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Structure of the accretionary prism, and the evolution of the Paleogene northern Caribbean subduction zone in the region of Camagüey, Cuba

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A B S T R A C T

The deformation history of sedimentary units incorporated in the North Cuban fold and thrust belt in the Paleocene to middle–late Eocene was associated with major shortening between the Caribbean and North American plates. This led to the formation of an intensely deformed tectonic pile comprising from top to bottom of a volcanic arc nappe, a deformed mafic–ultramafic complex with Mesozoic ophiolite components and a serpentinitic mélange with blocks of sedimentary (the Placetas belt) and metamorphic rocks; and the structurally lower unit composed of folded and thrusted sediments of the southern promontory of the Bahamas platform. In this paper we study the deformation history of sedimentary units incorporated in the North Cuban fold and thrust belt associated with this shortening history. We find that the occurrences of the Placetas sedimentary rocks within the foliated serpentinite mélange show varying styles and intensity of deformation, and varying number of deformation phases. They form isolated blocks within the serpentinite mélange and do not represent a coherent nappe underlying the allochtonous mafic–ultramafic complex. The deformation of the Remedios belt, part of the Bahamas platform, underwent a single phase of folding and thrusting, with shortening perpendicular to the plate contact. This folding occurred in the middle to late Eocene and marks the arrest of subduction and arc–continent collision. We find no evidence for a component of strike-slip during collision. The volcanic arc is thrusted upon the mafic–ultramafic complex, and the original forearc ophiolite appears to be shortened. This shortening may attest to a period of subduction erosion. Thrusting of the volcanic arc led to deposition of the Paleocene-lower Eocene Taguasco olistostrome which may date this event. We show that careful analysis of the complexly deformed Cuban fold and thrust belt may allow identification of subduction erosion and subduction accretion episodes. Expanding the analysis carried out in this paper to the scale of the northern Caribbean fold and thrust belt may provide a new and independent geological tool to constrain the geodynamic processes associated with subduction and arc–continent collision along the northern Caribbean margin.

1. Introduction

The Caribbean region between the North and South American plates is today surrounded by active and ancient convergent margins. GPS measurements indicate that the Caribbean plate is presently moving east-northeastwards with respect to North America (Mann et al., 2002), accommodated by a (south)westward dipping subduction zone along its (north)eastern margin in the Lesser Antilles Arc; in the west, the Nazca and Cocos plates subduct east and northeastwards below Central America; and along the southern and northern margins of the plate strike-slip fault systems occur (Fig. 1; Malfait and Dinkelmann, 1972; Mann and Burke, 1984).

The geology of the northern margin of the Caribbean plate, especially Cuba and Hispaniola, mainly consists of volcanic arc rocks, an intensely deformed mafic–ultramafic complex that includes elements of the overriding and underriding plate, high-pressure (HP) metamorphic rocks from the subduction channel,

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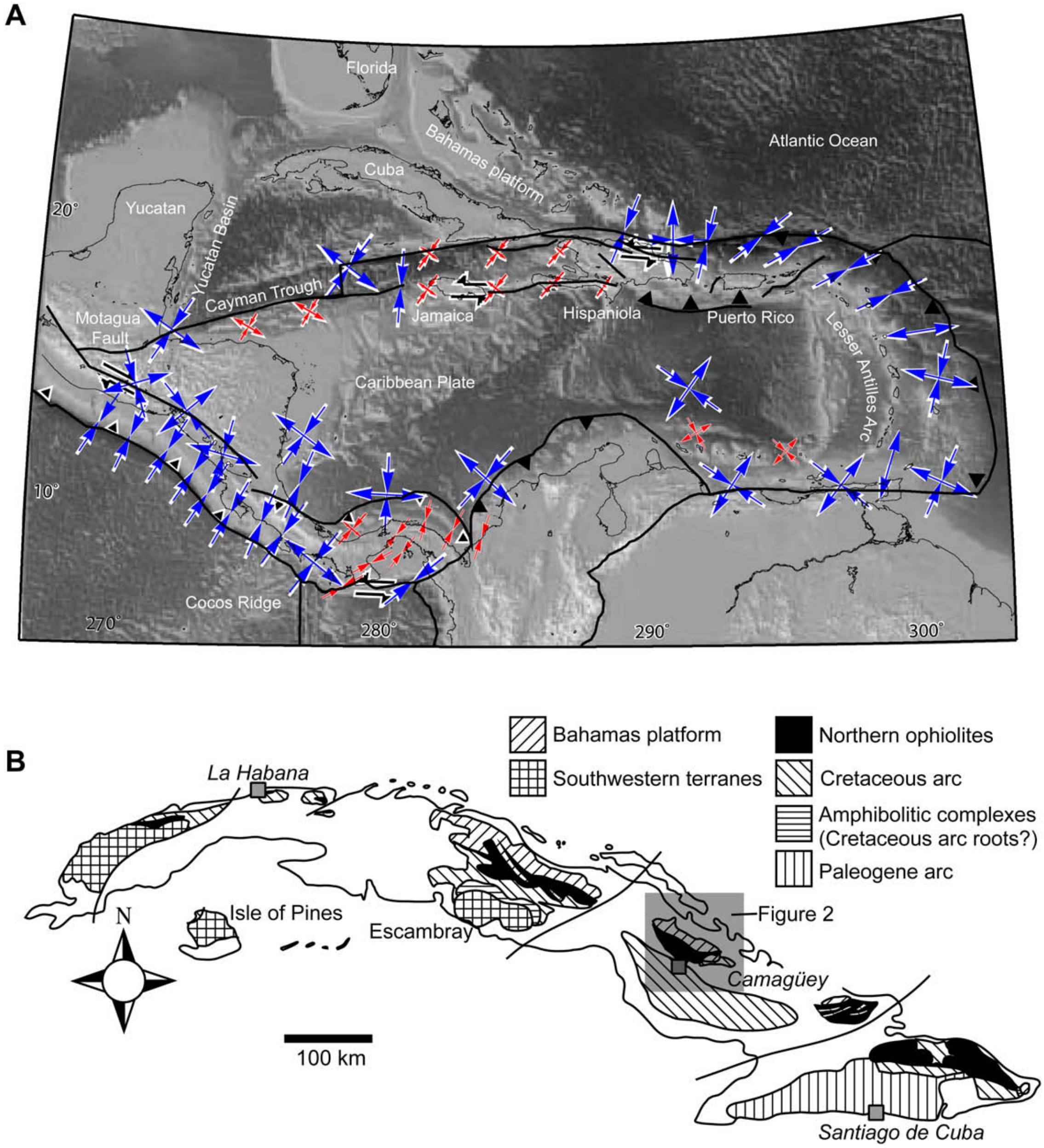

Fig. 1. (a) Tectonic setting of the Caribbean plate. Major tectonic elements and faults: AF, Anageda Fault; AR, Aves Ridge; BP, Bahamas Platform; BR, Barracuda Ridge; CB, Colombia Basin; CR, Cocos Ridge; CT, Cayman Trough; EPGF, Enriquillo Plantain Garden Fault zone; GB, Grenada Basin; HF, Hispaniola Fault zone; MB, Maracaibo Basin; MT, Muertos Trough; MR, Main Ridge; MS, Maracaibo Subduction zone; PTB, Panama Thrust Belt; SSF, San Salvador Fault zone; AF, Anageda Fault; SF, Septentrional Fault zone; HF, Hispaniola Fault zone; PGF, Plantain Garden Fault zone; SF, San Salvador Fault zone; PTB, Panama Thrust Belt; CT, Cayman Trough; GB, Grenada Basin, CR, Cocos Ridge; BR, Barracuda Ridge; MR, Main Ridge; TR, Tiburon Ridge; MB, Maracaibo Basin; MS, Maracaibo Subduction zone; BP, Bahamas Platform; VB, Venezuela Basin; CB, Colombia Basin. Interpreted principal stress directions from the World Stress Map Project (Heidbach et al., 2008) are shown in green/blue. Principal strain rate directions from the Global Strain rate model (Kreemer et al., 2003) are shown in red. The inset panel in the lower right shows vertical axis rotation from Kreemer et al. (2003). (b) Schematic geological map of Cuba, modified after Iturralde-Vinent (1994, 1998b).

and finally sedimentary units from the underriding plate (Pindell et al., 2005; García-Casco et al., 2008b; Krebs et al., 2008). Study of this geological record has revealed structural, petrological and stratigraphic evidence for older subduction, active during the Cretaceous and Paleogene (Pindell and Dewey, 1982; Pindell et al., 1988, 2005, 2006; Iturralde-Vinent, 1998b; Iturralde-Vinent and Lidiak, 2006), and is usually interpreted as southwestward subduction of Jurassic to upper Cretaceous oceanic (and possibly thinned continental) crust of the Proto-Caribbean basin that was attached to the North American plate (Pindell et al., 1988, 2006; García-Casco et al., 2008a), concurrent with the break-up and disruption of Pangaea (Müller et al., 1999).

Recent petrological and geochronological evidence from high-pressure metamorphic rocks embedded in the serpentinite mélanges on Cuba and the Dominican Republic, indicated that intraoceanic subduction may have started already around 120 Ma ago (Krebs et al., 2008; Lázaro et al., 2009). The youngest cooling ages reported from these high-pressure blocks in serpentinite mélanges cluster around ~70–60 Ma in Guatemala (Harlow et al., 2004; Brueckner et al., 2009), on Cuba (García-Casco et al., 2008b; Lázaro et al., 2009) and further east in the Dominican Republic (Krebs et al., 2008). The exhumation event of 70 Ma follows the subduction of a continental terrane, relics of which are found all along the northern Caribbean margin (the 'Caribeana' terrane of Iturralde-Vinent and García-Casco.

(2007) and García-Casco et al. (2008a)). Subduction and metamorphism of Caribeana more or less coincided with a sudden arrest of magmatic activity in the Cretaceous volcanic arc (Iturralde-Vinent, 1994; 1998b; Hall et al., 2004; Kesler et al., 2004). Palinspastic reconstructions, place Caribeana offshore the Yucatán peninsula, 1000 km away from present-day Cuba (Iturralde-Vinent and García-Casco, 2007; García-Casco et al., 2008a), in line with recent paleomagnetic data (Tait et al., 2009). Stratigraphic evidence from Cuba shows that the arrest of the northern Caribbean subduction zone, marked by the collision of the Caribbean volcanic arc and the mafic–ultramafic complex with the Bahamas platform, occurred much later, in the middle–late Eocene ($\sim$45 Ma; Meyerhoff and Hatten, 1968; Knipper and Cabrera, 1974; Pardo, 1975), which constrains the consumption of this $\sim$1000 km to the period of 70–45 Ma (Iturralde-Vinent et al., 2008).

The driving geodynamic mechanism behind the $\sim$1000 km of latest Cretaceous to Eocene shortening in the northern Caribbean is controversial, and arguments for subduction of a shallow-dipping slab (to explain the arrest of arc volcanism and the lack of subduction-related metamorphic rocks of this age) as well as a steeply dipping slab (leading to NE-ward roll-back) occur in literature (Pindell et al., 1988, 2005, 2006; Iturralde-Vinent, 1994; Iturralde-Vinent and Lidiak, 2006; Mann et al., 2006; Iturralde-Vinent and García-Casco, 2007).

Several studies have proposed relationships between the angle of the subducting slab and subduction accretion or subduction erosion at the plate boundary (Abers, 2005; Lallemand et al., 2005; De Franco et al., 2007; 2008; Manea and Gurnis, 2007; Guillaume et al., 2009) based on geophysical observations and modelling. Deduction of the accretion and/or subduction erosion history from the northern Caribbean fold and thrust belt may therefore provide an independent source of information to infer the geodynamics of Paleogene subduction in the Caribbean.

In this paper, we study the non-metamorphosed tectonostratigraphic units of the northern Camagüey province, central Cuba. This region exposes volcanic arc rocks, a deformed mafic–ultramafic complex and intensely deformed sedimentary rocks that became part of the fold and thrust belt between the late Cretaceous and the middle–late Eocene (Iturralde-Vinent et al., 1981, 2008; Iturralde-Vinent, 1996, 1998b; Pszczolkowski and Myczynski, 2003; Fig. 2). We combine our information on the style, setting and orientation of deformation with stratigraphic information to infer the tectonic events at the plate contact during the Paleogene northeastward migration of the subduction zone, and the subsequent Eocene arc–continent collision.

2. Geology of Camagüey region

The subduction of the Proto-Caribbean crust and the collision between the Caribbean and North American plates along the northern Caribbean margin led to an amalgamation of thrust-bounded units, which on Cuba can be subdivided from top to bottom into (1) a Cretaceous volcanic arc unit with lower Cenozoic piggy-back basins overriding, (2) a deformed mafic–ultramafic complex that contains (a) elements (gabbroids, diabases, peridotites, basalts and sedimentary rocks), derived from an ophiolite that probably formed the basement of the forearc of the overriding plate, (b) a serpentinite mélange including high-pressure, low-temperature (HP-LT) meta-sedimentary and meta-volcanic blocks, the protoliths of which may have belonged to the overriding and underriding plate, and (c) non-metamorphic sedimentary slivers belonging to the underriding proto-Caribbean crust. The mafic–ultramafic complex overlies (3) folded and thrusted sedimentary rocks derived from the underriding proto-Caribbean crust and the southern margin of the Bahamas Platform on the North American plate (Fig. 2). In west-central Cuba (Santa Clara region), these lower-plate derived tectono-sedimentary units comprise from south to north the Placetas, Camajuaní, Remedios and Cayo Coco belts (Meyerhoff and Hatten, 1968; Iturralde-Vinent, 1998b; Iturralde-Vinent et al., 2008).

The tectonostratigraphy of the Camagüey region in central Cuba, described below mainly based on Iturralde-Vinent et al. (1981, 2008), Iturralde-Vinent and Thieke (1986) and, Iturralde-Vinent (1994, 1998a), exposes some of the Mesozoic and Cenozoic sedimentary, igneous and metamorphic rocks of representatives of the units listed above (Fig. 2). The ?Valanginian to mid-Campanian volcanic arc is the highest tectonostratigraphic unit and comprises most of the central and south Camagüey region (Pushcharovski, 1988; Iturralde-Vinent, 1994, 1998b; Hall et al., 2004; Kesler et al., 2004). This mildly deformed nappe belonged originally to the Caribbean Plate. It is found both as thin skinned thrust sheets or klippen on top of the mafic–ultramafic complex, or as a thick north-northeast verging crustal nappe that dips southwestward. The volcanic arc suite is unconformably covered by ?uppermost Campanian–Maastrichtian and upper Paleocene–Eocene sedimentary rocks in tectonic depressions which may be characterized as remnants of piggy-back basins (Fig. 2). Locally, between the volcanic arc thrust sheets and the underlying mafic–ultramafic complex, occur Paleocene–lower Eocene 'Taguasco' olistostromes with debris derived from the Cretaceous arc, which represent short lasting small foredeep basins that collapsed due to the emplacement of the Cretaceous arc over the mafic–ultramafic complex (Iturralde-Vinent, 1996).

The region of Camagüey comprises a broad zone dominated by serpentinized mafic and ultramafic rocks (Fig. 2). The allochtonous mafic–ultramafic complex is subdivided into two main superimposed ophiolite nappes containing dominantly serpentinized peridotites, layered gabbroids, and Cretaceous basalts and cherts (Flint et al., 1948; Iturralde-Vinent, 1994, 1996). Along the northern 1–15 km of the mafic–ultramafic body occurs a belt of foliated serpentinites, which contains blocks of non-metamorphosed sedimentary rocks and metric angular blocks of metagabbroids, amphibolite, blueschist and eclogite (Rutten, 1936; MacGillavry, 1937; van Wessem, 1943; Millán, 1996), which probably formed part of the same subduction channel system as recorded in the serpentinites west and east of Camagüey (García-Casco et al., 2002, 2006, 2008b; see also Somin and Millán, 1981; Millán, 1996). No detailed petrological and geochronological studies have been carried out on the metamorphic blocks in the Camagüey region.

The Camagüey region does not expose all sedimentary belts of west-central Cuba: only rocks correlated to the Placetas, Remedios and Cayo Coco belts are present (Fig. 2; Meyerhoff and Hatten, 1968). The Camajuaní belt is not exposed, but has been suggested – based on gravity and magnetic field interpretations – to be buried below the mafic–ultramafic allochton (Iturralde-Vinent and Thieke, 1986). Rocks correlated to the Placetas belt are exposed in a NW to SE trending series of strongly deformed sedimentary blocks. They consist of regionally correlative upper Jurassic and Cretaceous hemipelagic and pelagic rocks locally covered by olistostromes of the Paleocene–lower Eocene Vega Alta Formation (Iturralde-Vinent et al., 2008; Fig. 3).

The largest sliver with a Placetas belt stratigraphy is formed by the Camaján hills (Giedt and Schooler, 1959; Iturralde-Vinent et al., 1981; Pszczolkowski and Myczynski, 2003). The oldest exposed part of the section (the lower Tithonian Nueva María Formation) consists of pillow basalts and hyaloclastites, with interbedded calcareous tuffites and limestones of about 60 m thickness. Above rests a section of nearly 1 km which from bottom upward includes the upper Tithonian to Aptian Velóz-Fidencia Formation (well-bedded hemipelagic limestones and shales), the Aptian-Albian Santa Teresa Formation (well-bedded radiolarites, silicified limestones),

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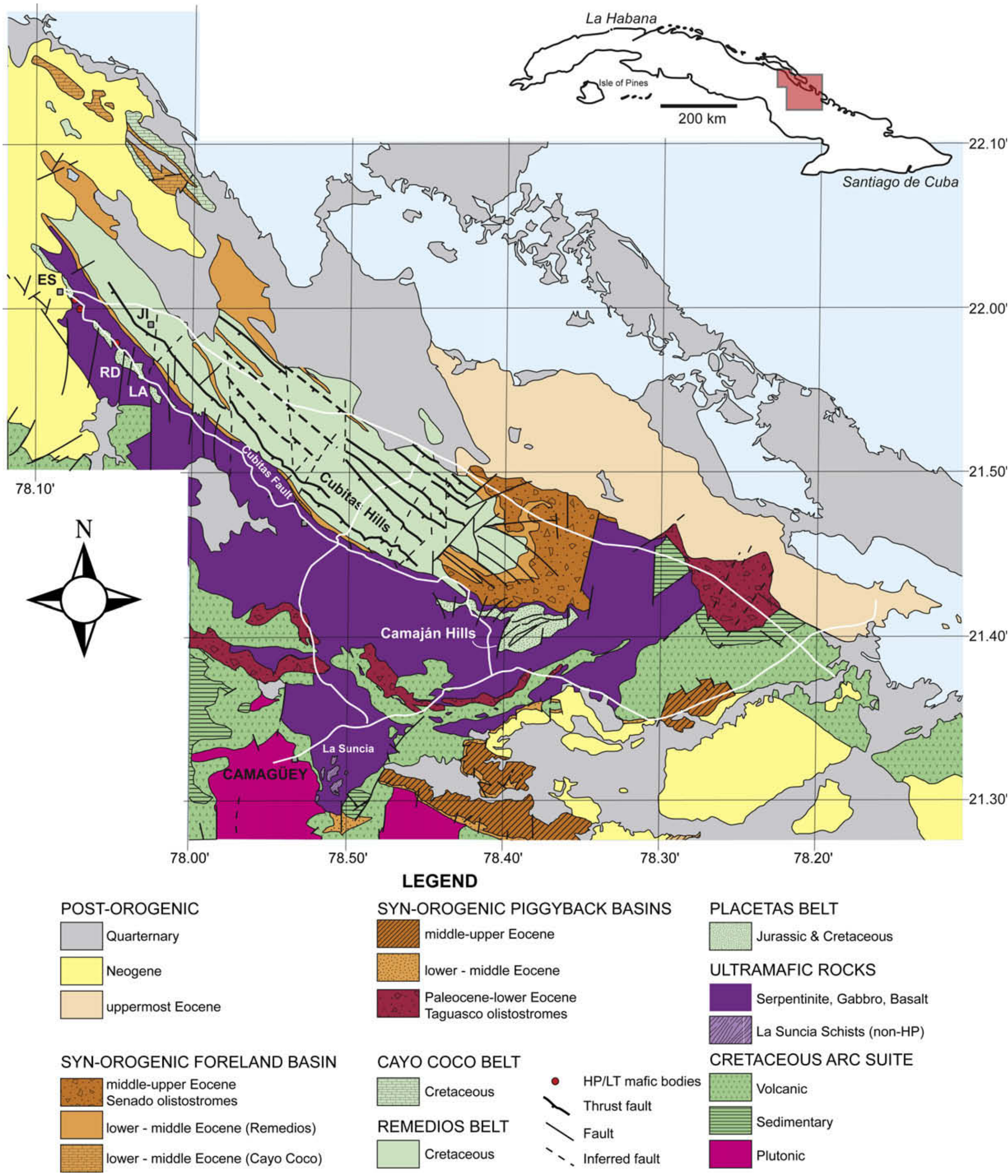

Fig. 2. Geological map of the Camagüey region, central Cuba, compiled from Iturralde-Vinent et al. (1981) and Iturralde-Vinent and Thieke (1986). BA, Banao; ES, Esmeralda, JI, Jiquí, RD, Reforma-Donato block; LA, Las Amarillas block.

Cenomanian to Turonian Carmita Formation (hemipelagic limestones, calcarenites, calcirudites and cherts) which ends in an eroded surface embracing a hiatus that encompasses the Coniacian to Campanian. The upper Maastrichtian Camaján Formation (calcirudites and calcarenites) can reach 350 m thickness and rests above the previous unit. It is crowned by the Paleocene Vega Alta Formation, more than 300 m thickness, an olistostrome rich in allochthonous debris of serpentinites, gabbroids, as well as blocks of the underlying Mesozoic section. Northwest of Camaján, within the same foliated serpentinites, occur a series of smaller outcrops which also belong to the Placetas belt, but were named 'Esmeralda Complex', because their stratigraphic section is incomplete and at some points differs from the Camaján hills (e.g. the upper Jurassic basalt section is missing (Iturralde-Vinent et al., 1981). It comprises the slivers of Reforma-Donato, Las Amarillas and Esmeralda town (Fig. 2). These NW-SE elongated tectonic slivers of 1–10 km^2 are surrounded by foliated serpentinites (Iturralde-Vinent et al., 1981). The oldest unit, exposed SW of Esmeralda town consists of poorly bedded, upward grading, coarse to mid grained quartz sandstones, less than 10 m thick in outcrops, which may be a local equivalent of the Oxfordian? to Berriasian Constancia Formation of west-central Cuba (Pszczolkowski and Myczynski, 2003). This unit sharply grades upward into the Las Amarillas shales (Iturralde-Vinent et al., 1981), composed of yellowish to light brown, very fine grained sandstones

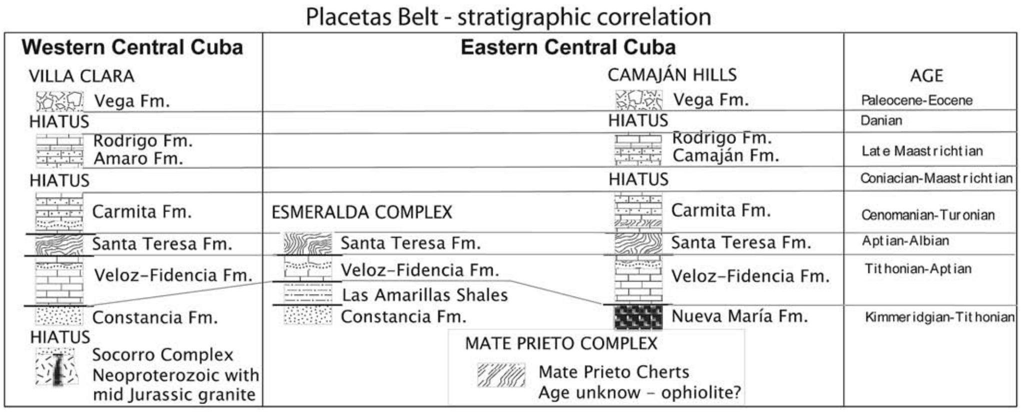

Fig. 3. Stratigraphic correlation chart of the Placetas belt which occurs as slivers within the serpentinite mélange of Camagüey, based on Iturralde-Vinent et al. (1981), Pszczolkowski and Myczynski (2003) and Iturralde-Vinent et al. (2008).

and shales, about 10 m thick, which bears no fossil remains. In west-central Cuba these rocks may have been included in the Constancia Formation. Above these shales occurs a thick succession of thin bedded light grey to cream coloured hemipelagic limestones and shales, which can be correlated with the late Tithonian to Aptian Velóz-Fidencia Formation (Iturralde-Vinent et al., 1981). The thickness of this part of the section is not measurable due to poor exposure and isoclinal deformation, but reaches more than 50 m. In one tectonic sliver occurs the late Aptian-Albian Santa Teresa Formation, which are thin bedded, strongly folded, radiolarian cherts and silicified sandstones (Iturralde-Vinent et al., 1981).

Generally it is assumed that the Placetas belt successions mostly represent the sedimentary cover of the Proto-Caribbean oceanic crust: The basalts at the base of the section in the Camaján hills possibly belonged to oceanic crust of the Proto-Caribbean (Iturralde-Vinent and Mari-Morales, 1988). In west-central Cuba, however, the Placetas section locally overlies pre-Mesozoic continental metamorphic basement (Socorro Complex: Fig. 3; Somin and Millán, 1981; Pszczolkowski and Myczynski, 2003).

Around Banao, a small (less than 0.3 km^2) NW-SE elongated tectonic sliver exposes well-bedded green, blue-grey and dark grey to black cherts, a few metres thick, which were named the Mate Prieto Cherts (Iturralde-Vinent et al., 1981), embedded within foliated serpentinites (Fig. 2). The age is unknown as they carry no fossils and the cherts do not lithologically resemble any formation known from the Placetas belt.

The mafic–ultramafic complex thrusts upon rocks which belong to the Bahamas Platform of the North American Plate, separated into two tectonostratigraphic successions named the Remedios and Cayo Coco belts, the former overthrusting the latter. The Remedios belt is exposed in the Cubitas hills (Fig. 2; Meyerhoff and Hatten, 1968).

The Remedios succession crops out as folded and thrusted Albian to Maastrichtian limestones and dolostones and in lesser amount calcirudites and calcarenites of the southernmost margin of the Bahamas platform (Díaz Otero et al., 1997). They consist of more than 3 km of massive and in places well-bedded limestones and dolostones of dominantly shallow marine facies. The Coniacian to Santonian interval is poorly represented (Díaz Otero and Iturralde-Vinent, 1981; Díaz Otero, 1985; Díaz Otero et al., 1997). The Cayo Coco succession is a mildly deformed series of Cretaceous hemipelagic limestones, shales and cherts overlain by calcirudites and calcarenites of an intraplatform channel facies. Both sections are unconformably overlain by lower Eocene to middle Eocene calcareous clastic rocks and limestones of a foredeep. The Paleocene hiatus may result from uplift of the bank as a forebulge, in response to the approaching subduction zone to the southwest (Pindell, 1993; Iturralde-Vinent et al., 2008). In the Cubitas hills these rocks are covered by the middle to lower upper Eocene 'Senado' olistostrome – a marine section of gravels, sandstones and marls with olistoliths and fragmentary material composed of ophiolite-derived rocks, volcanic arc rocks and elements of the Placetas belt (Iturralde-Vinent, 1998a; Iturralde-Vinent et al., 2008) – associated with the last phases of arc–continent collision and the final emplacement of the mafic–ultramafic allochton.

The thrust between the Cubitas hills and the overriding units is cross-cut by the Cubitas Fault. This is a post-middle Eocene NW-SE trending normal fault which forms a steep slope along the southern margin of the Cubitas hills (Fig. 2). Several cross sections of the contact between the Remedios limestones and the serpentinites show the thrust plane to dip from 30 to 70° SW, and the associated normal faults to dip between 70° and vertically (Fig. 4; Iturralde-Vinent and Roque Marrero, 1982). The kinematic of this fault is not without enigma: according to Furrazola-Bermúdez et al. (1964) it is a deep vertical fault, Flint et al. (1948) define it as South verging thrust but Giedt and Schooler (1959), Rigassi-Studer (1961), Meyerhoff and Hatten (1968), Knipper and Cabrera (1974), Iturralde-Vinent (1981) and Iturralde-Vinent and Roque Marrero (1982) consider it a NE verging thrust associated with sinistral strike slip, later cross-cut by a normal fault forming the modern escarpment.

An essentially non-deformed uppermost Eocene and younger sedimentary cover lies above all previously described units and dates the end of the tectonic convergence in the fold and thrust belt on Cuba. Offshore northern Cuba, evidence has been found that folding with very low strain rates continued into the Pliocene or even Quarternary (Masaferro et al., 1999, 2002), but significant plate convergence ended in the Eocene. The uplift of the Cubitas hills leading to its present-day elevation of up to ~200 m post-dates deposition of ?Plio-Pleistocene fluvial deposits north of the Cubitas hills with thick beds of ophiolite-derived lateritic soils from the San Felipe plateau south of Cubitas hills. It is likely that the uplift of the Cubitas hills occurred in the footwall of the Cubitas Fault, which would then be a relatively young feature (Iturralde-Vinent and Roque Marrero, 1982).

3. Structural geological analysis

3.1. Placetas belt: structure of the tectonic slivers in the serpentinite mélange

We have studied the structure, structural evolution and if possible, the contact of the Placetas slivers with the foliated serpentinite to test whether the outcrops of the Placetas belt within the serpentinites form windows into a regionally coherent nappe below the serpentinites, or whether they show diverse histories,

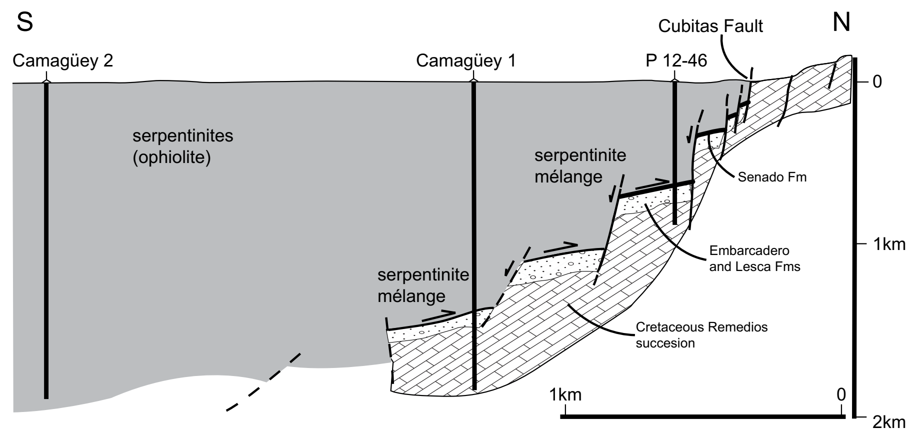

Fig. 4. Schematic cross section of the Cubitas Fault (after Iturralde-Vinent et al., 1981).

patterns and orientations, which would suggest that they are isolated blocks incorporated in the mélange.

The exposure of the Placetas occurrences is largely restricted to outcrops in small quarries and in the floor of dirt roads. They mainly expose folded upper Jurassic and Cretaceous sedimentary rocks (Fig. 3). Fortunately, the bedding is generally steeply dipping, so that surface-trace mapping provides a powerful tool to determine the structure of the bodies. We have mapped four occurrences of the tectonic slivers within the serpentinite mélange, which from southeast to northwest include the Camaján hills, Las Amarillas, Reforma-Donato and Esmeralda bodies (Fig. 2).

3.1.1. *Camaján hills block*

By far the largest tectonic sliver of the Placetas belt within the serpentinites of the Camagüey province forms the Camaján hills. Fig. 5 shows a surface map based on exposures in a dirt road that forms a loop through the Camaján hills north of the town of Minas, where rocks of the Velóz-Fidencia and Carmita Fm crop out. In the southwest, uppermost Cretaceous calcirudites of the Camaján Formation are exposed in an old quarry (Fig. 5C). In the central part of the Camaján hills, a second quarry exposes the transition between Nueva María and Velóz-Fidencia formations (Fig. 5G), which are in thrust contact with the underlying Maastrichtian Camaján Formation. Also the southern part exposes thin-bedded limestones of the Velóz-Fidencia Formation.

The thrust in the centre of the Camaján hills appears to divide the region in two structural domains. In the north as well as the south, two phases of folding have been recognised, but folds of both phases are more pronounced and tighter in the north than in the south.

The patterns of asymmetric, similar, close to tight, inclined plunging F1 folds of decimetre to metre scale (Fig. 5D,F) form parasitic folds that allow the recognition of large antiforms and synforms on a 100-m scale. In the fold hinges of these, box folds sometimes occur. The F1 100-m scale folds form open folds in the southern part of the Camaján hills, and close folds in the northern part. The F1 folds are refolded by close to tight, nearly upright plunging similar F2 folds. In the northern part of the Camaján hills we cannot demonstrate that these small folds form parasitic folds on larger folds on the scale of the observation ($\sim$750 m). In the south, the surface trace of the F1 folds shows part of a concentric F2 fold of kilometre scale. Small symmetric open F2 folds are occasionally encountered, notably as 10-m scale undulations (Fig. 5E,F).

The F1 fold axes plunge $\sim$30–50° E to SE (Fig. 5A). The F2 folds have $\sim$N-S striking axial planes and south-plunging fold axes (Fig. 5B). Note that throughout the Camaján hills, the F2 fold orientations are frequently constructed from bedding measurements. Since F1 folds are generally tight, the angle between their limbs is not very large, but nevertheless this approach leads to a somewhat increased scatter in the estimates of the F2 fold orientations.

Deformation is more intense in the north of the Camaján hills. The style of F1 and F2 folding is comparable to the south, but tighter. Constructed 100-m scale F1 folds (Fig. 5K) trend WNW-ESE with steeper, S to SE plunging fold axes (Fig. 5J). These F1 folds are refolded by symmetric F2 folds, which are much tighter here than in the south (Fig. 5L,M). The F2 fold axes strike sub-parallel in the northern and southern domains.

Due to the limited exposure it is not possible to correlate the northern and southern parts. The fact that the orientation of the F2 folds are comparable in both domains, but tighter in the north, may be the result of the position close to a kilometre scale F2 fold hinge in the north, as indicated by the high angles between F2 fold axes and the enveloping surface of F1. Alternatively, the north may have been shortened to a greater extent than the south, with the thrust exposed in the quarry in its central part (Fig. 5G) as the decollement between the two domains.

3.1.2. *Las Amarillas block*

A small outcrop of the Las Amarillas shales and Velóz-Fidencia Formation is exposed in a dirt road that runs from Esmeralda to the east, parallel to the Cubitas Fault (Fig. 2). The outcrop is several tens of metres wide and exposes folded, thin bedded shales and carbonate beds (Fig. 6F). The exposure is poor, but we recognise in this outcrop three deformation phases: the oldest F1 phase is seen in the northwestern part of the outcrop, and shows tight chevron folded bedding with an E-W trending axial surface (Fig. 6D). At high angles to this oldest folding, which cannot clearly be identified elsewhere in the outcrop, a second folding phase F2 forms the dominant structure. F2 folds are open concentric folds, which in the western part of the outcrop show a penetrative N-S striking S2 spaced axial planar cleavage (Fig. 6C,F). In some of the F2 fold hinges, calcite veins grew. The largest scale F2 folding that can be constructed here is on a 10-m scale, which may form an asymmetric parasitic fold. Plotting the F2 axial planes and fold axes (Fig. 6B), as well as the poles to the axial planes (Fig. 6A) reveals that the poles to the axial planes are dispersed along a great-circle. The regional importance of this third folding is difficult to assess, and is probably only a mild undulation.

3.1.3. *Reforma-Donato block*

The Reforma-Donato block is WNW of Las Amarillas along the same road (Fig. 2). It is also a poorly exposed dust-road outcrop

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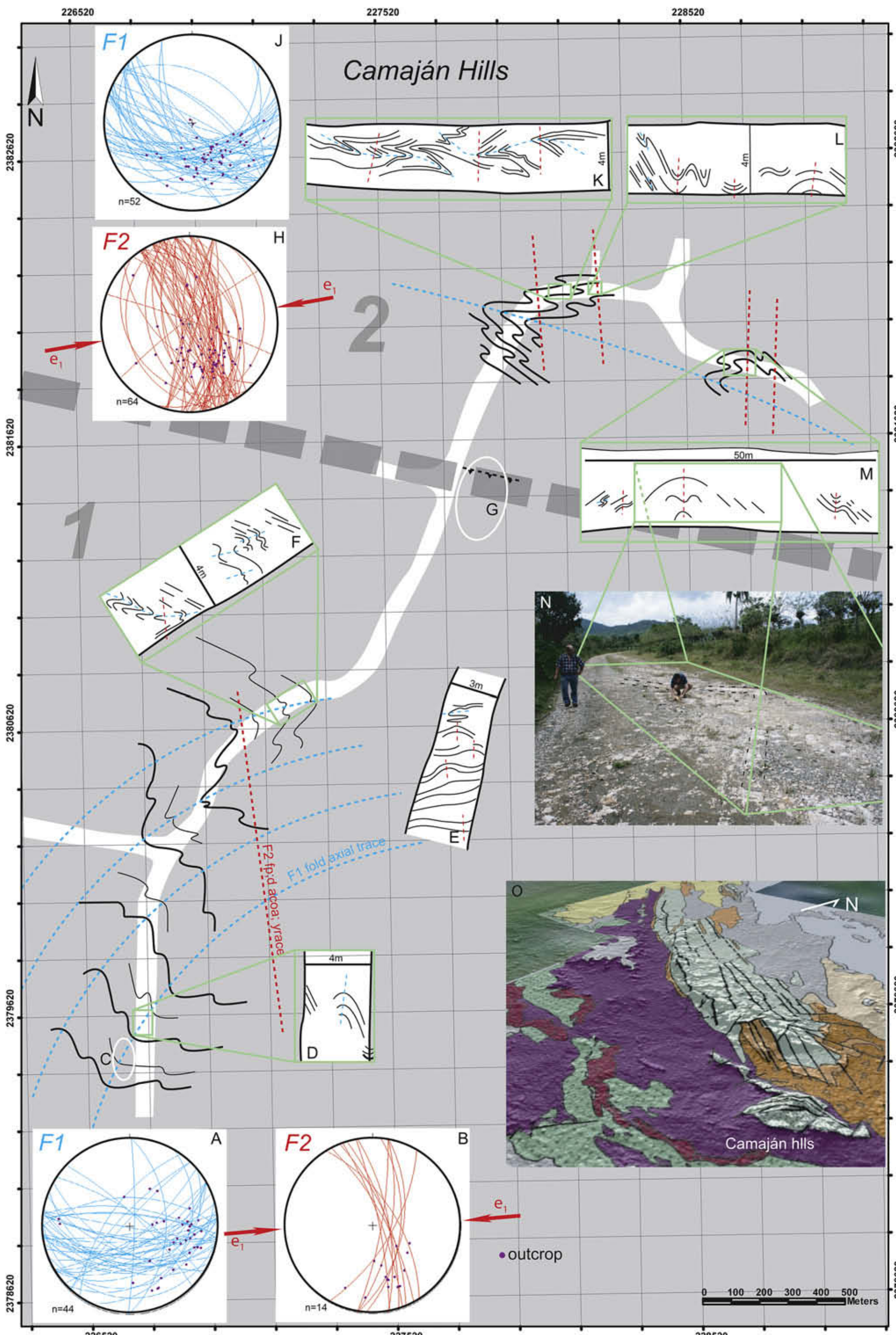

Fig. 5. Form trace map of the Placetas block of the Camaján hills (Placetas belt), documenting the two folding phases that affected this block. Domains 1 and 2 are separated by a thrust fault in the old quarry at location G, where Tithonian volcanic rocks and ammonite-bearing carbonates rest above Maastrichtian carbonates. Great circles represent axial planes. (M) The typical outcrop used for study of the Camaján hills structure.

spanning several tens of metres width, where thinly bedded, folded Velóz-Fidencia rocks occur (Fig. 7). In contrast to the blocks described above, only one phase of folding is recognised, although with a marked difference between the western and eastern side of the outcrop (domains 1 and 2 in Fig. 7). The eastern part of the outcrop reveals two limbs of an open concentric fold tens of m wide with a steeply, south-plunging fold axis in a ∼N-S striking axial plane. In the exposed hinge zone, box folds are exposed with conjugate axial planes (Fig. 7C), leading to the scattered pattern of axial planes and fold axes in Fig. 7D. The western side of the outcrop also shows folds consistent with one phase of folding, but although the axial planes strike more or less parallel to ones in the eastern

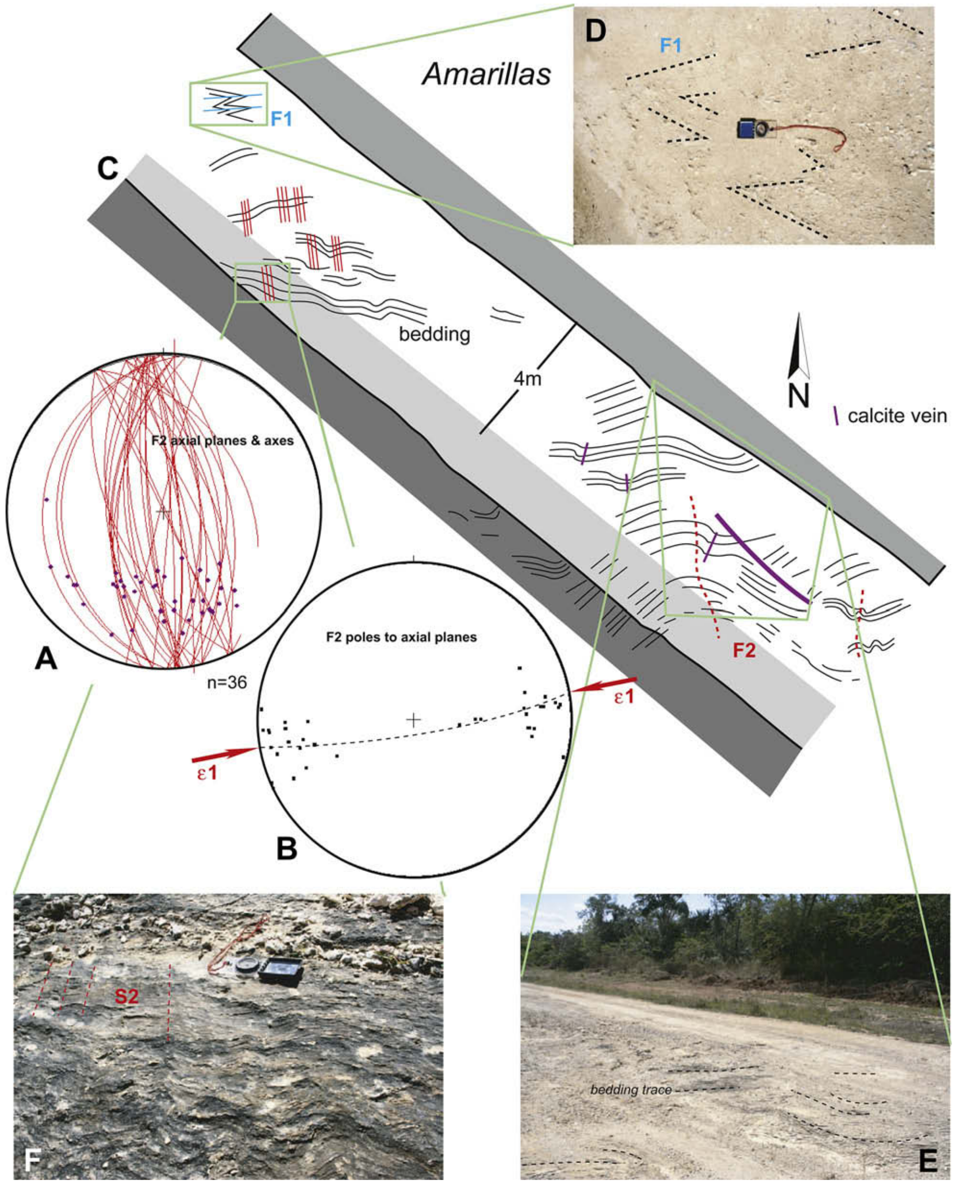

Fig. 6. Form trace map of the small road floor exposure of the Las Amarillas block (Placetas belt; see Fig. 2 for location). The deformation of the Las Amarillas block is characterized by a second phase of open folding and locally associated axial plane cleavage, which overprints a first phase of isoclinal folding. The spread in poles to F2 axial planes and F2 fold axes may indicate a third, weaker phase of folding, the shape of which cannot be constrained in this outcrop. (E) The typical outcrop used for study of the structure.

part of the outcrop, the fold axes of both domains are at high angle and plunge mildly northward in the western domain (Fig. 7A). Moreover, the fold hinges here are cross-cut by calcite veins, a feature unseen in the eastern domain (Fig. 7B). The two domains are separated from each other by an unexposed interval several metres wide and the change between fold orientations is abrupt. We infer a fault in between these two domains along which tilting occurred about a rotation axis orthogonal to the axial plane. It is unlikely, based on the abrupt change and the internal consistency of the fold orientations in both domains that a more ductile mechanism can account for the variation.

3.1.4. *Esmeralda block*

A few kilometres west of the town of Esmeralda (Fig. 2), some of the Placetas stratigraphic units are exposed in a deserted quarry. The outcrops are scattered and the relationships between the various outcrops are generally not straightforward. A schematic map of the quarry is shown in Fig. 8. The quarry shows three fold generations. The dominant and – on the scale of the quarry consistent – F3 fold pattern shows asymmetric, open to close, upright plunging, similar folds, with NW-SE striking fold axial planes and steeply NW plunging fold axes (Fig. 8B). The northern hinge of two 100-m scale hinges of this folding can be traced across the quarry (Fig. 8D) and contains parasitic folds that are consistent with the mapped pattern (e.g. Fig. 8E). Locally, an axial planar foliation developed in the carbonates of the eastern limb (Fig. 8F). Fig. 8A clearly shows the relationship between F3 and two earlier folding phases: the axial trace of F2 is clearly refolded by F3, but the northern limb of the F2 fold contains an F1 fold, since it has a vergence that is inconsistent with F2 and an orientation inconsistent with F3. The oldest phase of folding is not penetrative throughout the quarry and could represent synsedimentary slumping features. Cross-bedding is in some places encountered in the fine-grained carbonates (e.g. Fig. 8F), and shows that the eastern part of the

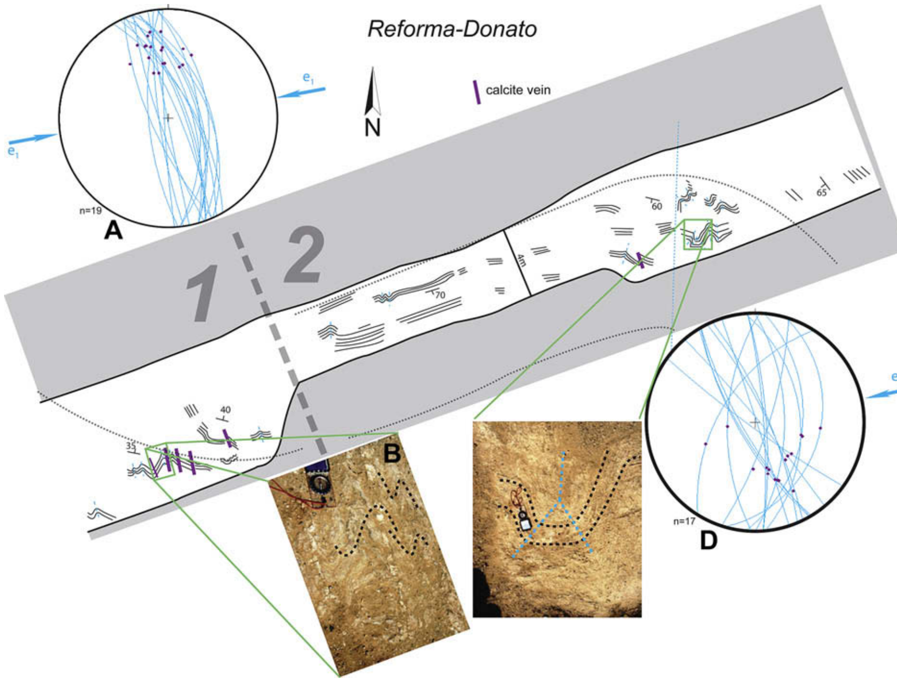

Fig. 7. Form trace map of the road floor outcrop Reforma-Donato block (Placetas belt; see Fig. 2 for location). Deformation here can be straightforwardly explained by a single phase. Domains 1 and 2 both experienced a single phase of folding, but the fold orientations of both domains differ. We inferred a fault separating the two domains, in an unexposed interval.

quarry exposes a near-vertical to overturned sequence, which becomes entirely overturned and flat-lying towards the north. The general change in bedding orientation from ∼20°W-dipping to subvertical attitude allows construction of a fold with NNE or SSW shallow plunging reclined to recumbent fold. The western part of the quarry exposes a normally graded sequence, suggesting that the second phase of folding is recumbent. The comparable vergence of metre scale asymmetric folds in both the normally graded and the overturned limb shows that the entire sequence exposed in the quarry is part of a single limb of an F3 fold beyond the scale of the quarry. As can be seen in Fig. 8, the fold hinges cannot be traced across the entire quarry. The western side exposes rocks of similar facies as in the east, but without large-scale folds. In the southern side of the quarry, the contact of the carbonates with the serpentinite is exposed as a brittle, chaotic zone. We infer a brittle, steep fault (Fig. 8C) exposed in the southern part of the quarry, and extend it over a non-exposed interval NNW-ward, separating the eastern and western domains to explain the discontinuity in the large-scale fold pattern in the eastern domain. The sense of shear along this fault is uncertain but may contain a component of normal WSW motion emplacing both limbs of the F2 recumbent fold against each other and/or a left-lateral strike-slip component.

3.2. *Cubitas hills: deformation of Bahamas Platform promontory*

The Cubitas hills exposes folded and thrusted rocks of the Remedios belt. It is not as strongly deformed as the slivers of the Placetas belt. The Cubitas hills form a NW-SE trending anticlinorium, which plunges SE below the overriding mafic–ultramafic complex in the SE (Iturralde-Vinent and Roque Marrero, 1982). The thrust contact between the mafic–ultramafic complex and the Remedios limestones and Senado olistostrome is dissected by the Cubitas Fault.

The geological map of the Cubitas hills of Pushcharovski (1988) contains bedding attitude information. Plotting the data indicated on the map allows estimation of an average fold axis plunging 5° to 139° (139/05) (Fig. 9A). Even though on a large scale the Cubitas hills can be regarded as an anticline, the internal structure is dominated by thrusts as indicated on the map (Figs. 2 and 9). Where bedding is thick (on a metre scale or more), such as in the quarries of Sierra de Cubitas and Jiquí (Fig. 9B,C,G), only local folding occurs. Notably in the Sierra de Cubitas quarry the bedding has a subparallel orientation over hundreds of metres of exposure. Along the dry creek of Paso de Vigueta (Fig. 9D,E) in the southeastern part of the Cubitas hills, thinner bedded limestones with bed thicknesses of ∼10 cm show mild undulations that allow the construction of folds with amplitudes of tens to hundreds of metres. We collected bedding attitude measurements, which reveal a fold axis of 132/13, which confirms the fold axis constructed from the bedding attitudes indicated on the geological map. The fold axial plane trends NW-SE and is near-vertical. The slightly higher SE-plunge of the fold axis constructed from the Paso de Vigueta section compared to the overall structure (Fig. 9E vs. A) may be related to the closer proximity to the SE part of the anticlinorium, but the scatter in Fig. 9A,E show that these two estimates are likely within error.

The thin bedded carbonates of the Paso de Vigueta section shows sedimentary structures including foresets, suggestive of shallow-marine conditions during deposition. In one place, foresets drape a recumbent fold, indicating that this fold is a syn-sedimentary slump feature (Fig. 9F).

One of the largest exposures in thin-bedded limestones of the Cubitas hills is found in the southeastern part, in the Hoyo de Bonet (a karstic sinkhole) and in the dry creek of Paso Paredones, that leads to it. The Hoyo de Bonet (Fig. 10) has a diameter close to 300 m and the floor of the doline lies 90 m below the average topography. Both the floor and the hills around the doline are heavily vegetated, but the walls of the sink hole provide in places good exposure (Fig. 10C).

In the cliffs alongside of the dry creek leading to the Hoyo de Bonet occurs a consistent ∼20–50° SW dipping bedding attitude of fine-bedded (∼10 cm) to massive limestones, without large-scale folding. In one place, a low-angle thrust fault emplaced massive limestones over thin-bedded limestones, but lineations or

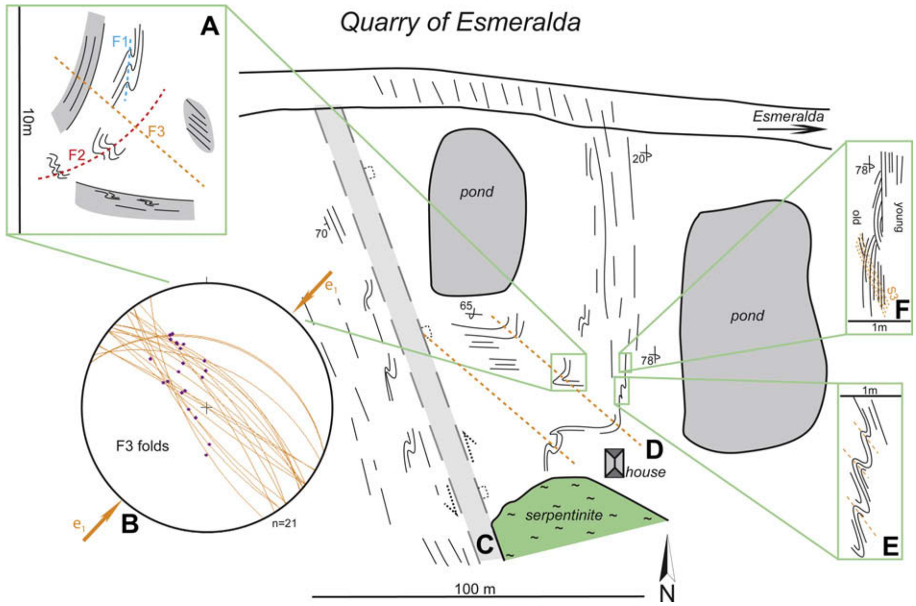

Fig. 8. Form trace map of the Esmeralde block exposed in the quarry west of the village of Esmeralde (Placetas belt; see Fig. 2 for location). Deformation here included at least three phases of folding, illustrated by the outcrop in (A). The structure of the western and eastern side of the quarry cannot be straightforwardly linked, and we infer a fault separating these domains, supported by the jump in the edge of the block in the south, where it is juxtaposed against serpentinite.

kinematic indicators were not recognised. Within the Hoyo de Bonet, the SW-dipping bedding orientation dominates. In the northwestern part of the doline, however, an anticline and syncline pair striking WNW-ESE, i.e. sub-parallel to the overall structural trend of the Cubitas hills, has been constructed. Superimposed on this we recognised in well-exposed parts of the doline walls similar, close, recumbent folds with axial planes close to the overall regional orientation of the bedding (e.g. Fig. 10B,D). Plotting the fold axes and axial planes leads to a scattered pattern (Fig. 10A). Even though in individual cases we cannot provide conclusive evidence that these folds are synsedimentary slumps, their restricted occurrence confined to the thin-bedded limestones in the Hoyo de Bonet, the lack of consistency in their orientation and the recognition of a slump-fold in the nearby thin-bedded limestones of the Paso de Vigueta (Fig. 9F) provide circumstantial evidence supporting this interpretation.

4. Discussion

4.1. Placetas belt in Camagüey: Nappe or blocks?

Each of the four isolated occurrences of the Placetas belt in the Camagüey region studied reveal comparable stratigraphies (Fig. 3), which suggests that these bodies were initially part of the same basin. However, each block has a distinct structural history: (1) the Esmeralda quarry revealed at least three folding phases (Fig. 8), (2) Las Amarillas shows evidence for only two (and possibly a very weak third) phases of folding (Fig. 6), whereas (3) the nearby exposure of Reforma-Donato experienced only one phase of folding (Fig. 7) and finally (4) in the Camaján hills, no evidence exists for more than two phases of folding (Fig. 5). Moreover, the shortening directions obtained from these blocks for these folding phases differ considerably. This heterogeneity is in line with their interpretation as isolated blocks within the serpentinite mélange, in which structural coherency is not expected (Iturralde-Vinent and Roque Marrero, 1982). The Placetas exposures in the Camagüey region are not windows exposing pieces of a coherent nappe.

The varying styles and numbers of folding phases within blocks only short distances apart renders it unlikely that they ever formed a coherent nappe that was later brittley broken up during for example the emplacement of the mafic–ultramafic complex over the Remedios belt, or even during the later activity of the Cubitas Fault. More likely, these blocks are small fragments that were accreted and incorporated in the serpentinite mélange during underthrusting of the Placetas sediments, which, given their stratigraphic range, occurred after the Maastrichtian (Iturralde-Vinent et al., 2008).

The question now arises where the rest of the sediments have gone from the Placetas belt, as well as those from the Camajuaní belt, both well known from west-central Cuba (Pushcharovski, 1988; Iturralde-Vinent, 1998b; Iturralde-Vinent et al., 2008). Iturralde-Vinent and Thieke (1986) showed that the mafic–ultramafic complex in the Camagüey region reaches up to 5 km thick, and overlies deformed carbonates. The nature of these carbonates is unknown, but Iturralde-Vinent and Thieke (1986) suggested that these may belong to the 'missing' Camajuaní belt. Our analyses cannot demonstrate the presence of coherent nappes between the mafic–ultramafic complex and the Remedios belt (Cubitas hills): a possible explanation may be that the vast majority of sediments of the Placetas and Camajuaní belts that were present on the proto-Caribbean crust and North American margin bypassed the accretionary wedge to be subducted, or underplated further to the south.

4.2. Deformation of the Remedios belt and arc–continent collision

The final emplacement of the mafic–ultramafic complex and the overlying Cretaceous arc suite over the Remedios belt, can be considered as the end of subduction in the Cuban segment of the subduction zone, and the finalization of arc–continent collision. The age is constrained by the middle to early late Eocene age of the syn-orogenic olistostrome of the Remedios belt and the unconformably uppermost Eocene cover of the deformed Remedios belt (Iturralde-Vinent and Roque Marrero, 1982) and must thus be early late Eocene (Iturralde-Vinent et al., 2008; Figs. 2 and 9). Our data show that this event led to a single deformation phase in the Remedios zone, which is characterized by dominantly open,

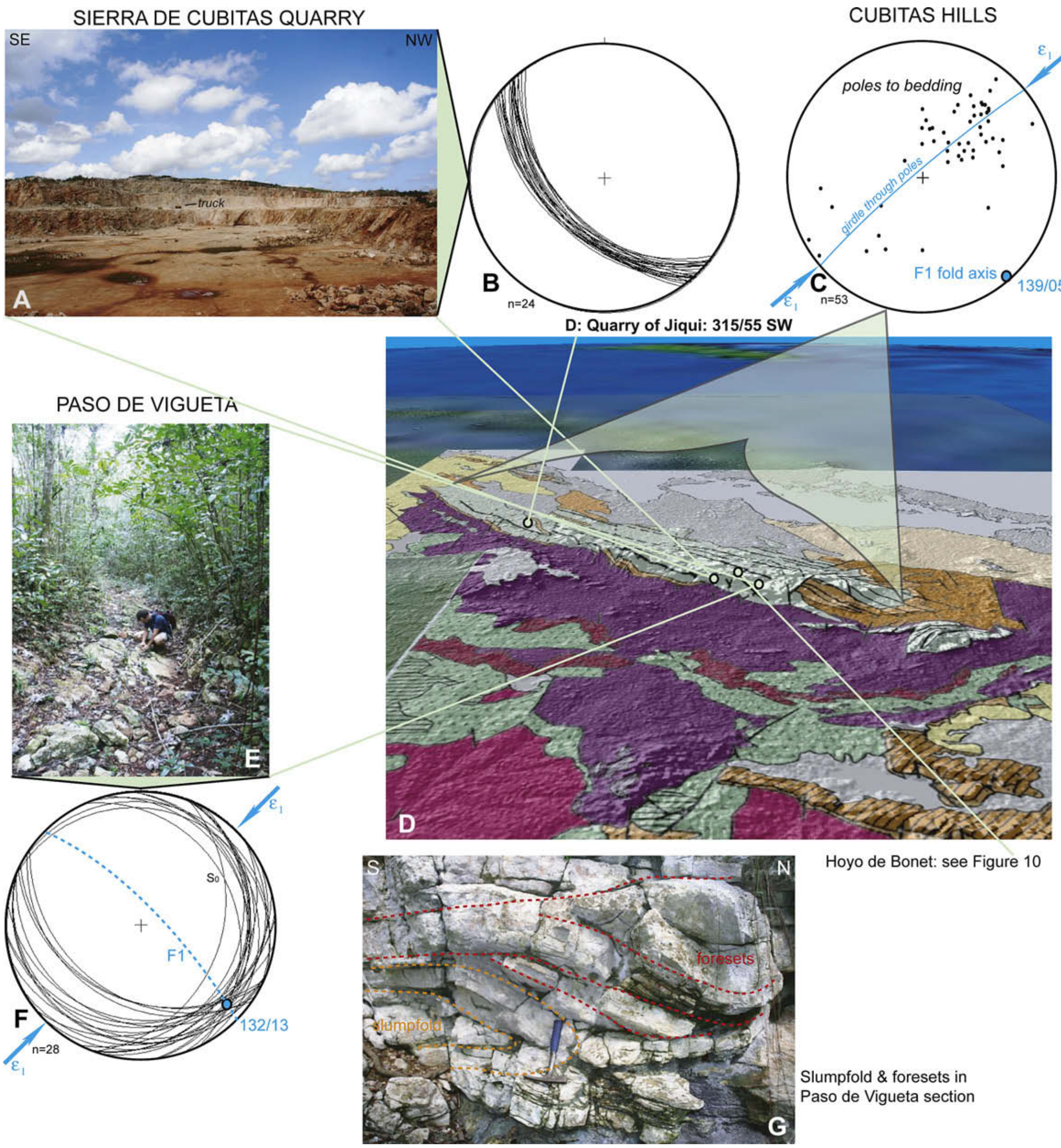

Fig. 9. Documentation of the deformation in the Remedios belt exposed in the Cubitas hills. Bedding orientations indicated on the geological map of the Camagüey province (Iturralde-Vinent et al., 1981; Iturralde-Vinent and Thieke, 1986) are plotted in (C). Our own observations measured in the Paso de Vigueta (E,F) are in line with the published measurements, and indicate a NE-SW contraction direction associated with this single phase of folding. Deformation is distributed over folds in thinner bedded limestones, and thrusts. Thick-bedded strata are unfolded and only tilted (A,B).

north-verging folding and thrusting with shortening in a NE-SW direction, perpendicular to the plate contact. Iturralde-Vinent and Roque Marrero (1982) suggested that the emplacement of the mafic–ultramafic complex and higher tectonic units over the Remedios belt was associated with a component of left-lateral NW-SE trending strike slip and although strain partitioning between strike-slip and thrust motion is a well-known phenomenon in transpressional settings (Cunningham, 2005, 2007), we have found no evidence for strike-slip motion associated with the deformation of the Cubitas hills.

Locally, Neogene to Recent contractional offshore deformation between Cuba and the Bahamas was reported by Masaferro et al. (1999, 2002), but since the late Eocene, the plate boundary of the Caribbean plate was formed by the Motagua–Cayman–Oriente fault, south of Cuba (Malfait and Dinkelmann, 1972; Pindell and Dewey, 1982; Rosencrantz and Slater, 1986; Rosencrantz et al., 1988; Leroy et al., 2000).

4.3. Evolution of the plate contact in the Camagüey region: subduction accretion and/or subduction erosion?

We now use the results from the above analyses, in combination with published information to assess the evolution of the northern Caribbean subduction zone in the region of Camagüey in terms of subduction erosion and/or accretion. As pointed out by Iturralde-Vinent and García-Casco (2007), García-Casco et al. (2008a) and Tait et al. (2009), the Cuban subduction zone likely accommodated approximately 1000 km of shortening after the accretion of Caribeana nappes in the late Cretaceous, and before early late Eocene arc–continent collision. Before the arrival of Caribeana in the subduction zone, there already had been many tens of millions of years of subduction (Lázaro et al., 2009), the amount of shortening associated with which is unknown. Using our analysis of the Camaguey region, we now attempt to identify whether and when either subduction event was associated with subduction accretion

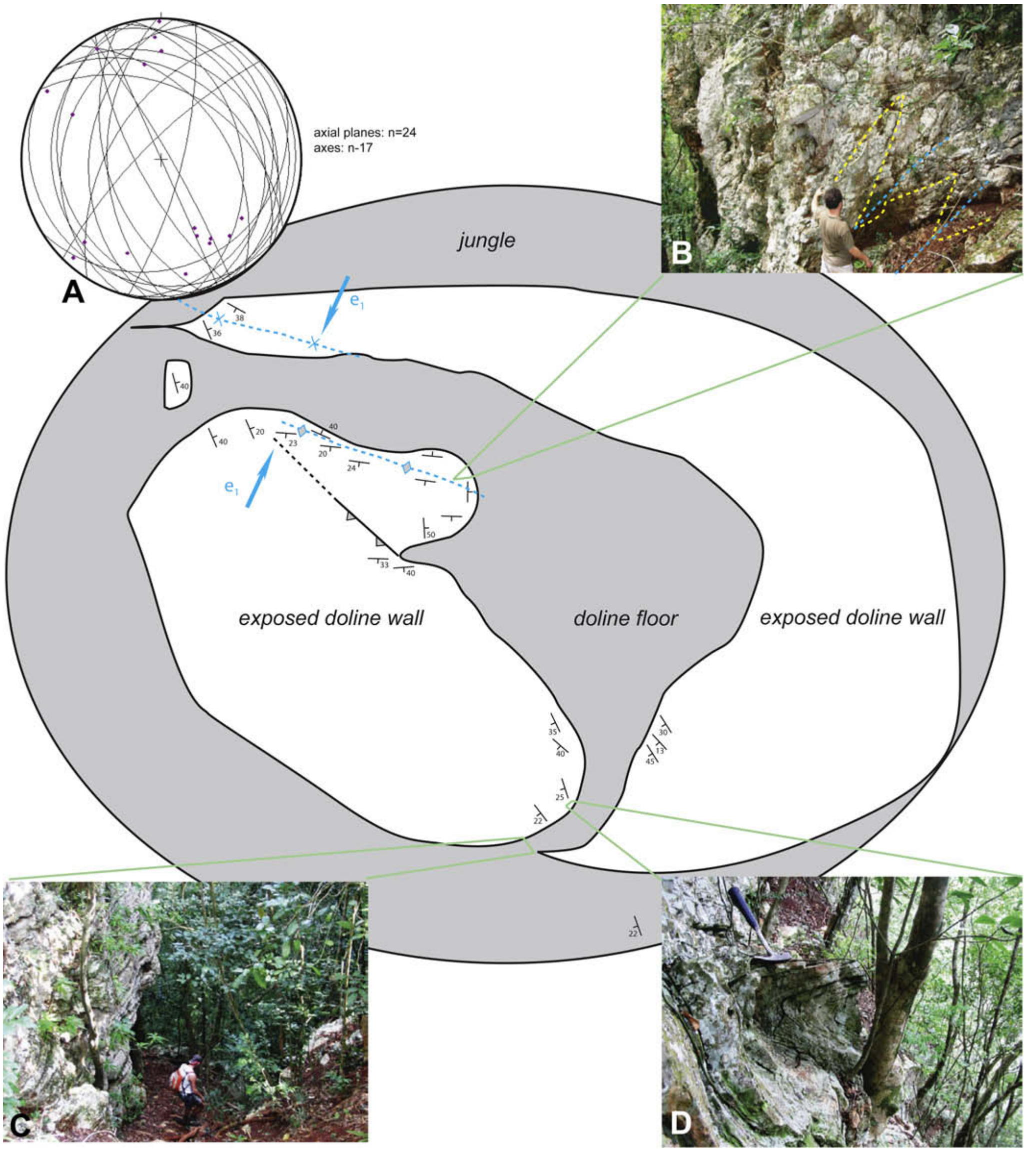

Fig. 10. Schematic map of the Hoyo de Bonet doline. The doline floor lies approximately 90 m below the surrounding hill surface, and the diameter is 300 m from wall to wall. Tight to isoclinal folds exposed in the walls show no consistent direction and are interpreted as synsedimentary slump folds, comparable to the one observed in the Paso de Vigueta section (Fig. 9G). The northwestern corner of the doline exposes a NE-SW trending antiform–synform couple, sub-parallel to the fold axis constructed from the Paso de Vigueta section (Fig. 9F) and the Cubitas hills in general (Fig. 9C).

or subduction erosion. To this end we first define what we mean precisely by these terms.

In line with von Huene and Scholl (1991), we use the term *subduction accretion* to indicate (tectonic) transfer of rocks from the underriding to the overriding plate, and *subduction erosion* to indicate (tectonic) transfer of rocks from the overriding to the underriding plate. In case subduction processes fail to accrete or remove rocks, *sediment subduction* occurs (Gilluly, 1963; Scholl et al., 1980). Subduction accretion leads to the formation of an *accretionary wedge*, which is an intensely deformed stack of sedimentary and igneous rocks that were scraped off from the underriding plate and accreted to the edge of the overriding plate (Davis et al., 1983; von Huene and Scholl, 1991; van Hinsbergen et al., 2005a,b). For a field geologist, the accretionary wedge can be identified as the bulk thrusted, folded and piled-up rock between a lowermost (sole) and an uppermost (roof) thrust.

Subduction erosion, instead, involves (under)thrusting of parts of the overriding plate that after becoming detached from the hanging wall start to move downward together with the underriding plate. This may equally lead to formation of nappes. At plate boundaries where both subduction erosion and subduction accretion has occurred, the uppermost nappes may be derived from the overriding plate, whilst the lower ones were accreted from the underriding plate.

Investigations of the HP metamorphic rocks of Cuba found within foliated serpeninite mélange have shown that the foliated serpeninite mélange with HP metamorphic blocks contains a wide span of peak metamorphic and cooling ages, from 120 to 65 Ma, and have been interpreted to represent a long-lasting subduction channel (Lázaro et al., 2009). Accretion of this subduction channel related mélange to the overriding plate likely occurred when the Caribeana terrane was subducted around 70–65 Ma (García-Casco et al., 2008a). The HP-LT blocks reported from the serpentinite mélange in the Camagüey region by Rutten (1936), MacGillavry (1937) and van Wessem (1943) likely formed within this context. Contemporaneous with the long-lasting subduction channel

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evolution, the volcanic arc at the surface, spanning the ?Valanginian to mid-Campanian (Iturralde-Vinent, 1994; 1998b; Hall et al., 2004; Kesler et al., 2004) developed, which seems to have been in a relatively stable position with respect to the subduction zone prior to its late Cretaceous extinction.

Normally, the volcanic arc and trench are separated by a forearc, which has typically a width on the order of 50–100 km (Duff, 1992). In the Camagüey region, the volcanic arc is in immediate contact with the deformed mafic–ultramafic complex which marks the plate contact. The fact that ophiolitic elements form the main part of the deformed mafic–ultramafic complex (Iturralde-Vinent and Thieke, 1986; Iturralde-Vinent, 1994, 1998b) attests to the presence of a forearc ophiolite, but its intense deformation, tectonic duplication and limited width (no more than ~30 km) may point at tectonic removal of part of the overriding plate, hence, subduction erosion. The Taguasco olistostrome between the volcanic arc nappe and the mafic–ultramafic allochton shows that there was thrusting between these two units in the Paleocene to early Eocene (Iturralde-Vinent, 1996), which provides time constraints for this event.

We cannot demonstrate from the exposed geology of the Camagüey region that nappes accreted below the mafic–ultramafic allochton prior to its emplacement over the Bahamas borderland, although underplated carbonates may be present below the mafic–ultramafic complex (Iturralde-Vinent and Thieke, 1986). Elsewhere on Cuba, e.g. in the regions of Santa Clara, and Guaniguanicó, nappe stacks are present (Pszczolkowski, 1994, 1999; Bralower and Iturralde-Vinent, 1997; Gordon et al., 1997; Saura et al., 2008), resembling the scenario of Camaguey. Further assessment of the amount of accretion in the Paleogene subduction history of Cuba therefore requires seismic studies in the Camagüey region. The folding and thrusting of the Remedios belt, finally, can be seen as accretion, but also marks arc–continent collision at the arrest of subduction.

Pindell et al. (1988, 2005), Iturralde-Vinent and García-casco, (2007) and García-Casco et al. (2008a) inferred a shallow slab angle during Paleogene subduction along the northern Caribbean margin based on the arrest of the volcanic arc and of exhumation of metamorphic rocks. Geophysical modelling and observations elsewhere generally suggest that shallow slabs generate subduction accretion (Abers, 2005; Lallemand et al., 2005; De Franco et al., 2007, 2008; Manea and Gurnis, 2007). The geology of the Camagüey province may provide arguments for an episode of subduction erosion, and although we cannot conclusively demonstrate nappe accretion, we need to await seismic sections to reach a firm conclusion on this. It was noted recently by Guillaume et al. (2009), that processes of accretion, as well as slab angle, may vary in space and time, and other factors, such as sediment thicknesses and overriding plate motion speed and direction may play a significant role. The analyses in this paper, however, show that the geology of the northern Caribbean margin allows the inference of episodes of subduction erosion and subduction accretion. This approach may provide a useful independent tool to assess the geodynamic processes that accommodated Paleogene subduction in the northern Caribbean, where metamorphic and geochemical techniques cannot be applied by deficit of appropriate rock records from this time period.

5. Conclusions

Major shortening, on the order of 1000 km, between the Caribbean and north-American plates in the Paleogene has led to the formation of an intensely deformed tectonic pile consisting from top to bottom of a volcanic arc nappe, a deformed mafic–ultramafic complex with Mesozoic ophiolite components and a serpentinitic melange with blocks of sedimentary (the Placetas belt) and metamorphic rocks; and the structurally lower unit composed of folded and thrusted sediments of the southern promontory of the Bahamas platform. In this paper we study the deformation history of sedimentary units which belong to the North Cuban fold and thrust belt associated with this shortening history. Our conclusions can be summarized as follows:

1. The exposures of the Placetas sedimentary belt within the mafic–ultramafic complex show varying styles and intensity of deformation, and varying number of deformation phases. They form isolated blocks of the Placetas sedimentary rocks within the foliated serpentinite mélange and do not represent a coherent nappe underlying the mafic–ultramafic allochton.
2. The deformation of the Remedios belt, part of the Bahamas platform, underwent a single phase of folding and thrusting, with shortening perpendicular to the plate contact. This folding occurred in the middle to late Eocene and marks the arrest of subduction and arc–continent collision. We find no evidence for a component of strike-slip during collision.
3. The volcanic arc is thrusted upon the mafic–ultramafic complex, and the original forearc ophiolite appears to be shortened. This shortening may attest to a period of subduction erosion. Thrusting of the volcanic arc led to deposition of the Paleocene–lower Eocene Taguasco olistostrome which may date this event
4. We find no conclusive evidence from the field observations from the Camagüey province for accretion of nappes during Paleogene convergence, prior to arc–continent collision as documented elsewhere on Cuba. Seismic analysis of the Camagüey region is required to further constrain the accretion history.
5. We show that careful analysis of the complexly deformed Cuban tectonostratigraphy may allow identification of subduction erosion and subduction accretion episodes. Geophysical models suggest relations between these processes and geodynamic parameters such as slab dip and plate convergence rates. Expanding the analysis carried out in this paper to the scale of the northern Caribbean fold and thrust belt may thus provide a new and independent geological tool to constrain the geodynamic processes associated with subduction and arc–continent collision in the northern Caribbean in the Paleogene.

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