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# Emplacement of Cuban Ophiolites

**J. L. COBIELLA - REGUERA**

**Departamento de Geología, Universidad de Pinar del Río**
Martí 270, Pinar del Río 20100, Cuba
E-mail: jcobiella@geo.upr.edu.cu

⊣ **ABSTRACT** ⊢

According to their lithological and structural characteristics, three ophiolite bearing structural units are recognized in Cuba: 1) The Northern Ophiolitic Belt, a complex mélange that stretches more than 1000 km along the island; 2) The metamorphic basement of the Cretaceous Volcanic Arc Terrane; and 3) The tectonic slices in the high pressure metamorphic Escambray (Guamuhaya) Massif of south central Cuba. The available age constrains indicate that relics of oceanic lithosphere in Cuba are Late Mesozoic in age and probably originated in two different tectonic environments; 1) in a Late Jurassic- Neocomian small oceanic basin resulting from drifting between North America and a southern continent; and 2) in a suprasubduction marginal basin developed between the North American passive margin and an Aptian- Albian volcanic arc. Serpentinite slices and the high pressure amphibolites in the Mesozoic metasedimentary rocks of the Escambray (Guamuhaya) Massif originated during closure of a small oceanic basin, possibly during the Albian. The basement metamorphic rocks of the Volcanic Arc Terrane were derived from Upper Jurassic- Neocomian oceanic crust, metamorphosed during the development on this crust of a Middle Cretaceous volcanic arc. Ophiolites of the northern belt were probably derived from both the formerly mentioned small oceanic basin and suprasubduction marginal basin, and were emplaced in several episodes from the Campanian to the Middle Eocene. The different ophiolite types in Cuba represent relics of the oceanic lithosphere (the Proto-Caribbean oceanic basin) that developed between North and South America after the Pangea breakup. An alternative plate tectonic model is proposed and discussed.

*KEYWORDS* | Ophiolites. Cuba. Proto-Caribbean. Oceanic lithosphere.

## INTRODUCTION

Relics of oceanic lithosphere preserved on land areas are keys to understanding the geology and evolution of the regions where they occur. Processes leading to oceanic crust generation have been active in the northwestern Caribbean-Gulf of Mexico area since the Jurassic (Marton and Buffler, 1994, 1999; central Gulf of Mexico, Proto-

Caribbean) and still continue today in the Cayman Trough. Later processes of convergence and subduction resulted in a complex evolution that included metamorphism and tectonic emplacement of oceanic litosphere.

This paper deals mainly with the stratigraphic and structural interpretation of the emplacement of the distinct ophiolite assemblages present in Cuba and its impli-

cation for the evolution of the Caribbean region. As some knowledge of the pre-emplacement history is necessary, some problems related to the age and origin of these rocks will be also briefly reviewed. This review is based on the relatively abundant literature on this subject published in Cuba and elsewhere in the last few decades.

## GEOLOGICAL SETTING

In the plate tectonic setting of the Caribbean region, Cuba is accreted to the margin of the North American Plate. The major geological features of the island indicate that it originated as a consequence of the complex interplay of processes, including oceanic crust generation and metamorphism, the growth of successive volcanic arcs and the emplacement of oceanic crust slices (ophiolites in stricto and lato sensu ) that were included in the orogenic thrust systems built up in the island (Fig. 1).

Two main structural levels can be distinguished in Cuba. The upper level is a mildly deformed Eocene- Quaternary cover. The lower level (sole) is a variably deformed sequence of older rocks (Iturralde-Vinent, 1996a, 1998; Cobiella-Reguera, 2000). This sole consists of two main parts: 1) the pre- Cenozoic basement and 2) an EarlyTertiary folded belt. The pre-Cenozoic basement includes three different terranes: a Northern Ophiolitic Belt (NOB), a Cretaceous Volcanic Arc Terrane  (KVT), and a Southern Metamorphic Terrane (SMT). These terranes were accreted to the North American continental margin during the Cretaceous (Fig.1; Cobiella- Reguera, 1998b, 2000).

Considering their ages, the Cuban ophiolites belong to the pre-Cenozoic basement. However, some of them were remobilized during the Early Tertiary Cuban orogeny and emplaced in relation to Paleogene rocks. Following (with minor modifications) Iturralde-Vinent (1996b) classification and taking into account the terminology recently proposed by Dilek (2003) three major ophiolite-bearing units, including at least three ophiolite types, can be distinguished in Cuba (Fig. 1):

(1) The northern ophiolitic belt (NOB).
(2) The metamorphic basement of the Cretaceous volcanic arc terrane.
(3) Tectonic slices in the Escambray massif (one of the metamorphic terranes), in central Cuba.

## THE NORTHERN OPHIOLITIC BELT

The term ophiolite became extensively accepted in Cuban geological literature during  the eighthies, after plate tectonic ideas became established in Cuba (i.e. Furrazola et al., 1964; Kozary, 1968; Knipper and Cabrera,
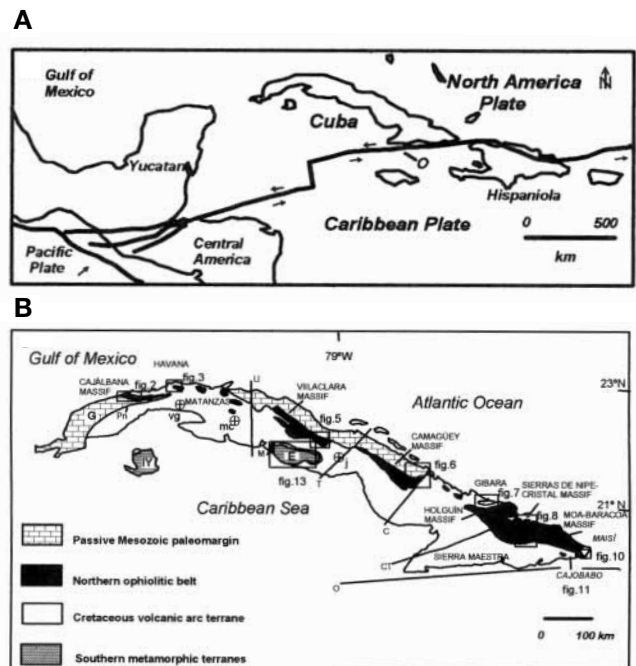
**A**

**B**

FIGURE 1 **A) Tectonic setting of Cuba in the Caribbean region. B) Map of Cuba showing the major Mesozoic domains and some Cenozoic tectonic features. Note the location of the main outcrop zones of the ophiolite bearing massifs described in the paper: Cajálbana-Bahía Honda, Havana-Matanzas, Villaclara, Camagüey, Holguin, Nipe- Cristal, Mayarí-Baracoa and Cajobabo and the location of the geological sketches shown in figures 2 to 8, 10 and 11.** *Major geological and relief features:* **C- Camagüey Lineament, Ct- Cauto Lineament, G- Guaniguanico mountains, LI- Llabre Lineament, IY- Isle of Youth, M- Mabujina complex, PN- Pinar Fault, T- La Trocha Fault, O- Oriente Fault, E- Escambray (Guamuhaya) mountains.** *Deep wells cited in the paper*: **j- Jatibonico 78, mc- Mercedes 1, vg- Vegas 1.**

1974). Over 90% of the oceanic lithosphere remains in Cuba are included in the Northern Ophiolitic Belt (NOB). A wealth of data that resulted from boreholes, geophysical surveys and surface geology (Echevarría-Rodríguez et al., 1991; Kozary, 1968; Meyerhoff and Hatten, 1968; Pardo-Echarte, 1996; and many others) have shown that the NOB ophiolite-bearing assemblage constitutes an almost continuous, strongly deformed body transported from the south over the north American continental margin.  The NOB is mainly a large mélange that stretches 1000 km along the northern half of Cuba (Fig. 1), whose blocks are formed mainly by ophiolitic suite components, floating in a serpentinitic matrix. Some of these blocks have undergone high-pressure metamorphism (Millán- Trujillo, 1996a; Kerr et al., 1999; García Casco et al., 2002). Despite structural complexity and mixing, all the components of a standard ophiolite sequence can be distinguished in the mélange. Tectonized ultramafic rocks (serpentinites) and the rocks of the cumulative complex (ultramafites and gabbros) are the most common lithologies, whereas the basalts and sedimentary rocks are poorly exposed (Kozary, 1968; Knipper and Cabrera, 1974; Iturralde-Vinent, 1990, 1996b; Cobiella-Reguera, 1984; and others).

Few age data are available for the NOB rocks. Several sedimentary samples yielded Tithonian, Hauterivian- Barremian and Aptian- Albian fossils (Llanes Castro et al., 1998; Andó et al.,1996; Iturralde-Vinent, 1990). Cenomanian fossils have also been reported from the Havana and Holguin massifs (Fig. 1), but the associated rocks are not typical of the ophiolitic suite (see below, Iturralde-Vinent, 1996b) or were found in zones of severe tectonic mixing (Andó et al., 1996). K/ Ar radiometric ages range from 126 to 52 Ma. A 160±24 Ma K- Ar age was obtained from anorthosites sampled in Camagüey (Somin & Millán, 1981; Iturralde-Vinent et al., 1996; Fig. 1).

In western and central Cuba, the rocks of the NOB overthrusted the Mesozoic sedimentary rocks of the North American margin and the Early Tertiary foreland basin developed on the paleomargin. However, the extensive ophiolites of easternmost Cuba and Holguin structurally overlie the Cretaceous Volcanic Terrane (KVAT; Fig. 1). The NOB shares many features with the Mediterranean type ophiolites of Dilek (2003).

Different tectonic settings occur along the strike of the Northern Ophiolitic Belt. From west to east, the following main outcrop areas are distinguished (Fig. 1): Cajálbana-Bahía Honda, Havana-Matanzas, Villaclara, Camagüey, Holguin, Mayarí-Baracoa. A small serpentinite body in easternmost Cuba (Cajobabo) would correspond to a distinct geologic setting and will be reviewed separately. A review of the main geological features related to NOB emplacement in each area is provided.

## Cajálbana – Bahía Honda area

The Cajálbana-Bahía Honda ophiolite bearing massif makes up the westernmost outcrops of the NOB (Fig. 1). The tectonized ultramafic rocks (mainly harzburgites) and the volcanosedimentary sections (basalts, cherts, limestones and siltstones of Encrucijada Fm), are the best represented members of the suite, whereas gabbros and diabases are relatively scarce in the mélange (Fig. 2; Fonseca et al., 1984). The limestones interbedded with basalts of the Encrucijada Fm yielded Aptian-Albian planktonic
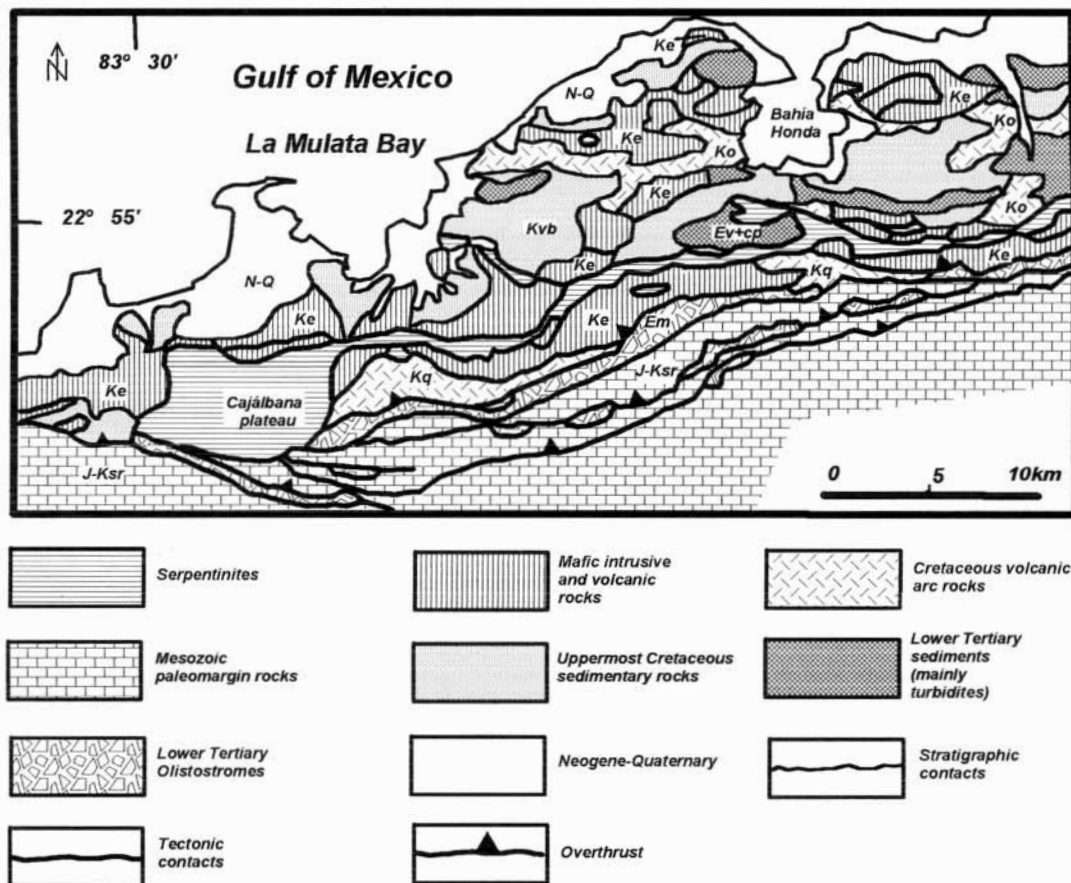


FIGURE 2 | **Geological map of northeastern Pinar del Río province (Cajálbana-Bahía Honda ophiolites). Simplified after Pushcharovsky (1988). See location in Fig. 1. *Ophiolites*: Ke- Encrucijada Fm. (Aptian-Albian). *Cretaceous Volcanic Arc Terrane*: Kq- Quiñones Fm (Upper Cretaceous), Ko- Orozco Fm (Upper Cretaceous). *Volcanic Arc Terrane cover*: Kvb-Vía Blanca Fm (upper Campanian-Maastrichtian). *Mesozoic paleomargin rocks*: J-Ksr-Jurassic and Cretaceous deep water deposits of Sierra del Rosario. *Lower Tertiary sedimentary rocks (mainly turbidites)*: Ev+cp - Ev Víbora Gr (upper Paleocene) + cp Capdevila Fm (Lower Eocene). *Foreland basin rocks*: Em- Manacas Fm (Lower Eocene). *Neogene and Quaternary deposits*: N-Q.**

foraminifera (Fonseca et al., 1984; Cruz Gámez and Simón Méndez, 1997; Iturralde-Vinent, 1996b). K/Ar dating in high pressure Cajálbana metamorphic blocks provided ages ranging from 115 ± 5 to 90 ± 5 Ma.

Less deformed Upper Cretaceous volcanic arc basalts, sedimentary rocks and tuffs (Orozco Fm), the overlying marine terrigenous deposits (Vía Blanca Fm) and a large K/T boundary megaturbidite (Peñalver Fm) overlie the ophiolite mélange. In some places, Middle Cretaceous sedimentary and volcanic arc rocks (Quiñones Fm) occur below the ophiolite bearing assemblage. Although the Quiñones Fm has been considered a part of the ophiolitic suite (Iturralde- Vinent, 1996b) its lithological composition (cherts, tuffites, shales and porphyritic basalts) does not accord to typical ophiolite suite. Both ophiolite plus Cretaceous volcanic terrane rocks were thrusted northward, along a northward dipping (i.e. northward tilted) thrust plane. This thrusting affected the allochthonous deep water Upper Jurassic-Paleocene sections of a deformed paleomargin and its overlying foreland basin. The foreland basin fill includes Early Tertiary olistostrome deposits that in its turn include clasts derived from the Mesozoic continental paleomargin rocks and the ophiolitic suite (Manacas Fm; Fig. 2), as well as some metamorphic blocks with K/Ar ages that range from 58 to 128 Ma (Iturralde-Vinent et al., 1996). These deposits are exposed in the Cordillera de Guaniguanico (western Cuba; Pszczolkowski, 1994b; Cobiella-Reguera, 1998d, 2000). Two significant occurrences in the Mesozoic Guaniguanico continental margin have to be considered; 1) the volcanomictic material and some tuffaceous beds interbedded in the Campanian Moreno Fm (Pszczolkowski, 1994a), i.e. the only volcanomictic sediments reported in the North American Mesozoic paleomargin in Cuba; and, 2) The K/T boundary Cacarajícara Fm, a several hundred meters thick megaturbidite (Kiyokawa et al., 2002) which is very similar to the Peñalver Fm. recognized in the Volcanic Arc Terrane, (Pszczolkowski, 1986). The K/T boundary megaturbidite has not been observed overlying the ophiolites but a few serpentinite clasts have been found in this turbidite unit (Kiyokawa et al., 2002). Both facts place some significant constraints on the ophiolite emplacement models in western Cuba.

The up to several hundred meters thick Manacas Fm deposits (uppermost Paleocene - lowermost Eocene; Pszczolkowski, 1994a) also occur along the ophiolite/ North American paleomargin tectonic boundary (Fig. 2). Finally, the Lower Eocene Capdevila Fm rests on the thrust sheet pile (Cobiella-Reguera et al., 2000).

## Havana – Matanzas area

In the Havana – Matanzas area, the ophiolites crop out as discrete bodies. Tectonic mixing between the ophiolites (mainly serpentinites, some gabbros, with rare

basalts, boninites and sedimentary rocks) and the volcanosedimentary arc rocks (Aptian?- Campanian?) seems more intense than in the Cajálbana – Bahía Honda area, resulting in a volcano-ophiolitic mélange (Fig. 3; Iturralde-Vinent, 1996b and c). Two K/Ar radiometric ages, 126 ± 10 y 105 ± 10 Ma in eclogitic rock blocks related to the ophiolites are reported in Matanzas province (Millán Trujillo, 1996a). Severely folded and faulted uppermost Cretaceous terrigenous turbidites, sometimes containing serpentinite and gabbro clasts (Vía Blanca Fm), and a K/T boundary megaturbidite bed (Peñalver Fm) unconformably overlie the mélange (Pushcharovsky, 1988), suggesting a pre-upper Campanian age for this mélange. Upper Paleocene beds (piggyback basin turbidites) are also strongly folded and faulted, but deformation is less severe than in the older rocks. No lower Tertiary olistostrome crops out, but these rocks, with similar features, age and tectonic setting to their equivalents in western Cuba (the Manacas Fm of Cajálbana – Bahía Honda area) occur in many deep boreholes, at the contact between the ophiolites or volcanic arc rocks (mélange) with the underlying allochthonous deep water deposits of the North American Mesozoic paleomargin sequences (Iturralde-Vinent, 1996a). The Lower Eocene flyschoid Capdevila Fm is also present in the Havana city area, unconformably resting on the thrust sheet pile (Fig. 3).

Iturralde-Vinent (1996b) has reported near Matanzas city a 30 m thick section (Margot mine) where ophiolitic tholeiitic aphiric to variolitic basalts, with interbedded limestones and cherts that yielded Albian - Cenomanian fossils occur. These deposits are covered by tuffs, tuffites, cherts, limestones and Cenomanian fossil bearing calcareous siltstones, that Iturralde-Vinent (1996b) has considered to be also ophiolitic in origin. It is here proposed that these upper beds show features that enable one to relate them to the Volcanic Arc Terrane. This section is one of the few localities where the original non-tectonic contact between ophiolites / volcanic arc rocks seems to be preserved.

To the south of the outcrop area ophiolite material has been recorded at depth in the Vegas 1 and Mercedes 1 wells (Figs. 1 and 4), where Upper Cretaceous volcanic and sedimentary rocks rest upon massive altered diabases. No evidences of either tectonic mixing between both rock types or of volcanic arc related rocks intruding the diabases were found.

## Villaclara Massif

In northern central Cuba the ophiolites located to the east of the Llabre lineament (Villaclara Massif; Fig. 1) crop out extensively and the upper members of the ophiolite suite show the most complete development in Cuba. The Villaclara Massif is similar to the previously

described localities (Fig. 5) but it shows new additional features. As in western Cuba, tectonic mixing between the ophiolites and the KVT is observed near their contact (Knipper and Cabrera, 1974). However the northward thrusting of the KVT rocks over the ophiolites is conspicuous in many places (Meyerhoff and Hatten, 1968; Pardo, 1975). An upper Paleocene - middle Eocene olistostrome unit (Vega Alta Fm, very similar to Manacas Fm of western Cuba) includes serpentinite and ophiolitic (gabbro and diabase) clasts. This olistostrome unit occurs along or very near the tectonic contact between the ophiolites and the underlying allochthonous deep water deposits. These deposits are strongly folded and were deposited along the North American Upper Jurassic-Cretaceous paleomargin. In some areas (Fig. 5, north of Perea) the ophiolite klippen overthrust the southward dipping Cretaceous carbonate bank rocks of the Bahamas platform

fringe (Remedios Group), showing that in some places of central Cuba the ophiolite thrust sheets reached the southern margin of the Bahamas platform.

Petrological and geochemical data from the Villaclara ophiolites are scarce and disseminated in the geological literature. Beccaluva et al. (1996) have reported a MORB crystallization order of primary minerals referable to MORB magmatism (olivine-plagioclase-clinopyroxene) in gabbroid rocks. Giunta (2002) also has reported MORB with LREE depleted patterns in the Villaclara ophiolites. Kerr et al. (1999) report basalts (their sample SAG 1) not enriched in LILE, with no negative Nb anomaly and an island arc tholeiite composition (perhaps generated in a backarc basin, after Kerr et al., 1999) near Santa Clara (Fig. 1). Another two samples from blocks in serpentinites in the same area were considered as island
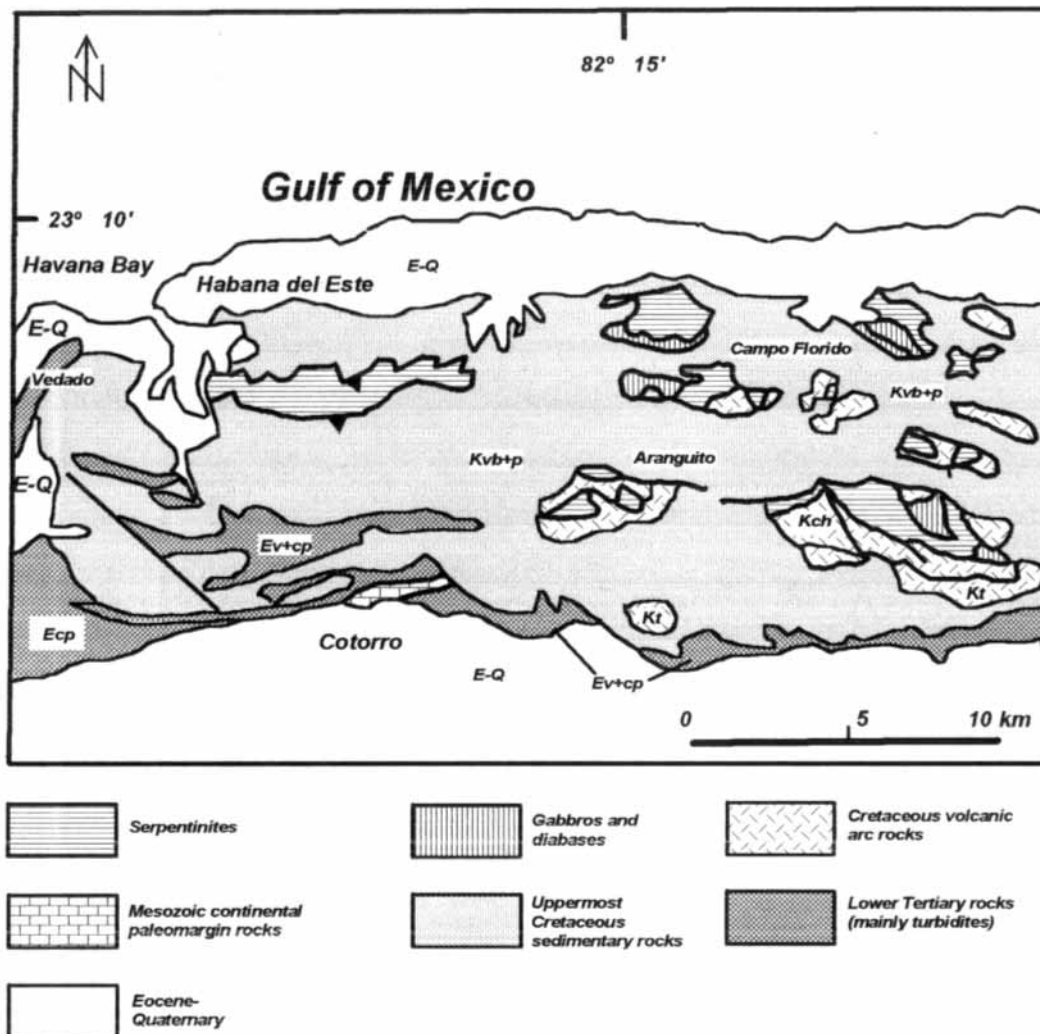


FIGURE 3 | **Geological map of eastern Havana City and its surroundings (simplified after Puscharovsky, 1988). See location in Fig. 1 and legend of geological contacts in Fig. 2. *Cretaceous Volcanic arc terrane*: Kch- Chirino Fm (Lower Cretaceous), Kt- La Trampa Fm (Upper Cretaceous). *Volcanic Arc Terrane cover*: Kvb+p- Vía Blanca (upper Campanian-Maastrichtian), p- Peñalver Fm (K/T boundary megaturbidite deposit). *Lower Tertiary sedimentary rocks (mainly turbidites)*: E v+cp- Víbora Gr (upper Paleocene) and Capdevila Fm (Lower Eocene), Ecp- Capdevila Fm, *Lower Eocene. Eocene-Quaternary cover*: E-Q. Formal litostratigraphic units have been no recognized in the paleomargin rocks.**
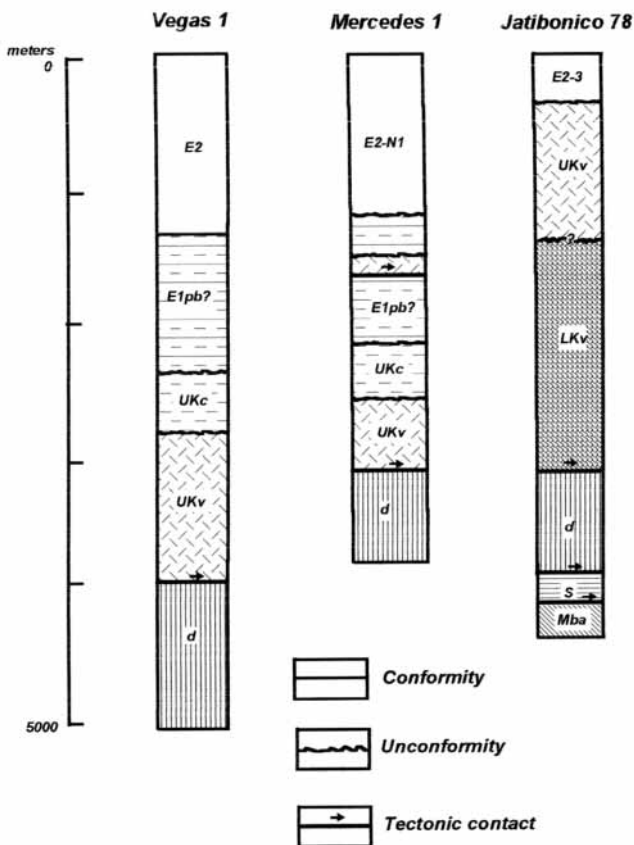
FIGURE 4 | **Deep wells in western (Vegas 1 and Mercedes 1) and central (Jatibonico 78) Cuba. See location in Fig. 1** *Ophiolites*: **d- altered diabases, Mba- Mabujina complex (mainly amphibolites), S- Serpentinites.** *Cretaceous volcanic arc terrane*: **UKv- Upper Cretaceous (Campanian and/or older) volcano-sedimentary sequence, LKv- Lower Cretaceous mainly volcanic sequence.** *Volcanic arc terrane cover*: **UKc- Upper Campanian-Maastrichtian siliciclastic sedimentary rocks.** *Paleocene piggyback basins sediments (mainly turbidites)*: **E1pb,** *Eocene-Quaternary cover*: **E2- Eocene, E2-N1- Eocene- Miocene, E2-E3- Eocene-Oligocene.**

arc tholeiites by these authors (Kerr et al., 1999, their table 2). Finally, late Jurassic (Tithonian) radiolaria have been reported in the sedimentary interbeds of the volcanosedimentary member (Fig. 5, Zurrapandilla Fm, Castro Llanés et al., 1998).

High pressure metaophiolite and metagreywacke blocks (Millán, 1996a) included within serpentinite crop out in the western part of the Villaclara ultramafic Massif. García-Casco et al. (2002) report that the minimum age for eclogite facies metamorphism in these blocks is pre 118 Ma, while the rock experienced final uplift and cooling between 118 and 103 Ma. Auzende et al. (2002) have recorded blocks with eclogitic facies metamorphism near Santa Clara. Not far from this locality, blocks with low pressure amphibolitic assemblages and low grade greenschist facies are embedded in the serpentinite matrix. This lithological variety accords well with the mélange setting which characterizes the NOB.

A great development of the mafic members of the ophiolite suite is present in the eastern part of the massif (Fig. 5). In the area between the villages of Iguará and Perea, plagiogranites with island arc composition intrude the low pressure, severely deformed metamafites. The granitoids are deformed and show schistosity development. K/Ar ages in these rocks are 70±5 Ma, and an 88 Ma age was obtained in a quartzdiorite intruding diabases, (Millán and Somin, 1985). A few kilometers southward, some serpentinite xenoliths occur in the granitoids (Millán and Somin, 1985). Iturralde-Vinent et al. (1996), reported an 82 ± 4 Ma K/Ar age in low pressure metagabbros of the Villaclara Massif. In the massif southern rim, the volcanic arc rocks of the Carlota Fm (Santonian-Campanian) unconformably overlie the ophiolites, without evidences of metamorphism (Fig. 5). Millán and Somin (1985) considered that the NOB in this region was in fact the basement of the Cretaceous volcanic sequences.

## Camagüey Massif

The Camagüey Massif is located between La Trocha fault and the Camagüey lineament (Figs. 1 and 6). It forms a southward dipping body that is overlain by the KVAT and rests on the Cretaceous rocks of the Bahamas platform. At least 20 km of tectonic overlap of the ophiolite rocks on the North American Mesozoic paleomargin can be estimated (Fig. 6). The serpentinites and gabbro cumulates are the main members. Diabase dikes are abundant, cutting both the serpentinites and gabbros. Evidences of low pressure metamorphism are frequent in gabbros and diabases. Some high pressure amphibolite and eclogite blocks occur near the massif western end (Millán Trujillo, 1996b). The volcano-sedimentary member is limited to a few outcrops to the north of Camagüey city (Iturralde-Vinent, 1996b). Paleontological data (planctonic foraminifera) in the vulcano-sedimentary member provide an Aptian-Albian age (Iturralde-Vinent, 1996b).

The tectonic setting is similar to the Villaclara massifs. However, several new features are present: 1) the olistostromes with ophiolitic clasts that rest on the Mesozoic North American paleomargin (Senado Fm) and below the ophiolites are younger (upper Middle Eocene or lower Upper Eocene) than in the western massifs (Pscszolkowski and Flores, 1986; Iturralde Vinent, 1996b); 2) a Lower Eocene olistostrome is developed along the tectonic contact between the ophiolites and the overlying KVAT (Iturralde Vinent, 1996b); 3) the ophiolite front lies on the Cretaceous carbonate sequences (Remedios zone) of the Bahamas platform, and 4) a K/Ar dating in anorthosites of the gabbro complex provided a 160±24 Ma age (Somin and Millan, 1981).
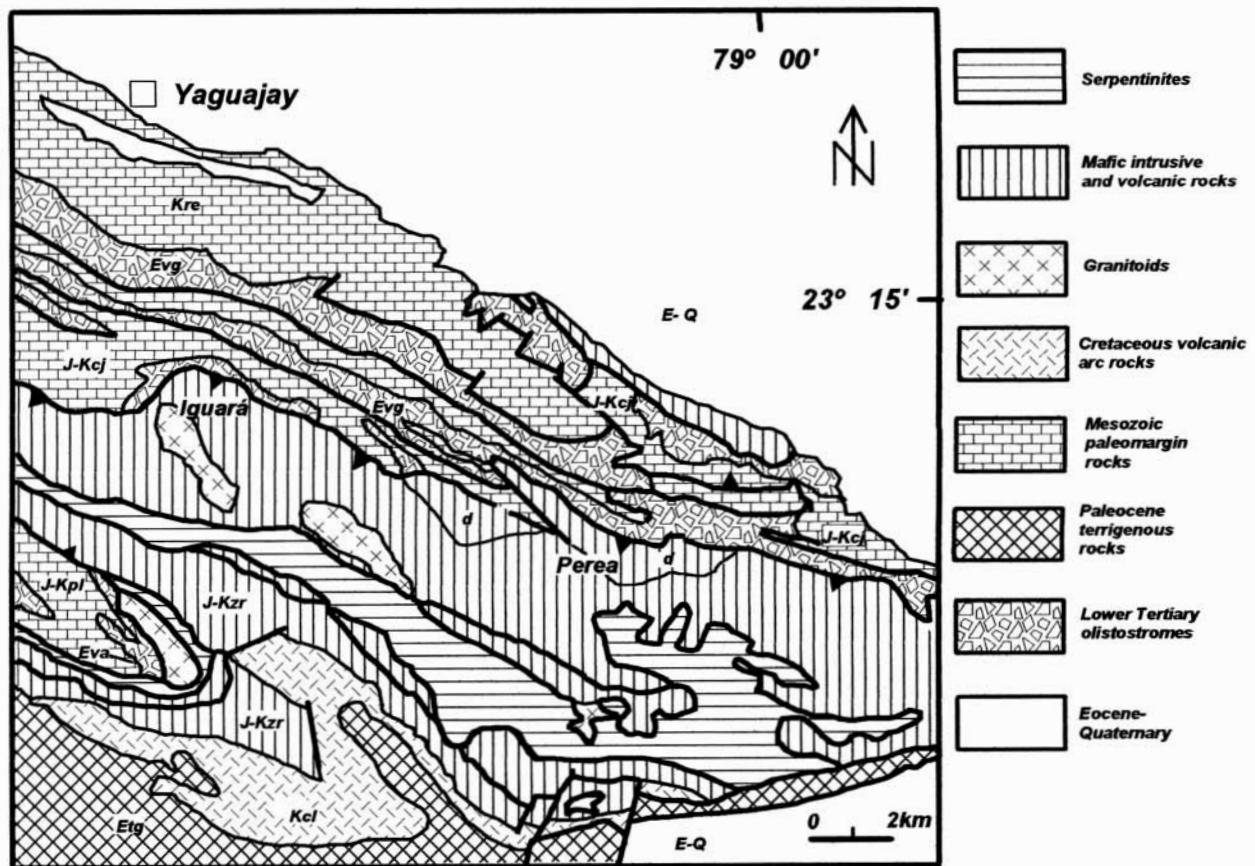
FIGURE 5 | **Geological map of eastern Villaclara ophiolite massif and its surroundings (simplified after Pushcharovsky, 1988). See location in Fig. 1 and legend of geological contacts in Fig. 2.** *Ophiolites*: J-Kzr- Zurrapandilla Fm (Tithonian-Lower Cretaceous), d- sheeted complex. *Volcanic arc terrane*: Kcl- Carlota Fm (Upper Cretaceous). *North American Mesozoic paleomargin*: Kre- Remedios zone (carbonate banks), J-Kcj- Camajuaní zone (deep water, toe of the continental slope deposits), J-Kp- Placetas zone (basin deposits). *Lower Tertiary sedimentary rocks*: Etg-Taguasco Fm (Paleocene). *Foreland basin olistostromes*: Eva- Vega Alta Fm (Paleocene-Middle Eocene), Evg-Vega Grande Fm (Lower-Middle Eocene- abundant clasts of Cretaceous carbonate banks). *Eocene-Quaternary cover*: E-Q.

## Holguin Massif

The Holguin Massif (Figs. 1 and 7) is perhaps the most complex of all the Cuban ophiolite bearing zones. An excellent review of its petrology and geochemistry is provided by Andó et al. (1996), whereas the geological setting has been studied by Kozary (1968) and Knipper and Cabrera (1974). The massif consists of anastomosing bands of strongly deformed ophiolite suite rocks, separated by south dipping thrust faults of the intervining strongly deformed terrigenous and volcanic rocks "intercalations" (Iberia Fm, Kozary, 1968; Jakus, 1983). According to Andó et al. (1996), much of the "Iberia Fm" rocks are severely deformed greywackes that probably form a forearc accretionary prism. This mélange is mainly foliated and brecciated serpentinite (tectonized peridotite), whereas the other liholgies of the ophiolitic suite are very subordinate and mainly appear as disseminated, tectonically mingled blocks in the serpentinite (Kozary, 1968; Knipper and Cabrera, 1974). Kerr et al. (1999) have reported boninite among the volcanic member of the ophiolite. Members of a cumulative complex

crop out in a few places, mainly in the south. In cherts, spatially related with basalts, Andó et al. (1996) found in one sample Hauterivian-Barremian radiolaria. The same authors report Cenomian radiolaria in a tectonic breccia. Because of its tectonic setting, this latter age determination seems to have little confidence. Eight K/Ar radiometric ages in basalts and diabases varies from 126.3 ± 8.3 to 57.8 ± 5.4 Ma (Iturralde-Vinent et al., 1996). Meanwhile, in high pressure metamafites K/Ar ages span from 125 ± 12 to 91± 6 Ma and, in one sample of low pressure metamorphic rocks, a 68.2 ± 3.5 Ma age was obtained.

A belt with a polymictic breccia made up mainly by serpentinite blocks, but also by high pressure metamorphic rocks, volcanic rocks and carbonates of the Bahamas paleomargin, occurs near the tectonic contact with the underlying Cretaceous carbonate rocks of the Bahamas platform fringe (Andó et al., 1996). These authors suggest that this breccia originated during the collision of oceanic terranes against the Bahamas platform. Many authors claim for a strong Early Tertiary
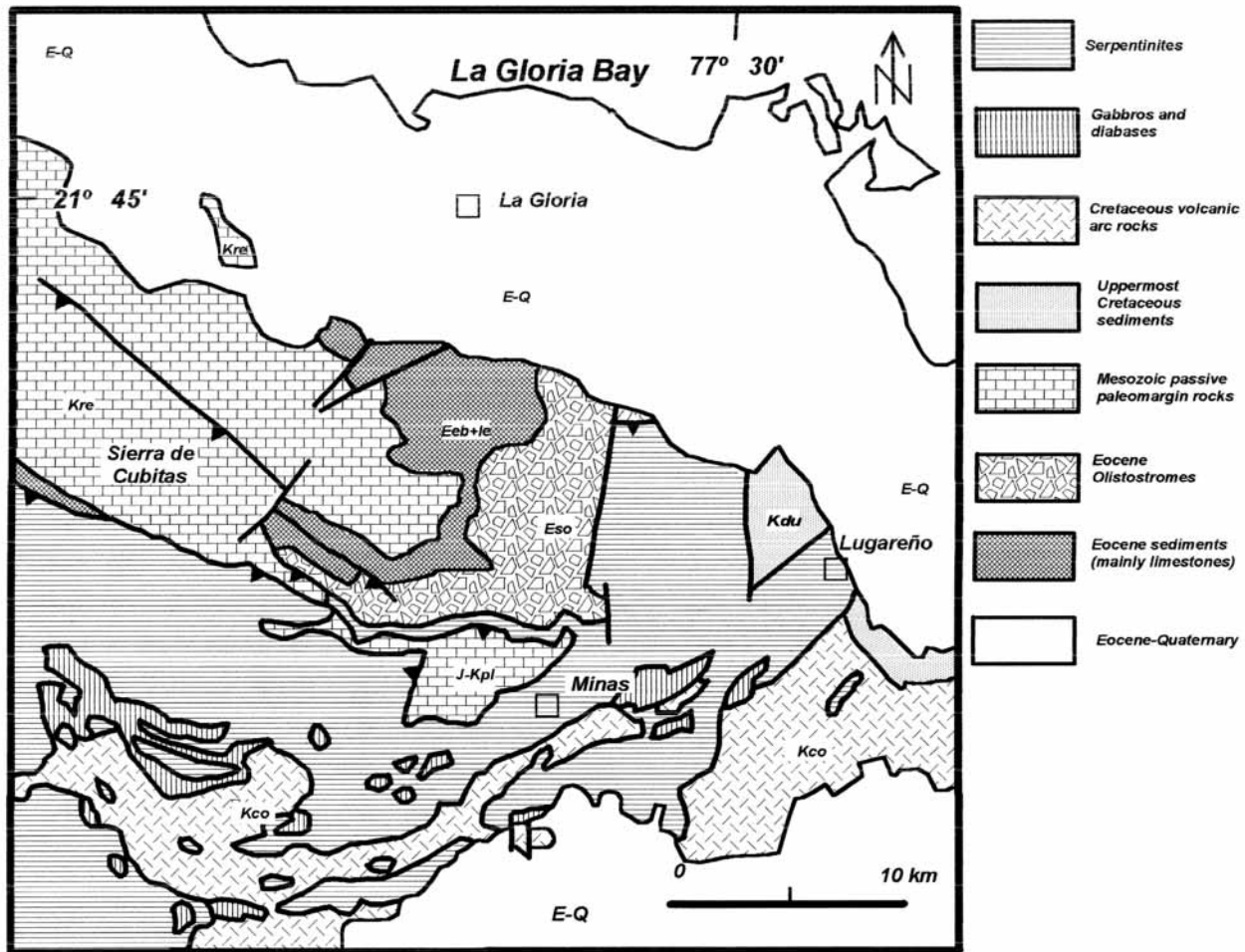
FIGURE 6 | **Geological map of northeastern Camagüey (simplified after Pushcharovsky, 1988). See location in Fig. 1 and legend of geological contacts in Fig. 2.** *Cretaceous volcanic arc terrane*: **Kco-Caobilla Fm (Upper Cretaceous).** *Volcanic arc terrane cover*: **Kdu- Durán Fm (upper Campanian-Maastrichtian).** *North American Mesozoic paleomargin*: **Kre- Remedios zone (carbonate banks), J-Kpl- Placetas zone (deep water deposits).** *Lower Tertiary clastic carbonate deposits*: **Eeb+l; Embarcadero Fm (lower Eocene) + Lesca Fm (middle Eocene).** *Foreland basin olistostromes*: **Eso- Senado Fm (Upper Eocene).** *Eocene–Quaternary sedimentary cover*: **E-Q.**

deformation (Cuban orogeny) in the Holguin Massif (Kozary, 1968; Knipper and Cabrera, 1974; Andó et al., 1996), but no definitive evidence of such deformation in the lower Tertiary rocks has been demonstrated. In fact, strong Paleocene-Eocene deformations in the Holguin Massif were not reported by Nagy (1984), Brezsnyansky and Iturralde-Vinent (1984) and Cobiella-Reguera et al. (1984b). Contrary to the other massifs located to the west of Camagüey lineament, no Lower Tertiary olistostrome with ophiolitic and continental paleomargin clasts is present. Instead, a strongly deformed chaotic breccia, with ophiolitic suite clasts (and also from the KVT, Yaguajay Fm) has been reported in the northern half of the Holguin area (Jakus, 1983). These deposits are very similar to those of Maastrichtian age in the Mayarí- Baracoa Massif (La Picota Fm). Upper Paleocene breccias with some tuffaceous beds (Haticos Fm) are the oldest rocks that unconformably overly these mélanges.

Some geochemical data (Cr/Y) show both MORB and island arc tholeiites (IAT) signatures, according to Ando et al. (1996). In the Zr/Y vs Zr discriminating diagram for basalts, these authors (op.cit.) have distinguished three groups of samples: 1) MORB, 2) MORB or IAT, and 3) without specific trend (Andó et al., 1996). Finally, the study of the rare earth elements in gabbros and diabases also suggests that two different kinds of ophiolite occur, with transitional representatives (Andó et al., 1996).

## Eastern Cuba ophiolites

At surface the Holguin Massif is separated from the eastern Cuba massifs by Cenozoic deposits, but in depth both ophiolite bearing units form a single body (Fig. 1; Cobiella-Reguera et al., 1984b). The eastern Cuba ophiolite bearing assemblages constitute two large massifs, Sierras de Nipe - Cristal (Mayarí) in the West and Moa - Baracoa, in the East, separated by the Sagua de Tánamo
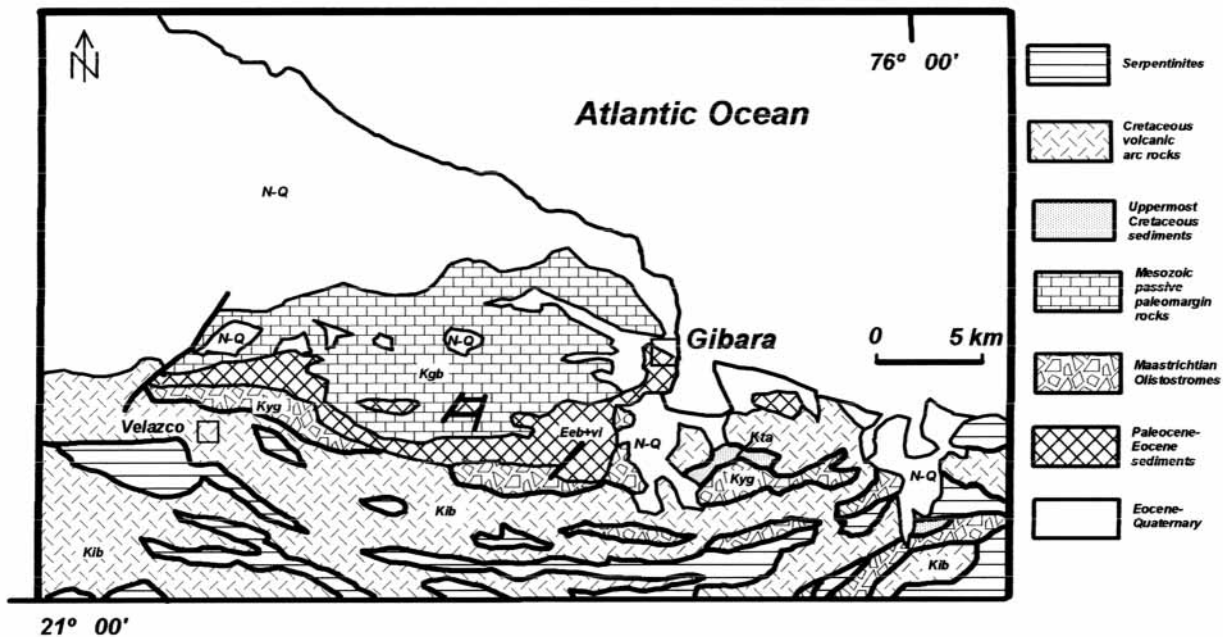
FIGURE 7 | Geological map of the northern Holguin ophiolites, south of Gibara City. (simplified after Pushcharovsky, 1988). See location in Fig. 1 and legend of geological contacts in Fig. 2. *Cretaceous volcanic arc terrane*: Kib- "Iberia Fm" (mélange). *Volcanic arc terrane cover*: Kta- Tinajita Fm (Campanian-Maastrichtian shallow water limestones), Ky- Yaguajay Fm (Maastrichtian?). *North American Mesozoic paleomargin*: Kre- Remedios zone (carbonate banks). *Lower Tertiary sedimentary units*: vi+eb- Vigia Fm (Lower-Middle Eocene)+Embarcadero Fm (Paleocene?). *Neogene and Quaternary*: N-Q.

river valley (Fig. 8). All the members of the ophiolite suite are represented, specially the lower ones (Ríos and Cobiella, 1984; Proenza et al., 1998a and b; Proenza et al., 1999; Rodríguez et al., 2001).

The main feature that separates the eastern Cuba ophiolite bearing massifs from the other massifs of the NOB (except the Holguín area) is their tectonic superposition upon the KVAT (Knipper and Cabrera, 1974; Cobiella, 1978; Iturralde-Vinent, 1996b). The eastern massifs make up an almost horizontal tectonic prism about 1 km in maximum thickness that was thrusted several ten kilometers to the north (Knipper and Cabrera, 1974; Cobiella, 1978). In some areas of this massif the deformations and tectonic mixing is not as strong as in the other Cuban ophiolites. Recent field and structural data suggest that in the Sierra de Nipe - Cristal Massif a section of mantle tectonite thicker than 5 km is exposed, whereas the Moa – Baracoa Massif comprises thicker than 2.2 km mantle tectonites, which are capped by a thin (300 m thick) crustal section of lower gabbros and unconformably overlying volcanics (Quibiján Fm; Proenza et al., 2003).

Large blocks of high presssure metamorphic rocks (mainly amphibolites) are disseminated in both massifs (Fig. 8). K/Ar radiometric ages in high pressure blocks vary from 125 ± 5 to 96 ± 4 Ma in La Corea metamorphic rocks (Fig. 8) and 88 ± 7 Ma in Sierra del Convento, west of Maisi (Fig. 1).

In many places, severely deformed olistostromes (with blocks of serpentinite, diabase, gabbros, basalts and amphibolite, up to several hundred meters in diameter) of Maastrichtian age (La Picota Fm; Cobiella, 1978), occur below the ophiolites. The oldest rocks with stratigraphic contact above the ophiolites are uppermost Maastrichtian or lowermost Paleocene (upper Micara Fm), with abundant serpentinite olistoliths (Figs. 8 and 9). Therefore, a Maastrichtian age for ophiolite emplacement is evident. No evidence of significant Cenozoic deformation is present. Paleocene – Middle Eocene tuffs and sedimentary rocks rest upon the older rocks. They belong to the Early Tertiary volcanic arc developed in southeastern Cuba.

In easternmost Cuba (Maisí area; Figs. 1 and 10), the rocks of the Moa-Baracoa Massif lie in tectonic contact upon metamorphic Jurassic and Cretaceous rocks, probably corresponding to a passive continental margin section (Pardo, 1975; Cobiella et al., 1984a; Somin and Millán, 1981; Iturralde-Vinent, 1996a; Cobiella-Reguera, 2000). Some metamafites occur in this region. According to Garcia Casco et al. (2002), samples from the Güira de Jauco amphibolites (Fig. 10) have a tholeiitic character and MORB patterns. Thermobaric estimates yield conditions of 600-700° C and 6-8 kbar. García Casco et al. (2002) relate this pressure and strong synmetamorphic deformations to collision metamorphism. K/Ar ages fluctuate between 72 ± 3 and 58 ± 4 Ma. The amphibolites
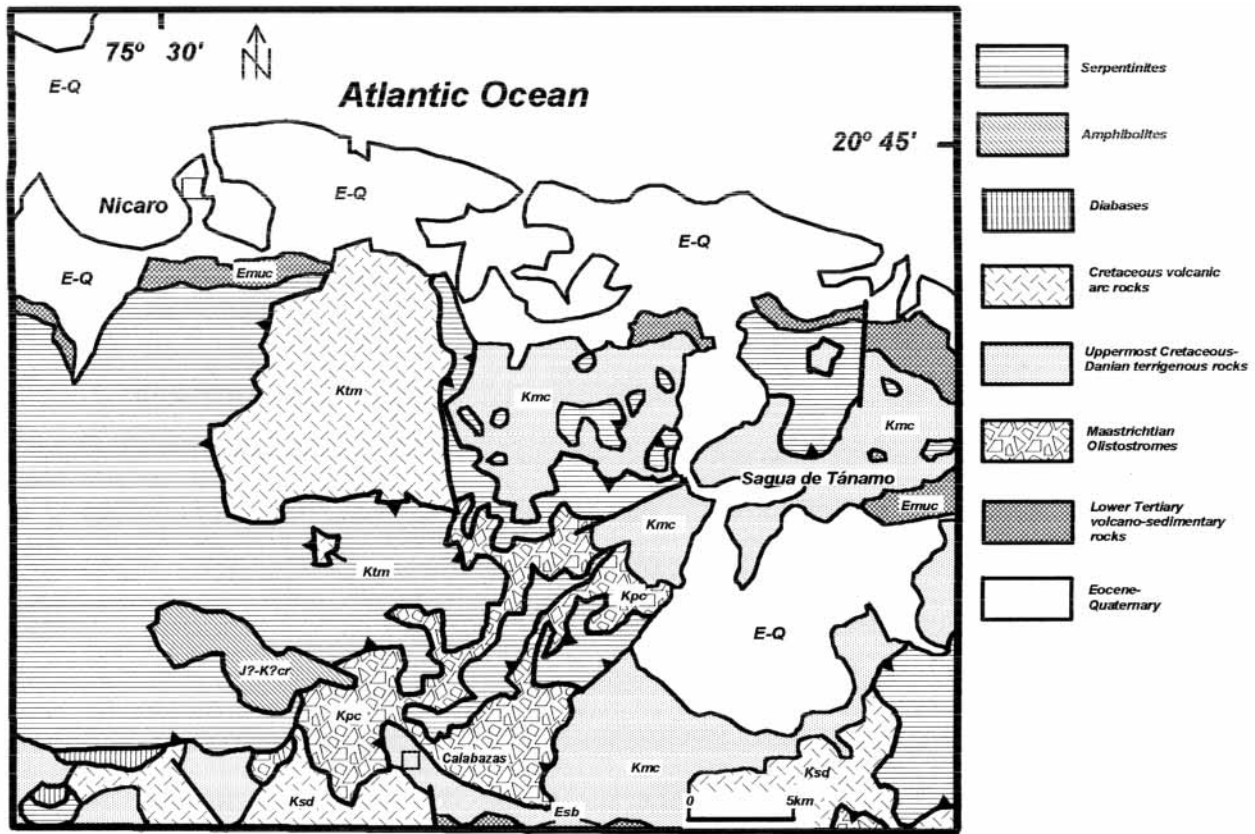
belong to the eastern Cuba nappe pile (Cobiella-Reguera et al., 1984a) and, therefore, are pre-Maastrichtian in age.

A wealth of new data on the primary structure, petrology and geochemistry of several areas of the eastern Cuba ophiolites has been published in the last years (Proenza et al., 1998a and b, 1999a and b, 2003). Geochemical and petrological data in the NOB from easternmost Cuba suggest a suprasubduction (backarc) or middle oceanic ridge origin for ophiolites of the Moa-Baracoa and Sierra de Nipe-Cristal Massifs (Proenza et al., 1998a and b, 1999a and b; Rodríguez et al., 2001).

### Cajobabo body (easternmost Cuba)

Near the mouth of Cajobabo river, in Sierra del Purial, easternmost Cuba, a small serpentinite body rests on Middle - Upper Eocene submarine fan deposits of the San Luis Fm, that includes olistostromes with clasts of serpentine, gabbro, amphibolite and other members of the ophiolite suite, mixed with clasts derived from an Early Tertiary volcanic arc (Cobiella et al., 1977; Figs. 1 and 11). The allochthonous Early Tertiary volcanics (El

Cobre Fm) are thrusted upon the Eocene turbidites and the Cretaceous metavolcanic rocks and lie with unconformity below the Upper Miocene- Quaternary strata (Iturralde-Vinent, 1996; Cobiella et al., 1977, 1984a; Fig. 11). Despite its small size, the Cajobabo body is a key piece in northern Caribbean geology, because its emplacement seems to be related to the first recorded horizontal movements along the Oriente fault in the Caribbean / North American plate margin (Cobiella et al., 1984a).

## THE METAMORPHIC BASEMENT OF THE CRETACEOUS VOLCANIC TERRANE

Amphibolites derived from oceanic crust form the basement of the KVAT. The KVAT is composed mainly of several thousand meter thick island-arc sequences that extends through a large part of Cuba below the Cenozoic deposits (Fig. 1). This volcanic terrane tectonically overlies the Northern Ophiolitc Belt, except in eastern Cuba. Three distinct stratigraphic and structural levels occur in this volcanic terrane (Fig. 12): 1) the oceanic basement
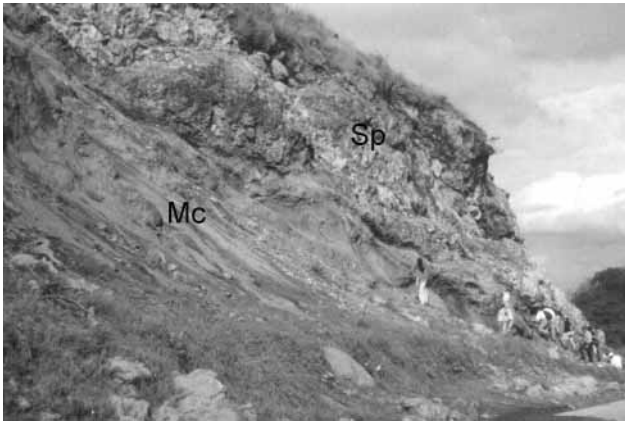
FIGURE 9 | **Serpentinite olistolith (Sp) resting on upper Mícara Fm silicilastics (Mc), near Rancho Quemado, 5 km SSW of Sagua de Tánamo city, Holguin province. The serpentinite/Micara Fm contact cuts bedding at a very low angle and shear deformation occurs along it. The outcrop is about 15 m high.**

made up by metamorphic sequences upon which an arc was built; 2) the Cretaceous volcano-sedimentary sequences (Aptian-Campanian), and 3) the Campanian-Maastrichtian sedimentary cover.

The oceanic basement is an amphibolitic complex (Haydoutov et al., 1989; Millán Trujillo, 1996b; Iturralde-Vinent, 1996b). The amphibolites (low pressure/high temperature) are exposed in central Cuba, in the Mabujina complex (Figs. 1 and 13; Somin and Millán, 1981), which comprises a sequence of melanocratic rocks, with minor serpentinites, metamorphosed to amphibolites. These rocks are also present in the Jatibonico 78 well, several 10's of kilometers to the east of Mabujina complex outcrops (Somin and Millán, 1981; Figs. 1 and 4). Most of the rocks in the complex were originally gabbros (cumulates), but some have been diabases, mafic volcanic rocks and cherts (Haydoutov et al., 1989; Millan Trujillo, 1996b). Amphibolites shown high contents of Ti, FeO, MgO, V, Cr, Sr and Zr, that Haydoutov et al. (1989) related to MORB composition. Nevertheless, a part of the Mabujina complex was also derived from volcanic arc rocks and intrusives that were transformed into gneisses (Somin and Millán, 1981; Millán Trujillo, 1996b; Kerr et al., 1999). K/Ar ages in the amphibolites span from $89 \pm 3$ to $80.7 \pm 1.6$ Ma. The complex also contains Albian-Campanian granitoid intrusives with K/Ar ages ranging from $95 \pm 2$ to $52 \pm 4$ Ma (Iturralde- Vinent et al., 1996). The highest metamorphic grade in the complex is attained in the lowest sections, near the contact with the southern metamorphic terranes (Escambray Massif). Haydoutov et al. (1989) and Millán - Trujillo (1996b) interpreted the mafic protolith of the Mabujina complex as the basement of the Aptian-Campanian volcanic arc in central Cuba. Following this reasoning, the ophiolites of the Mabujina complex must be pre-Aptian in age. The MORB geo-

chemistry of most of the metamorphic rocks of the Mabujina complex suggests an oceanic ridge origin (Millán Trujillo, 1996b). Greenschist facies mafic and felsic volcanic rocks occupy in part the highest structural levels of the complex. Weakly metamorphosed dykes of lamprophyre and andesite also cut the amphibolites. In addition, the Cretaceous volcanic arc rocks near Mabujina complex show evidences of dynamic metamorphism (Millán Trujillo, 1996b).

Collectively, the above data indicate that a volcanic arc was built on an oceanic crust, and that these former relationships were later modified by tectonic movements. According to Grafe et al. (2001), epidote-amphibolite facies rocks in the SE Mabujina complex were metamorphosed at < 5-9 kbar and temperatures of $610° – 710°$ C, before coming into contact with the Escambray (Guamuhaya) Massif. Several Rb/Sr radiometric age determinations in post-metamorphic pegmatites intruding the
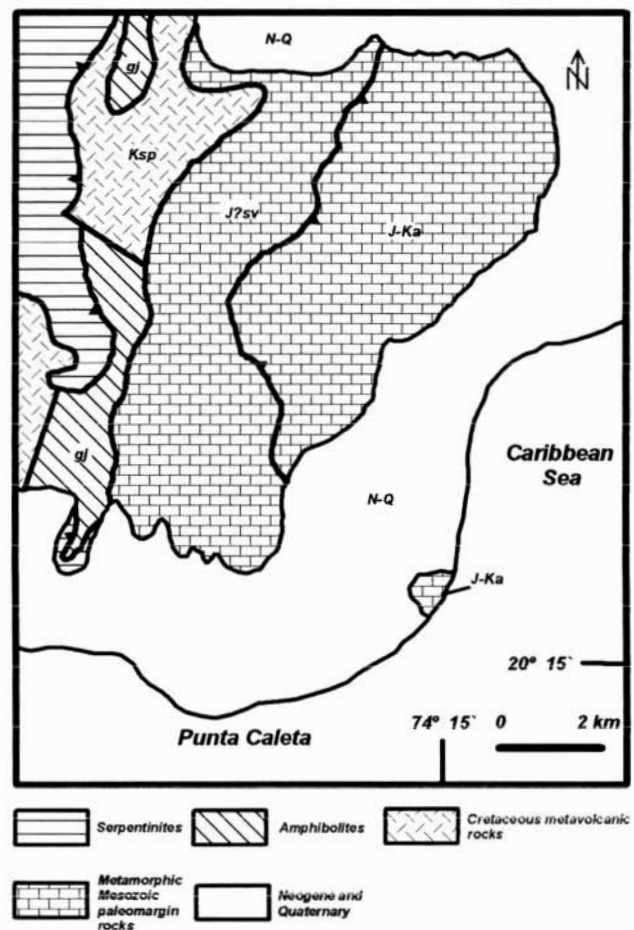


FIGURE 10 | **Geological map of Maisí area (easternmost Cuba). Simplified and slightly modified after Cobiella et al. (1984a). See location in Fig. 1 and legend of geological contacts in Fig. 2. *Ophiolites*: gj-Güira de Jauco Fm. *Cretaceous volcanic arc terrane*: Ksp- Sierra del Purial Fm. *Mesozoic paleomargin rocks*: J?sv- Sierra Verde Fm, phyllites and metasandstones with minor metamafic bodies (Jurassic?), J-Ka- Asunción Fm, marbles (Upper Jurassic and Cretaceous).**

FIGURE 11 | **Schematic geologic profile along Cajobabo valley (same vertical and horizontal scales). See location in Fig. 1.** *Cretaceous volcanic arc terrane*: **Ksp- Sierra del Purial or Farola Fm (metavolcanic rocks).** *Paleoc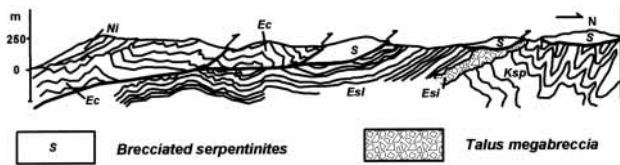ene-Eocene volcanic arc*: **Ec- El Cobre Fm (Lower Eocene).** *Eocene basin*: **Esi- Middle Eocene talus megabreccia (San Ignacio Fm), Esl- San Luis Fm -middle and upper Eocene submarine fan deposits (turbidites) with isolated clasts of the ophiolite suite.** *Upper Miocene-Quaternary marine talus deposits* (Imias or Maya Fm)**: Ni. Thick lines: overthrusts. Caribbean coast is on the left border of the profile.**

rocks of the epidote-amphibolite facies at two localities gave 88 and 81 Ma. These data place a minimum age for the metamorphism at two localities of the Mabujina complex (Grafe et al., 2001).

Recent geochemical data on the Mabujina complex questioned the above interpretation that considers the complex as the in situ basement of the volcanic arcs terrane. Thus Blein et al. (2003) have reported Nd, Sr and Pb isotopic compositions in the Mabujina complex rocks that are interpreted as indicators of sourcing from a depleted mantle, contaminated by subducted arc basement sediments. Blein et al. (2003) have suggested that the Mabujina rocks are the remains of an Upper Jurassic – Lower Cretaceous volcanic arc accreted to the Early Cretaceous arc and then composed the basement of the Late Cretaceous arc. The same authors (op.cit) emphasize several geochemical resemblances of the volcanic arc terrane in Cuba with the Guerrero terrane in western Mexico. Dilek (2003) included the Mabujina complex ophiolites in his Sierran – Type ophiolites.

## TECTONIC SLICES IN THE ESCAMBRAY (GUAMUHAYA) MOUNTAINS OF CENTRAL CUBA

The Escambray Massif of central Cuba (Figs. 1 and 13) is part of the Southern Metamorphic Terranes and is composed of metamorphosed Jurassic and Cretaceous passive continental margin carbonate dominated sequences, characterized by low to moderate temperature and high pressure metamorphism (Somin and Millan, 1981). These rocks tectonically underlie the Cretaceous Volcanic Arc Terrane, including the Mabujina complex. Two types of incomplete, dismembered ophiolites can be distinguished in the Escambray Massif:

1) High pressure/low temperature amphibolites, with a tholeiitic basalt protolith (Yayabo Fm). The Yayabo

amphibolites form large tectonic slices in northeastern Escambray, associated with serpentinites. Their protoliths were tholeiithic basalts with some chert interbeds (Millán Trujillo, 1996a). According to Grafe et al. (2001), the Yayabo barroisite-bearing garnet amphibolites were metamorphosed at pressures ranging from 13 to 14,5 kbars and temperatures ranging from 580 to 675ºC.

2) Slices of serpentinite mélange with eclogites and other metamorphic rocks sandwiched between the metasedimentary Mesozoic rocks. U-Th radiometric ages from metamorphic zircons within the eclogites are Albian (106-102 Ma; Hatten et al., 1988; Millán-Trujillo, 1996a). Metamorphism in the eclogites was developed at pressures ranging from 16 to 25 kbars and temperatures ranging from 580º to 630ºC (Grafe et al., 2001). Auzende et al. (2002) have reported pressure conditions of 12 kbar and temperature above 450ºC in other eclogites of similar tectonic setting.

Both assemblages are in tectonic contact with the Mesozoic metasedimentary rocks along thrust planes. Granitic pegmatites, 90-80 Ma old cut the shear zone between the volcanic arc rocks and the Escambray high pressure metamorphic rocks (Stanek et al., 2000).



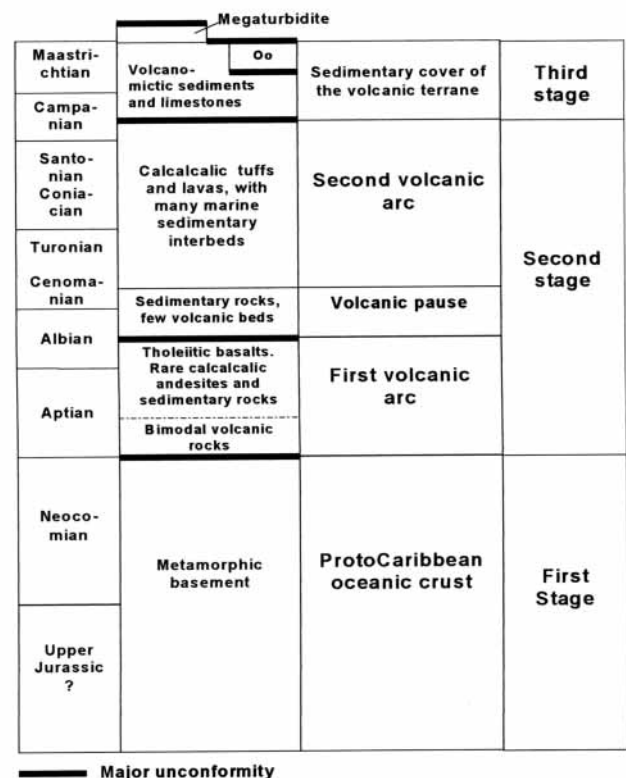| | | | |
|---|---|---|---|
| Maastrichtian | Volcano-mictic sediments and limestones | Oo | Sedimentary cover of the volcanic terrane | Third stage |
| Campanian | | | | |
| Santonian Coniacian | Calcalcalic tuffs and lavas, with many marine sedimentary interbeds | Second volcanic arc | Second stage |
| Turonian | | | |
| Cenomanian | Sedimentary rocks, few volcanic beds | Volcanic pause | |
| Albian | Tholeiitic basalts. Rare calcalcalic andesites and sedimentary rocks | First volcanic arc | |
| Aptian | Bimodal volcanic rocks | | |
| Neocomian | Metamorphic basement | ProtoCaribbean oceanic crust | First Stage |
| Upper Jurassic ? | | | |

FIGURE 12 | **General stratigraphy and main structural stages of the Cretaceous volcanic arc terrane. Oo: Olistostrome rich in ophiolitic clasts (La Picota and Yaguajay formations).**
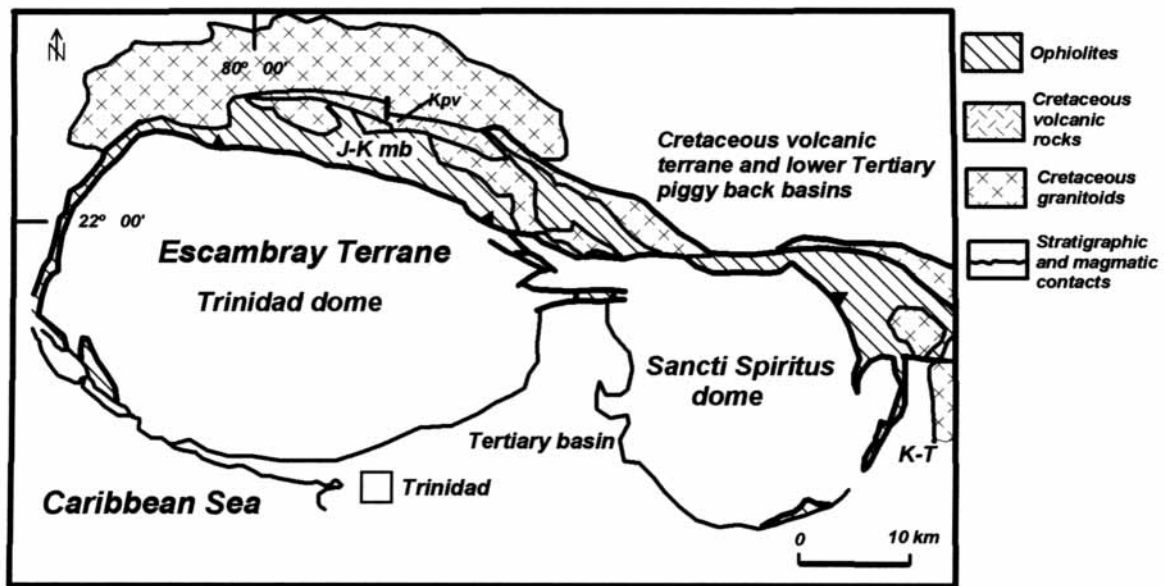
FIGURE 13 | **Schematic geological map of the Mabujina complex. See location in Fig. 1 and legend of geological contacts in Fig. 2. The Jurassic-Cretaceous Mabujina complex rests (with tectonic contact) and surrounds the high presssure Escambray (Guamuhaya) terrane. The Porvenir Fm contains greenschist facies rocks.** *Ophiolites:* **J-Kmb-Mabujina complex.** *Cretaceous volcanic arc rocks:* **Kpv- Porvenir Fm.**

## DISCUSSION

### Origin of Cuban ophiolites

The successive emplacements of Cuban ophiolites and ophiolite-bearing assemblages are late episodes of their history. Therefore, a brief review on the origin of these rocks is necessary for a better understanding of the dynamics and timing of their emplacement.

The Northern Ophiolite Belt was transported from the south over the North American paleomargin and the Lower Tertiary foreland basin of northern Cuba. This ophiolite bearing unit was in turn overridden from the south by the Cretaceous Volcanic Arc Terrane (Hatten, 1967; Pardo, 1975; Pszczolkowski, 1994; Iturralde-Vinent, 1996a and b; and others). Therefore, at least in central and western Cuba (west of Camagüey lineament, Fig. 1) the suggested original position of these units before their tectonic emplacements could be, from south to north: volcanic arc, oceanic basin and North-American passive continental margin (Iturralde- Vinent, 1996a; Cobiella-Reguera, 2000). The Escambray (Guamuhaya) massif is interpreted here as a huge tectonic window (Figs. 1 and 13). In this tectonic window highly deformed and metamorphosed rocks of a Mesozoic passive paleomargin, which included thin tectonic slices of metamorphosed oceanic lithosphere, crop out below the Mabujina complex and the Cretaceous volcanic terrane (Somin and Millán, 1981; Millán, 1990; Millán Trujillo, 1996; Auzende et al., 2002). The movement of this volcanic terrane in relation to the Southern

Metamorphic Terrane seems to have been southward from north to south (at present coordinates; Millán and Somin, 1985; Millán, 1990), whereas the passive paleomargin, represented by the Escambray rocks was originally situated to the south of the volcanic arc. Nevertheless, this is not the only postulated interpretation since Stanek et al. (2000) considered that the volcanic terrane moved northward upon the Southern Metamorphic Terrane.

The ophiolites in the Mabujina complex (Figs. 1 and 13) seem to be derived from a Late Jurassic- Neocomian oceanic crust, created in a basin to the south of the Mesozoic passive margin of North America during the Pangea breaking up (Cobiella-Reguera, 1998c, 2000). Probably these rocks were metamorphosed during the formation of a middle Cretaceous magmatic arc, as was proposed by Haydoutov et al. (1989). Middle Late Cretaceous radiometric ages from pegmatites intruding these metamorphic rocks have been recently obtained (Grafe et al., 2001). These data indicate an older age for the intruded metamorphics, a fact that accords well to Haydoutov's (1989) interpretation. Other proposals that consider the Mabujina complex a Pacific derived terrane (Blein et al., 2003) are suggestive but would need support from additional analytical and field work data.

The geological, geochemical and petrological data reviewed in this paper (Andó et al., 1996; Beccaluva et al., 1996; Fonseca et al., 1984; García-Casco et al., 2003; Proenza et al., 2003; Kerr et al., 1999; and others) suggest that the NOB rocks probably originated in two distinct tectonic settings: 1) a small oceanic basin originated during

Pangea breakup and, 2) a marginal basin located between the North American paleomargin and a volcanic arc.

The oldest ages of the northern ophiolites are Jurassic (Somin and Millán, 1981; Llanes Castro et al., 1998). According to Pindell (1985, 1994), Marton and Buffler (1994, 1999), and other sources, this was the time of the breakup of Pangea in Meso-America, when the North American plate began splitting from neighboring continents. Oxfordian (middle? and late) continental margin magmatism recorded in western Cuba (Iturralde-Vinent, 1996d, Cobiella- Reguera, 1996) supports this interpretation. Late Tithonian radiolaria reported from the volcanosedimentary elements of the NOB in central Cuba (Llanes Castro et al., 1998) also support drifting and creation of oceanic lithosphere by this time. Therefore, it seems likely that the first oceanic lithosphere preserved in present-day Cuba formed south of the North American plate and was created from late Oxfordian (or Kimmeridgian) to late Tithonian.

The youngest northern ophiolites are coeval with the oldest volcanic arc rocks (Aptian- Albian). As noted earlier, this age overlaps with that of the first volcanic arc, which grew on an oceanic basement (Haydoutov et al., 1989; Iturralde-Vinent, 1996a; Cobiella-Reguera, 1998c, 2002). According to plate tectonic models and modern examples, marginal basins often develop behind volcanic arcs (Miyashiro et al., 1984). Generation of new oceanic crust is possible in such basins and, as formerly shown, geochemical data suggest that part of the northern ophiolites, at least in eastern Cuba, (Proenza et al., 1998a and b, 1999; Rodríguez et al., 2001; and others) and Villaclara (Kerr et al., 1999) show such suprasubduction backarc zone signatures. Convincing evidence of Upper Cretaceous ophiolites has not been found (Cobiella-Reguera, 1998c, 2000). Therefore, the generation of oceanic crust in this marginal basin probably ended during the Albian, when the southern continental massifs (Escambray and Isle of Youth) arrived to the subduction zone (see Cobiella-Reguera, 2000 for further details). Some of the high pressure metamorphic rocks of Escambray (Guamuhaya) massif contain metamorphic zircons which yielded Albian 106-102 My U-Th ages (Hatten et al., 1988), suggesting that thin slices of oceanic crust may have been emplaced into the former southern margin during a subduction/collisional event (Millán-Trujillo, 1996a). It is here proposed that these rocks (including the Yayabo Fm) were part of the Upper Jurassic - Neocomian oceanic crust that was obducted and /or overthrusted during the collision (Cobiella-Reguera, 2000). Granitic pegmatites, 90-80 Ma old, cut the footwall shear zone between the volcanic arc rocks and the Escambray high pressure metamorphic rocks (Stanek et al., 2000). Therefore, at least a pre-Campanian age (possibly Albian?) can be assumed for the (micro) continent/volcanic arc collision and the first tec-

tonic emplacement of Cuban ophiolites. Neither this pre-Campanian collision nor, in general, the role of the SMT in the northwestern Caribbean geology are accepted in the most commonly accepted models of Caribbean tectonic development (Pindell and Barret, 1990; Pindell, 1994; Kerr et al., 1999). The model of the Early Cretaceous (Aptian – Albian) geological history of the Cuban OLRs proposed here is shown in Fig. 14A (see Cobiella-Reguera, 2000, p. 608-609 for further detail).

García Casco et al. (2003), on the base of the geochemical data resulting from twelve samples from the Güira de Jauco amphibolites, suggested that the easternmost Cuban ophiolites may represent Upper Cretaceous Caribbean lithosphere (90-80 Ma?), which originated either within the Caribbean plate or in the Pacific plate. However the 72 Ma K/Ar radiometric (cooling?) age in
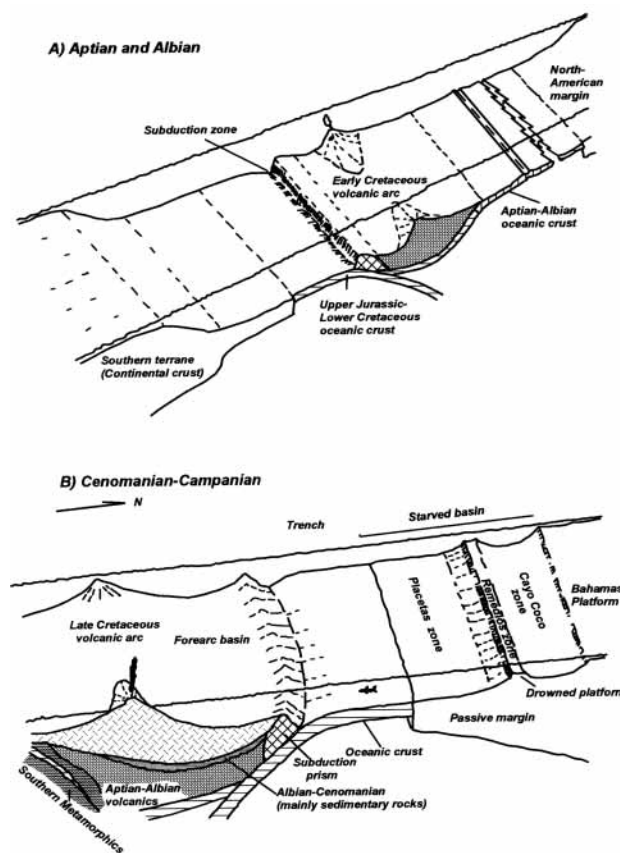


FIGURE 14 | **Aptian-Albian and Late Cretaceous (Turonian-Early Campanian) paleotectonic conceptual models of Cuba and its surroundings (Cobiella-Reguera 1998c). A) Aptian-Albian stages. A young (Upper Jurassic- Neocomian) oceanic lithosphere is subducted northward beneath the volcanic arc. During the Albian, the southern continental mass collided with the Aptian-Albian volcanic arc. A first metamorphic episode in the southern metamorphic terranes, and the tectonic emplacement of oceanic lithosphere in and upon Escambray massif may be related to this collision. Note the accretion of Aptian-Albian oceanic lithosphere to the older Jurassic- Neocomian lithosphere in the marginal basin that would have developed to the north of the arc. B) Turonian-Campanian stages. Oceanic lithosphere is southward subducted beneath a Late Cretaceous volcanic arc. The arc-continental margin collision occurred during the Campanian.**

the Güira de Jauco amphibolites and the Maastrichtian tectonic and erosional event that affected eastern Cuba ophiolites are very difficult to explain in the light of this hypothesis. There would be short time (8-18 Ma) for both 1) the generation of the oceanic crust in the central Caribbean (even more problematic in the case of a Pacific ocean crust), several hundred kilometers to the south of the Güira de Jauco amphibolite location; and 2) its transport through hundred to thousand of kilometers, metamorphism and thrusting.

After a late? Albian-Cenomanian pause in volcanism (Fig. 12) a second Cenomanian to Campanian magmatic arc developed, resulting from a subduction zone that probably dipped south (present coordinates), and consumed the oceanic lithosphere located between the new arc and the continental margin of North America in Cuba (Fig. 14B; Cobiella-Reguera, 1998c, 2000, 2002). Probably, this subduction reversal was related to a volcanic pause, followed by a change from the generation of arc tholeiites in the Aptian-Albian arc to the emplacement of calc-alkaline rocks in the Cenomanian-Campanian arc (Fig. 14B). The same, more or less coeval picture has been suggested in Hispaniola (Lebrón and Perfit, 1994; Draper et al., 1996; Iturralde-Vinent and Gahagan, 2002) and Puerto Rico (Lebrón and Perfit, 1994; Jolly et al., 1998; Iturralde-Vinent and Gahagan, 2002). In western Cuba (Vega 1 and Mercedes 1 wells, Fig. 4) and in the Iguará-Perea area of the Villaclara massif, the weak metamorphism of the metadiabase pre-Upper Cretaceous basement rocks and the scarce development of granitoids might suggest that part of the Cretaceous volcanic-sedimentary sections may have accumulated on a SSZ suprasubduction zone oceanic crust, mildly affected by magmatic and hydrothermal activity (might be the forearc basin in Figure 14B).

It must be emphasized that the outstanding "similarity" of the K/Ar maximum ages found in high pressure metaophiolites of the NOB. In Havana-Matanzas (126 ± 10 Ma), Holguin (125 ± 12 Ma) and eastern Cuba (125 ± 5 Ma), the average value reported would correspond to the Barremian stage (Cretaceous Stratigraphic Commission in the International Stratigraphic Chart, UNESCO/IUGS, 2000). The K/Ar maximum age in Cajálbana (115 ± 5) and the Ar/Ar age in Villaclara massif (118 Ma) are Aptian, according to the same chart. The whole age data probably record postmetamorphic cooling ages, perhaps related to uplift in subduction zones (even though no convincing evidence of pre Aptian volcanic arc rocks has been found in Cuba; Cobiella-Reguera, 2000; Colectivo de Autores, 1996). Kerr et al. (1999) proposed that high pressure metamorphic blocks in the NOB may represent the exhumed subduction zone of a Lower Cretaceous primitive boninite arc. However, this proposed boninite arc is based only on two samples that fulfill the exact cri-

teria to be classified as boninite. Additionally, the age of these samples is not well established (Kerr et al., 1999). Therefore, this primitive boninite arc hypothesis is an attractive idea that needs additional field and analytical support to become fully established. On the other hand, the hypothesis that proposes two subduction zones explains several major features of Cuban geology, although the radiometric ages older than Albian (>112 Ma) reported in some subduction? related high pressure metamorphic blocks of the NOB by Iturralde-Vinent et al. (1996) and García-Casco et al. (2002) would remain without clear explanation in this model, that propounds that the north facing subduction zone should begin in the late Albian or Cenomanian. Obviously, the relationship of the high pressure metaophiolite ages to subduction events is a key piece for unraveling the NOB development.

## Emplacement of the NOB bodies

### *The Campanian emplacement event*

The end of volcanism in Cuba during Campanian time (Fig. 12) suggests that subduction stopped. Several evidences suggest a Campanian ophiolite emplacement episode.

Indirect evidence of the closing of the oceanic basin between the second, Late Cretaceous volcanic arc and the North American Mesozoic paleomargin (Fig. 14) has been recorded in the Campanian sedimentary rocks of western Cuba, where the Moreno Fm. of the Cordillera de Guaniguanico contains clastic materials derived from the KVAT (Pszczolkowski, 1994). As suggested in Fig. 14, this fact could be only possible if the oceanic basin between the Late Cretaceous volcanic arc and the continental margin was not developed in Late Campanian.

In western Cuba, the Upper Campanian- Maastrichtian turbidites (Via Blanca Fm, Figs. 2, 3 and 15) lies on the ophiolites and volcano-ophiolitic mélange as well on the KVAT rocks (Pszczolkowski and Albear, 1982; Pushcharovsky, 1988). Therefore, a Campanian (pre Via Blanca Fm.) tectonic event took place in this area. The unconformity that separates the KVAT from its upper Campanian- Maastrichtian sedimentary cover should be related to this event (Fig. 12).

The Campanian - Maestrichtian deposits of the KVAT cover are volcanomictic sediments and there is no evidence of important ophiolite outcrops at that time. However, the coarse serpentinite and gabbro clasts in some upper Campanian conglomerates in western Cuba (Vía Blanca Fm.; Brönnimann and Rigassi, 1963; Albear Fránquiz and Iturralde-Vinent, 1985) suggest coeval minor local ophiolite obduction from near surface bodies, following Closs (1984) model.

Finally, the same several ten to hundred meter thick K/T boundary megabed (Pszczolkowski, 1986; Cobiella-Reguera, 1998b, 2000; Kiyokawa et al., 2002) occurs on the continental paleomargin of western (Cacarajícara Fm.), central (Amaro Fm) and central-eastern Cuba (Camaján Fm) and in the KVAT sedimentary cover (Peñalver Fm; Fig. 12) of western Cuba. No report exists that this K/T boundary megabed was deposited on the ophiolites. This fact suggests that oceanic crust was not exposed in the sea floor where the megabed was deposited.

A probable explanation for the preceding facts is that the oceanic crust between the continental margin and the volcanic arc during the Late Cretaceous was subducted, and the North American paleomargin and the former Cretaceous arc juxtaposed (Fig. 15; see also fig. 17 in Cobiella-Reguera, 2000). Despite the fact that it is almost concealed by the thrusting related to the Early Tertiary Cuban orogeny, the Late Cretaceous episode seems to be the main event in the NOB emplacement history (Cobiella-Reguera et al., 1984b, Cobiella-Reguera, 2002). The latest Cretaceous (Campanian) arc/continent collision in Cuba is not included in most of the regional plate tectonics models (Pindell, 1994; Kerr et al., 1999; and many others) because this event is considered as Early Tertiary (Bralower and Iturralde-Vinent, 1997).

### The Maastrichtian emplacement event

In easternmost Cuba and Holguin, ophiolite derived clasts (sometimes with evidences of lateritic paleoweathering) are the main component in the upper? Maastrichtian olistostromes (La Picota and Yaguajay formations, Figs. 7 and 8; Cobiella, 1978; Cobiella et al., 1984b; Jakus, 1983). The emplacement of these olistostromes was coeval to the northward thrusting of the ophiolite massifs in that region (Nuñez-Cambra et al., 2003). The chaotic nature of the deposits, their monotonous composition (almost all the clasts belong to the ophiolite suite) and their lack of rounding suggest that the Maastrichtian emplacement of the eastern Cuba ophiolites was an intense but short lived tectonic event, that obducted these rocks on the surface and then displaced them horizontally northward (Nuñez Cambra et al., 2003). This displacement took place on the floor of a marine basin, attained at least 30 km and is observable through a wide thrust belt (Fig. 8). A several hundred meter thick olistostrome deposits accumulated at the thrust front and later were overrode and pushed as the thrust sheets continued moving northward (Cobiella, 1978). In the Moa-Baracoa massif, the horizontal movement was no less than 60 km. Considering that ophiolite emplacement took place in the last half of the Maastrichtian (Fig. 16, circa 3.5 Ma, UNESCO and IUGS, 2000), a rough velocity estimation of 17 mm/year can be calculated for the ophiolite thrusting in this region.
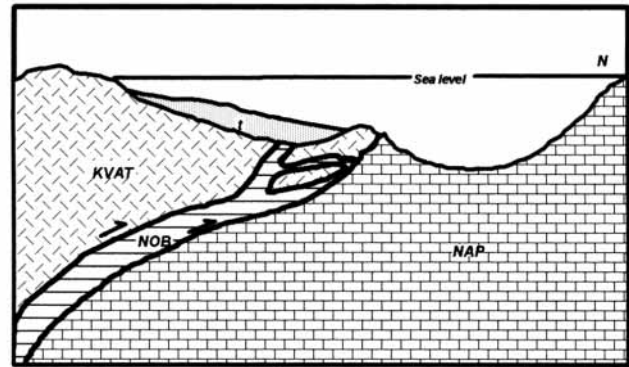


FIGURE 15 | **Sketchy geological profile showing the relationships among the main tectonic units in central Cuba during late Campanian-Maastrichtian. KVAT- Cretaceous volcanic arc terrane; NOB- Northern Ophiolite Belt; NAP- North America paleomargin; t- Campanian-Maastrichtian turbidites. Thick lines correspond to overthrusts.**

The unconformity between Maastrichtian and Paleocene deposits in The Havana area and the poor distribution of upper Maastrichtian and lower Paleocene deposits in Cuba suggest a period of tectonic activity at the Cretaceous/Paleocene transition (Pardo, 1975). The Maastrichtian episode was the third ophiolite emplacement event in Cuba (Fig. 16). The tectonic environment where it was developed remains unclear. In eastern Cuba (including the Holguín massif) the ophiolite outcrops rest on the volcanic arc terrane, and the SMT rocks do not occur. In spite of these significant differences with the western and central NOB, in eastern Cuba the Mesozoic oceanic lithosphere and the Cretaceous volcanic arc terrane were also pushed from the south upon the North American paleomargin (Figs. 7 and 10; Cobiella-Reguera et al. 1984b; Iturralde-Vinent, 1996b). Therefore, even though the Maastrichtian tectonic environment in eastern Cuba remains not well established, it seems clear that all the NOB bodies share a common pre-Maastrichtian history.

### Ophiolite emplacement during the Cuban orogeny

The last major event that affected the NOB was the Early Tertiary Cuban orogeny (Meyerhoff and Hatten, 1968; Furrazola et al., 1964; Lewis and Draper, 1990). This deformation was developed by steps, in blocks bounded by strike slips faults or lineaments (Fig.1; Cobiella-Reguera, 1997; Gordon et al., 1997). In all the areas, ophiolite emplacement is coeval to olistostrome deposits. In this case however, besides serpentinite and other ophiolite suite rock olistoliths, derived from the North American Mesozoic continental margin accumulated at the foot of the fronts of the northward displaced thrust sheets (Fig. 17). In some cases, as in the Cajálbana - Bahía Honda area, structural and stratigraphic evidences indicate that the ophiolites were thrusted to the north upon the North American paleomargin and its overlying Lower Tertiary foreland basin. This was a short lived process (Lower Eocene
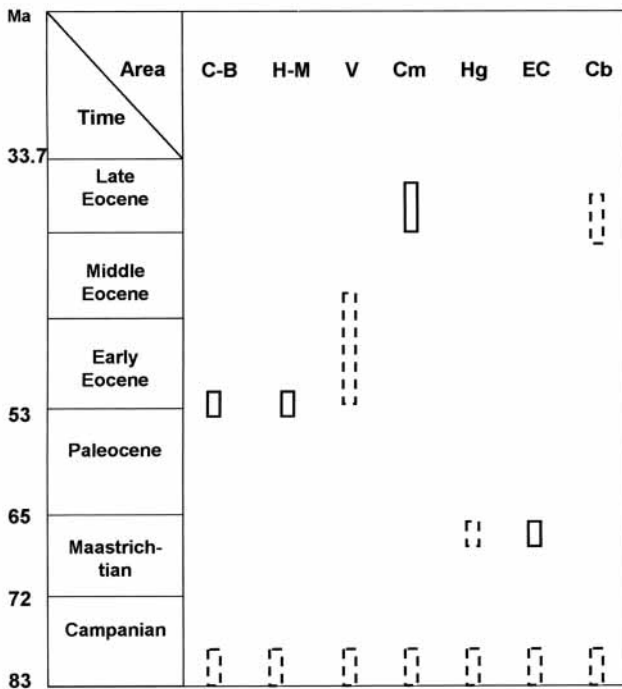
FIGURE 16 | **Chronology of the emplacement ages of the Cuban northern ophiolitic belt. The rectangles with solid lines represent the events whose age is well established. In spite of the fact that the late Campanian event was probably the most important, it was masked by the later early Tertiary episodes. Legend of the Areas: C-B- Cajálbana – Bahía Honda; H-M- Havana-Matanzas; V- Villaclara; Cm- Camagüey; Hg-Holguin; EC- eastern Cuba; Cb- Cajobabo. See locations in Fig. 1.**

deposits cover the uppermost Paleocene-Lower Eocene thrust-related olistostromes in easternmost Guaniguanico). In western Cuba, West of the Llabre lineament (Fig. 1) the ophiolite thrusting ended in the Early Eocene (Bralower and Iturralde-Vinent, 1997; Cobiella-Reguera, 1998d; Gordon et al., 1997). In central Cuba, between the Llabre lineament and the La Trocha fault (Villaclara ophiolites, Fig. 1), the same process ended in the Middle Eocene (Pardo, 1975; Hatten et al., 1988). Finally, in eastern central Cuba, between the La Trocha fault and the Camagüey lineament, the emplacement of the Camagüey massif developed in Late Eocene (Fig. 16; Iturralde-Vinent, 1996a). In this last area, the ophiolite thrusting attained no less than 20 km of displacement (Fig. 6), and they are overlain by Upper Eocene deposits. In a rough calculation, considering that ophiolite emplacement developed in the first half of the Late Eocene, and assuming circa 1.75 Ma for the early Late Eocene (UNESCO and IUGS, 2000), a emplacement velocity of 11.4 mm/year can be calculated. In Camagüey, a first deformation event in the Late Paleocene – Early Eocene is related to the thrusting of the Cretaceous volcanic terrane upon the ophiolites (Iturralde-Vinent, 1996b).

East of the Camagüey lineament there are no traces of ophiolite emplacement related to the Cuban orogeny. The

Early Tertiary thrusting in the western and central ophiolite belt is coeval with a new (Paleocene-Middle Eocene) volcanic arc, developed after several million years of magmatic quiescence (late Campanian to Danian). This new arc is represented by volcano-sedimentary hundred, to thousand meter thick sequences in SE Cuba (Sierra Maestra and its surroundings, Fig. 1; Lewis and Straczek, 1955; Khudoley and Meyerhoff, 1971; Cobiella-Reguera, 1988, 1997; Iturralde-Vinent, 1996c), the Cayman Rise (Shipboard Scientific Party, 1997), and Haiti (Butterlin, 1960). The regional geology indicates that the arc was nearly E-W, with a subduction zone along its southern border (Cobiella-Reguera, 1988, 1997; Shipboard Scientific Party, 1997; Iturralde-Vinent, 1996c). The stress fields during the Early Tertiary Cuban orogeny have not been studied in detail, but this tectonic event shows its maximum development in the southern part of the North American Mesozoic paleomargin (and its overlying foreland basin) and in the northern ophiolites (Fig. 17). In other regions deformation was less intense (Pszczolkowski and Flores, 1986; Cobiella-Reguera, 1997). This fourth, Early Tertiary, emplacement is the most preserved tectonic event in the NOB (Fig. 15).

In the Kerr et al. (1999) model the final deformation and thrusting of the Cretaceous volcanic arc rocks and the ophiolites upon the North American paleomargin (their Fig.12, p.1596) is related to the "Cayman fault system"(CFS; Oriente fault in Fig.1). In their figure, the CFS is located north of the Paleogene volcanic arc, a fact not supported by regional geology data (Khudoley and Meyerhoff, 1971; Calais and de Lepinay, 1991; Iturralde-Vinent, 1996a; Shipboard Scientific Party, 1997). Moreover, if Kerr et al. (1999) suggested relationships between the CFS and the Early Tertiary Cuban orogeny were valid, the deformations of that age should be very intensive in SE Cuba (northward of Sierra Maestra mountains), and much less marked in western and central Cuba, located far from the fault system. However, the reverse is true, and the Late Paleocene-Middle Eocene folding and faulting in the eastern Cuba ophiolites and surrounding areas were very mild (Fig. 8; Pushcharovsky, 1988).

### Ophiolite emplacement related to the Oriente fault

This last geodynamic episode has been recognized previously in several tectonic models (Iturralde-Vinent 1996a; Pindell and Barret, 1990; and others) and it would correspond to the fifth event of ophiolite emplacement in Cuba. The Oriente fault belongs to the present-day boundary between the Caribbean and the North American plates. The last emplacement event affecting the NOB is recorded in a small area near Cajobabo river mouth, in Sierra del Purial, easternmost Cuba (Fig. 1), where a serpentinite body overthrusted the Middle - Upper Eocene deposits of the San Luis Fm, which contain ophiolite suite and Lower Paleogene volcanic rocks clasts (Fig. 11). This
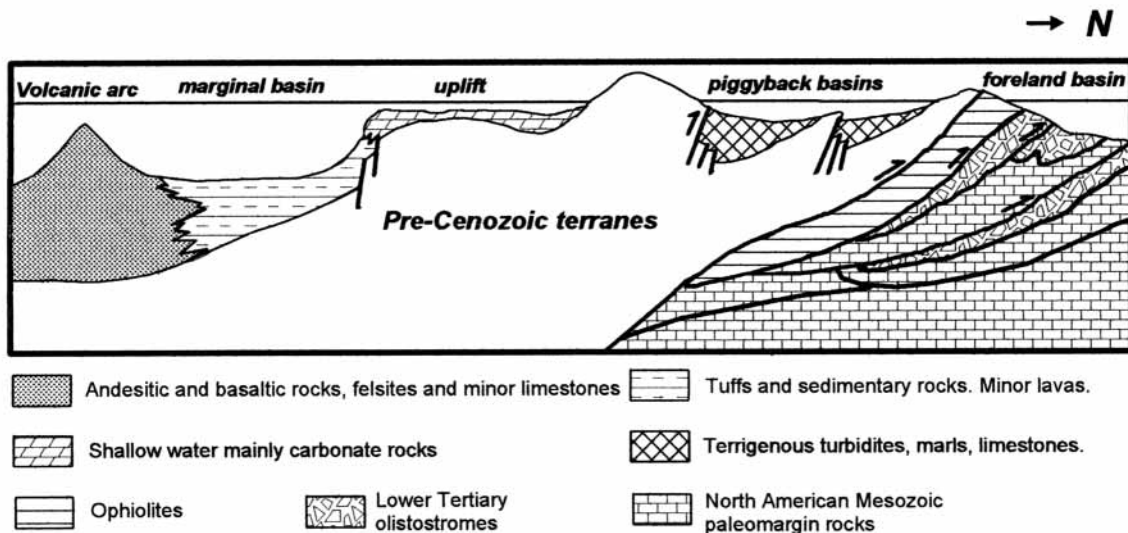
FIGURE 17 | **Early Tertiary conceptual paleotectonic and paleogeographic cartoon profile during the Cuban orogeny (modified from Cobiella-Reguera, 1997). This profile is about 300 km long, vertically exaggerated and located to the west of Camagüey lineament (see Fig. 1). This sketch summarizes the proposed relationships between a Paleocene-middle Eocene southern volcanic arc, which stretched along SE Cuba and the Cayman crest, and the coeval piggyback and foreland basins that developed northward as a consequence of the thrust belt evolution. Note that the foreland olistostrome deposits rest on the North American paleomargin sequences. All the structural units shown in the profile belong to the North American plate. A subduction zone consuming Caribbean crust should be located southward of the lower Tertiary volcanic arc (Shipboard Scientific Party, 1997).**

local thrusting seems to be related to the first strike slip movements along the Oriente fault that displaced the Eocene volcanic rocks several tens of kilometers from the west. The activity of this fault resulted in the later northward thrusting of these Eocene volcanites and of a small NOB serpentinite sliver, which were emplaced over the turbidites of the San Luis Fm (Cobiella et al., 1977). A modern example of a similar situation is recorded in the "Santiago fold and thrust belt" of the easternmost Cayman Trough (Calais and de Lepinay, 1991).

## CONCLUSIONS

The different types of oceanic lithosphere in Cuba represent parts of an oceanic basin (the so-called Proto-Caribbean basin), that developed between North and South America after the Pangea break-up (Pindel, 1985, 1994; Giunta et al., 2002). A small part of this short lived (circa 80 Ma) Proto-Caribbean lithosphere is now represented by different ophiolites and ophiolite-bearing terranes in Cuba and other of the Greater Antilles.

The geological data in Cuba suggest that the Proto-Caribbean oceanic basin originated in two episodes. The first lasted from Late Jurassic to Early Cretaceous and was related to Pangea fragmentation and the splitting of North America from South America. The southern part of this ocean basin was closed during the Aptian and Albian as a consequence of its subduction below a volcanic arc (Cobiella-Reguera, 1998c, 2000). Relics of

this relatively short lived basin (50-60 m. y.) are preserved in the metamorphic basement of the Cretaceous volcanic terrane and in the oceanic lithosphere slices in the Escambray massif of south central Cuba, as well as in the Northern Ophiolite Belt.

The second episode of oceanic crust formation took place in the backarc marginal basin that spread between the Aptian-Albian volcanic arc and the North American margin. The change in subduction polarity (from northward to southward in present coordinates) at the beginning of the Late Cretaceous caused the closure of the formerly generated Aptian-Albian marginal basin during the Campanian. Therefore, about 40 m.y. after its birth the basin was finally consumed and the Proto-Caribbean lithosphere welded to the North-American plate. The Early Cenozoic deformation in western and central Cuba reinforced this assembly.

The timing of the tectonic emplacement of oceanic lithosphere slices changed along the strike of the NOB during the Late Paleocene-Middle Eocene Cuban orogeny (Fig. 15). To the west of the Camagüey lineament, the last ophiolite emplacement took place during the Late Paleocene- Middle Eocene (locally Late Eocene), with emplacement ages becoming younger from west to east. In the extensive ophiolitic massifs to the east of the Camagüey lineament, Early Tertiary deformation was milder, and evidences of the Cuban orogeny are virtually absent. Middle or Late Eocene serpentinite emplacement in easternmost Cuba is related to strike slip movements along the Oriente fault.

The history of Cuban ophiolites and ophiolite bearing units is complex. Serpentinite flow during deformation strongly masks previous contacts and structures, mixing and deforming not only the different ophiolite members, but also their country rocks. A multidisciplinary approach in some key areas would be the best way to better understand the emplacement of these outstanding rock suites.

## ACKNOWLEDGEMENTS

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