International Geology Review, Vol. 50, 2008, p. 1–22. DOI: 10.2747/0020-6814.50.9.1

Paleogene Foredeep Basin Deposits of North-Central Cuba: A Record of Arc-Continent Collision between the Caribbean and North American Plates

MANUEL A. ITURRALDE-VINENT,[1]
Museo Nacional de Historia Natural, Obispo no. 61, Plaza de Armas, La Habana Vieja 10100, Cuba, and Departamento de de Geociencias, Instituto Superior Politécnico J. A. Echeverría, La Habana, Cuba

CONSUELO DÍAZ OTERO,
Instituto de Geología y Paleontología, Ministerio de Industria Básica, La Habana, Cuba

ANTONIO GARCÍA-CASCO,
Departamento de Mineralogía y Petrología, Universidad de Granada, and Instituto Andaluz de Ciencias de la Tierra, Universidad de Granada-CSIC, Avda. Fuentenueva sn, 18002 Granada, Spain

AND DOUWE J. J. VAN HINSBERGEN
Paleomagnetic Laboratory 'Fort Hoofddijk', University of Utrecht, Budapestlaan 17, 3584 CD Utrecht, the Netherlands

Abstract

Paleogene deposits of north-central Cuba have been identified as a deformed foredeep basin, whose stratigraphy recorded very well the collision of the Bahamas–Proto-Caribbean realm (North American plate) with the Caribbean plate, a process that occurred since latest Cretaceous to early Late Eocene time. The debris incorporated in the foredeep basin has two provenance regions and four tectonostratigraphic sources, including: (1) the Caribbean Plate (1a = allochthonous Cretaceous arcs, 1b = serpentinite mélanges and ophiolites); (2) the North American plate (2a = Pre-Paleogene sedimentary rocks derived from the substrate of the foredeep basin, 2b = Cretaceous Bahamian carbonate platform rocks). Evaluation of the age, size, and volume of the debris demonstrate the formation of a forebulge within the Bahamas platform in response to the collision between the Caribbean and North American plates, and the northeastward migration of the axis of maximum subsidence of the foredeep basin since the Paleocene. By the early Late Eocene, structural NE-SW shortening ended in central Cuba, with uplift and deep erosion, followed by a quick transgression before the end of the Eocene. The resulting Upper Eocene sediments unconformably cover the deformed foredeep deposits and underlying rocks, finishing the formation of the North Cuba–Bahamas fold-and-thrust belt. Palinspastic reconstructions suggest that this belt accommodated nearly 1000 kilometers of shortening, during underthrusting of the Proto-Caribbean crust below the Caribbean Plate.

Introduction

THE EVOLUTION of the Caribbean realm is characterized by two major stages. During the first, the autochthonous Proto-Caribbean crust was created during the break-up and disruption of Pangaea. During the second, a southwestward-dipping subduction zone consumed most of the crust of the Proto-Caribbean basin below the Caribbean plate (Pindell et al., 1988; Iturralde-Vinent and Lidiak, 2006). Recent petrological and geochronological evidence from exhumed high-pressure metamorphic portions of subducted Proto-Caribbean crust on Cuba, and the Dominican Republic, indicated that its southwestward, intraoceanic subduction started around 120 Ma (García-Casco et al., 2008b; Krebs et al., 2008). The youngest cooling ages reported from high-pressure blocks in serpentinite mélanges of the subduction channel, now exposed below the ophiolites of the overriding Caribbean plate, cluster around ~70 Ma in Guatemala and Cuba (Harlow et al., 2004; García-Casco et al., 2008b), and somewhat younger farther east in the Dominican Republic (Krebs et al., 2008). Late Cretaceous cooling

[1]Corresponding author; email: maiv_cu@yahoo.com

ages of ~70 Ma associated with exhumation are also found in metasedimentary rocks that were subducted below the mélange, now exposed in the Cuban Escambray hills and the Isle of Youth (García-Casco et al. 2001, Schneider et al. 2004). This phase of exhumation and extension followed the arrest of magmatic activity in the Cuban Cretaceous volcanic arcs (Iturralde-Vinent, 1994, 1998).

Some authors have suggested that this event represents the onset of collision between the Bahamas platform (i.e., the North American plate) and the overriding Caribbean plate (e.g., Draper 1994; Schneider et al., 2004; Stanek et al., 2006). Palinspastic reconstructions, however, render it more likely that it was not the Bahamas platform (Pindell et al., 2005), but the offshore sedimentary promontory of the Yucatán Peninsula, depicted as the "Caribeana" terrane by Iturralde-Vinent and García-Casco (2007) and García-Casco et al. (2008a), that entered the subduction zone in the Late Cretaceous. This interpretation would suggest that following the Late Cretaceous collision of the Caribbean plate with Caribeana, another 1000 km of shortening occurred prior to final arc-continent collision with the Bahamas platform. The Cuban north-central fold-and-thrust belt exposes deformed clastic to olistostromic sequences of Paleogene age that suggest that the collision between the Caribbean plate with the Bahamas platform occurred in the Middle–Late Eocene (Meyerhoff and Hatten, 1968; Rosencrantz, 1990; Bralower and Iturralde-Vinent, 1997; Iturralde-Vinent, 1998), which would be in line with this postulation.

There is little lithologic and paleontologic documentation published in widely accessible literature about this latest Cretaceous to Late Eocene history, to fully justify the palinspastic inferences of Iturralde-Vinent and García-Casco (2007) and García-Casco et al. (2008a). In this paper, we review the available literature and unpublished reports, and document the Paleogene sedimentary successions of north-central Cuba. We discuss the implications of the Paleogene stratigraphy of the north-central fold-and-thrust belt of Cuba for the timing of the arc-continent collision between the Caribbean plate and the Bahamas.

Geologic Setting

As part of the Circum-Caribbean Orogenic Belt, a fold-and-thrust belt developed in north-central Cuba–Bahamas which is composed of amalgamated rock sections of Jurassic to Eocene age. This belt rests upon the North American Plate, with representatives, from base to top, of the Pangean and Proto-Caribbean, covered by Paleogene clastic successions (Iturralde-Vinent, 1994, 1998, 2006). These are tectonically imbricated and overthrusted by an allochthonous suite derived from the Caribbean plate to the SSW, consisting of Cretaceous subduction mélanges overlying ophiolites of Mesozoic oceanic lithosphere and Cretaceous volcanic arcs suites, and their uppermost Cretaceous–Eocene sedimentary cover (Fig. 1; Pushcharovsky, 1988; Iturralde-Vinent, 1994, 1998; Kerr et al., 1999; García-Casco et al, 2002; 2006).

The Paleocene–early upper Late Eocene clastic successions, developed within imbricated thrust slices derived from the proto-Caribbean crust, have a lithostratigraphy that seems best interpreted as typical for a foreland basin—i.e., basin developed at the front of active thrust belts where the bulk transport direction is toward the basin, and the basin itself became involved in the deformation (Allen and Allen, 1990)—and more specifically a foredeep basin (Bally and Snelson, 1980; Allen and Allen, 1990; DeCelles and Giles, 1996). Within the Caribbean, the foredeep basin developed on top of the proto-Caribbean crust (North American plate), in front of the northeastern leading edge of the Caribbean plate, while this plate overrode the proto-Caribbean crust, and in the process deformed its sedimentary cover.

The tectonic units involved in the Circum-Caribbean Orogenic Belt have been repeatedly deformed during distinct episodes, younging from southwest to northeast, later to the east, creating foreland basin within the North and South American continental margins (Pindell et al., 2006). In Cuba, Bralower and Iturralde-Vinent (1997) studied the Paleocene to Eocene foredeep sedimentary sections of western Cuba, and concluded that it represents a syn-collisional sedimentary record of the collision between the Caribbean and North American plates. Similar studies for central Cuba have not been published in international journals.

In general, the exposure of these Paleogene clastic rock sections in north-central Cuba is poor, and restricted to some road cuts, rivers, or hillsides, where it is sometimes obliterated by karstification. These rocks have been investigated over the last century as part of geological cartography and drilling by petroleum companies (Hatten et al., 1958; Giedt and Schooler, 1959; Pardo, 1975), and during

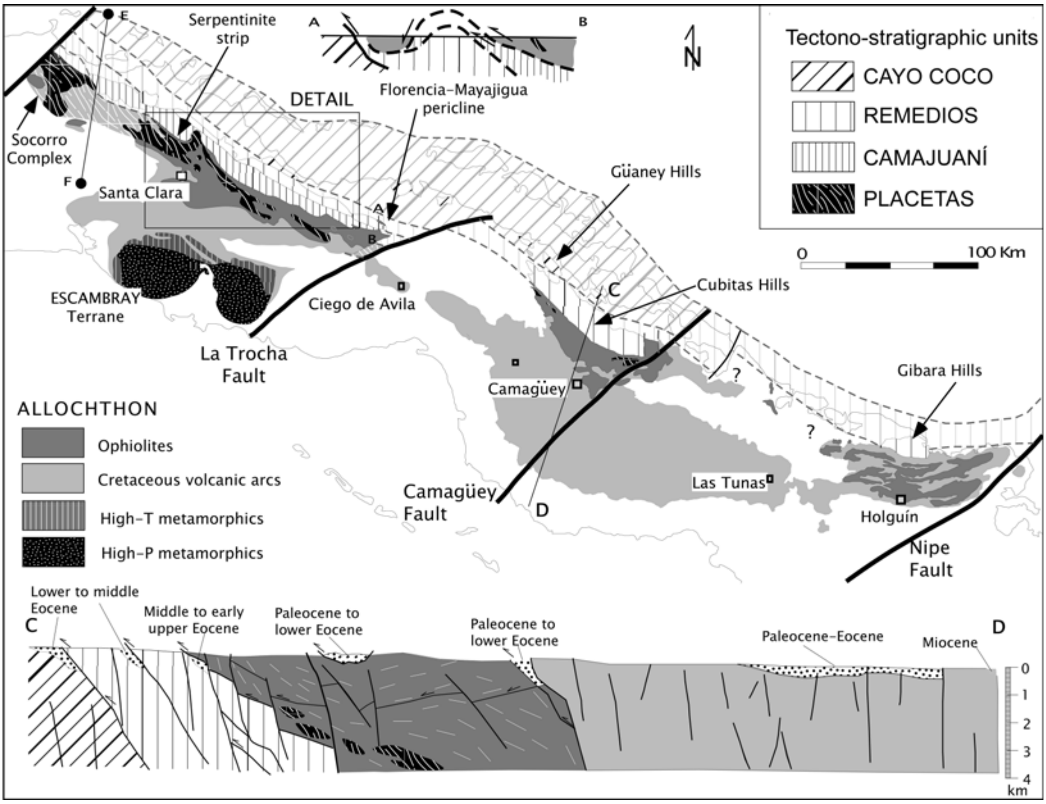

FIG. 1. Simplified tectonic map and cross sections of central Cuba, showing the distribution and tectonic relationships of the north-central Cuba–Bahamas fold-and-thrust belt. Light-colored patterns suggest subsurface prolongation of the northern belts. The C–D cross section is vertically exaggerated 2×1. Simplified from Pushcharovsky et al. (1989).

the last decades as part of the systematic 1:250,000 and 1:50,000 geological mapping of Cuba (Kantshev, 1976; Iturralde-Vinent et al., 1981; Iturralde-Vinent and Thieke, 1986), but the bulk of this information remained unpublished. Several papers have been published derived from this undertaking (Ducloz and Vuagnat, 1962; Khudoley, 1967; Meyerhoff and Hatten, 1968, 1974; Khudoley and Meyerhoff, 1971; Pardo, 1975; Roque Marrero and Iturralde-Vinent, 1982, 1987; Jakus, 1983; Pszczolkowski, 1983, 1986; Hatten et al., 1988; Pushcharovsky, 1988; Pushcharovsky et al., 1989; Díaz et al., 1997; García and Torres, 1997; Pszczolkowski and Myczynski, 2003), but some of these are not easily accessible for the English-language scientific community. We will here synthesize the documentation of the Paleogene sedimentary successions of north-central Cuba and place these deposits in their geodynamic context.

North-central Cuba–Bahamas fold-and-thrust belt

The north-central Cuba–Bahamas fold-and-thrust belt is formed by a stack of imbricate units separated by SSW-dipping thrust faults, exposed along the northern half of the island of Cuba, and also recognized within its shelf (Fig. 1). It forms a series of "en echelon" elongated low hills, trending NW-SE (bearing 120–140°). Early geologists working in this area found that a particular set of Jurassic to Eocene lithostratigraphic formations characterize different stacks of thrust units, each with a distinctive tectonic structure. Consequently, they distinguished several "belts" (Pardo, 1975; see Khudoley and Meyerhoff, 1971 for discussion) or "tectono-stratigraphic units" (Hatten et al., 1988) based primarily on stratigraphy. The more widely accepted subdivision of belts embraces four tectonostrati-

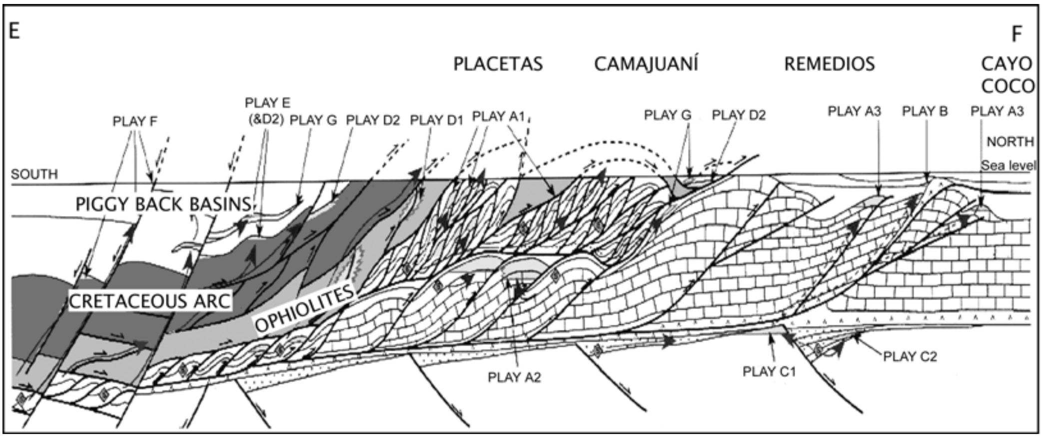

FIG. 2. Structural cross section of the Cuban fold-and-thrust belt (modified from by Rafael Tenreyro, CubaPetroleo). This cross section illustrates the deep detachment surface and the amalgamated thrust nappes between the Bahamas platform and the allochthonous Caribbean plate (serpentinite mélange, ophiolites, and Cretaceous volcanic arc suites). The foredeep basin deposits crown the Mesozoic stratigraphic sections, and represent the seal of the petroleum systems. Location in Figure 1.

graphic units, including from northeast to southwest: Cayo Coco, Remedios, Camajuaní, and Placetas (Ducloz and Vuagnat, 1962; Khudoley, 1967; Meyerhoff and Hatten, 1968, 1974, Hatten et al., 1988). Each tectonostratigraphic unit (TSU) consists predominantly of clastic and carbonate sedimentary rocks of Jurassic–Cretaceous age deposited in a passive margin–oceanic basin setting, covered by Paleocene to Eocene clastic deposits. In general, the Mesozoic sections of the Cayo Coco and Remedios TSU consist of carbonate-platform facies rocks of the Bahamas platform, whereas those to the southwest are representative of the continental slope and rise deep- marine facies (Camajuaní TSU), and the Mesozoic proto-Caribbean basin deposits (Placetas TSU). Description of the Mesozoic stratigraphy of these units is beyond the scope of this paper, but is available in the literature (Ducloz and Vuagnat, 1962; Meyerhoff and Hatten, 1968, 1974; Hatten et al., 1988; Iturralde-Vinent, 1994, 1998; Pszczolkowski and Myczyñski, 2003, and references therein).

Within the north-central fold-and-thrust belt, as illustrated by cross section of Figure 2, the degree of deformation increases from open folds and thrusts that can be explained by a single folding phase in the northeast (Cayo Coco and Remedios TSU) to strongly polyphase deformed rocks in the southwest (Placetas TSU) (Ducloz and Vuagnat, 1962; Meyerhoff and Hatten, 1968; Pardo, 1975; van Hinsbergen et al., 2008). The Cayo Coco TSU exposes large open folds and steep reverse faults, and is partially overlaid by the Remedios TSU. The Remedios TSU is strongly shortened and elongated NW-SE, with a fold-and-thrust structure formed by a stack of NE-verging thrust nappes.

This structure was particularly investigated by detailed mapping in the Cubitas Hills (Iturralde-Vinent and Thieke, 1986), where the Remedios TSU is strongly folded, probably because the thick ophiolite allochthon partially overrode the Remedios TSU. The Camajuaní TSU was strongly contracted and elongated NW-SE, shortening being larger than within Remedios, with tight isoclinal and recumbent folds in a stack of many superimposed thin-skinned thrust nappes as illustrated in Figure 2. In many places it rests tectonically on the Remedios TSU, and even overthrusted it, as in the Florencia-Mayajigua pericline (Fig. 1: cross section A–B). On the other hand, the Camajuaní was totally overridden locally by the ophiolite-volcanic arc allochthon, as geophysical investigations suggest in Camagüey (Fig. 1: cross section B–C; Fig. 2; Iturralde-Vinent and Thieke, 1986).

The maximum extent of deformation is recorded in the Placetas TSU, whose rocks are partially recrystallized in some sections, with very tight folds and a thrust nappe structure forming large NW-SE slivers. Two cross sections in the Camagüey area exemplify the complex internal structure of

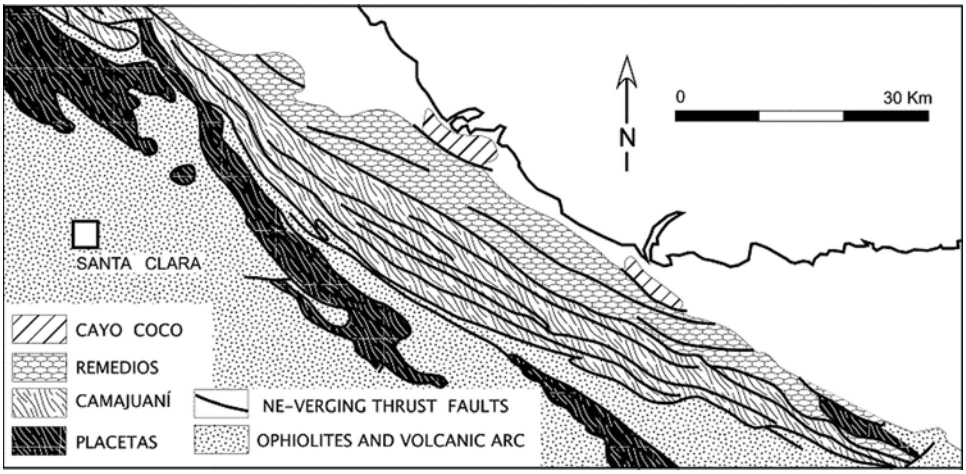

FIG. 3. Detail of the tectonic map of north-central Cuba, to illustrate the structural fragmentation of the tectonostratigraphic units by NW-SE–stacking thrust faults. Note the isolated position of the Placetas unit, as relatively independent bodies incorporated within the allochthonous serpentinite mélange associated with the overriding ophiolites and volcanic arc rocks. Modified from Pushcharovsky et al., 1989. Location in Figure 1.

Remedios and Placetas (Fig. 4). The contact between the Placetas and Camajuaní TSUs is represented by a thrust plane with a strip of serpentinites in the northwesternmost outcrops (Fig 1), suggesting that it is a deep-seated detachment surface (Fig. 2). Notably, southeastward along the trend of the structure, Placetas TSU occurs as a series of tectonic slivers deeply embedded within a strongly deformed serpentinitic mélange, with blocks of HP-metamorphic rocks and blocks of Placetas rocks, as illustrated in Figures 1 and 3 (Pushcharovski, 1988; Iturralde-Vinent, 1981, 1989; van Hinsbergen et al., 2008). This structural pattern has been interpreted as ophiolite slivers that overrode Placetas rocks and subsequently were folded together (see Fig. 2; Meyerhoff and Hatten, 1968), as a result of sinister wrench faulting along the trend of the belt (Iturralde-Vinent, 1981; Ducloz, 1989), but also as Placetas tectonic slivers incorporated into a subduction channel serpentinite mélange (e.g., van Hinsbergen et al., 2008). Placetas nappes may partially overlie the Camajuaní, and the southwestern portion of the Remedios units (Fig. 2). On the other hand, elements of the allochthonous Caribbean plate (serpentinite mélanges, ophiolite and volcanic arc suites) generally have overthrusted the Placetas, but as described above, also overlie both the Camajuaní and Remedios TSUs (Figs. 1–4; Pushcharovsky et al., 1989). The Mesozoic sections of the Placetas, Camajuaní, Remedios, and Cayo Coco TSUs are deformed together with their Paleogene rocks, implying a major Tertiary tectonic event (Meyerhoff and Hatten, 1968; Mattson, 1984; Pszczolkowski and Flores, 1984; Iturralde-Vinent, 1994, 1998).

Stratigraphy of the Paleogene Deposits

The Mesozoic sections in each of the Cayo Coco, Remedios, Camajuaní and Placetas TSUs are covered by Paleocene and Eocene sedimentary rocks representative of the foredeep basin (Figs. 5 and 6). The bulk of the stratigraphic research done in these rocks is not fully available to the general reader (Hatten et al., 1958; Giedt and Schooler, 1959; Kantshev, 1976; Iturralde-Vinent et al., 1981), but its cartographic representation (Pushcharovsky, 1988; Pushcharovsky et al., 1989) and some summary papers (Khudoley and Meyerhoff, 1971; Pardo, 1975; Jakus, 1983; Iturralde-Vinent, 1997, 1998; García and Torres, 1997) have been published. The quality of the stratigraphic and mapping work in the different outcropping areas of the fold-and-thrust belt is good (Pushcharovsky, 1988; Pushcharovsky et al., 1989), but it is most detailed and accurate in the Camagüey area.

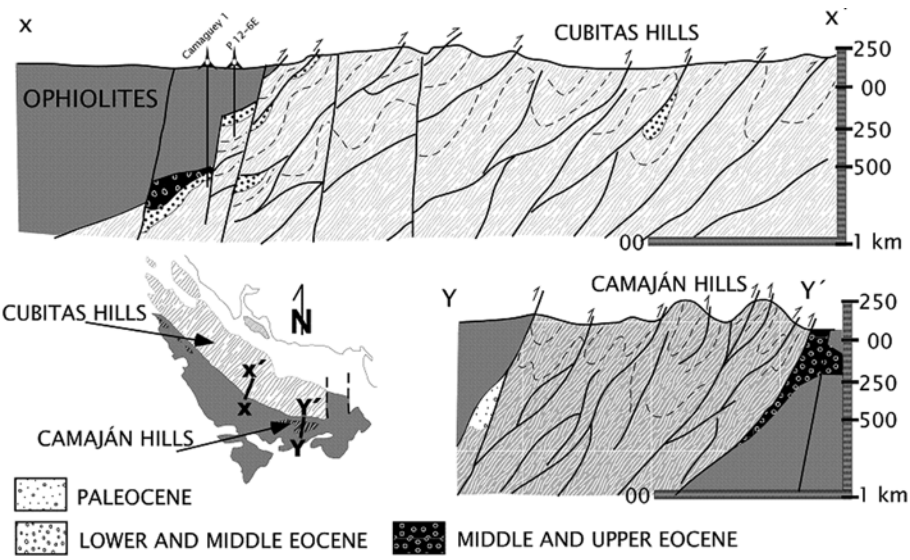

FIG. 4. Schematic cross-sections of the Remedios (Cubitas Hills) and Placetas (Camaján Hills) sequences in Camagüey, exemplifying the complex structure of those areas. Adapted from Iturralde-Vinent et al. (1981).

The age of the Paleogene formations is based on the biostratigraphic scheme presented by Luterbacher et al. (2004), but also taking into account the stratigraphic position and relationships between the units. A more detailed biostratigraphic framework is not possible at this time, inasmuch as most samples of the thick clastic deposits are non-fossiliferous or only contained non-diagnostic taxa, with the exception of the limestone units; moreover, exposures are limited. Figure 5 represents the stratigraphy and tectonic relationships of the Paleogene sections that characterize each tectonostratigraphic unit. The stratigraphic relationships illustrated in Figure 6 show that the same lithology, and in some cases the same stratigraphic formations, can be present in more than one unit, strongly suggesting that they belong to the same sedimentary basin. In this respect, it is interesting to note the presence of calcareous breccia beds (calcirudites and calcarenites in Fig. 6) that were named "Sagua breccia" and described in almost every Paleogene section of the fold-and-thrust belt (Hatten et al., 1958; Giedt and Schooler, 1959). The term is used informally, as it is not a regular stratigraphic unit, and its composition varies laterally (see Figs. 8A and 10).

In this paper, we summarize the stratigraphy of the Paleogene sections within each tectonostratigraphic unit, from northeast to southwest.

Cayo Coco section

The Cayo Coco section crops out in low hills and flat terrain along the north-central part of Cuba (Fig. 1), and has been intersected by many deep on- and offshore wells. The Paleogene section north of Camagüey consists of two stratigraphic units: the Paso Abierto and Venero Formations (Iturralde-Vinent et al., 1981), but north of Santa Clara the equivalent section was subdivided into the Caibarién and Grande formations (Figs. 5–7; Hatten et al., 1958; Kantshev, 1976; García and Torres, 1997).

In northern Camagüey (Fig. 1) according to Iturralde-Vinent et al. (1981), Cretaceous carbonate rocks are topped by an erosional unconformity covered by the Lower Eocene *Paso Abierto Formation*, which has a thickness of about 100 m (Fig. 6). It comprises thick, poorly bedded calcareous breccias (calcirudites) and biodetritic limestones (biocalcarenites) with many rudist fragments. The subrounded to subangular clastic material ranges in size from mm to 15 cm, up to 50 cm, with sparry insterstitial or contact cement. The bulk of the clastic materials are rudist fragments, reworked biodetrital uppermost Cretaceous grains and limestone fragments. The rocks can be locally recrystallized to sparite. Grading upward is the Middle Eocene

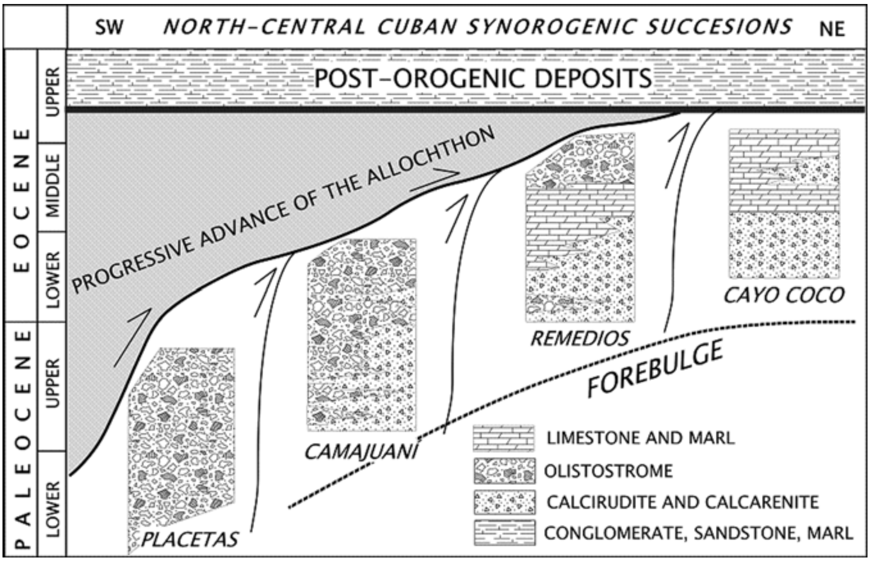

FIG. 5. Generalized relationships between the three main lithofacies of the synorogenic Paleogene deposits. Note that the olistostrome with allochthonous debris has mainly a southwestern provenance, whereas calcirudites and calcarenites (Sagua breccia) with debris are sourced from the carbonate platform located to the northeast. Limestones and marls generally have minor, if any, allochthonous input. Modified from Iturralde-Vinent (1998).

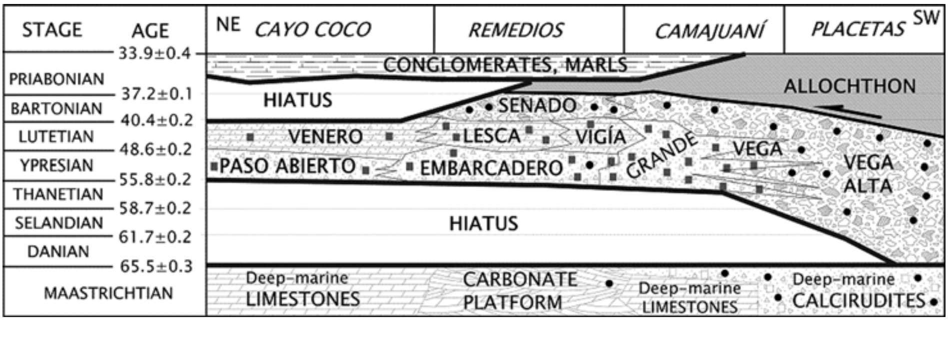

FIG. 6. Composite stratigraphic chart of the Paleogene deposits of north-central Cuba–Bahamas. Dots indicate the presence of allochthonous debris from the ophiolites and, to a lesser extent, Cretaceous volcanic arc rocks. Squares indicate the debris derived from the Bahamas carbonate platform. Time scale after Luterbacher et al. (2004).

Venero Formation, which has a thickness of about 150 m. The transition is represented by detritic and biodetritic limestones and intercalated calcirudites, with fragments less than 1 cm across. It contains isolated globular segregations of diagenetic hyaline flint. The bulk of the formation is characterized by calcirudites with 30 to 40 cm thick beds, containing angular limestone fragments up to 0.5 cm, intercalated with biocalcirudites similar to those of the Paso Abierto Formation, and coarse calcirudite strata with brown flint and limestone fragments. The section contains diagenetic lenses of brown flint, 2–5 cm thick and 20–50 cm long. Higher in the section are more common micrite, biomicrite, and biodetritic limestones with limestone fragments up to 5 cm across, followed by calcirudites with white carbonate platform–derived limestone fragments up to 5 cm across, interbedded with white to pale brown, fine-grained biogenic limestones, in layers 40–60 cm thick. Diagenetic hyaline flint is irregularly present, up to 30% of the rock. The top is eroded.

In general, the deposits can be described as a calcareous mass flow sequence, deposited in sublittoral to bathyal depths, with older clastic and bioclastic material, likely derived from the interior of the Bahamas platform. Fossils in the underlying Paso Abierto Formation are all redeposited from an uppermost Cretaceous carbonate platform; those in the Venero Formation are also reworked uppermost Cretaceous elements, washed away penecontemporaneous biodetritus derived from shallow depths, but also contemporaneous planktonic microfossils. The fossil assemblage (Table 1) suggests a Middle Eocene age for the Venero Formation and an Early Eocene age for Paso Abierto Formation according to its stratigraphic position (Fig. 6).

In the area north of Villa Clara (Fig. 1) Pardo (sensu Kantshev, 1976; García and Torres, 1997) described the Caibarién Formation, which is quite probably an equivalent of both the Paso Abierto and Venero formations of Camagüey. It is of the same age interval and contains similar lithologies and the peculiar hyaline diagenetic flint (Fig. 7), not common in the other belts.

Remedios section

This section crops out in three main regions of northern Cuba as karstic hills and flat terrains southwest of the Cayo Coco sequence (Fig. 1), and has been intersected by many deep onshore wells. The Paleogene section rests with an erosional unconformity on Cretaceous platform carbonate rocks. In Gibara, the Paleogene has been subdivided into three formations (Embarcadero, Vigía and Rancho Bravo)—north of Camagüey it is represented by the Embarcadero, Lesca, and Senado Formations, and north of Santa Clara the equivalent section was mapped as the Grande Formation (Hatten et al., 1958; Kantshev, 1976; García and Torres, 1997).

In Gibara (Figs. 1 and 3; Jakus, 1983; García and Torres, 1997) the *Embarcadero Formation* has a thickness of about 150–200 m, consisting of non-bedded carbonate breccias. Clasts are angular and to less degree subangular, poorly sorted, ranging in size from mm to a few meters, composed of limestones, rudist fragments, dolostones, and chert, with contact cement. Non-reworked fossils have been reported, and its stratigraphic position and correlation with lithostratigraphically similar outcrops in Sierra de Cubitas leads to an estimated age of Early to early Middle Eocene (Fig. 3). The *Vigía Formation* is a well-stratified unit that transitionally overlies the Embarcadero Formation. It has a thickness of about 150 m, but Jakus (1983) reported 700 m, which seems to be *a lapsus calami*. The lower half includes interbedded sandstones, mudstones, marls, and marly limestones; the upper half consists of interbedded white and greenish tuffites, marly limestones, and marls. The fossils (Table 1) suggest an Early to Middle Eocene age (Fig. 3). In the Gibara region, a Middle to Upper Eocene olistostromic unit (the *Rancho Bravo Formation* of Jakus, 1983) overlies the previous unit and seems to be a lithological and temporal equivalent of the Senado Formation described below.

In the Sierra de Cubitas (Figs. 1 and 6; Iturralde-Vinent and Roque Marrero in Iturralde-Vinent et al., 1981; García and Torres, 1997), the following formations have been identified:

Above the Cretaceous, the *Embarcadero Formation*, which has a thickness of about 300 m, rocks rests on an erosional unconformity. It represents a carbonate turbidite sequence formed by thick beds of poorly sorted calcirudites with a few intercalations of calcarenites. Clastic material is angular to subangular, composed of platform limestones, rudist fragments, dolostones, and some chert, with contact cement (Fig. 8A).

In one locality, at the eastern termination of Sierra de Cubitas, a layer of breccio-conglomerates was found with assorted clastic material including both calcareous angular fragments and rounded to well-rounded igneous rocks (serpentinites, gabbroids, and volcanics), derived from the allochthonous overriding units. Its age is Early to early Middle Eocene according to the fossils in the calcarenites (Table 1).

Transitionally overlying the Embarcadero Formation rests a fine-grained calcareous turbidite sequence, the *Lesca Formation* (Iturralde-Vinent and Roque Marrero in Iturralde-Vinent et al., 1981) which has a thickness of about 150 m. It consists of well-bedded upward sorted biogenic and biodetritic limestones with red cherts, intercalating with calcirudites, marls, sandstones, and some tuffites (Fig. 8B). It differs from the Vigía Formation in having only a few tuffites and sandstones. Lower Middle Eocene fossils are abundant (Table 1). The pyroclastic material in both the Vigía and Lesca formations is likely derived from the activity of the Danian–

TABLE 1. Fossils and Age of the Paleogene Formations of the North-Central Fold-and-Thrust Belt[1]

Fossils/formations:	Vega Alta	Vega	Grande	Paso Abierto	Embarcadero	Lesca	Vigía	Venero
Stratigraphic range:	Paleocene	Upper Paleocene-Lower Eocene		Lower Eocene	Lower to Middle Eocene			Middle Eocene
Amphistegina cf. A. pregrimsdalei					XXX			
Amphistegina cubensis								XXXX
Amphistegina lopeztrigoi					XXX		XX	XXXX
Amphistegina parvula								XXXX
Asterocyclina habanensis								XXXX
Asterocyclina monticellensis								XXXX
Asterocyclina sp.					XXX			XXXX
Cushmania americana							XX	XXXX
Fallotella floridana					XXX			
Discocyclina barkeri		XXX	XXXX					
Discocyclina spp.		XXX			XXX			XXXX
Eoconuloides wellsi			XXXX		XXX			XXXX
Eorupertia bermudezi								XXXX
*Fabiania cassi*s								XXXX
Fabiania cubensis								XXXX
Fallotella cookei							XX	
Gypsina globularis								XXXX
Lepidocyclina spp.								XXXX
Nummulites sp.								XXXX
Pseudophragmina (Proporocyclina) cedarkeyensis		XXX	XXXX					
Pseudophragmina baindridgenensis					XXX			
Pseudophragmina spp.								XXXX
Acarinina pentacamerata							XX	
Acarinina bullbrooki		XXX					XX	
Acarinina soldadoensis			XXXX					
Turborotalia cerroazulensis s.l.								XXXX
Globanomalina aff. G. wilcoxensis								XXXX
Globigerinatheka mexicana kugleri					XXX			
Globigerinatheka sp.								XXXX
Globigerina triloculinoides	XXXX							
Morozovella cf. M. acuta	XXXX				XXX			
Morozovella aequa		XXX	XXXX		XXX			
Morozovella angulata		XXX	XXXX					
Morozovella aragonensis		XXX	XXXX		XXX		XX	XXX
Morozovella conicotruncata	XXXX							
Morozovella formosa							XX	
Morozovella lehneri					XXXX			XXXX
Morozovella velazcoensis		XXX	XXXX				XX	
Morozovella spinulosa								XXXX
Planorotalites pseudomenardii			XXXX					
Truncorotaloides topilensis					XXXX			XXXX
Kainoconus ovalis					XXXX			
Braarudosphaera bigelowi					XXXX			
Distichoplax biserialis					XXXX			
Lithonella floridana					XXXX			
Spongiodiscus quartus					XXXX			
Theocotyle sp.					XXXX			
Xophospira circularis					XXXX			
Mollusk's fragments								XXXX
Equinoderm's fragments								XXXX
Coral's fragments								XXXX
Reworked rudist fragments		XXX		XXXX				XXXX
Radiolaria							XX	

[1]Time scale after Luterbacher et al. (2004). Senado Formation is not listed because it contains only reworked Lower Eocene and older rocks fragments.

Sources: Compiled from Kantshev, 1976; Iturralde-Vinent, et al., 1981; Jakus, 1983; García and Torres, 1997.

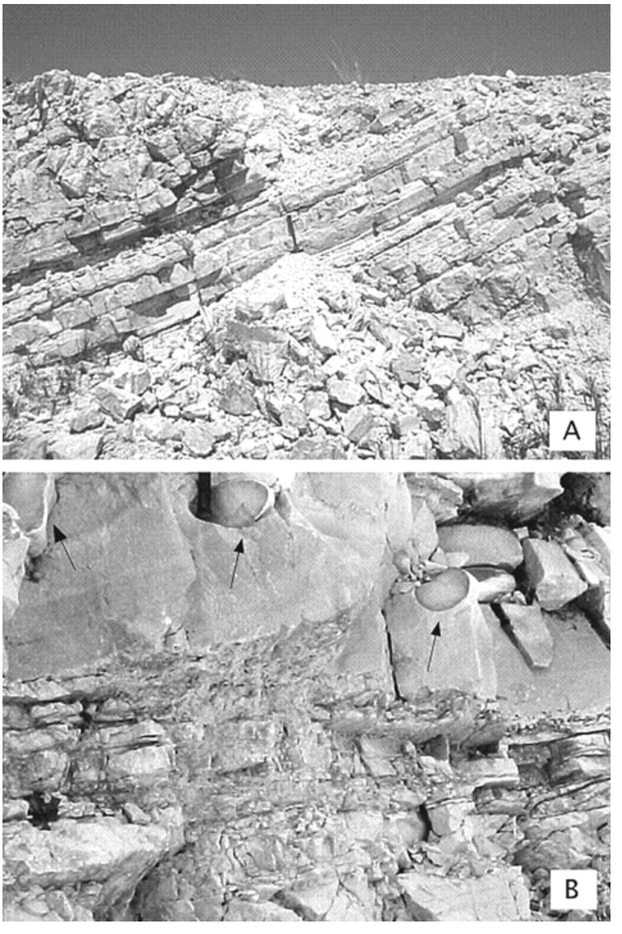

FIG. 7. Paleogene Cayo Coco section, Caibarién Formation (Venero and Paso Abierto equivalent). A. Well-bedded calcarenites of the upper part of the section. B. Hyaline cherts in the calcarenites. Sierrezuela, Villa Clara.. Photographs courtesy of Rolando García.

Middle Eocene Cayman–Sierra Maestra volcanic arc (Iturralde-Vinent, 1994, 1998).

Above the Lesca Formation rest is the *Senado Formation*, originally defined as a "tectonic-sedimentary breccia" by Giovanni Flores in an unpublished report, and formalized by Iturralde-Vinent (1984). Its thickness ranges from few meters to several hundreds and even 1000 m. Two types of sections can be recognized, which were distinguished as the El Cercado and Máximo members (Iturralde-Vinent in Iturralde-Vinent et al., 1981). The formation is unconformably overlain by uppermost Eocene rocks (Fig. 6).

The El Cercado member is formed by well-bedded to massive serpentinitic sandstones and conglomerates, with a few gabbroids and rare limestone pebbles. Clastic material is well rounded and cemented by very fine grained serpentinitic sand. It is well exposed in the southeastern termination of Sierra de Cubitas (El Cercado), and was intersected by a well drilled just south of Sierra de Cubitas. Its transition with the limestones of the Lesca Formation takes place in a couple of meters from pure limestones into well-sorted sandy limestones, calcareous sandstones, and monotonous serpentinitic sandstones, suggesting a distal depositional setting. South of Sierra de Cubitas the sandstones are tectonically covered by the allochthonous serpentinitic mélange (Fig. 4).

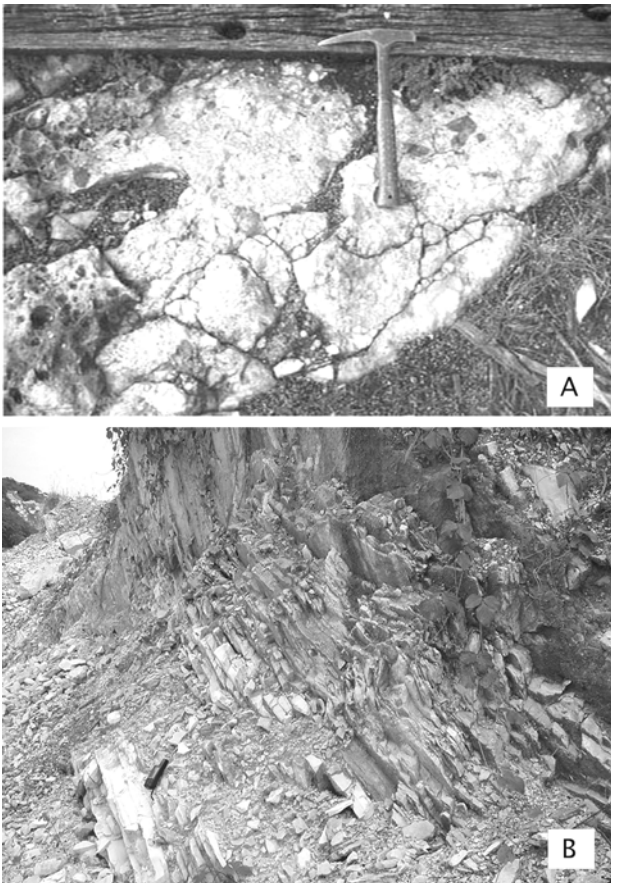

FIG. 8. Paleogene Remedios section. A. Strata of flint, limestone, and flint breccia of the Embarcadero Formation. B. Well-bedded limestones of the Lesca Formation. Sierra de Cubitas Hills, near Esmeralda, Camaguey. Photographs courtesy of Rolando García.

Outcrops along the eastern termination of Sierra de Cubitas also show limestones of the Lesca Formation transitionally covered by the Máximo member. The Máximo member is the true olistostromic part of the Senado Formation. Lithologically, it is a very thick bedded to massive olistostrome, with very large (up to 1 km long) olistoliths of foliated serpentinites and strongly deformed uppermost Jurassic and Cretaceous deep-marine limestones and cherts of the Mesozoic Placetas succession. The matrix consists of well-cemented breccio-conglomerate composed of rounded and subrounded sand and gravel. Some of the volcanic pebbles are coated by a calcareous crust, or are deeply weathered, suggesting that the elements were derived from the extinct Cretaceous volcanic arcs, and were exposed and transported over large distances. The serpentinitic and gabbroic pebbles are generally poorly rounded and subangular, suggesting transportation from a nearby source, probably near the thrust front. A clear separation between the debris derived from the allochthonous and local sources does not exist, but the first definitely dominates. Typically, olistoliths and olistoplates of allochthonous ophiolites rest on top of the unit that is unconformably covered by non-deformed uppermost Eocene conglomerates and marls (Pushcharovsky, 1988; Iturralde-Vinent, 1994, 1995).

The Senado Formation lacks non-reworked fossils, but it can be dated as late Middle Eocene to early Late Eocene, according to its stratigraphic position and because it contains some pebbles of

FIG. 9. Paleogene Camajuaní and Placetas sections. A. Green-colored flyschoid sections of the Vega Formation, representing a matrix of the olistostromes, with abundant clastics derived from ophiolites and a volcanic arc. Excavation at the Florencia artificial lake. B. Boulders of limestones and breccias of the Vega Alta Formation, near El Copey, Villa Clara. Photographs courtesy of Rolando García.

Early Eocene biocalcarenites (Fig. 6; Iturralde-Vinent et al., 1981).

The Paleogene Remedios section has been described in a slightly different manner northeast of Santa Clara (Figs. 1 and 3; Kantshev, 1976; García and Torres, 1997). It includes only two stratigraphic units: the Grande Formation, which probably encompass the different units described in the Camagüey region, and the Vega Formation, which is more widespread and representative for the Camajuaní section (Figs. 1 and 6). The *Grande Formation* was defined by Pardo (*sensu* Kantshev, 1976; García and Torres, 1997). It has an assumed thickness between 170 and 530 m (probably exaggerated), being a lateral temporal and lithological equivalent of the Embarcadero and Lesca formations, but it lacks tuffites. Lithologically it consists of massive to coarse-bedded calcareous breccia (Fig. 9B) and breccio-conglomerates, intercalated with layers of biogenic limestones and detritic, micritic, and marly limestones. Angular limestone, dolostone, and flint fragments in the breccias vary from a few mm to 10 cm. Within the biogenic limestones, fossil remains of late Paleocene to early Eocene age are present (Table 1).

Camajuaní section

The Camajuaní Paleogene section is represented by the Vega Formation, which grades laterally and northeastward into the Upper Paleocene to Lower Eocene Grande Formation (Remedios section). This Paleogene section crops out along NW-SE elongated strips capping Jurassic to Maastrichtian marine rocks (Kantshev, 1976; Pushcharovsky et al., 1988). This olistostromic unit is covered in this part of the belt by thrust-faulted tectonic slivers of both the Placetas and Camajuaní Mesozoic and Paleogene rocks.

The Upper Paleocene to Lower Eocene *Vega Formation* was described by Pardo (sensu Kantshev, 1976; García and Torres, 1997). It has a thickness estimated at several hundreds of meters. Lithologically this section resembles the Senado Formation, but differs in having numerous thick beds of calcirudites and huge olistoliths several kilometers across. The calcirudites (Sagua breccia) contain limestone, dolostone, and flint fragments likely derived from a carbonate platform to the northeast. The olistoliths are mostly fragments derived from the southwest, represented by Camajuaní Mesozoic rocks (Mata, Margarita, and Paraiso formations; Kantshev, 1976; Pushcharovsky, 1988). The matrix of the olistostrome is locally composed of breccio-conglomerates but generally by sandstones with clastic material derived from the allochthonous ophiolites and Cretaceous volcanic rocks to the southwest. Green sandstone-shale flysch units, which reach thicknesses of several tens of meters, are intercalated with the olistostrome (Fig. 9A). The Vega Formation contains Upper Paleocene to Lower Eocene microfossils of penecontemporaneous shallow- and deep-marine environments, with reworked Cretaceous elements (Table 1). This, and the presence of distal turbidites, suggests that the environment of deposition was a deep-water basin connected to the open sea.

Placetas section

The Paleogene Placetas section is represented by the Paleocene *Vega Alta Formation*, which grades laterally and northeastward into the Upper Paleocene to Lower Eocene Vega Formation (Camajuaní section). This Paleogene section, which closely resembles the Senado Formation, crops out along NW-SE–elongated strips crowning the Jurassic to Maastrichtian marine rocks (Kantshev, 1976; Pushcharovsky et al., 1988; Pszczolkowski and Myczyñski, 2003). It is a typical olistostrome covered by—and intermingled with—tectonic slivers of both the older Placetas sequence, and the allochthonous ophiolite and Cretaceous volcanic arc suites (Figs. 1, 2, and 3).

The thickness of the Vega Alta Formation is roughly estimated at more than 200 m, but this figure seems to be a minimum. It was introduced in Kantshev (1976) to characterize the Paleogene section that crowns the Placetas Mesozoic stratigraphic column (Fig. 5). The matrix of the olistostrome consists of sandy shales, sandstones, conglomerates, and some breccias, which yield few Paleocene planktonic microfossils (Table 1), suggesting deposition in bathyal to sublittoral marine environment. Clastic material in the Vega Alta includes olistoliths and large boulders of tectonic slices detached from the Mesozoic Placetas section, represented by the uppermost Jurassic and Cretaceous Formations (Fig. 9B; Kantshev, 1976). The breccia layers, up to 2–3 meters thick, contain angular fragments of limestones and flint of the same stratigraphic range (Sagua Breccia; Fig. 10). Conglomerates and sandstones contain fragments of serpentinite, volcanics, and few metamorphics rocks that have not been described in detail.

Sediment Provenance and Basin Evolution

General statement

The following analyses of the peculiarities of the foredeep sediments provides useful information to place the evolution of the basin in its regional tectonic context. In general, the following two general provenance areas and four detrital sources can be identified:

Provenance area A: Caribbean plate: (1) Cretaceous volcanic arc; (2) ophiolites and serpentinitic mélanges.

Provenance area B: North American plate: (3) Jurassic and Cretaceous rocks of the Placetas and Camajuaní TSUs; (4) Cretaceous carbonate platform (limestones, dolostones, and flints) of the Bahamas platform (Remedios and Cayo Coco TSUs and northern successions) (Table 2, Fig. 6).

The components derived from the leading edge of the Caribbean plate (Cretaceous volcanic arcs, serpentinitic mélanges, and ophiolite) are allochthonous, in that they do not belong to the North American plate. The pattern of distribution in terms of age, size, and volume of the allochthonous component in the Paleogene basin is very important for constraining interactions between this source and

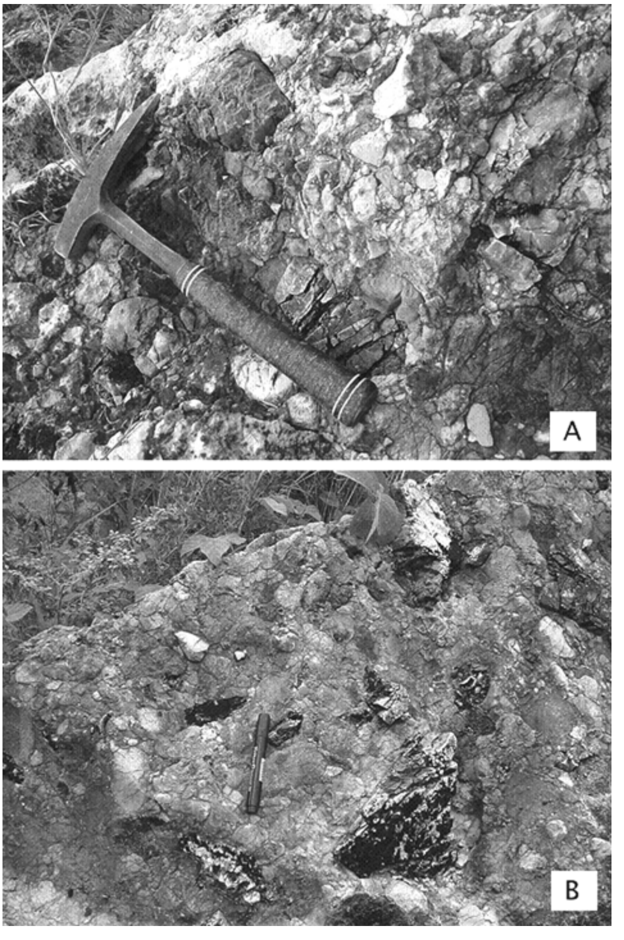

FIG. 10. Paleogene Placetas succession. A and B are two aspects of the "Sagua Breccia" of the Vega Alta Formation, near Los Ramones, Villa Clara. The clasts are mainly flint and limestones. Photographs courtesy of Evelio Linares.

the basin (Table 2). In terms of age, the first allochthonous input into the foredeep took place in the Early Paleocene, within the Placetas section. This event was followed by a more important input during the Early Eocene that reached farther northeast to the Camajuaní section, and even minor amounts of this debris reached the Remedios section locally in the Cubitas Hills (Figs. 5 and 6). Later in the Middle to Late Eocene, large amounts of these clastics filled the basin as far as the Remedios section, which we interpret as a response to the emplacement of thick ophiolite and volcanic arc thrust sheets, ending the frontal collision between the Caribbean and the North American plates along the NW-SE edge of Bahamas (Figs. 2 and 5). Interestingly, the Cayo Coco stratigraphic section was never reached by allochthonous debris from the Caribbean plate, suggesting that a combination of physical barrier and distance between the Remedios and Cayo Coco parts of the foredeep basin controlled the arrival of debris from the southwest. Another important consequence derived from the analysis of this source of material, is that the first and larger allochthonous input from the southwest is represented by serpentinized mafic and ultramafic rocks. The same conclusion was reached by Iturralde-Vinent (1988, 1994, 1998) in the example of the Paleogene synorogenic deposits of westernmost Cuba (Guaniguanico terrane). Consequently, it can be accepted that the first allochtonous tectonic element that interacted with and overrode the foredeep basin were large slivers (olistoliths) of oceanic lithosphere and Cretaceous subduction mélanges.

Eroded debris, large boulders, and olistoplates of ophiolites and subduction mélanges are also present in uppermost Cretaceous–lower Danian deposits formed in piggyback basins above the extinct Cretaceous deformed volcanic arcs suite (Bralower and Iturralde-Vinent, 1997; Iturralde-Vinent, 1994, 1998; Pszczolkowski and Myczyñski, 2003). This evidence suggests that these rocks of the Caribbean plate were at the Earth's surface by the end of the Cretaceous. On the other hand, the Maastrichtian rocks underlying the foredeep basin sections in north-central Cuba only rarely contain grains of igneous and volcanic rocks (Kantshev, 1976; Iturralde-Vinent et al., 1981), suggesting that, during this time interval, some kind of barrier—physical or distance—existed between the volcanic arc-ophiolite suites (Caribbean plate) and the Placetas, Camajuaní, and Remedios depositional areas on the proto-Caribbean basin (North American plate). According to Iturralde-Vinent and García-Casco (2007), this barrier is interpreted as a submarine promontory extended off the Maya Block within the proto-Caribbean (North American) plate, which they named "Caribeana." Present-day representatives of Caribeana occur as HP-metamorphic terranes along the circum-Caribbean orogeny, between Yucatán and the Virgin Islands (García-Casco et al., 2008a).

The clastic component in the Paleogene rocks, sourced from the Jurassic and Cretaceous rock sections of the Placetas, Camajuaní, Remedios, and Cayo Coco stratigraphic succesions also shows a definite pattern of distribution (Table 2). Large boulders up to olistoplates are present from the Paleocene upward in the Placetas and Camajuaní sections (Fig. 10B), and reached the Remedios section only during the late Middle to early Late Eocene. This particular component was sourced without subjection to subaereal weathering, from the underlying Mesozoic Placetas and Camajuaní sections within the foreldeep basin, strongly suggesting that detachment and separation of tectonic slivers from the Placetas and Camajuaní sections took place since the very beginning of the evolution of the foredeep basin. It also suggests that the basin was being deformed from its southwestern edge toward the northeast during sedimentation, driving a northeastward migration of the depocenter. Taking into account that the basin is presently deformed and its original morphology lost (Figs. 1 and 2), the facts

TABLE 2. Classification of Clastic Materials according to Size and Composition[1]

Source/formations:	Vega Alta	Vega	Grande	Embarcadero	Lesca	Vigía	Paso Abierto	Venero	Senado	Rancho Bravo
Thickness:	≥200 m	≥200 m	530 (?) m	300 m	150 m	150 m	100 m	150 m	1 km	?
Cretaceous volcanic arcs	Peb.	Sand.		Sand.					Peb., Sand.	Peb., Sand.
Ophiolite and serpentinitic mélanges	Olist.	Sand.		Peb., sand.					Olist., Peb.	Olist., Peb.
Cretaceous carbonate platform	Peb.	Peb.	Peb.	Peb., bould.	Sand., peb.	Sand., peb.	Peb., sand.	Peb., Sand.		
Jurassic and Cretaceous rocks of the Camajuaní and Placetas sections	Olist., Bould.	Olist.		Peb.					Olist., Bould., Peb.	Olist., Bould., Peb.
Stratigraphic range:	Paleocene	Upper Paleocene– Lower Eocene		Lower to Middle Eocene			Lower Eocene	Middle Eocene	Middle–Upper Eocene	Middle-Upper Eocene

[1]Abbreviations: olist.= olistolith and olisthoplate; bould. = boulder; peb. = pebble; sand.= sandy grains.

that olistostrome deposits are the thickest in each section, and become younger from Placetas to Remedios, corroborate the shifting of the axis of subsidence, which we interpret as northeastward advance of the thrust front, as postulated in Figure 5 and Table 2.

The clastic component derived from the interior of the Bahamas Cretaceous carbonate platform is very common in the foredeep, and displays an interesting pattern of distribution. It is mainly derived from Upper Cretaceous rocks and fossils, and represents the only clastic-carbonate component in the Cayo Coco section. It is also widely represented southwestward in the Remedios section, where its composition is diverse in terms of age and lithology, suggesting deeper erosion of the carbonate platform. Furthermore, this clastic component wedges out to the southwest, and is almost absent in the Placetas section (Figs. 5 and 6).

Comparison with Western Cuba

Western Cuba exposes a Paleogene synorogenic foredeep section in the Guaniguanico terrane (Pszczolkowski, 1978; Iturralde-Vinent, 1994, 1998) whose age and composition were investigated by Bralower and Iturralde-Vinent (1997). These studies demonstrate that, comparable to the Camajuaní section of central Cuba, the synorogenic deposits of Guaniguanico are Late Paleocene to early Middle Eocene in age, including thick olistostromes dominated by pebbles to boulders and olistoplates of serpentinites, gabbroids, and elements of Cretaceous subduction mélanges (García Casco et al., 2006), intermingled with debris derived from the underlying Mesozoic and Danian sections. Another similarity with the Camajuaní section is the strong level of fold-and-thrust deformation of the NNW-verging Guaniguanico tectonic stack, embracing both Mesozoic and Paleogene rocks (Pszczolkowski, 1978, 1999). This serves to illustrate that the basin evolution we inferred from central Cuba has regional geological importance, including at least also western Cuba.

Basin Analysis and Plate Tectonic Implications

The analysis of the age, composition, and deformation of the foredeep basin deposits in Cuba reveals key aspects of North American–Caribbean plate interactions. For this purpose we here consider the Cretaceous volcanic arcs, ophiolites, and subduction channel mélanges cropping out in central Cuba as representatives of the northeastern leading edge of the Caribbean overriding plate. The north-central fold-and-thrust belt is regarded as the deformed proto-Caribbean segment of the North American plate. In this respect, during the Mesozoic, the Cayo Coco and Remedios parts of the belt represent the southwestern edge of the Bahamas platform facing the proto-Caribbean crust, whereas the Camajuaní and Placetas TSUs represent the continental slope, rise and basin deposits of the proto-Caribbean basin (Fig. 1; Iturralde-Vinent, 1994, 1998; Kerr et al., 1999; Pindell and Kennan, 2001). Based on this palinspastic configuration, it is possible to analyze relationships between both plates taking as a base the evidence derived from the lithostratigraphic analysis of synorogenic rocks in the foredeep.

The sediments filling the Paleogene foredeep basin, as demonstrated above, are largely clastic with material of very different sizes and roundness, including olistostromes and flysch, younging from southwest to northeast, as indicated in Figures 5 and 6. We interpreted this basin as a typical foredeep (*sensu* Allen and Allen, 1990), which is now a stack of thrust slivers tectonically imbricated along thrust faults that dip subparallel to the subduction zone. The northeastward younging trend of the foreland basin deposits in the imbricated thrust stack shows that, with time, the depocenter migrated northeastward, as a result of progressive northwestward incorporation of thrust slices in the fold-and-thrust belt, and the consequent northeastward stepping of the subduction zone. These basins are characterized as having a dual sediment source (Bally and Snelson, 1980), fully in accordance with the composition and diachronous trend of the foredeep deposits as described above.

The crust underlying the foredeep basin

A typical foredeep basin was created and filled as a result of continent-continent collision, developed, according to Bally and Snelson (1980), within an "A-subduction scenario." Intra-oceanic subduction zones leading to arc-continent collision upon arrival of a continent in the trench are typically not characterized by major foreland basin deposits, because the overriding plate is normally largely submerged, but exceptions occur.

Palinspastic reconstructions of the original width of the proto-Caribbean ocean in the Maastrichtian range from 900 to 1200 km, so its southwestern edge reached as far as present Central America (Pindell and Kennan, 2001, Iturralde-Vinent, 2006). This entire paleogeographic area was reduced to the present fold-and-thrust belt, whose width does not exceed a few tens of kilometers (Fig. 1). The Proto-Caribbean crust therefore likely underthrusted below the oceanic Caribbean plate. However, for our paleogeographic analysis, it is important to note that in one locality northwestward within the Placetas TSU (Fig. 1), the Socorro complex, composed of Neoproterozoic rocks, underlies the Placetas section (Pszczolkowski, 1986; Renne et al., 1989). At the southeastern edge of the outcrops of Placetas TSU (Sierra de Camaján; Figs. 1 and 4), upper Jurassic continental margin basalts occur (Iturralde-Vinent and Marí-Morales, 1988), suggesting eruption within an extensional continental environment (Iturralde-Vinent, 1988). Additional clues are provided by Paleozoic and Neoproterozoic continental debris reported from Mesozoic sedimentary rocks in the Placetas and other sections, and especially a thick quartz-rich clastic unit derived from a continental source (Constancia Formation) that underlies the uppermost Jurassic Placetas rocks (Meyerhoff and Hatten, 1968; Pardo, 1975; Somin and Millan, 1981; Pszczolkowski, 1986; Renne et al., 1989). Therefore, it can be suggested that the Proto-Caribbean may had had an extended thin continental and oceanic crust.

On the other hand, the oceanic crust of the Caribbean plate is anomalously thick as the result of mantle plume–produced flood basalts, leading to the formation of the Caribbean plateau basalt (Pindell, 1990) with an age of ~91–88 Ma (Sinton et al., 1998). For these reasons, the overriding oceanic plate was abnormally thick, allowing the formation of a flexural foredeep and erosion of the overriding plate, so that the arc-continental collision between the Caribbean plate and the Bahamian platform (North American plate) took place in geodynamic conditions resembling those of ocean-continent to continent-continent collision, as characterized by the A-subduction scenario described by Bally and Snelson (1980) as typical to produce a foredeep basin with mass-flow deposits on top of the downgoing slab.

Forebulge development

The consistent unconformities between the open marine series and the foredeep deposits in the Placetas, Camajuaní, Remedios, and Cayo Coco sections leads us to propose that these units were uplifted in a forebulge prior to their subsidence into the foredeep, in response to the interaction between the allochthon (Caribbean plate), approaching from the southwest, and the proto-Caribbean crust underthrusting the Caribbean plate toward the southwest (Iturralde-Vinent, 1998). The presence of this forebulge is also suggested by the hiatus related to the lack of Paleocene deposits in the Cayo Coco and Remedios sections, which, in contrast, are well developed in the Placetas section (Figs. 5 and 6), and the thin overall thickness of the Cayo Coco section (Iturralde-Vinent, 1998; Table 2). Based on the composition and lithology of the calcirudite facies with clastics of the Cretaceous carbonate platform, it can be argued that the forebulge exposed the deeper part of the Bahamian stratigraphic sections, possibly due to horst-and-graben tectonics, facilitating the incorporation of these materials in the foredeep basin deposits. The angular shape of the carbonate pebbles, showing no sign of long-term subaerial exposure, and the rare matrix and poor sorting of these breccias also suggest that they were deposited by submarine debris flows along channels cutting into the slope of the forebulge, providing a collection of debris from different ages and lithologies (Figs. 5 and 6).

Origin of the fold-and-thrust belt

The north-central Cuba–Bahamas fold-and-thrust belt is the consequence of detachment and off-scraping, and accretion of sedimentary slivers that once overlay the subducting proto-Caribbean plate, onto the thick Bahamian continental crust and carbonate platform. Sediment input into the original Placetas basin clearly indicates that the Caribbean plate was already interacting with the proto-Caribbean basin during the very beginning of the Paleocene. Afterwards, tectonic elements and debris derived from the Caribbean plate started filling the proto-Caribbean basin as the foredeep basin migrated northeastward, and sedimentation ended when the allochthonous thrust sheets covered the basin, or the basin subducted below the allochton. In any case, the allochthon overrode the Placetas section near the end of the Paleocene, the Camajuaní section by the end of the Early Eocene, and the Remedios part of the basin by the beginning of the Late Eocene (Figs. 5 and 6).

In this process, the entire sedimentary section of the basin was subsequently deformed, starting with the Placetas TSU and ending in the Cayo Coco TSU . This is the reason why the number and degree of

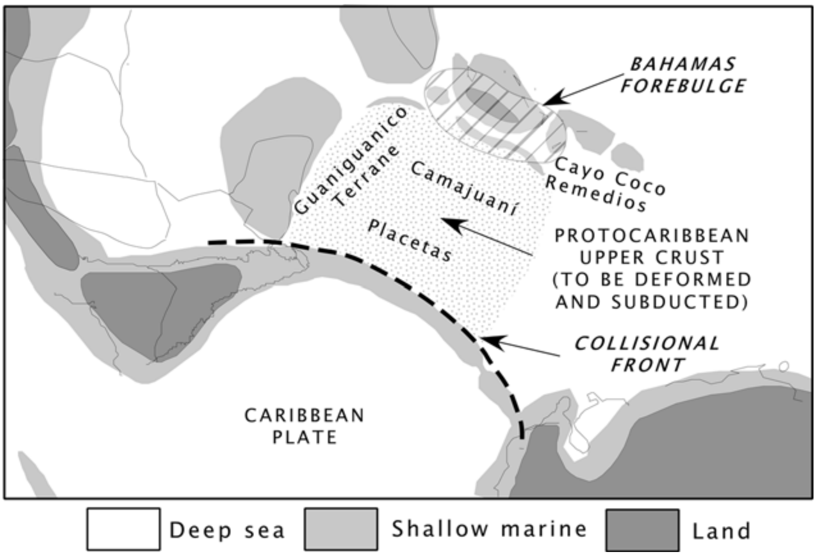

FIG. 11. Paleogeographic sketch of the Caribbean realm showing the position of the collisional front at the end of the Cretaceous. The assumed position of the different successions in the original foredeep basin is illustrated, as well as the Paleocene forebulge.

deformations of Placetas rocks is strongest (Figs. 1–4), as described above and demonstrated by structural studies in Camagüey (van Hinsbergen et al., 2008).

As was argued before, the Caribbean plate collided during the latest Cretaceous–Early Paleocene with the Pacific margin of the North and South American plates (Pindell and Kennan, 2001; Iturralde-Vinent and Lidiak, 2006), as well as with Caribeana (García-Casco et al., 2008a). After this event, the continental margins and internal sections of the proto-Caribbean basin off the Bahamas and off Yucatán were deformed between the Paleocene and the early Late Eocene, as part of the foredeep basin. The proto-Caribbean crust underthrusting the Caribbean plate was depressed near the subduction zone, and a flexural bulge produced a forebulge migrating together with the foredeep towards, and including the Bahamian platform, embracing the Cayo Coco, Remedios, and partially the Camajuaní TSUs (Fig. 11). This forebulge lasted only the Paleocene, because the slab was soon stabilized by subsidence, while the axis of the depocenter migrated northeastward, contemporaneously with the migration of the leading edge of the Caribbean plate. This process ended, probably, due to the impossibility of underthrusting the thick, buoyant Bahamian continental crust and carbonate platform. As a consequence, tectonic shortening and amalgamation of the sedimentary piles and uppermost crust ended, and the fold-and-thrust belt remained attached to the Bahamas since the end of the Eocene, as demonstrated above (see Figs. 6 and 11). If one accepts the palinspastic reconstructions of Pindell and Kennan (2001) and Iturralde-Vinent (2006), this age span allows a rough estimate of plate convergence rate of around 3 cm/year.

Conclusions

Along the northeastern part of Cuba and its shelf, a fold-and-thrust belt exposes deformed Jurassic to Upper Eocene sedimentary sections with a degree of deformation and shortening increasing from northeast to southwest. This fold-and-thrust belt encompasses four juxtaposed tectonostratigraphic units, which from southwest to northeast include the Placetas, Camajuaní, Remedios, and Cayo Coco sections, each distinguished according to stratigraphy. In particular, the Paleogene synorogenic deposits capping the Mesozoic sections display a number of sedimentary and structural features recording Caribbean–North American plate collision.

The foredeep basin evolved on the downgoing slab with thin extended continental crust (proto-Caribbean crust of the North American plate), being overridden by the Caribbean plate with anomalously thick oceanic crust (Caribbean plateau basalts). The thick, elevated Caribbean plate allowed the long-term evolution of foredeep basins on top of the subducting North American plate (Proto-Caribbean), followed by arc-continent collision in the early Late Eocene.

This collision is very well illustrated by the variations in age, size, composition, and provenance of the clastic materials, by the age span and composition of the olistostromes crowning the stratigraphic sections, and by the progressive development of fold-and-thrust deformation and basin filling from southwest to northeast between the Paleocene and early late Eocene. During this time span, the Placetas, followed by the Camajuaní subsided as a foredeep and the Remedios and Cayo Coco were uplifted in a forebulge. This Paleocene event was followed by underthrusting of Placetas, Camajuaní, and Remedios below the allochtonous Caribbean plate. Uppermost Eocene, slightly deformed marine deposits unconformably drape previous rocks and structures, marking the end of arc-collision in western and central Cuba.

Acknowledgments

This is a contribution to IUGS-UNESCO IGCP Project 546, Subduction Zones in the Caribbean. Field and laboratory work was partially supported by Cuban Project PNCT 01301179 Geología y Palaeogeografía de Cuba to M. Iturralde Vinent and Spanish MEC project CGL2006-08527/BTE Metamorphic evolution in convergent plate margins: From onset of oceanic subduction to arc-continent collision in the northern margin of the Caribbean Plate, Cuba to A. García-Casco. DJJvH acknowledges an NWO-VENI grant of the Dutch Council for Scientific Research.

REFERENCES

Allen, P. A., and Allen, J. R., 1990, Basin analysis. Principles and applications: Oxford, UK, Blackwell Scientific, 451 p.

Bally, A. W., and Snelson, S., 1980, Realms of subsidence, *in* Miall, A. D., ed., Facts and principles of world petroleum occurrences: Canadian Society of Petroleum Geologists Memoir 6, p. 9–94.

Bralower, T. J., and Iturralde-Vinent, M. A., 1997, Micropaleontological dating of the collision between the North American plate and the Greater Antilles arc in Western Cuba: Palaios, v. 12, p. 133–150.

Decelles, P. G., and Giles, K. A., 1996, Foreland basin systems: Basin Research, v. 8, p. 105–123.

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

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

Ducloz, C., 1989, Transcurrent faulting: A major tectonic feature of north-central Cuba [abs.], *in* Resúmenes y Programa, Primer Congreso Cubano de Geología, p. 102.

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

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

García-Casco, A., Iturralde-Vinent, M. A., and Pindell, J., 2008a, Latest Cretaceous collision/accretion between the Caribbean plate and Caribeana: Origin of metamorphic terranes in the Greater Antilles: International Geology Review, v. 50, in press.

García Casco, A., Lázaro, C., Rojas-Agramonte, Y., Kröner, A., Torres-Roldán, R. L., Núñez, K., Neubauer, F., Millán, G., and Blanco-Quintero, I., 2008b, Partial melting and counterclockwise P-T path of subducted oceanic crust (Sierra del Convento Mélange, Cuba): Journal of Petrology, v. 49, p. 129-161.

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

García-Casco, A., Torres-Roldan, R., Millan, G., Monié, P., and 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 Carribean collisional belt: Journal of Metamorphic Geology, v. 19, p. 699–715.

García-Casco, A., Torres-Roldan, R., Millan, G., Monié, P., and Schneider, J., 2002, Oscillatory zoning in eclogite garnet and amphibolite, Northern Serpentinite Mélange, Cuba: A record of tectonic instability during subduction?: Journal of Metamorphic Geology, v. 20, p. 581–598.

Giedt, N., and Schooler, O. E., 1959, Geology of Sierra de Cubitas and Camaján Hills, Camagüey, Cuba: La Habana. Cuba, Archivo del Servicio Geológico Nacional, unpubl. report.

Harlow, G. E., Hemming, S. R., Avé Lallemant, H. G., Sisson, V. B., and 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, v. 32, p. 17–20.

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

Hatten, C. W., Somin, M. L., Millan, G., Renne, P., Kistler, R. V., and Mattinson, J. M., 1988, Tectonostratigraphic units of Central Cuba, *in* Memoirs of the XI Caribbean Geological Conference, Barbados, p. 1–13.

Iturralde-Vinent, M., 1981, Nuevo modelo interpretativo de la evolución geológica de Cuba: Revista Ciencias de la Tierra y del Espacio, v. 3, p. 51–90.

Iturralde-Vinent, M., 1984, Olistostromas de la provincia de Camagüey [abs.], *in* Resúmenes X Jornada Científica del Instituto de Geología y Paleontología, p. 34.

Iturralde-Vinent, M., 1988, Consideraciones generales sobre el magmatismo de margen continental de Cuba: Revista Tecnológica, v. XVIII, no. 4, p. 17–24.

Iturralde-Vinent, M., 1989, Las ofiolitas en la constitución geológica de Cuba: Revista Ciencias de la Tierra y del Espacio, v. 17, p. 8–26 [also Geotectonics, v. 4, p. 63–76].

Iturralde-Vinent, M., 1994, Cuban geology: A new plate tectonic synthesis: Journal of Petroleum Geology, v. 17, p. 39–71.

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

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

Iturralde-Vinent, M., 1998, Sinopsis de la constitución geológica de Cuba: Acta Geológica Hispánica, v. 33, p. 9–56 (publ. March 2000).

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

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

Iturralde-Vinent, M. A., and Lidiak, E. G., eds., 2006, Caribbean plate tectonics. Stratigraphic, magmatic, metamorphic, and tectonic events (UNESCO/IUGS IGCP Project 433): Geologica Acta, v. 4, 341 p.

Iturralde-Vinent, M., and Marí-Morales, T., 1988, Toleitas del Tithoniano de la Sierra de Camaján, Camagüey: Posible datación de la corteza oceánica: Revista Tecnológica, v. XVIII, p. 25–32.

Iturralde-Vinent, M., and Roque Marrero, F., 1982, La falla Cubitas: Su edad y desplazamientos: Revista Ciencias de la Tierra y del Espacio, v. 4, p. 47–70.

Iturralde-Vinent, M., Tchounev, D., and Cabrera, R., eds., 1981, Geología del territorio de Ciego-Camagüey-Las Tunas: Resultados de las investigaciones científicas y del levantamiento geológico escala 1:250 000: La Habana. Cuba, Archivo del Servicio Geológico Nacional (unpubl.).

Iturralde-Vinent, M., and Thieke, H. U., eds., 1986, Informe final sobre los resultados del levantamiento geológico complejo y las búsquedas acompañantes a escala 1:50 000 del polígono CAME-III, Camagüey: La Habana. Cuba, Archivo del Servicio Geológico Nacional (unpubl.)

Jakus, P., 1983, Formaciones vulcanógeno-sedimentarias y sedimentarias de Cuba Oriental, *in* Contribución a la Geología de Cuba Oriental: La Habana, Cuba, Editorial Científico-Técnica, p. 17–85.

Kantshev, I., 1976, Geología de la provincia de Las Villas. Resultado de las investigaciones y levantamiento geológico a escala 1:250 000: La Habana, Cuba, Archivo del Servicio Geológico Nacional, unpubl. report.

Kerr, A. C, Iturralde-Vinent, M. A., Saunders, A. D., Babbs, T. L., and 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, v. 111, p. 1581–1599.

Khudoley, C., 1967, Principal features of Cuban geology: Bulletin of the American Association of Petroleum Geologists, v. 51, p. 668–677.

Khudoley, K., and Meyerhoff, A., 1971, Paleogeography and geological history of Greater Antilles: Geological Society of America Memoir, v. 129, p. 1–199.

Krebs, M., Maresch, W. V., Schertl, H.-P., Münker, C., Baumann, A., Draper, G., Idleman, B., and Trapp, E., 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, in press.

Luterbacher, H. P., Ali, J. R., Brinkhuis, H., Gradstein, F. M., Hooker, J. J., Monechi, S., Ogg, J. G., Powell, J., Röhl, U., Sanfilippo, A., and Schmitz, B., 2004, The Paleogene Period, *in* Gradstein, F. M., Ogg, J. G., and Smith, A. G., eds., A geologic time scale 2004: Cambridge, UK, Cambridge University Press, p. 384–408.

Mattson, R., 1984, Caribbean structural breaks and plate movements, *in* Bonini, W. E., Hardgrave, R. B., and Shagam, R., eds., The Caribbean–South American plate boundary and regional tectonics: Geological Society of America Memoir, v. 162, p. 131–152.

Meyerhoff, A. A., and Hatten, C. W., 1968, Diapiric structure in Central Cuba: Memoir, American Association of Petroleum Geologists, v. 8, p. 315–357.

Meyerhoff, A. A., and Hatten, C. W., 1974, Bahamas salient of North America; tectonic framework, stratigraphy and petroleum potential: Bulletin of the American Association of Petroleum Geologists, v. 58, p. 1201–1239.

Pardo, G., 1975, Geology of Cuba, *in* Nairn, A. E. M., and Stehli, F. G., eds., Ocean basins and margins, v. 3. The Gulf of Mexico and Caribbean. New York, NY, Plenum Press, p. 553–616.

Pindell, J. L. 1990, Geological arguments suggesting a Pacific origin for the Caribbean plate, *in* Larue, D. K., and Draper, G., eds., Transactions of the Twelfth Caribbean Geological Conference, St. Crib, Virgin Islands: Miami, FL, Miami Geological Society, p. 1–4.

Pindell, J. L., Cande, S. C., Pitman, W. C., III, Rowley, D. B., Dewey, J. F., Labrecque, J., and Haxby, W., 1988, A plate-kinematic framework for models of Caribbean evolution: Tectonophysics v. 155, p. 121–138.

Pindell, J., and Kennan, L., 2001, Kinematic evolution of the Gulf of Mexico and Caribbean, *in* 21st Annual GCSSEPM Research Conference, Houston, Texas.

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

Pindell, J. L, Kennan, L., Stanek, K. P., Maresch, W. V., and Draper, G. 2006, Foundations of Gulf of Mexico and Caribbean evolution: Eight controversies resolved, *in* Iturralde-Vinent, M. A., and Lidiak, E. G., eds. Caribbean plate tectonics. Stratigraphic, magmatic, metamorphic, and tectonic events. UNESCO/IUGS IGCP Project 433: Geologica Acta, v. 4, p. 303–341.

Pszczolkowski, A., 1978, Geosynclinal sequences of the Cordillera de Guaniguanico in western Cuba: Their lithostratigraphy, facies development, and paleogeography: Acta Geologica Polonica, v. 28, p. 1–96.

Pszczolkowski, A., 1983, Tectónica del miogeosinclinal cubano en el área limítrofe de las provincias de Matanzas y Villa Clara: Revista Ciencias de La Tierra y del Espacio, v. 6, p. 53–61.

Pszczolkowski, A., 1986, Secuencia estratigráfica de Placetas en el área limítrofe de las provincias de Matanzas y Villa Clara (Cuba): Bulletin of the Polish Academy of Sciences, v. 34, no. 1, p. 67–79.

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

Pszczolkowski, A., and Flores, R., 1986, Fases tectónicas del Cretácico y Paleógeno en Cuba occidental y central: Bulletin of the Polish Academy of Sciences: Earth Science, v. 134, no. 1, p. 95–111.

Pszczolkowski, A., and Myczynski, R., 2003, Stratigraphic constraints on the Late Jurassic–Cretaceous paleotectonic interpretations of the Placetas Belt in Cuba, *in* Bartolini, C., Buffler, R. T., and Blickwede, J., The circum–Gulf of Mexico and the Caribbean: Hydrocarbon habitats, basin formation, and plate tectonics: AAPG Memoir, v. 79, 545–581.

Pushcharovsky, Yu., ed., 1988, Mapa Geológico de la República de Cuba escala 1:250,000 (40 sheets). La Habana, Cuba/Moscow, USSR: Academy of Sciences of Cuba/USSR Academy of Sciences.

Pushcharovsky, Yu., Mossakovsky, A., Nekrasov, G., Sokolov, S., and Iturralde-Vinent, M., 1989, Tectonic map of Cuba, scale 1:500,000 (4 sheets). La Habana, Cuba/Moscow, USSR: Academy of Sciences of Cuba/ USSR Academy of Sciences.

Renne, P. R., Mattinson, J. M., Hatten, C. W., Somin, M., Onstott, T. C., Millfin, G., and Linares, E., 1989, ^{40}Ar/ ^{39}Ar and U-Pb evidence for Late Proterozoic (Grenville-age) continental crust in north-central Cuba and regional tectonic implications: Precambrian Research, v. 42, p. 325–341.

Roque Marrero, F., and Iturralde-Vinent, M., 1982, Nuevos datos sobre las estructuras diapíricas de Punta Alegre y Turiguanó, Ciego de Avila: Revista Ciencias de la Tierra y del Espacio, v. 4, p. 47–55.

Roque Marrero, F., and Iturralde-Vinent, M., 1987, Redefinición de la zona de Cayo Coco en la provincia de Camagüey: Revista Tecnológica, v. XVII, p. 18–21.

Rosencrantz, E., 1990, Structure and tectonics of the Yucatán basin, Caribbean sea, as determined from seismic reflection studies: Tectonics, v. 9, no. 5, p. 1037–1059.

Schneider, J., Bosch, D., Monié, P., Guillot, S., Garcia-Casco, A., Lardeaux, J. M., Torres-Roldan, R. L., and Millan Trujillo, G., 2004, Origin and evolution of the Escambray Massif (Central Cuba): An example of HP/ LT rocks exhumed during intraoceanic subduction: Journal of Metamorphic Geology, v. 22, p. 227–247.

Sinton, C. W., Duncan, R. A., Storey, M., Lewis, J., and Estrada, J. J., 1998, An oceanic flood basalt province within the Caribbean plate: Earth and Planetary Science Letters, v. 155, p. 221–235.

Somin, M. L., and Millán, G., 1981, Geology of the metamorphic complexes of Cuba: Moscow, USSR, Nauka Press, 218 p. (in Russian).

Stanek, K. P., Maresch, W. V., Grafe, F., Grevel, C., and Baumann, A., 2006, Structure, tectonics, and metamorphic development of the Sancti Spiritus Dome (eastern Escambray massif, Central Cuba): Geologica Acta, v. 4, p. 151–170.

Van Hinsbergen, D. J. J., Iturralde-Vinent, M. A., Van Geffen, P. W. G., Garcia-Casco, A. and Van Benthem, S., 2008, Structural evolution of the Bahamian borderlands and serpentinite mélange units near Camagüey (central Cuba): A shallow subduction channel until Eocene arc-continent collision?: Journal of Structural Geology, submitted.