). The differences in the rotation values are suggested to be related to an oroclinal bending of Cuba (Bazhenov *et al.* 1996). Palaeomagnetic studies of Paleocene and Eocene sediments in Oriente show that the Early Palaeogene position of eastern Cuba was only 1–2° (100–200 km) south of its present location, whereas the position of Upper Eocene sediments shows similar latitude to today's (Pérez Lazo *et al.* 1994).

The continental margin of Yucatán and the Bahamas

The oldest sediments that bear witness to the rifting stage of the Proto-Caribbean ocean are the ?Lower to Middle Jurassic San Cayetano fluvio-deltaic sandstone and shale and the overlying Upper Jurassic marine deposits and intercalated volcanic rocks in the Sierra Guaniguanico, which represents the palaeo-eastern Yucatán margin that rifted from Venezuela (Pindell 1985). As for the Bahamas margin, Atlantic opening kinematics indicate a Late Jurassic–Early Cretaceous diachronous transform fault relationship along the southern Bahamas and the Guyana margin of NE South America (Pindell 1985; Fig. 13). Essentially passive margin conditions are then thought to have prevailed along these margins until the Turonian (*c.* 92 Ma), when arc-derived lithic clasts and minerals such as glaucophane first appear in the Placetas Belt deep marine sediments (Linares & Smagoulov 1987) and Escambray and Pinos complexes. However, contrary to the view (Hempton & Barros 1993) that the Placetas Belt is the basinal facies of the Bahamian margin, the Placetas Belt must have lain farther to the SW, somewhere south of Yucatán, such that it does not constrain Bahamian development at all. As discussed herein and also by Pindell *et al.* (1988, 2005, 2006) and García-Casco *et al.* (2008), the Caribbean Arc did not arrive at southern Yucatán until the Campanian, as recorded by the Sepur foredeep in northern Guatemala. Thus, any Turonian strata with arc debris must have been deposited even farther south or southwest (Pindell *et al.* 2006). The Placetas Belt is best considered as part of the Cuban accretionary prism; it does not physically connect with coherent fold trains in Cuba today, and thus it cannot be used to rigorously reconstruct amounts of total shortening in the Cuban thrustbelt. The 450 km estimated displacement of Hempton & Barros (1993) is, as they openly state, a minimum only.

No Upper Cretaceous pelagic sediments younger than Turonian have been observed in the North Cuban fold and thrust belt. Tada *et al.* (2002) suggested that this may be a hiatus due to erosion from the giant tsunami wave after the Chicxulub impact, but because we are talking about the basin floor of the Proto-Caribbean (*c.* 4 km deep at the time), a more likely explanation is that most Upper Cretaceous pelagic sediment simply was subducted rather than accreted at the arc's accretionary prism, as at Barbados and the south Caribbean Fold Belt today. An Upper Cretaceous hiatus is also known from the immediate area of the Florida Straits (Angstadt *et al.* 1985), probably created by bottom currents flowing through this gap between the Atlantic and the Gulf of Mexico/Western Interior Seaway. It is not known, of course, how far to the SE of the Straits in the Proto-Yucatán Basin this hiatus might have developed. It might be that both explanations are responsible at least in western and central Cuba. The Upper Cretaceous hiatus discussed thus far here is not to be confused with true Bahamian Platform hiati: there, a Maastrichtian hiatus, at which arc-derived tuffs first appear in the Bahamian section, record the advancing Caribbean Plate's peripheral bulge as it arrived some 300 km ahead of the arc at the Bahamas (Pindell *et al.* 1988, 2005). Thereafter, as the arc came nearer, load-induced foreland subsidence and sedimentation rates were strong in the Bahamas (Mullins & Lynts 1977; Pindell 1985).

In the Guaniguanico terrane in western Cuba, the Campanian Moreno Formation contains abundant volcaniclastic detritus (Fig. 13). The facies development and the stratigraphic relationships to the older sediments suggest that the Moreno Fm is a sedimentary piggy-back basin at the top of the fold and thrust belt north of the Cretaceous island arc (Pszczółkowski 1999). The suggested palaeogeographic position of the Upper Cretaceous piggy-back basin is at the eastern margin of Yucatán when the recently dormant island arc started to move into the area east of the Yucatán platform (Saura *et al.* 2008).

Timing of tectonic events in the northwestern Caribbean

Circa 120–80 Ma. Three important evolutionary events in the geotectonic history of the Caribbean Arc are the onset and the cessation of magmatism, and the obduction of the arc onto the Proto-Caribbean continental margins (Fig. 13). The onset of arc magmatism has been dated at least as old as Aptian (*c.* 120 Ma; Kesler *et al.* 2005; Escuder Viruete *et al.* 2006; Rojas-Agramonte *et al.* 2006*a*, *b*; García-Casco *et al.* 2007). Subduction related magmatism in central Cuba persisted until the Middle Campanian, a period exceeding 45 million years, after which it appears to have shifted south to the offshore. There is no interruption in this interval of Cretaceous island arc activity. Thus, if there was an arc polarity reversal (Pindell & Dewey 1982; Pindell 1993; Lebrón & Perfít 1993; Draper *et al.* 1996), then in Cuba it must have pre-dated 120 Ma, and all subduction that built this arc occurred by southwestward subduction of Proto-Caribbean crust. However, a number of fragments or small terranes of older arc, subduction complexes and possibly continental crust may have migrated SE from the west flank of Chortís along a sinistral transform spanning the Neocomian gap between Chortís and Ecuador, which could now lie beneath the Aptian and younger Great Arc (Pindell 2008).

As argued above, the palaeogeographic position of the arc in the Campanian was along southern Yucatán, such that it still had another 1000 km to travel before reaching the Bahamas. Assuming a minimum convergence rate of 20 mm a^{-1} in order for the Central Cuban arc to develop, the origin of the arc must have been some 900 km farther SW than southern Yucatán. The cessation of magmatism in the Middle Campanian coincides with the time of collision and stacking of the accretionary complex of the Caribbean Arc with the southern continental margin of the Yucatán platform (Fig 15).

80–75 Ma. The blueschist-facies meta-ophiolitic rocks of the El Tambor group, whose metamorphic ages range from about 125 Ma to about 75 Ma (Harlow *et al.* 2004), and amphibolite facies gneisses of the Chuacus complex, were generated during the period of normal (steep) subduction as the Caribbean arc approached southern Yucatán (Ratschbacher *et al.* 2009). These authors further suggest that the slab broke off as the trench was choked by Yucatán, as a means of generating the nearly contemporaneous intrusion of pegmatites in the Maya Block in southern Yucatán, and Pindell & Kennan (2009) argue that slab break-off must have occurred as a means of allowing North American continental crust to continue its westward drift across the mantle. Concurrently to the south, arc magmatism ceased in central Cuba (75 Ma) and HP metamorphism in the Escambray and Pinos sediments was culminating shortly thereafter (70 Ma). The end of arc magmatism would relate to the flattening of the slab as the continental margin entered the trench, while intrusion of the late orogenic granites (LOG) and pegmatites in central Cuba may relate to fluid fronts from the subduction of the continental margin sediments as they began to be metamorphosed. Peak metamorphism of the subducted sediments and igneous rocks of the thinned continental margin would lag (about

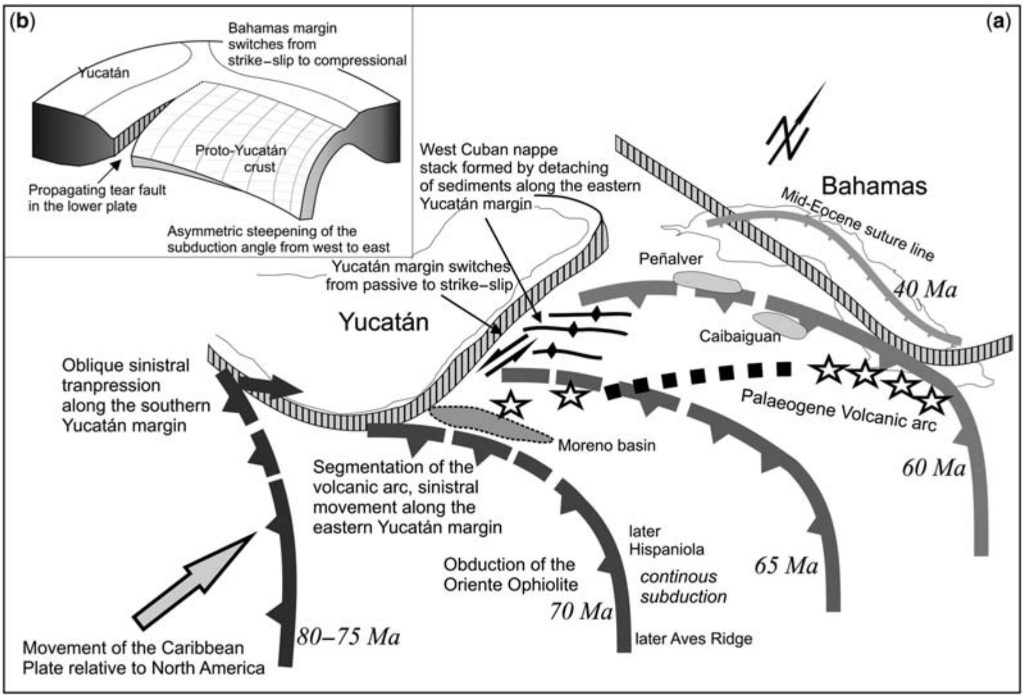

Fig. 15. Model of the 'indenting' northern part of the Caribbean Arc from Maastrichtian to Mid Eocene (adapted from Pindell *et al.* 2005, 2006). (**a**) 80–75 Ma: oblique sinistral collision of the Caribbean Arc with the southern Yucatán margin, subduction of parts of the thinned continental crust, end of subduction-related magmatism in the volcanic arc. 70 Ma: HP metamorphism and rapid uplift of the subducted rocks, movement of the collision complex away from the suture zone into the Proto-Yucatán area. 65 Ma: sinistral movement of the fragmented northwestern part of the Caribbean Arc along the eastern Yucatán margin. The subduction continued in the southern part of the Caribbean Arc. 60 Ma: Formation of a new volcanic arc 'consuming' the Proto-Yucatán oceanic crust by shifting of the magmatic axis. Thrusting started in the North Cuban fold and thrust belt. 40 Ma: final obduction of the remnants of the northern Cretaceous Caribbean Arc onto the Bahamas platform. (**b**) Model of the subducting Proto-Yucatán oceanic crustal slab with asymmetric subduction angles.

70 Ma) while the sediments were heated and subducted by several tens of kilometres. In the area of slab detachment, anomalous heat flow could be expected as rising asthenosphere displaces the slab. This could be a mechanism for explaining the unsually 'warm' $P–T–t$ path of the Pinos complex (Fig. 11), situated over the detaching slab. The Escambray complex, which was situated farther south in the subduction channel, was uplifted in more normal 'colder' geothermal conditions (Fig. 11).

The subducted metasediments then underwent rapid exumation and cooling. This probably began in the subduction channel during flat-slab subduction, but may have been subsequently facilitated by backstop thrust tectonics (see model by Schwartz *et al.* 2007), or, especially at Pinos, by extensional detachment during the initial opening of the Yucatán Basin (Pindell *et al.* 2006). The initial tectonic segmentation of the Central Cuban part of the Caribbean Arc probably owes its origin to the Campanian–Maastrichtian interaction with southern Yucatán; the Cuban cross faults lie parallel to the sigma one direction of that transpressive interaction, and sediments as old as Maastrichtian lie on the hanging walls of the normal faults (Pindell & Kennan 2009).

70 Ma. By this time, the Cuban part of the Caribbean Arc had been deformed, locally uplifted, deeply eroded as it passed the SE corner of Yucatán, and then covered by the Late Maastrichtian carbonate platform (Iturralde-Vinent 1998) as it began to migrate toward the Bahamas. Arc magmatism probably continued, or was re-established, eastward where slab break-off had not occurred, but south of onshore Cuba due to a flatter slab geometry. With the separation of the Cuban arc terranes from the Cayman Ridge/Caribbean Plate as the Yucatán Basin opened, the northwestern

Caribbean region became the site of a three-plate kinematic problem. The Caribbean Plate continued to move to the NE relative to North America, but the westernmost Cuban arc terranes moved NNW along the Yucatán margin. This difference was manifested by NW–SE extension across the site of the Yucatán Basin (Pindell *et al.* 1988, 2005, 2006). In essence, after the southward shift in arc magmatism, and possible forearc tectonic erosion at 75–70 Ma, the original Cretaceous Cuban arc terranes were now in a forearc tectonic setting, relative to a new and hypothetical arc axis, and within only 20–40 km of the Cuban trench. These forearc slivers were incrementally unroofed as trench roll-back sucked them extensionally to the NW relative to the Cayman Ridge/Caribbean Plate, which was concurrently migrating NE relative to North America. Although the initial extensional faulting that helped unroof the southern Cuban HP zones was of Maastrichtian age, the fact that Paleocene arc intrusions occur in the Cayman Ridge (Lewis *et al.* 2005) suggests that much of the extension in the deep Yucatán Basin was Paleocene and Early Eocene, such that any subsequent and final arc magmatism beneath the Yucatan Basin lay north of the Cayman Ridge. The assumed extensional detachments that had cut down through the Cretaceous arc level and into the subduction channel allowed unroofing of the metamorphic complexes on a multi-kilometric scale. The domal structure is due to isostatic rebound of the footwalls as they were tectonically unloaded. Both Pinos and Escambray rapidly cooled between 68 and 45 Ma, as shown by Ar/Ar and zircon/apatite fission track cooling ages. Prior to this crustal level unroofing, the exhumation of deeper parts of the SAC was probably accommodated by backstop thrusts of the accretionary wedge. Following the modelling by Ellis *et al.* (1999) and Goffé *et al.* (2003), mass flow trajectories suggest that parts of the metamorphosed subduction–accretionary complex could rise up to erosional levels along these faults. This could explain the appearance of metamorphosed continental margin sediments to the rear of the overthrust island arc sequences. The Maastrichtian age of initiation of the Cuban cross faults is shown by the basal Maastrichtian sediments in the basins adjacent to them. They are all extensional, and their extension continued into the Eocene. In contrast, at the front of the forearc in the accretionary prism, including the Sierra Guaniguanico, compressional structural development continued as the forearc slivers migrated toward eventual transpressional collision with NE Yucatán and orthogonal collision with the Bahamas.

65–60 Ma. Chicxulub impact-related sediments unconformably cover parts of the Cretaceous sediments of the continental margin, as well as those of the fold and thrust belt. Also, parts of the Caribbean Arc were eroded during the Paleocene, providing a key stratigraphic marker horizon. Most of the white mica in the southern Cuban metamorphic complexes began to pass through the cooling temperature of the K–Ar decay systems at about 65 Ma, implying exhumation to depths of about 10 km by that time. Piggy-back basins developed after the Early Paleocene (*c.* 60 Ma) in a foreland position (Peñalver Formation) on top of the island arc during its folding and thrusting (Caibaiguan Basin), accumulating the clastic debris from the Maastrichtian carbonate platform, the eroding island arc, and the rising metamorphic complexes.

Although there is a 10–15 Ma gap in the record in the latest Cretaceous, subduction related magmatism is again evident along the Cayman Ridge, in southern Cuba (Sierra Maestra Arc, Rojas-Agramonte *et al.* 2004), and extending into Hispaniola, Puerto Rico and at least the Saba Bank of the Aves Ridge. Starting at Oriente, Cuba, this arc axis veers southwards from the Central Cuban trench, indicating a westward-shallowing subduction angle (Pindell *et al.* 2005). Lewis *et al.* (2005) claim a continental influence in the Paleocene Cayman Ridge plutonic rocks, which we suggest was due to subduction of some volume of continental slope and rise sediments off southeastern Yucatán as Cuba moved NNE along the margin. The Sierra Maestra Arc remained active through the Middle Eocene, as it, like the Central Cordillera of Hispaniola, always lay on the arc axis until the time of collision (Pindell *et al.* 1988); the Palaeogene volcanic sequences cover both the Cretaceous volcanic arc and the overthrust Oriente ophiolite. In southern Cuba near Holguín, Paleocene olistostromes are intercalated with felsic tuffs, forming distal deposits of Sierra Maestra arc volcanism.

Accepting this model of southward subduction for all the arc activity noted, the oceanic lithosphere being subducted is that of the Proto-Caribbean Basin, formed between the two American continental plates. A Late Middle to Late Jurassic age for the Proto-Yucatán Basin can be modelled on the basis of plate kinematics (Pindell 1985) and tholeiitic syn–rift intrusions into the passive margin strata of Sierra Guaniguanico. In contrast, a Paleocene to Middle Eocene age for the present Yucatán Basin is predicted as a result of the inferred period of intra-arc rifting and NW–SE spreading, driven by roll-back of the Jurassic Proto-Yucatán slab (Pindell *et al.* 2005); this age is supported by heat-flow data from the basin (Rosencrantz 1990). Note that, although extension in the Yucatán and the Cuban onshore basins was to the NW away from the Cayman Ridge, the direction of collision between the Cuban arc fragments and the

Bahamas Platform (i.e. relative to North America) was mainly toward the NNE. This is why the small pull-apart basin mapped by Rosencrantz (1990) along the western deep Yucatán Basin records NNE–SSW opening: it is a basin along the Cuba–North America boundary, and not the Cuba–Cayman Ridge boundary. Any diachroneity in the Cuba-Bahamas collision, although commonly proposed to be eastward, is actually difficult to prove due to small amounts of Miocene eastward extensional collapse of Cuba above its suture zone.

45–40 Ma. The final thrusting of the Caribbean Arc related units onto the sediments of the eastern Yucatán and southern Bahamas margin took place in the Middle Eocene at about 40–45 Ma (Iturralde-Vinent 1994; Fig. 15). The metamorphic complexes reached the level of erosion; clasts of HP-metamorphic rocks are deposited in Eocene sections of the surrounding basins. In eastern Cuba, the Palaeogene arc was folded with northern vergence. In western Cuba the Bahia Honda ophiolitic unit was thrust to the north on top of the sediment thrust stack. In central Cuba, the ophiolite belt overrode the Eocene foreland basins, and the carbonate sequences of the Bahamas Platform were folded with roughly NNE vergence.

The initial sinistral strike–slip event in the Cauto Depression moved the southeastern part of Cuba (Sierra Maestra) to the east by about 80–100 km, before the fault system jumped to the south to the recent Cayman Trough (Leroy *et al.* 2000). The activation of the strike–slip faults should post-date the magmatism in the Palaeogene arc.

Arguments in favour of an 'indenter' (Pacific provenance) model

1. Considering the period of activity of the Cretaceous Caribbean (Great Antillean) Arc, at least 45 Ma in Cuba, the island arc should have subducted at least 900 km before the Campanian/Maastrichtian collision with southern Yucatán. In Hispaniola, the period of arc activity is 70 Ma, indicating at least 1400 km of SW-dipping subduction before Eocene collision with the Bahamas. Note that these figures are minima, because they assume orthogonal convergence.
2. The oblique northeastward thrusting onto southern Yucatán indicates a south-dipping subduction zone. The subduction polarity and the collision geometry require an origin for the Caribbean Arc somewhere in the Pacific SW of Yucatán.
3. The occurrence of Mid-Cretaceous shallow-water limestones both in the continental margin settings and in the Caribbean Arc was used as an argument in favour of a geographically close position of both units by James (2006). The Albian shallow-water limestones of the Caribbean Arc suggest uplift in the arc, whereas the coeval limestones mentioned by James (2006) belong to carbonate platforms of the Bahamas or Yucatán blocks. If these limestones had been formed in close proximity, there should be a record of the intense magmatism of the Caribbean Arc in the platforms, yet there is little to no evidence of such an influence.
4. The continuous subduction-related magmatism during 45 Ma in Cuba indicates a continuous movement of the Caribbean Arc to the ENE until the Campanian. If a polarity reversal occurred, it must have been pre-120 Ma. In the Late Cretaceous and Palaeogene the northern part of the Caribbean Arc was stretched and split off by intra-arc spreading as the Cuban portion overrode the triangular shaped Proto-Yucatán Basin between the Bahamas and Yucatán Blocks.
5. The data on subduction-related magmatism and the HP metamorphic record reported from Cuba trace the geotectonic history of the Caribbean Arc until the Late Cretaceous collision of the arc with southern Yucatán, and predate the collision with the Bahamas Block. In this framework, the protoliths of the Pinos and Escambray metamorphic complexes were part of the sedimentary margin of the North American Yucatán Block, subcreted to and metamorphosed at the base of the Great Antillean forearc during the Late Cretaceous collision with Yucatán, and progressively exhumed by subduction flow, intra-arc extensional detachment, and eventually uplift and erosion in the Bahamian collision.

Following the above model, the Late Jurassic to Cretaceous oceanic crust of the Proto-Yucatán Basin must have been subducted to allow a north-northeastward movement of the Caribbean Arc. Therefore the oceanic crust bordering the Cayman Trough forms the back arc of the Caribbean Arc and could be Jurassic or Cretaceous in age, but should have a Pacific origin, and is not related to the opening of the Proto-Caribbean ocean with some continental slivers, as suggested by James (2006). The new data on Cuban and other geochronology, petrology, geophysics and structural geology derive largely from work in the last two decades, and indicate continuous subduction over many tens of millions of years. In the plate tectonic concept, we cannot escape the fact that extensive horizontal movements must have been necessary

for the generation of such a long-lived magmatic island arc. The NE-, E- and SE-facing island arc at the leading edge of the Caribbean Plate only allowed movement of the Great Arc in these directions, relative to the Americas, supporting a provenance of the Caribbean Arc to the west or SW of its Late Cretaceous to recent position. There are still many gaps to explain in detail, but continued application of modern '4D data' in combination with traditional surface data should continue to bear fruit.

Summary lithostratigraphic chart

Stratigraphic names used in this paper are based on the explanation notes of the Geological Map of Cuba 1985.

- *Punta Alegre Fm*: gypsum breccia with blocks of gypsum, limestone, dolomite, siltstone, sandstone and tuff; Lower to Middle Jurassic, forming diapirs along the north coast of Cuba, Bahamas Platform.
- *San Cayetano Fm*: intercalation of sandstone, siltstone and pelitic schist, rare conglomerates and gravels; Lower to Middle Jurassic, western Cuba, Yucatán margin.
- *El Sabalo Fm*: sequence of basalt and diabase intercalated with limestone, tuff and siltstone; Oxfordian–Lower Kimmeridgian, western Cuba, Yucatán margin (Pszczółkowski 1994).
- *Santa Teresa Fm*: radolarian cherts intercalated with siltstone, bentonite, marl and limestone; Albian to Turonian, western and central Cuba, Proto-Yucatán Basin.
- *Mata Fm*: intercalation of pelitomorphic limestone, marl, siltstone, chert, limy conglomerates, Albian to Turonian, central Cuba, Proto-Yucatán Basin.
- *Moreno Fm*: marly limestone, shale, sandstone and siltstone; Campanian, western Cuba, Proto-Yucatán Basin (Pszczółkowski 1994).
- *Encrucijada-Fm*: aphyric basaltic lavas, lava breccia, chert and rare blocks of massive sulphides; supposed Late Upper Cretaceous, Bahia Honda unit, western Cuba, West Cuba anticlinal stack (Fonseca *et al.* 1984).
- *Via Blanca Fm*: polymictic sandstones, greywacke, conglomerates, tuff, siltstone and marl; Campanian–Lower Maastrichtian, western and western-central Cuba, Proto-Yucatán Basin.
- *Ancon Fm*: limestones with chert lenses, limy conglomerates; Palaeogene, western Cuba, West Cuba anticlinal stack.
- *Capdevila Fm*: polymictic sandstone, siltstone and shale, conglomerates and limestone; Lower Eocene, western Cuba, West Cuba anticlinal stack.
- *Manacas Fm*: olistostrome with blocks of sedimentary and volcanic rocks, the ground mass consists of siltstone with fine-grained limestone layers; Lower–Middle Eocene, western Cuba, West Cuba anticlinal stack.
- *Senado Fm*: polymictic olistostrome containing bolders of serpentinite, volcanic rocks, limestone in conglomeratic groundmass; Lower Eocene, central Cuba, North Cuba fold and thrust belt.
- *La Palma Fm*: polymictic serpentinitic mélange with boulders of metaterrigenous rocks, garnet schist; gneiss and metagranodiorite; supposed Upper Cretaceous, north of Holgúin, North Cuba fold and thrust belt (Kosak *et al.* 1988).
- *Los Pasos Fm*: plagiorhyolitic lavas and basaltic lavas and tuffs, volcanomictic sand- and siltstones; supposed Upper Neocomian, Las Villas, central Cuba, Caribbean Arc.
- *Matagua Fm*: basaltic and andesitic lavas and tuffs, minor limestone; Aptian–Albian, Las Villas, central Cuba, Caribbean Arc.
- *Cabaiguan Fm*: basaltic to dacitic tuffs, sandstone and minor limestone; Aptian–Albian, Las Villas, central Cuba, Caribbean Arc.
- *Provincial Fm*: limestones, marl, polymictic conglomerates and minor tuff; Upper Albian–Cenomanian, Las Villas, central Cuba, Caribbean Arc.
- *Calderas Fm*: volcano-sedimentary sequences with intercalations of basaltic and andesitic lava flows; Cenomanian–Turonian, Las Villas, central Cuba, Caribbean Arc.
- *Arimao Fm*: volcano-sedimentary sequences with intercalations of basaltic and andesitic lava flows; Coniac–Santonian, Las Villas, central Cuba, Caribbean Arc.
- *La Rana Fm*: volcano-sedimentary sequences with intercalations of basaltic and andesitic lava flows; Santonian–Campanian, Las Villas, central Cuba, Caribbean Arc.
- *Bruja Fm*: dacitic and rhyolitic lavas and tuffs, volcanosedimentary sequences; Santonian–Campanian, Las Villas, central Cuba, Caribbean Arc.
- *San Pedro Fm*: sandstones, siltstones, shale, conglomerates, minor limestone; Upper Campanian–Maastrichtian, Las Villas, central Cuba, Proto-Cuban Maastrichtian Platform.
- *Cantabria Fm*: limestone; Maastrichtian, Las Villas, central Cuba, Proto-Cuban Maastrichtian Platform.
- *Santo Domingo Fm*: andesitic to rhyolitic lavas, tuffs, volcanomictic sandstones and shales, minor limestone; Cenomanian–Turonian, Oriente, Caribbean Arc.
- *Téneme Fm*: basaltic lavas and tuffs; supposed Cenomanian–Turonian, Oriente, Caribbean Arc (Proenza *et al.* 2006).

- *La Picota Fm*: sedimentary breccia containing volcanomictic blocks as well as serpentinites, sandstones, siltstone; ?Campanian–Maastrichtian, Oriente, Maastrichtian Platform.
- *Mícara Fm*: gravel, polymictic sandstones, siltstone, marl; ?Campanian–Maastrichtian, Oriente, Maastrichtian Platform.
- *Yaguaneque limestones*: Upper Maastrichtian, Oriente, Maastrichtian Platform (Cobiella *et al.* 1984).

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References

ANGSTADT, D. M., AUSTIN, J. A. & BUFFLER, R. T. 1985. Early Late Cretaceous to Holocene seismic stratigraphy and geologic history of southeastern Gulf of Mexico. *American Association of Petroleum Geologists Bulletin*, **69**, 977–995.

BATCHELOR, R. A. & BOWDEN, P. 1985. Petrogenetic interpretation of granitoid rock series using multicationic parameters. *Chemical Geology*, **48**, 43–55.

BAZHENOV, M. L., PSZCZÓłKOWSKI, A. & SHIPUNOV, S. V. 1996. Reconnaissance paleomagnetic results from western Cuba. *Tectonophysics*, **253**, 65–81.

BELMUSTAKOV, I., CABRERA, R., ITURRALDE-VINENT, M. A. & TSHUNEV, D. (eds) 1981. *Informe del levantamiento geologico a escala 1 : 250.000 del teritorio Ciego-Camaguey Las Tunas 1975–1979*. Academia de Ciencias de Cuba, MINBAS, CNFG, La Habana, unpublished internal report.

BIBIKOVA, E. V., SOMIN, M. L., GRACEVA, T. V., MAKAROV, V. A., MILLÁN, G. & CHUKOLJUKOV, J. A. 1988. Pervye rezultaty U–Pb-datirovanija metamorficeskich porod Bolschoi Antillskoi dugi: vozrast kompleksa Mabuchina Kuby. *Doklady Akademii Nauk SSSR, Seria Geologičeskaya*, **301**, 924–928.

BLANCO-QUINTERO, I., GARCÍA-CASCO, A. ET AL. 2008. *Geochemistry and age of the partially melted subducted slab. La Corea mélange (Eastern Cuba).* Abstracts and Program 18th Caribbean Geological Conference, Santo Domingo 2008, 8. World Wide Web Address: http://www.ugr.es/~agcasco/igcp546/DomRep08/Abstracts_CaribConf_DR_2008.pdf.

BLEIN, O., GUILLOT, S. ET AL. 2003. Geochemistry of the Mabujina Complex, Central Cuba: Implications on the Cuban Cretaceous Arc Rocks. *Journal of Geology*, **111**, 89–110.

BOITEAU, A., MICHARD, A. & SALIOT, P. 1972. Métamporphisme de haute pression dans le complexe ophiolitique du Purial (Oriente, Cuba). *Comptes Rendus de l'Académie des Sciences Paris*, **274** (série D), 2137–2140.

BRALOWER, T. J. & ITURRALDE-VINENT, M. A. 1997. Micropaleontological dating of the collision between the North American plate and the Greater Antillen arc in western Cuba. *Palaios*, **12**, 133–150.

BUCHER, K. & FREY, M. 2002. *Petrogenesis of Metamorphic Rocks*. Springer, Berlin.

BUSH, V. A. & SHERBAKOVA, I. N. 1986. Novye danny po glubinnoi tektonike Kuby. *Geotektonika*, **3**, 25–41.

CAZAÑAS, X., PROENZA, J. A., MATTIETTI-KYSAR, G., LEWIS, J. & MELGAREJO, J. C. 1998. Rocas volcánicas de las series Inferior y Media del Grupo El Cobre en la Sierra Maestra (Cuba Oriental): volcanismo generado en un arco de islas tholeiítico (Volcanic rocks from the lower and intermediate series of the El Cobre Group, Sierra Maestra, Eastern Cuba: a case of island arc tholeiites). *Acta Geologica Hispanica*, **33**, 57–74.

CHAUVIN, A., BAZHENOV, M. L. & BEAUDOUIN, T. 1994. A reconnaissance paleomagnetic study of Cretaceous tocks from central Cuba. *Geophysical Research Letters*, **12**, 1691–1694.

CLOOS, M. 1982. Flow melanges: Numerical modelling and geologic constraints on their origin in the Franciscan subduction complex, California, *Geological Society of America Bulletin*, **93**, 330–345.

CLOOS, M. & SHREVE, R. L. 1988*a*. Subduction-channel model of prism accretion, melange formation, sediment subduction, and subduction erosion at convergent plate margins, 1. Background and description. *Pure and Applied Geophysics*, **128**, 455–500.

CLOOS, M. & SHREVE, R. L. 1988*b*. Subduction-channel model of prism accretion, melange formation, sediment subduction, and subduction erosion at convergent plate margins, 2. Implications and discussion. *Pure and Applied Geophysics*, **128**, 501–545.

COBIELLA, J. L. 1996. El magmatismo Jurásico (Caloviano?–Oxfordiano) de Cuba occidental: Ambiente de formación e implicaciones regionales. *Revista de la Asociación Geologica de Argentina*, **51**, 15–28.

COBIELLA, J. L., QUINTAS, F., CAMPOS, M. & HERNÁNDEZ, M. M. 1984. *Geología de la región central y suroriental de la provincia de Guantanamo*. Editorial Oriente, Santiago de Cuba.

CRUZ, E. M., MARESCH, W. V., CÁCERES, D. & BALCÁZAR, N. 2007. Significado de las paragénesis de anfíboles en metagrabos relacionados con secuencias de margen continental en el NW de Cuba. *Revista Mexicana de Ciencias Geológicas*, **24**, 318–327.

DIAZ DE VILLALVILLA, L. 1997. Caracterización geológica de las formaciones volcánicas y volcanosedimentarias en Cuba Central, provincias Cienfuegos–Villa Clara–Sancti Spiritus. *In*: FURRAZOLA BERMÚDEZ, G. F. & NÚÑEZ CAMBRA, K. (eds) *Estudios sobre Geología de Cuba*. Instituto de Geología y Paleotología, La Habana, 325–344.

DILLON, W. P. & VEDDER, J. G. 1973. Structure and development of the continental margin of British Honduras. *Geological Society of America Bulletin*, **84**, 2713–2732.

DONNELLY, T. W. & ROGERS, J. J. W. 1980. Igneous Series in Island Arcs: the Northeastern Caribbean compared with worldwide island arc assemblages. *Bulletin of Volcanology*, **43**, 347–382.

DRAPER, G. 2001. The southern metamorphic terranes of Cuba as metamorphic core complexes exhumed by low angle extensional faulting, *Transactions of the 4th Congreso Cubano de Geologia y Mineria*, La Habana, Cuba, 19–23 March, 2001.

DRAPER, G. & BARROS, J. A. 1994. Cuba. *In*: DONOVAN, S. K. & JACKSON, T. A. (eds) *Caribbean Geology: an Introduction*. University of the West Indies Publishers Association and University of the West Indies Press, Kingston, Jamaica, 65–86.

DRAPER, G., GUTIERREZ, G. & LEWIS, J. F. 1996. Thrust emplacement of the Hispaniola peridotite belt: Orogenic expression of the Mid-Cretaceous Caribbean arc polarity reversal? *Geology*, **24**, 1143–1146.

DUBLAN, L. & ALVAREZ, H. (eds) 1986. *Informe final del levantamiento geologico y evaluacion de minerales utiles, en escala 1:50.000, del poligono CAME I, zona Central*, Academia de Ciencias de Cuba, MINBAS, CNFG, La Habana, unpublished internal report.

DUCLOZ, C. & VUAGNAT, M. 1962. A propose de l'age des serpentinites de Cuba. *Archives de Sciences de Physique et d'Histoire Naturelle, Geneve*, **15**, 309–332.

ELLIS, S., BEAUMONT, C. & PFIFFNER, O. A. 1999. Geodynamic models of subcrustal-scale episodic tectonic accretion and underplating in subduction zones. *Journal of Geophysical Research*, **104**, 15169–15190.

ERNST, W. G. 1988. Tectonic history of subduction zones inferred from retrograde blueschist *P–T* paths. *Geology*, **16**, 1081–1084.

ESCUDER VIRUETE, J., DÍAZ DE NEIRA, A. *ET AL*. 2006. Magmatic relationships and ages of Caribbean Island arc tholeiites, boninites and related felsic rocks, Dominican Republic. *Lithos*. **90**, 161–186.

FONSECA, E., ZELEPUGUIN, V. & HEREDIA, M. 1984. Particularidades de la estructúra de la asociación ofiolitica de Cuba. *Ciencias de Tierra y Espacio (La Habana)*, **9**, 31–46.

FONSECA, E., DIAZ DE VILLALVILLA, L., MARY, T. & CAPOTE, C. 1988. Nuevos datos acerca de la relación entre las vulcanitas de la asociación ofiolitica y la parte inferior del arco volcanico en Cuba central-oriental. *Serie Geológica (La Habana)*, **2**, 3–12.

GARCÍA-CASCO, A., TORRES-ROLDÁN, R. L., MILLÁN, G., MONIÉ, P. & HAISSEN, F. 2001. High-grade metamorphism and hydrous melting of metapelites in the Pinos terrane (W-Cuba). Evidence for crustal thickening and extension in the northern Caribbean collisional belt. *Journal of Metamorphic Geology*, **19**, 699–715.

GARCÍA-CASCO, A., TORRES-ROLDÁN, R. L., MILLÁN, G., MONIÉ, P. & SCHNEIDER, J. 2002. Oscillatory zoning of eclogitic garnet and amphibole, Northern Serpentinite melange, Cuba: a record of tectonic instability during subduction? *Journal of Metamorphic Geology*, **20**, 581–598.

GARCÍA-CASCO, A., TORRES-ROLDÁN, R. L. *ET AL*. 2006. High pressure metamorphism of ophiolites in Cuba. *Geologica Acta*, **4**, 63–88.

GARCÍA-CASCO, A., LAZARO, C., ROJAS-AGRAMONTE, Y., KRONER, A. & NEUBAUER, F. 2007. From Aptian onset to Danian demise of subduction along the northern margin of the Caribbean Plate (Sierra del Convento Melange, Eastern Cuba). *EOS Transactions AGU*, **88**, Fall Meeting Supplement, Abstract T11D-06.

GARCÍA-CASCO, A., ITURRALDE-VINENT, M. A. & 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*, **50**, 1–29.

GERYA, T. V. & STÖCKHERT, B. 2002. Exhumation rates of high pressure metamorphic rocks in subduction channels: the effect of rheology. *Geophysical Research Letters*, **29**, 1261.

GERYA, T. V. & STÖCKHERT, B. 2006. Two-dimensional numerical modeling of tectonic and metamorphic histories at active continental margins. *International Journal of Earth Sciences*, **94**, 250–274.

GERYA, T. V., STÖCKHERT, B. & PERCHUK, A. L. 2002. Exhumation of high-pressure metamorphic rocks in a subduction channel: a numerical simulation. *Tectonics*, **142**, 6-1–6-19.

GIUNTA, G., BECCALUVA, L. & SIENA, F. 2006. Caribbean Plate margins: constraints and current problems. *Geologica Acta*, **4**, 265–277.

GOFFÉ, B., BOUSQUET, R., HENRY, P. & LE PICHON, X. 2003. Effect of the chemical composition of the crust on the metamorphic evolution of orogenic wedges. *Journal of Metamorphic Geology*, **21**, 123–141.

GORDON, M. B., MANN, P., CÁCERES, D. & FLORES, R. 1997. Cenozoic tectonic history of the North America–Caribbean Plate boundary zone in western Cuba. *Journal of Geophysical Research*, **102**, 10055–10082.

GRAFE, F. 2000. *Geochronologie metamorpher Komplexe am Beispiel der kretazischen Inselbogen-Kontinent-Kollisionszone Zentralkubas*. PhD thesis, Ruhr Universität Bochum.

GRAFE, F., STANEK, K. P. *ET AL*. 2001. Rb-Sr and $^{40}Ar/^{39}Ar$ mineral ages of granitoid intrusives in the Mabujina Unit, Central Cuba: thermal exhumation history of the Escambray Massif. *Journal of Geology*, **109**, 615–631.

GREVEL, C. 2000. *Druck- und Temperaturentwicklung der metamorphen Deckeneinheiten des Escambray Massives, Kuba*. PhD thesis, Ruhr Universität Bochum.

GREVEL, C., MARESCH, W. V., STANEK, K. P., GRAFE, F. & HOERNES, S. 2006. Petrology and geodynamic significance of deerite-bearing metaquartzites from the Escambray Massif, Cuba. *Mineralogical Magazine*, **70**, 527–546.

HACZEWSKI, G. 1976. Sedimentological reconnaissance of the San Cayetano formation: an accumulative continental margin in the Jurassic of western Cuba. *Acta Geologica Polonia*, **26**, 331–353.

HALL, C. M., KESLER, S. E. *ET AL*. 2004. Age and tectonic setting of the Camagüey volcanic-intrusive arc, Cuba: evidence for rapid uplift of the western Greater Antilles. *Journal of Geology*, **112**, 521–542.

HATTEN, C. W., SOMIN, M., MILLÁN, G., RENNE, P., KISTLER, R. W. & MATTINSON, J. M. 1988. Tectonostratigraphic units of Central Cuba. *Transactions of the 11th Caribbean Geological Conference*, Barbados, 35:1–35:13.

HARLOW, G. E., HEMMING, S. R., AVÉ LALLEMANT, H. G., SISSON, V. B. & SORENSEN, S. S. 2004. Two high-pressure–low-temperature serpentinite-matrix mélange belts, Motagua fault zone, Guatemala: a

record of Aptian and Maastrichtian collisions. *Geology*, **32**, 17–20.

HEMPTON, M. R. & BARROS, J. A. 1993. Mesozoic stratigraphy of Cuba: deposition architecture of a southeast facing continental margin. *In*: PINDELL, J. L. & PERKINS, R. F. (eds) *Mesozoic and Early Cenozoic Development of the Gulf of Mexico and Caribbean Region – a Context for Hydrocarbon Exploration.* GCSSEPM Foundation Thirteenth Annual Research Conference, 193–209.

HSU, K. J. 1971. Franciscan melange as a model for eugeosynclinal sedimentation and underthrusting tectonics. *Journal of Geophysical Research*, **76**, 1162–1170.

HUTSON, F., MANN, P. & RENNE, P. 1998. $^{40}Ar/^{39}Ar$ dating of single muscovite grains in Jurassic siliciclastic rocks (San Cayetano Formation). Constraints on the paleoposition of western Cuba. *Geology*, **26**, 83–86.

ITURRALDE-VINENT, M. A. 1992. A short note on the Cuban Late Maastrichtian megaturbifite (an impact-derived deposit?). *Earth and Planetary Science Letters*, **109**, 225–228.

ITURRALDE-VINENT, M. A. 1994. Cuban geology: a new plate-tectonic synthesis. *Journal of Petroleum Geology*, **17**, 39–70.

ITURRALDE-VINENT, M. A. 1996. Estratigrafía del Arco Volcánico en Cuba. *In*: ITURRALDE-VINENT, M. A. (ed.) *Cuban Ophiolites and Volcanic Arcs*. Miami, IGCP Project 364 Special Contributions, **1**, 190–227.

ITURRALDE-VINENT, M. A. 1998. Sinopsis de la Constitución Geológica de Cuba. *In*: MELGAREJO, J. C. & PROENZA, J. A. (eds) *Geología y Metalogénia de Cuba: Una Introducción. Acta Geologica Hispanica*, **33**, 9–56.

ITURRALDE-VINENT, M. A. & THIEKE, U. (eds) 1987. *Informe final sobre los trabajos del levantamiento geológico complejo y busqueda acompañante a escala 1:50.000 en el polígono CAME III 1981–1987.* Academia de Ciencias de Cuba, MINBAS, CNFG, La Habana, unpublished internal report.

ITURRALDE-VINENT, M. A. & MORALES MARÍ, T. 1988. Toleitas del Titoniano medio en la Sierra de Camajan, Camagüey. *Revista Tecnologica, Seria Geologica, La Habana*, **18**, 25–32.

ITURRALDE-VINENT, M. A. & LIDIAK, E. G. 2006. Foreword: Caribbean tectonic, magmatic, metamorphic, and stratigraphic events. Implications for plate tectonics. *Geologica Acta*, **4**, 1–5.

ITURRALDE-VINENT, M. A., STANEK, K. P., WOLF, D., THIEKE, H. U. & MÜLLER, H. 2000. Geology of the Camagüey Region, Central Cuba – evolution of a collisional margin in the northern Caribbean. *Zeitschrift für Angewandte Geologie, Hannover*, **SH 1**, 267–273.

ITURRALDE-VINENT, M. A., DÍAZ-OTERO, C., RODRÍGUEZ-VEGA, A. & DÍAZ-MARTÍNEZ, D. 2006. Tectonic implications of paleontologic dating of Cretaceous–Danian sections of Eastern Cuba. *Geologica Acta*, **4**, 89–102.

JÄGER, W. 1972. Zur Lithlogie, Tektonik und Vererzung im Gebiet vom Matahambre (Provinz Pinar del Rio, Kuba). *Jahrbuch Geologie (Berlin)*, **4** (1968), 347–385.

JAMES, K. H. 2002. A simple synthesis and evolution of the Caribbean region. *In*: *Abstracts, 16th Caribbean Geological Conference,* Barbados, 16–21, June 2002. World Wide Web Address: http://www.ig.utexas.edu/CaribPlate/forum/james/james_carib_model.pdf.

JAMES, K. H. 2006. Arguments for and against the Pacific origin of the Caribbean Plate: discussion, finding for an inter-American origin. *Geologica Acta*, **4**, 279–302.

KANČEV, I. (ed.). 1978. *Informe geológico de la provincia Las Villas – Resultados de las investigaciones geologicas a escala 1:250.000 durante el periodo 1969–1975.* Academia de Ciencias de Cuba, MINBAS, CNFG, La Habana, unpublished internal report.

KERR, A. C., ITURRALDE-VINENT, M. A., SAUNDERS, A. D., BABBS, T. L. & TARNEY, J. 1999. A new plate tectonic model of the Caribbean: implications from a geochemical reconnaissance of Cuban Mesozoic volcanic rocks. *Geological Society of America Bulletin*, **111**, 1581–1599.

KERR, A. C., WHITE, R. V., THOMPSON, P. M. E., TARNEY, J. & SAUNDERS, A. D. 2003. No oceanic plateau – no Caribbean Plate? The seminal role of an oceanic plateau in Caribbean Plate evolution. *In*: BARTOLINI, C., BUFFLER, R. T. & BLICKWEDE, J. (eds) *The Circum-Gulf of Mexico and the Caribbean: Hydrocarbon Habitats, Basin Formation, and Plate Tectonics.* American Association of Petroleum Geologists, Memoirs, **79**, 126–168.

KESLER, S. E., CAMPELL, I. H. & ALLEN, C. M. 2005. Age of the Los Ranchos Formation, Dominican Republic: timing and tectonic setting of primitive island arc volcanism in the Caribbean region. *Geological Society of America Bulletin*, **117**, 987–995.

KNIPPER, A. L. 1975. *Okeaničeskaja kora v strukturje al'piskoy skladčatoy oblasti. (Jug. Evropy, Zapadnaja čast Azii i Kuba).* Izdatelstvo Nauka, Moskva, 5–205.

KNIPPER, A. L. & CABRERA, R. 1974. *Tectonica y geologia historica de la zona de articulacion entre el mio- y eugeosinclinal y del cinturon hiperbasico de Cuba.* Academia de Ciencias de Cuba Special Publications, **2**, 15–77.

KOSAK, M., ANDO, J., JAKUS, P. & MARTINEZ, Y. R. 1988. Desarollo estructural del arco insular volcanico-Cretacico en la region de Holguin. *Revista Mineria y Geologia, Moa*, **5**, 33–55.

KREBS, M., STANEK, K. P., SCHERER, E., MARESCH, W. V., GRAFE, F., IDLEMAN, B. & RODIONOV, N. 2007. Age of High pressure metamorphism from the Escambray Massif, Cuba. *In*: *Goldschmidt Conference, Cologne, Germany*. Cambridge Publications, Abstract A522.

KREBS, M., MARESCH, W. V. *ET AL*. 2008. The dynamics of intra-oceanic subduction zones: A direct comparison between fossil petrological evidence (Rio San Juan Complex, Dominican Republic) and numerical simulation, *Lithos*, **103**, 106–137.

KUDĚLÁSEK, V., KUDĚLÁSKOVÁ, M., ZAMARSKÝ, V. & OREL, P. 1984. On the problem of Cuban ophiolites. *Krystalinikum, Prague*, **17**, 159–173.

KYSAR, G., MORTENSEN, J. K. & LEWIS, J. F. 1998. U–Pb zircon age constraints for Paleogene igneous rocks of the Sierra Maestra, Southeastern Cuba; implications for short-lived arc magmatism along the northern Caribbean margin. *Geological Society of America, Abstracts with Programs*, **30**, A185.

LÁZARO, C. & GARCÍA-CASCO, A. 2008. Geochemical and Sr–Nd isotope signatures of pristine slab melts and their residues (Sierra del Convento mélange, eastern Cuba). *Chemical Geology*, **255**, 120–133.

LEBRÓN, M. C. & PERFIT, M. R. 1993. Stratigraphic and petrochemical data support subduction polarity reversal of the Cretaceous Caribbean island arc. *Journal of Geology*, **101**, 389–396.

LEROY, S., MAUFRET, A., PATRIAT, P. & MERCIER DE LÉPINAY, B. 2000. An alternative interpretation of the Cayman trough evolution from a reidentification of the magnetic anomalies. *Geophysical Journal International*, **141**, 539–557.

LEWIS, J. F. & DRAPER, G. 1990. Geological and tectonic evolution of the northern Caribbean margin. *In*: DENGO, G. & CASE, J. E. (eds) *The Caribbean Region*. The Geology of North America, **H**. Geological Society of America, Boulder, CO, 77–140.

LEWIS, J. F., PERFIT, M. R. *ET AL.* 2005. Anomalous granitoid compositions from the northwestern Cayman Trench: Implications for the composition and evolution of the Cayman Ridge. *17th Caribbean Geological Conference*, Puerto Rico, Abstracts, 49–50.

LINARES, E. & SMAGOULOV, R. 1987. Resultados de análisis de minerales pesados de rocas de algunas formaciones lithostratigraficas del miogeosinclinal Cubano. *Revista Tecnologica, Seria Geologica, La Habana*, **4**, 75–99.

LLANES-CASTRO, A., GARCÍA-DELGADO, D. & MEYERHOFF, D. 1998. *Hallazgo de fauna jurásica (Tithoniano) en ofiolitas de Cuba central*. Memorias II Geología y Minería, **98**, Havana, Centro Nacional de Informacion Geológica, 241–244.

MAKAROV, V. I. 1986. Noveishaja tektonika vostocnoi Kuby, stat'ja pervaja. *Geotektonika*, **6**, 85–96.

MARI MORALES, T. 1997. Particularidades de los granitoides de Ciego-Camagüey-Las Tunas y consideraciones sobre su posición dentro del arco de isla. *In*: FURRAZOLA BERMÚDEZ, G. F. & NÚÑEZ-CAMBRA, K. (eds) *Estudios sobre la geología de Cuba*, Centro Nacional de Información Geológica, La Habana, 399–416.

MARTENS, U., LIOU, J., SOLARI, L., MATTINSON, C. & WOODEN, J. 2007. SHRIMP RG U/Pb age of Chuacús complex zircon: evidence for Cretaceous HP metamorphism in the Maya block. In: MARTENS, U. & GARCÍA-CASCO, A. (eds) *High-Pressure Belts of Central Guatemala: The Motagua Suture and the Chuacús Complex*. IGCP 546 Special Contributions, 1, 7–13.

MESCHEDE, M. & FRISCH, W. 1998. A plate-tectonic model for the Mesozoic and Cenozoic history of the Caribbean Plate. *Tectonophysics*, **296**, 269–291.

MEYERHOFF, A. A. & HATTEN, C. W. 1974. Bahamas salient of North America: tectonic framework, stratigraphy and petroleum potential. *American Association of Petroleum Geologists Bulletin*, **58**, 1201–1239.

MILLÁN, G. 1972. *El metamorfismo y mesodeformaciones de la unidad tectonica mas suroriental de la Sierra de los Organos*. Boletin Actas, Instituto de Geologia, La Habana, **N2**.

MILLÁN, G. 1975. El complejo cristalino Mesozoico de Isla de Pinos. Su metamorfismo. *Serie Geológica, La Habana*, **23**, 3–16.

MILLÁN, G. & MYCZYNSKI, R. 1978. *Fauna Jurasica y consideraciones sobre la edad de las secuencias metamorficas del Escambray*. Informe Cientifico y Tecnico, Academia de Ciencias de Cuba, **80**, 1–14.

MILLÁN, G. & SOMIN, M. L. 1985. *Contribucion al conocimiento geologico de las metamorfitas del Escambray y del Purial*. Academia de Ciencias de Cuba, La Habana, **1985**, 74.

MORENO TOIRAN, B. 2003. The crustal structure of Cuba derived from receiver functions analysis. *Journal of Seismology*, **7**, 359–375.

MULLINS, H. T. & LYNTS, G. W. 1976. Stratigraphy and structure of northeast Providence Channel, Bahamas. *American Association of Petroleum Geologists Bulletin*, **60**, 1037–1053.

NAGLE, F. 1974. Blueschist, eclogite, paired metamorphic belts and the early tectonics of Hispaniola. *Geological Society of America Bulletin*, **85**, 1461–1466.

OTERO, R., PROL, J. L., TENREYRO, R. & ARRIAZA, G. L. 1998. Características de la corteza terrestre de Cuba y su plataforma marina. *Minería y Geología, La Habana*, **15**, 31–35.

PARDO, G. 1975. Geology of Cuba. *In*: NAIRN, A. E. M. & STEHLI, F. G. (eds) *The Ocean Basins and Margins*, **3**. Plenum Press, New York, 553–615.

PERERA-FALCÓN, C. M., BLANCO-BUSTAMANTE, S., SEGURA-SOTO, R., DÍAZ DE VILLALVILLA, L. & PÉREZ-ESTRADA, L. 1998. Estratigrafía del arco Cretácico de Cuenca Central, Cuba. *In*: *Geología y Minería '98*. Centro Nacional de Información Geologica del IGP, **2**, 245–248.

PÉREZ LAZO, J., FUNDORA GRANDA, M., GARCÍA, A., KROPÁČEK, V. & HORÁČEK, J. 1994. Paleomagnetic investigations in Cuba from Late Jurassic to Middle Eocene times and tectonic implications. *Acta Universitatis Carolinae, Geologica, Prague*, **38**, 3–19.

PEREZ-OTHON, J. & YARMOLIUK, V. A. 1985. *Mapa Geologica de Cuba*. MINBAS: CIG, La Habana.

PINDELL, J. L. 1985. Alleghenian reconstruction and subsequent evolution of the Gulf of Mexico, Bahamas, and the Proto-Caribbean. *Tectonics*, **4**, 1–39.

PINDELL, J. L. 1990. Geological arguments suggesting a Pacific origin for the Caribbean Plate. *In*: LARUE, D. K. & DRAPER, G. (eds) *Transactions of the 12th Caribbean Geological Conference*, St Croix. Miami Geological Society, 1–4.

PINDELL, J. L. 1993. Regional synopsis of Gulf of Mexico and Caribbean evolution, *In*: PINDELL, J. L. & PERKINS, R. (eds) *Mesozoic and Early Cenozoic Development of the Gulf of Mexico and Caribbean Region. GCSSEPM 13th Annual Research Conference Proceedings*, 251–274.

PINDELL, J. L. 2008. Early Cretaceous Caribbean tectonics: models for genesis of the Great Caribbean Arc, *Abstract Volume of the 18th Caribbean Geological Conference*, 24–28 March 2008, Santo Domingo, Dominican Republic. World Wide Web Address: http://www.ugr.es/~agcasco/igcp546/DomRep08/Abstracts_CaribConf_DR_2008.pdf.

PINDELL, J. L. & DEWEY, J. F. 1982. Permo-Triassic reconstruction of Western Pangea and the evolution of the Gulf of Mexico/Caribbean region, *Tectonics*, **1**, 179–212.

PINDELL, J. L. & BARRETT, S. F. 1990. Geologic evolution of the Caribbean region: a plate-tectonic perspective. *In*: DENGO, G. & CASE, J. E. (eds) *The Caribbean Region*. The Geology of North America, **H**. Geological Society of America, Boulder, CO, 405–432.

PINDELL, J. L. & DRAPER, G. 1991. Stratigraphy and geological history of the Puerto Plata area, northern Dominican Republic. *In*: MANN, P., DRAPER, G. & LEWIS, J. F. (eds) *Geologic and Tectonic Development if the North American–Caribbean Plate Boundary in Hispaniola*. Geological Society of America, Special Paper, **262**, 97–114.

PINDELL, J. L. & KENNAN, L. 2001. Kinematic evolution of the Gulf of Mexico and the Caribbean. *GCSSEPM Foundation 21st Annual Research Conference, Petroleum Systems of Deep-water Basins*, 193–220.

PINDELL, J. L. & KENNAN, L. 2009. Tectonic evolution of the Gulf of Mexico, Caribbean and northern South America in the mantle reference frame: an update. *In*: JAMES, K. H., LORENTE, M. A. & PINDELL, J. L. (eds) *The Origin and Evolution of the Caribbean Plate*. Geological Society, London, Special Publications, **328**, 1–55.

PINDELL, J. L., CANDE, S. *ET AL*. 1988. A plate-kinematic framework for models of Caribbean evolution, *Tectonophysics*, **155**, 121–138.

PINDELL, J., KENNAN, L., MARESCH, W. V., STANEK, K. P., DRAPER, G. & HIGGS, R. 2005. Plate-kinematics and crustal dynamics of the circum-Caribbean arc-continent interactions: tectonic controls on the basin development in the Proto-Caribbean margins. *In*: AVÉ LALLEMANT, H. G. & SISSON, V. B. (eds) *Caribbean–South American plate interactions, Venezuela.* Geological Society of America, Boulder, CO, Special Papers, **394**, 7–52.

PINDELL, J. L., KENNAN, L., STANEK, K. P., MARESCH, W. V. & DRAPER, G. 2006. Foundations of Gulf of Mexico and Caribbean evolution: eight controversies resolved. *Geologica Acta*, **4**, 303–341.

PIOTROWSKA, K. 1987. Nappe structure in the Sierra de los Organos, western Cuba. *Acta Geologica Polonia*, **28**, 97–170.

PROENZA, J., GERVILLA, F., MELGAREJO, J. C. & BODINIER, J. L. 1999. Al- and Cr-rich chromitites from the Mayarí-Baracoa ophiolitic belt (eastern Cuba) consequence of interaction between volatile-rich melts and peridotites in suprasubduction mantle. *Economic Geology*, **94**, 547–566.

PROENZA, J., DÍAZ-MARTÍNEZ, R. *ET AL*. 2006. Primitive Cretaceous island-arc volcanic rocks in eastern Cuba: the Téneme Formation. *Geologica Acta*, **4**, 103–121.

PSZCZÓłKOWSKI, A. 1985. Sobre la edad del metamorfismo y la estructura tectónica de la faja Cangre, Provincia de Pinar del Rio, Cuba. *Ciencias de la Tierra y del Espacio*, **10**, 31–36.

PSZCZÓłKOWSKI, A. 1986*a*. Secuencia estratigrafica de Placetas en el área limitrofe de las provincias de Matanzas y Villa Clara (Cuba). *Bulletin of Polish Academy of Sciences, Earth Science*, **34**, 67–79.

PSZCZÓłKOWSKI, A. 1986*b*. Megacapas del Maestrichtiano en Cuba occidental y central. *Bulletin of Polish Academy of Sciences, Earth Science*, **34**, 81–94.

PSZCZÓłKOWSKI, A. 1987. Paleogeographic and paleotectonic evolution of Cuba and adjoining areas during the Jurassic–Early Cretaceous. *Annales Societatis Geologorum Poloniae*, **57**, 127–142.

PSZCZÓłKOWSKI, A. 1994. Geological cross-sections through the Sierra del Rosario thrust belt, western Cuba. *Studia Geologica Polonia*, **105**, 67–90.

PSZCZÓłKOWSKI, A. 1999. The exposed passive margin of North America in western Cuba. *In*: MANN, P. (ed.) *Caribbean Basins*. Sedimentary Basins of the World, **4**. Elsevier Science, Amsterdam, 93–121.

PSZCZÓłKOWSKI, A. 2002. Crustacean burrows from the Upper Maastrichtian deposits of south-central Cuba. *Bulletin of Polish Academy of Sciences, Earth Science*, **50**, 147–163.

PSZCZÓłKOWSKI, A. & ALBEAR, J. F. 1982. Subzona estructuro-facial de Bahia Honda, Pinar del Rio, su tectonica y datos sobre la sedimentación y paleogeografia del Cretacico Superior y del Paleógeno. *Ciencias de la Tierra y del Espacio*, **5**, 3–25.

PUSHAROVSKI, J. M., MOSSAKOVSKI, A. A., NEKRASOV, G. E., ORO, J., FLORES, R. & FORMEL-CORTINA, F. 1989. *Tektonitscheskaja karta Kuby, 1:500 000*. Izdat. Nauka, Moskva.

RATSCHBACHER, L., FRANZ, L. *ET AL*. 2009. The North American–Caribbean Plate boundary in Mexico–Guatemala–Honduras. *In*: JAMES, K. H., LORENTE, M. A. & PINDELL, J. L. (eds) *The Origin and Evolution of the Caribbean Plate.* Geological Society, London, Special Publications, **328**, 219–293.

RENNE, P. R., MATTINSON, J. M. *ET AL*. 1989. $^{40}Ar/^{39}Ar$ and U–Pb evidence for the Late Proterozoic (Grenville-age) continental crust in north-central Cuba and regional tectonic implications. *Precambrian Research*, **42**, 325–341.

RENNE, P. R., SCOTT, G. R., DOPPELHAMMER, S. K., HARGRAVES, R. B. & LINARES, E. 1991. Discordant Mid-Cretaceous paleomagnetic pole from the Zaza Terrane of central Cuba. *Geophysical Research Letters*, **18**, 455–458.

ROJAS-AGRAMONTE, Y., NEUBAUER, F. *ET AL*. 2004. Geochemistry and age of late orogenic island arc granitoids in the Sierra Maestra, Cuba: evidence for subduction magmatism in the Early Paleogene. *Chemical Geology*, **213**, 307–324.

ROJAS-AGRAMONTE, Y., NEUBAUER, F., BOJAR, A. V., HEJL, E., HANDLER, R. & GARCÍA-DELGADO, D. E. 2006*a*. Geology, age and tectonic evolution of the Sierra Maestra Mountains, southeastern Cuba. *Geologica Acta*, **4**, 123–150.

ROJAS-AGRAMONTE, Y., KRÖNER, A., GARCÍA-CASCO, A., ITURRALDE-VINENT, M. A., WINGATE, M. T. D. & LIU, D. Y. 2006*b*. Geodynamic implications of zircon ages from Cuba. *Geophysical Research Abstracts*, **8**, 04943; SRef-ID: 1607- 7962/gra/EGU06-A-04943.

ROJAS-AGRAMONTE, Y., KRÖNER, A. *ET AL*. 2008. Detrital zircon geochronology of Jurassic sandstones of western Cuba (San Cayetano Formation): implications for the Jurassic paleogeography of the NW Proto-Caribbean. *American Journal of Science*, **308**, 639–656.

ROSENCRANTZ, E. 1990. Structure and tectonics of the Yucatán Basin, Caribbean Sea, as determined

from seismic reflection studies. *Tectonics*, **9**, 1037–1059.

ROSENCRANTZ, E., ROSS, M. I. & SCLATER, J. G. 1988. Age and spreading history of the Cayman Trough as determined from depth, heat flow, magnetic anomalies. *Journal of Geophysical Research*, **93**, 2141–2157.

SAURA, E., VERGÉS, J. *ET AL*. 2008. Structural and tectonic evolution of western Cuba fold and thrust belt. *Tectonics*, **27**, TC4002.

SCHLAGER, W. & BUFFLER, R. T. 1984. Deep Sea Drilling Project, Leg 77, southeastern Gulf of Mexico. *Geological Society of America Bulletin*, **95**, 226–236.

SCHNEIDER, J., BOSCH, D. *ET AL*. 2004. Origin and evolution of the Escambray Massif (Central Cuba) an example of HP/LT rocks exhumed during intraoceanic subduction. *Journal of Metamorphic Geology*, **22**, 3, 227–247.

SCHWARTZ, S., LARDEAUX, J. M., TRIEART, P., GUILLOEAND, E. & LABRIN, S. 2007. Diachronous exhumation of HP-LT metamorphic rocks from southwestern Alps: evidence from fission-track analysis. *Terra Nova*, **19**, 133–140.

SEGURA-SOTO, R., MILIAN, E. & FERNANDEZ, J. 1985. Complejos litológicas del extremo noroccidental de Cuba y sus implcaciones estratigráficas de acuerdo con los datos de las perforaciones profundas. *Revista Tecnologica, Seria Geologica, La Habana*, **15**, 32–36.

SHREVE, R. L. & CLOOS, M. 1986. Dynamics of sediment subduction, melange formation, and prism accretion. *Journal of Geophysical Research*, **91**, 10229–10245.

SIGURDSSON, H., LECKIE, M., ACTON, G. & And ODP Leg 165 Scientific Party. 1997. *Proceedings of the Oceanic Drilling Program. Initial Report of Ocean Drilling Project Leg 165*. Ocean Drilling Program, College Station TX.

SOMIN, M. L. & MILLÁN, G. 1981. *Geologija metamorficheskich kompleksov Kuby*. Isdat. Nauka, Moscow, **1981**, 219 p.

SOMIN, M. L., ARAKELJANZ, M. M. & KOLESNIKOV, E. M. 1992. Vozrast i tektoniceskoje znacenije vysokobariceskich metamorficeskich porod Kuby. *Izvestija Akademii Nauk, Rossiiskaja Akademia Nauk, Serija Geologicheskaya*, **N 3**, 91–104.

SOMIN, M. L., MATTINSON, J. M. *ET AL*. 2005. The Arroyo Charcon, an unusual eclogite from the Escambray Massif, Cuba: petrology and zirconology. *Mitteilungen der Österreichischen Mineralogischen Gesellschaft*, **150**. World Wide Web Address: www.uni-graz.at/IEC-7/PDF-files/Somin.pdf.

SOMIN, M. L., LEPECHINA, E. N. & TOLMACHEVA, E. V. 2006. El Guayabo gneiss sialic basement boulder in Western Cuba. *Geophysical Research Abstracts*, **8**, 03377; Sref-ID: 1607-7962/gra/EGU06-A-03377.

SPEAR, F. S. 1993. *Metamorphic Phase Equilibria and Pressure–Temperature–Time Path.* Mineralogical Society of America Monograph Series, **1**.

STANEK, K. P. & CABRERA, R. 1992. Tectono-magmatic development of Central Cuba. *Zentralblatt für Geologie und Paläontologie*, **6,** 1571–1580.

STANEK, K. P. & VOIGT, S. 1994. Model of Meso-Cenozoic evolution of the NW-Caribbean. *Zentralblatt für Geologie und Paläontologie*, **6**, 1571–1580.

STANEK, K. P., COBIELLA-REGUERA, J. L., MARESCH, W. V., MILLÁN TRUJILLO, G., GRAFE, F. & GREVEL, C. 2000. Geologic development of Cuba. *Zeitschrift für Angewandte Geologie, Hannover*, **SH 1**, 259–265.

STANEK, K. P., RIßE, A., RENNO, A., ROMER, R. & GRAFE, F. 2005. The history of the Great Antillean Island Arc: example from Central Cuba. *Abstract, Colloquium on Latin American Geosciences*, Potsdam, Terra Nostra, **2005/1**, 117.

STANEK, K. P., MARESCH, W. V., GRAFE, F., GREVEL, C. & BAUMANN, A. 2006. Structure, tectonics and metamorphic development of the Sancti Spiritus Dome (eastern Escambray Massif, Central Cuba). *Geologica Acta*, **4**, 151–170.

SZAKMÁNY, G., TÖRÖK, K. & GÁL-SÓLYMOS, K. 1999. Nagynyomású metamorfit blokkok a keletkubai Holguíntól északra húzódó ofiolitos melanzs zónából (High pressure metamorphic blocks from the ophiolitic melange zone, north of Holguín, Eastern Cuba). *Földtani Kötzlöny (Budapest)*, **129**, 541–571.

TADA, R., NAKANO, Y. *ET AL*. 2002. *Complex Tsunami Waves Suggested by the Cretaceous–Tertiary Boundary Deposit at the Moncada Section, Western Cuba*. Geological Society of America, Boulder, CO, Special Papers, **356**, 109–123.

TAKAYAMA, H., TADA, R. *ET AL*. 2000. Origin of the Penalver Formation in northwestern Cuba and its relation to the K/T boundary impact event. *Sedimentary Geology*, **135**, 295–320.

UCHUPI, E., MILLIMAN, J. D., LUYENDYK, B. P., BOWIN, C. O. & EMERY, K. O. 1971. Structure and origin of the southern Bahamas. *American Association of Petroleum Geologists Bulletin*, **55**, 687–704.