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High pressure metamorphism of ophiolites in Cuba

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ABSTRACT

High-pressure metamorphic complexes of ophiolitic material in Cuba trace the evolution of the northern margin of the Caribbean Plate during the Mesozoic. In the northern ophiolite belt of western and central Cuba, these complexes document cold (i.e., mature) subduction of oceanic lithosphere. Age data indicate subduction during pre-Aptian times followed by mélange formation and uplift during the Aptian-Albian. The P-T evolution is clockwise with relatively hot geothermal gradient during exhumation (i.e., "Alpine-type"), suggesting that exhumation may have been triggered by unroofing processes ensuing arrest of subduction. It is hypothesized that tectonic processes related to termination of subduction led to formation of characteristic oscillatory zoning of garnet recorded in blocks separated by ca. 800 km along strike of the belt. In eastern Cuba, the complexes document hot subduction with peak conditions at ca. 750 ºC, 15-18 kbar followed by near-isobaric cooling (i.e., counterclockwise P-T path). The contrasting petrologic evolution in the two regions indicates that the correlation of eastern and western-central Cuban mélanges is doubtful. The age and tectonic context of formation of these hot-subduction complexes is uncertain, but available data are consistent with formation during the Aptian-Albian due to a) the birth of a new subduction zone and/or b) subduction of young oceanic lithosphere or a ridge. Furthermore, tectonic juxtaposition of high-pressure ophiolitic material and subducted platform metasediments in the Escambray complex (central Cuba) that were decompressed under relatively cold geothermal gradients ("Franciscan-type" P-T paths) indicates syn-subduction exhumation during the uppermost Cretaceous (ca. 70 Ma). The diversity of P-T paths, ages and tectonic settings of formation of the high-pressure complexes of ophiolitic material in Cuba document a protracted history of subduction at the northern margin of the Caribbean Plate during the Mesozoic.

KEYWORDS High-pressure. Metamorphism. Ophiolite. Subduction. Caribbean.

INTRODUCTION

Volcanic-arc and ophiolitic rocks constitute important geological elements of the Caribbean realm (Fig. 1A), and deciphering their origin and evolution is fundamental to achieving well-founded plate-tectonic reconstructions for the region. Volcanic-arcs provide insights into the age of subduction and the processes triggering it. In contrasts, ophiolites are related to generation of oceanic lithosphere either at mid-ocean ridges or at suprasubduction environments. However, ophiolitic rock assemblies, in the Caribbean and elsewhere, normally enclose high pressure (HP) metamorphic complexes indicative of the location, age and tectonic processes accompanying subduction. When associated with non-metamorphosed ophiolitic bodies, as in Cuba, high-pressure complexes are exotic relative to their enclosing ophiolitic matrix, and can be used in combination with associated non-metamorphosed ophiolites and volcanic arc terranes to constrain the geometry of plate boundaries.

In Cuba, ophiolitic material metamorphosed to high-pressure is found as blocks within serpentinite-matrix mélanges in a number of geological settings (Somin and Millán, 1981; Millán, 1996a). The most important ophiolitic assembly is the "northern ophiolite belt" (Iturralde-Vinent, 1989, 1996a ,b, 1998), a discontinuous belt of more than 1000 km in length composed of discrete, variously sized bodies exposed in the north of the island, from W to E, Cajálbana, Mariel-La Habana-Matanzas, Las Villas, Camagüey, Holguín, Mayarí, Moa-Baracoa (Fig. 1B). All these bodies have been widely considered to represent a single geologic element formed within the same paleogeographic/paleotectonic setting during the Mesozoic, although more recently Iturralde-Vinent et al. (this volume) argued that eastern Cuba bodies should not be included as part of this belt. In this paper, we follow this subdivision.

The ophiolitic bodies are composed mostly of chrysotile-lizardite serpentinites, which are the metamorphic products of harzburgite, dunite and, less abundantly, pyroxenite, wehrlite and lherzolite, though they also contain fragments of the crustal sections of ophiolite, including layered and isotropic gabbros and associated cumulate rocks, chromite ores, diabase, basalt and pelagic sediments (see Iturralde-Vinent, 1996b for review; additionally, see Khudoley, 1967; Khudoley and Meyerhoff, 1971; Pardo, 1975; Somin and Millán, 1981; Fonseca et al., 1985; Iturralde-Vinent, 1989; Millán, 1996a; Kerr et al., 1999; Proenza et al., 1999). These bodies of serpentinite have been the subject of controversy concerning the origin of Alpine-type ultramafic rocks in the 1950's, when H.H. Hess proposed a primary hydrated ultramafic magma but N.L Bowen disputed this hypothesis and interpreted the bodies as solid intrusions of serpentinized peridotite (Young, 1998, p. 201-209). In the 1970's the bodies were recognized as oceanic fragments accreted to the Yucatan/North American margin during late Upper Cretaceous to Paleogene collision of this margin with the Upper Cretaceous volcanic arc of Cuba. Oceanic transformations resulted in serpentinization and low-pressure metamorphism (Somin and Millán, 1981; Millán, 1996a; Auzende et al., 2002; Proenza et al., 2003; García-Casco et al., 2003). During accretion, the bodies were strongly sliced off, fractured and brecciated. In fact, most of them can be considered as tectonic serpentinite-matrix mélanges that contain, in addition to co-genetic igneous and sedimentary materials, exotic blocks incorporated from adjacent platform sedimentary sequences, volcanic-arc and subduction complexes. Other ophiolitic assemblies appear as tectonic slices within continental terranes that probably represent fragments of the Mesozoic platform of the Maya block (i.e., Escambray and Guaniguanico terranes of central and western Cuba, respectively; Iturralde-Vinent, 1989, 1996a; Pszczólkowski, 1999; Fig. 1B). These ophiolitic slices are composed of chrysotile-lizardite serpentinite-matrix mélanges in the Guaniguanico terrane, while in the Escambray massif they are made of a) massive garnet amphibolites (Yayabo amphibolites, Millan, 1997b) and b) antigorite-bearing serpentinite-matrix mélanges containing high-pressure rocks (Somin and Millán, 1981; Millán, 1996a, 1997b; Auzende et al., 2002; Schneider et al., 2004).

Notwithstanding the important contributions by M.L. Somin and G. Millán (1981), the evolution of metamorphism is perhaps one of the least known geological issues of Cuba. In this paper, we review and provide new data concerning the metamorphic evolution of high-pressure rocks of basic composition and oceanic origin present in mélanges forming part of a) the northern ophiolite belt, b) the eastern Cuba ophiolites and c) tectonically intercalated slices within the Guaniguanico and Escambray terranes. Our principal focus is the nature, age and tectonic significance of high pressure metamorphism.

SUMMARY OF CUBAN GEOLOGIC HISTORY

The Cuban orogenic belt formed as a result of convergence between the North American and Caribbean plates in Mesozoic to Tertiary times (Iturralde-Vinent, 1988, 1994, 1996a). The process involved a large amount of oceanic material including ophiolites and intra-oceanic volcanic arc rocks that appear as complexly imbricated tectonic slices for the most part of the Cuban orogenic belt.

The earliest age of formation of the northern ophiolite belt is constrained to be Upper Jurassic by Tithonian through Albian-Cenomanian oceanic sediments that locally cover the igneous rocks in different parts of the belt (Iturralde-Vinent and Morales, 1988; Iturralde-Vinent, 1994, 1996b; Llanes et al., 1998). Isotopic (mostly K-Ar) ages of igneous rocks span an interval of 160-50 Ma (see review by Iturralde-Vinent et al., 1996). Of these data, only the Upper Jurassic to Lower Cretaceous dates are commonly considered to represent formation of oceanic lithosphere, while Upper Cretaceous to Paleogene K-Ar dates are thought to represent subsequent arc-related magmatism or isotopic resetting due to post-formation alteration and deformation events. Middle-Upper Jurassic

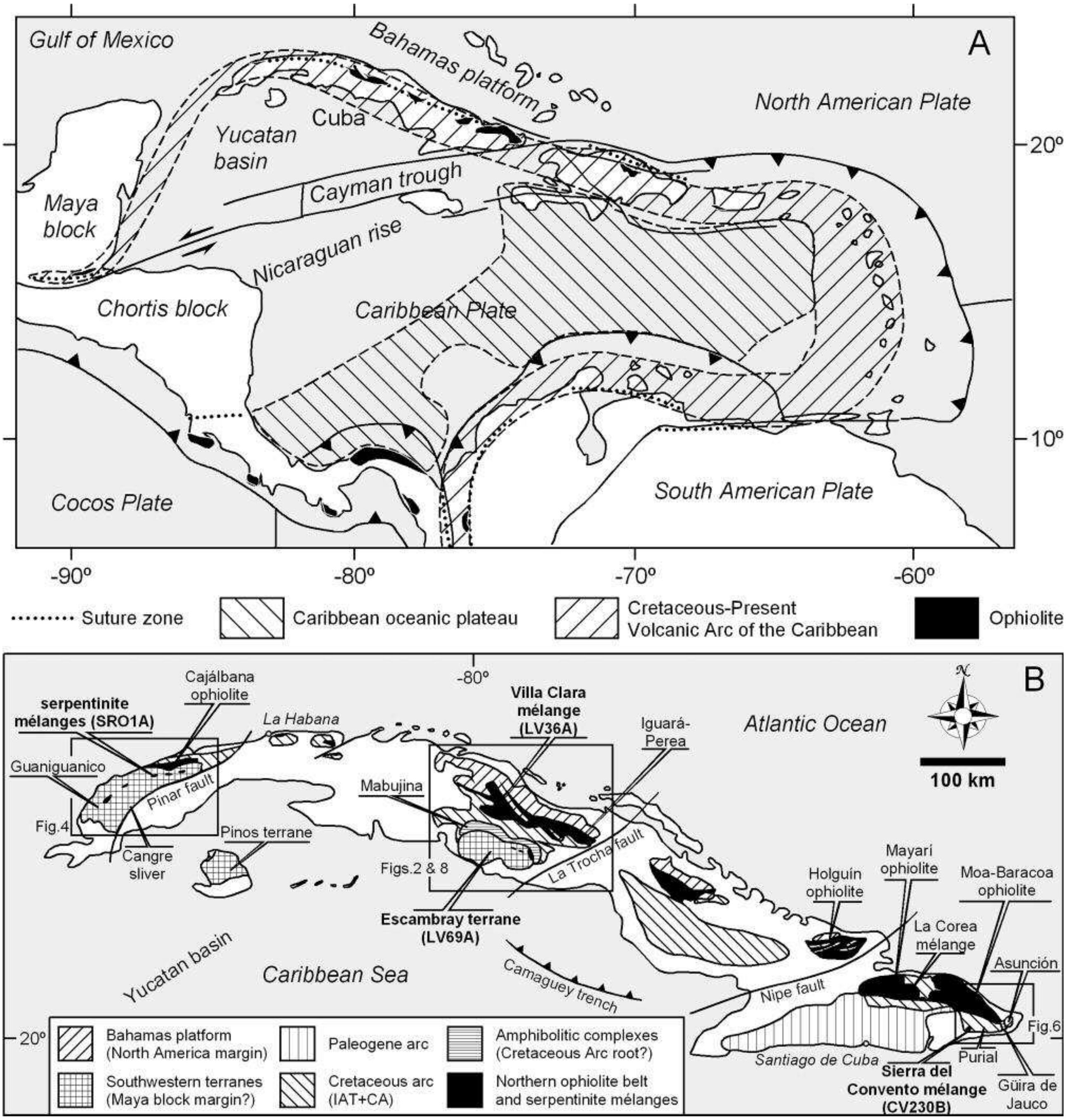

FIGURE 1 **A) Plate tectonic configuration of the Caribbean region, with important geological features including ophiolitic bodies and Cretaceous-Tertiary suture zones (compiled after Draper et al., 1994; Meschede and Frisch, 1998; and Mann, 1999). B) Geological sketch of Cuba (after Iturralde-Vinent, 1996a) showing location of the northern ophiolite belt and other important geologic elements mentioned in the text, and the studied areas with indication of studied samples (see Figs. 2, 4, 6 and 8 for further detail).**

is the time of break-off of Pangea in the region and the onset of formation of an oceanic basin connected with the Atlantic, the Proto-Caribbean (Pindell, 1985, 1994; Mann, 1999 and references therein), which opened as the Americas drifted away since that time until the Maastrichtian. According to most workers, the northern and eastern ophiolite belts of Cuba formed in the inter-Americas gap (Somin and Millán, 1981; Iturralde-Vinent, 1996a; Kerr et al., 1999), a conclusion that is strengthened by the scarcity of associated plateau basalts (or B" material; Burke et al., 1984; Kerr et al., 1999), which are typical of the Caribbean crust. However, increasing geochemical evidence accumulated recently from Early and Late Cretaceous basaltic rocks associated with these ophiolitic complexes favors supra-subduction environments (including back-arc, fore-arc and arc settings) instead of mid-ocean ridges as the locus of basalt generation. García-Casco et al. (2003) indicated IAT signatures of basaltic rocks from the Cajálbana ophiolite body metamorphosed in an Early Cretaceous (130 Ma) volcanic arc environment. Fonseca et al. (1989) and Kerr et al. (1999) described boninitic rocks in the northern ophiolite belt (Havana region) of unknown age, but the latter authors suggested that they may represent an Early Cretaceous (Aptian-Albian or older) boninite volcanic arc. In this same belt the Margot Formation (Matanzas region) consists in back arc basalts (Kerr et al., 1999) dated as Cenomanian-Turonian (Pszczólkowski, 2002). García-Casco et al. (2003) indicated probable calc-alkaline signatures in basaltic rocks from the Iguará-Perea region (northern ophiolite belt, Las Villas) metamorphosed in a Turonian-Coniacian (88 Ma) volcanic arc environment. Andó et al. (1996) indicated calc-alkaline trend in magmatic rocks of suggested Upper Cretaceous age in the Holguín ophiolite body. Cenomanian-Turonian island arc tholeiitic basalts are recorded in eastern Cuba ophiolites (Proenza et al., 1998, 1999, this volume; Iturralde-Vinent et al., this volume). Thus, volcanic material in the northern and eastern ophiolite belts document suprasubduction environments during the Early and Late Cretaceous and, possibly, a number of intra-oceanic subduction events. The paleotectonic/paleogeographic location of the tectonic slices of (meta)ophiolitic material in the Guaniguanico and Escambray terranes, on the other hand, remains uncertain due to their complex tectonic relationships and lack of detailed geochemical studies.

A belt of tectonic units consisting of volcanic, volcanic-sedimentary and plutonic arc rocks of basic through acid composition all along the island (Fig. 1B) documents an Early Cretaceous (Late Neocomian-mid Albian age) island arc of tholeiitic (IAT) affinity rooted by oceanic lithosphere that developed into a voluminous calc-alkaline (CA) and high-alkaline arc (Albian-Campanian; Iturralde-Vinent, 1996c, d; Díaz de Villalvilla, 1997; Kerr et al., 1999; Iturralde-Vinent et al., this volume, and references therein). This sequence of Cretaceous arc volcanism in Cuba is similar to that identified all along the Caribbean region (Donnelly and Rogers, 1978; Burke, 1988; Donnelly et al., 1990; Lebron and Perfit, 1993, 1994; Jolly et al., 2001). Burke (1988) named this arc the Great Arc of the Caribbean, which would have evolved as a response to Cretaceous subduction in the region, but the relationship between this volcanic-arc terrane and the various types of suprasubduction magmatic events recorded in northern and eastern ophiolite belts is uncertain.

Intense collisional tectonics, ophiolite obduction and olistostrome formation of latest Cretaceous through Paleocene-Middle Eocene age relate to the collision of the oceanic volcanic arc terranes with the ophiolites and the continental margins of the Maya and Bahamas blocks (Pszczólkowski and Flores, 1986; Iturralde-Vinent, 1994, 1996a, 1998; Bralower and Iturralde-Vinent, 1997; Gordon et al., 1997). The Campanian termination of the volcanic arc and the Upper Cretaceous isotopic ages of continental metamorphic terranes (Escambray, Isle of Pines) and of the oceanic roots of the volcanic arc (Mabujina complex) (Iturralde-Vinent et al., 1996; García-Casco et al., 2001; Grafe et al., 2001; Schneider et al., 2004) indicates onset of arc-continent collision in the Cuban segment of the Caribbean orogenic belt in Upper Cretaceous times. However, Kerr et al. (1999) suggested that the earliest collision event in Cuba is of Aptian-Albian age and of intra-oceanic nature, unrelated to the Upper Cretaceous-Paleogene arc-continent collision event. This intra-oceanic event was identified by García-Casco et al. (2002) in mélanges of the northern ophiolite belt of central Cuba.

ANALYTICAL METHODS

Mineral compositions were obtained with a CAMECA SX-50 microprobe (University of Granada) operated at 20 kV and 20 nA, and synthetic SiO_2, Al_2O_3, $MnTiO_3$, Fe_2O_3, MgO and natural diopside, albite and sanidine, as calibration standards, and a ZEISS DSM 950 scanning microscope equipped with a LINK ISIS series 300 Analytical Pentafet system operated at 20 kV and 1-2 nA beam current, with counting times of 50-100 s, and the same calibration standards. Representative analyses are given in Table 1. Elemental XR images were obtained with the same CAMECA SX-50 machine operated at 20 kV and conditions indicated in Figs. 5, 7 and 9. The images were processed using unpublished software by Torres-Roldán and García-Casco. Fe^{3+} in clinopyroxene, amphibole, garnet and epidote was calculated after normalization to 4 cations and 6 oxygens (Morimoto et al., 1988), 23 oxygens (Leake et al., 1997), 8 cations and 12

TABLE 1 **Representative composition of mineral phases in studied samples (see also García-Casco et al., 2002, and Schneider et al., 2004).**

Sample	CV230B	LV69A	SRO1A	SRO1A	LV69A	LV69A	CV230B	LV69	SRO1A
Phase	Grt	Grt	Grt	Pl	Omp	Ms	Ep	Ep	Ep
Tie line	peak	peak	peak	peak	peak	peak	peak	peak	peak
SiO_2	37.83	38.28	37.60	68.36	55.73	49.56	38.43	38.48	38.01
TiO_2	0.07	0.02	0.06		0.08	0.41	0.06	0.09	0.10
Al_2O_3	21.32	21.84	21.32	19.68	10.19	30.49	31.82	28.37	25.83
FeO_{tot}*	21.90	23.92	26.87	0.44	4.40	1.80	1.96	5.82	9.29
MnO	1.28	0.50	0.13		0.04	0.00	0.02	0.17	0.02
MgO	3.62	7.75	1.67		8.52	3.18	0.02		0.02
CaO	13.03	7.22	12.31	0.19	13.51	0.00	24.34	24.00	23.81
Na_2O				11.73	6.69	1.08			
K_2O				0.01	0.00	9.39			
Sum	99.09	99.52	99.97	100.42	94.44	95.91	95.75	92.32	96.11
Oxygen	12	12	12	8	6	22	12.5	12.5	12.5
Si	2.97	2.95	2.98	2.98	2.00	6.53	2.97	3.00	2.99
Ti	0.00	0.00	0.00		0.00	0.04	0.00	0.01	0.01
Al	1.97	1.98	1.99	1.01	0.43	4.74	2.90	2.61	2.39
Fe^{3+}	0.07	0.11	0.05	0.02	0.04	0.00	0.13	0.38	0.61
Fe^{2+}	1.37	1.43	1.73	0.00	0.09	0.20	0.00	0.00	0.00
Mn	0.08	0.03	0.01		0.00	0.00	0.00	0.01	0.00
Mg	0.42	0.89	0.20		0.46	0.62	0.00		0.00
Ca	1.10	0.60	1.04	0.01	0.52	0.00	2.01	2.00	2.00
Na				0.99	0.46	0.28			
K				0.00		1.58			

Sample	CV230B	CV230B	CV230B	LV69A	LV69A	LV69A	SRO1A	SRO1A	SRO1A
Phase	Pargasite	Gl	Act	Bar	Gl	Act	MgKat	Gl	Act
Tie line	peak	retro	retro	peak	retro	retro	peak	relict (inclusion)	retro
SiO_2	43.48	57.21	55.29	50.81	57.06	52.87	47.52	57.88	55.47
TiO_2	0.87	0.09	0.05	0.21	0.05	0.10	0.29	0.00	0.00
Al_2O_3	13.69	11.33	1.57	10.70	9.56	5.93	12.64	11.07	2.71
FeO_{tot}*	13.33	12.73	11.83	8.73	10.01	9.06	14.83	11.28	10.93
MnO	0.15	0.14	0.20	0.05	0.07	0.11	0.06	0.03	0.00
MgO	11.29	8.61	16.20	14.39	11.56	16.22	9.61	9.25	16.13
CaO	11.49	0.60	11.71	8.17	1.91	10.04	8.25	1.09	11.44
Na_2O	2.48	7.17	0.92	3.87	6.38	2.19	4.29	6.85	1.11
K_2O	0.47	0.01	0.03	0.23	0.03	0.11	0.26	0.00	0.07
Sum	95.57	96.09	96.94	97.15	95.66	96.64	97.81	99.94	100.90
Oxygen	23	23	23	23	23	23	23	23	23
Si	6.41	7.91	7.88	7.18	7.92	7.52	6.91	8.00	7.86
Ti	0.10	0.01	0.00	0.02	0.00	0.01	0.03		
Al	2.38	1.85	0.26	1.78	1.57	0.99	2.17	1.80	0.45
Fe^{3+}	0.11	0.13	0.08	0.16	0.18	0.17	0.06	0.03	0.03
Fe^{2+}	1.53	1.34	1.33	0.87	0.99	0.91	1.74	1.28	1.26
Mn	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.00	
Mg	2.48	1.78	3.44	3.03	2.39	3.44	2.09	1.90	3.41
Ca	1.81	0.09	1.79	1.24	0.28	1.53	1.29	0.16	1.74
Na	0.71	1.92	0.25	1.06	1.72	0.60	1.21	1.83	0.31
K	0.09	0.00	0.01	0.04	0.00	0.02	0.05		0.01

* Total Fe expressed as FeO.

oxygens and 8 cations and 12.5 oxygens ($Fe_{total}=Fe^{3+}$) per formula unit (pfu), respectively. Mineral and end-member abbreviations are after Kretz (1983), except for amphibole (Amp).

NORTHERN OPHIOLITE BELT

Central Cuba

Central Cuba is used informally to embrace the area from Havana to Holguín, which bears the most complete representation of geologic complexes in the island (Figs. 1B and 2A). In this region, the continental North American margin and foreland to the north includes middle Jurassic to Eocene sedimentary formations of Cayo Coco, Remedios, Camajuaní and Placetas belts, of which the latter is of deep water affinity and related to the oceanic Proto-Caribbean realm (Iturralde-Vinent, 1996a, 1998). The northern ophiolite belt is formed by a number of tectonic slices thrusted northward and partially intermingled with the Placetas belt. To the south, the Cretaceous volcanic-plutonic arc belt is tectonically emplaced above the northern ophiolite belt, but in the Havana-Matanzas and Holguín regions it is tectonically intermingled with the northern ophiolites. The Cretaceous volcanic arc belt contains Neocomian?-Albian tholeiitic rocks covered by Albian-Campanian calc-alkaline and high-alkaline rocks. The suites are formed by volcanic, plutonic and volcanic-sedimentary sequences. The volcanic-arc units tectonically overlie the Mabujina complex, composed mainly of arc-derived medium- to high-grade, low to intermediate pressure, metamorphic rocks of ultrabasic, basic, intermediate and acid composition that are crosscut by slightly to strongly metamorphosed and deformed plutonic bodies (Somin and Millán, 1981; Millán, 1996b; Grafe et al., 2001; Blein et al., 2003). This complex is interpreted as the metamorphosed roots of the island arc and its oceanic sole (Somin and Millán, 1981; Millán, 1996b) or as a separate arc system (Blein et al., 2003). The Mabujina complex is in turn tectonically underlain by the Escambray terrane, described below. The thrust-and-fold belt was complexly assembled during late Upper Cretaceous-Middle Eocene times, when syn-tectonic sedimentary-olistostromic formations of Paleogene age were deposited above the northern ophiolite belt and the continental margin sections (Iturralde-Vinent., 1998).

Mélanges containing m- to dm-sized blocks of eclogite, garnet amphibolite, amphibolitite, blueschist, greenschist, quartzite, metapelite and antigoritite occur within the northern ophiolite belt. Important localities are in the Villa Clara (Fig. 2B) and the Holguín-Gibara regions (Kubovics et al., 1989), which are separated by ca. 450 km along strike of the major geological structure (Fig. 1B). Available K-Ar ages from samples of high-pressure blocks in the region range from 130 to 60 Ma, but data cluster about 110±10 Ma (Somin and Millán, 1981; Somin et al., 1992; Iturralde-Vinent et al., 1996) suggesting an Early Cretaceous age for the subduction zone; younger ages are inferred to represent reworking during Upper Cretaceous-Paleogene tectonism associated with collision.

García-Casco et al. (2002) provided detailed descriptions of representative eclogite samples from blocks of mélanges associated with the northern ophiolilte belt in Villa Clara and Holguín regions (Figs. 1B and 2B). The rocks conform to the type-C eclogites of Coleman et al. (1965) and the low-T eclogites of Carswell (1990), consisting of an assemblage containing garnet porphyroblasts up to 3 mm width set in a matrix of faintly oriented medium grained omphacite, calcic to sodic-calcic amphibole (locally also porphyroblastic), epidote, rutile, sphene, apatite and occasional phengite. These rocks are not classified as eclogite s.s. as defined by Carswell (1990), but rather as amphibole-eclogite (cf. Newton, 1986) since they contain less than 75% of garnet plus omphacite, and amphibole bears textural relationships (position, inclusions, chemical zoning, replacements) that clearly indicate its stability during pre-, syn- and post-peak-eclogitic metamorphism. Porphyroblasts of garnet and amphibole commonly bear inclusions of epidote, rutile, sphene, omphacite, amphibole, albite, quartz and chlorite. The main eclogitic assemblage (Grt+Omp+NaCa Amp+Ep+Rt+Spn) is affected by localized replacement by albite (Ab), actinolitic amphibole, epidote and sphene generated by a late-stage albite-epidote amphibolite to greenschist facies overprint (Fig. 3). The general P-T paths of the samples are clockwise, with prograde increase in temperature and pressure followed by strong decompression accompanied by moderate cooling during the retrograde exhumation paths (Fig. 3). However, XR-mapping of the samples demonstrated the presence of complex oscillatory zoning in garnet and amphibole porphyroblasts. Based on a) the chemical nature of the oscillations and b) phase-relations modeling, García-Casco et al. (2002) concluded that oscillatory zoning formed as a result of widespread and recurrent changes in P-T conditions during prograde metamorphism (Fig. 3). Such thermal disturbances are incompatible with steady state subduction of the slab and it was proposed that they were produced instead by tectonic processes related to the demise of the subduction system.

Age determinations for the eclogite sample LV36A yielded 103.4±1.4 ($^{40}Ar/^{39}Ar$ plateau age of amphibole), 115.0±1.1 ($^{40}Ar/^{39}Ar$ plateau age of phengite; 123.1±1.0 to 117.1±0.9 intragrain laserprobe fusion ages) and 118.2±0.6 Ma (Rb/Sr isochron for phengite-omphacite-whole-rock; Schneider, 2000; García-Casco et al., 2002).

These data indicate that the minimum age of eclogite facies metamorphism is pre-118 Ma (Aptian or older), while final uplift and cooling dates to Aptian-Albian times (118-103 Ma). Thus, it is concluded that block

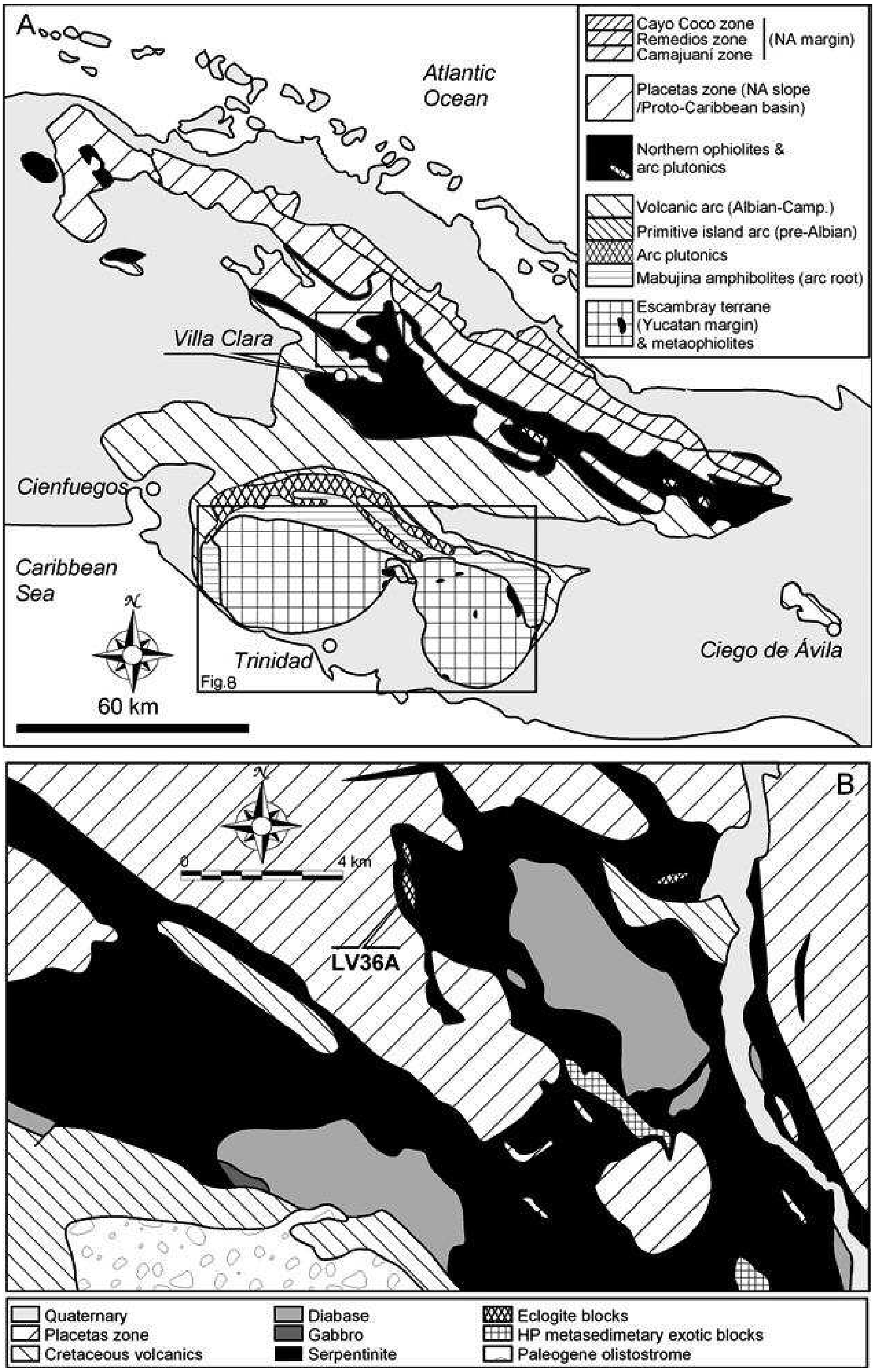

FIGURE 2 | **A) Basic geologic features of central Cuba (from Iturralde-Vinent, 1996a). The insets show the location of the studied areas in the Northern ophiolites (2B) and the Escambray Terrane (see Fig. 8). B) Geologic map of the studied area in the Northern ophiolite belt including the Villaclara mélange (slightly modified and simplified after García Delgado et al., 1998) with indication of LV36A sample locality (see García Casco et al., 2002).**

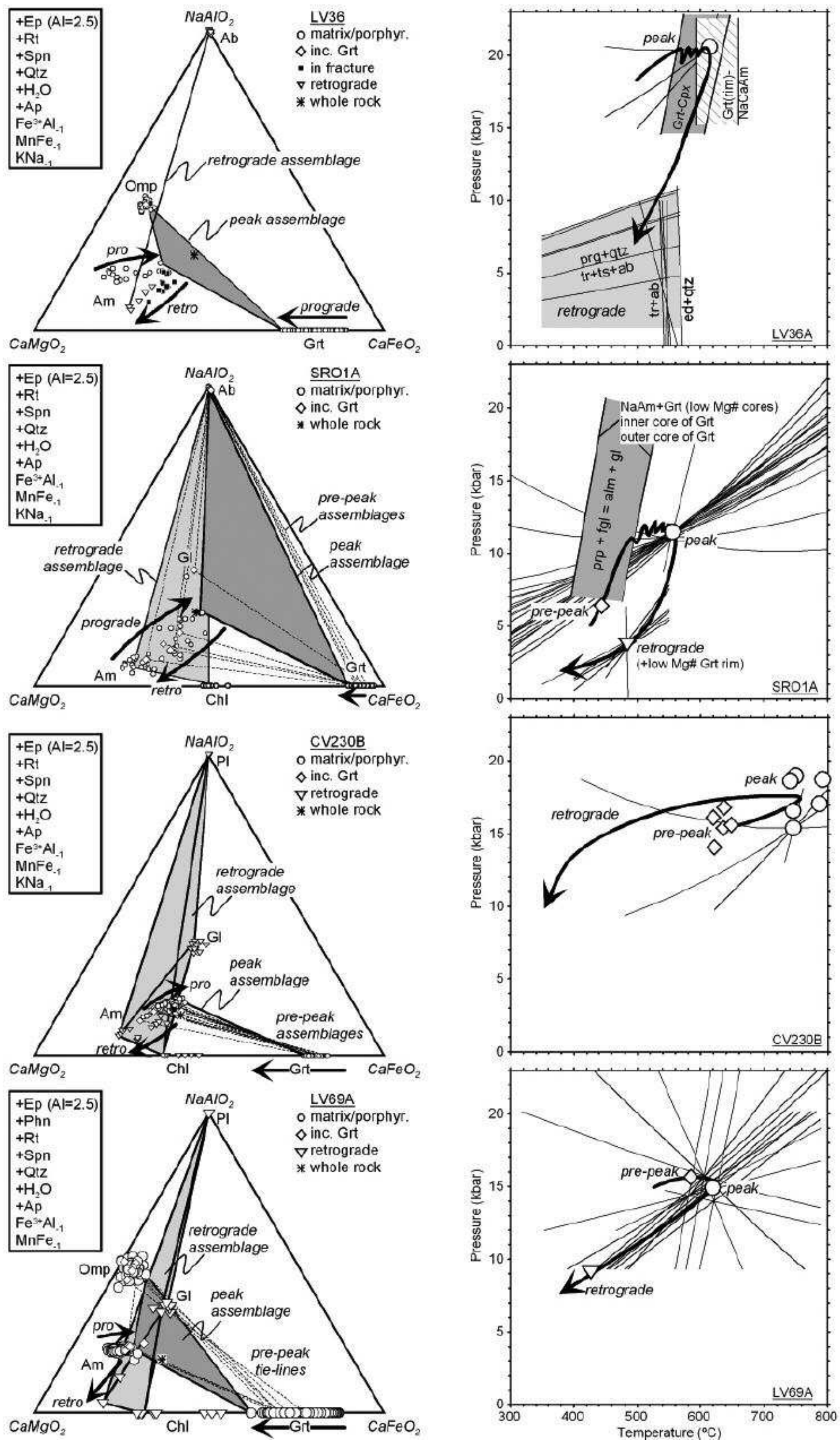

FIGURE 3 **$AlNaO_2$-$CaMgO_2$-$CaFeO_2$ phase diagrams and associated P-T calculations and paths for the studied samples (see location in Figs. 2, 4, 6 and 8). The phase diagram was constructed after projection from average epidote, rutile, sphene, quartz, apatite, H_2O (±phengite) and the exchange vectors $Fe^{3+}Al_{-1}$ and $MnFe_{-1}$ (±KNa_{-1}). The thin lines in the P-T diagrams correspond with results of Thermocalc (see also García-Casco et al., 2002, and Schneider et al., 2004, for samples LV36A and LV69A, respectively).**

LV36A formed in a subduction system of pre-Aptian age and that it was incorporated into the mélange and exhumed during the Aptian-Albian. The tectonic nature of the mélange-forming event is uncertain. However, the near-isothermal decompression sections of the retrograde part of the P-T paths followed by the HP block offer some insights into this problem. The decompression-dominated retrograde paths are similar to that termed Alpine type (Ernst, 1988), which is normally interpreted as the result of rapid exhumation in a relatively hot geothermal gradients imposed by tectonic unroofing after arrest of subduction. Though arrest of subduction is generally thought to be caused by collision of the subduction-forearc system with a buoyant down-going continental, oceanic, or arc lithosphere (Ernst, 1988; Ring et al., 1999; Wakabayashi, 2004), other collision tectonic processes, such as reversals of subduction polarity, have similar consequences, as discussed below. In either case, however, the retrograde paths of exotic blocks within the northern ophiolite belt in central Cuba are consistent with collision tectonics accompanying termination of subduction during the mid-Cretaceous.

Western Cuba

Western Cuba is here used informally to represent the geological units which crop out mostly in the Pinar del Río province (Figs. 1B and 4A). The Geology of this region diverges from that of central Cuba in that the continental Guaniguanico terrane represents the Mesozoic

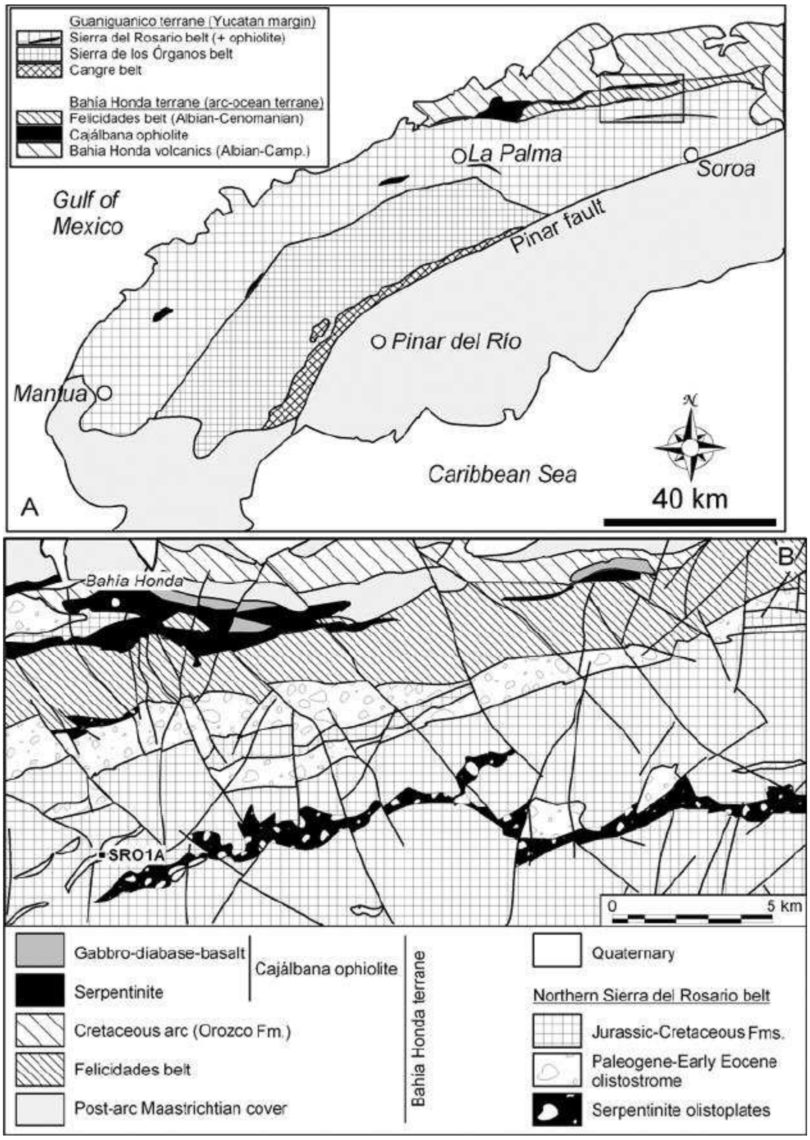

FIGURE 4 | **A) Basic geologic features of western Cuba (compiled after Pszczólkowski, 1994 and Iturralde-Vinent, 1996a). The inset corresponds to the studied area shown in B. B) Geologic map of the studied area (slightly modified and simplified after Martínez González et al., 1994) with indication of sample locality SRO1A.**

margin of the Maya block (Iturralde-Vinent, 1994; Pszczólkowski, 1999), though the oceanic terranes correlate with central Cuba. The Cajálbana ophiolite body is the western counterpart of the northern ophiolite belt. The body is noticeably elongated and tectonically sandwiched in between tectonic slices of two Cretaceous arc sequences: the Albian-Campanian volcanic-sedimentary sequences of the Bahía Honda belt to the north and the Albian-Cenomanian Felicidades belt to the south (Fig. 4). The Bahía Honda belt constitutes the western equivalent of the calc-alkaline Albian-Campanian volcanic arc belt while the Felicidades belt is interpreted as an adjacent marginal-sea basin of nearly the same age (Iturralde-Vinent, 1996a, b; Kerr et al., 1999). The Cajálbana ophiolite and the Bahía Honda and Felicidades belts are grouped within the oceanic Bahía Honda allochthonous terrane, which overrides the Guaniguanico terrane along NW-directed thrusts (Iturralde-Vinent, 1994; 1996a). The Guaniguanico terrane is formed by north verging thrust belts, namely the Quiñones, Sierra del Rosario, Sierra de los Órganos and Cangre belts (Fig. 4A), composed of Jurassic and Cretaceous sedimentary sequences related to the eastern margin of the Maya block (North American Plate) and syntectonic Paleocene to Middle Eocene foreland sediments (Iturralde-Vinent, 1994, 1996a; Rosencrantz, 1990, 1996; Bralower and Iturralde-Vinent, 1997; Pszczólkowski, 1999). Iturralde-Vinent (1994, 1996a) and Pszczólkowski (1999) considered that thrusting and gravitational sliding during the Paleogene completely reversed the original relative paleogeographic positions of the Guaniguanico thrust units. Gordon et al. (1997) identified a complex Paleogene tectonic history with at least five phases of deformation. The terrane is non-metamorphic, except the Cangre belt, metamorphosed to high pressure low temperature conditions (Somin and Millán, 1981; Pszczólkowski and Albear, 1985; Millán, 1988, 1997a). The age of metamorphism has not been precisely determined. Somin et al. (1992, sample M-3) reported a K-Ar whole-rock data of 113 ± 5 Ma in a sample of mica-quartz schist that probably represents a mixture of detritic and metamorphic ages (Hutson et al., 1998).

In the Guaniguanico terrane, mostly in the Sierra del Rosario belt, metamorphosed and non-metamorphosed ophiolitic material appears as medium-to large-sized exotic blocks and olistoplates incorporated into syn-tectonic olistostromic formations having a Lower Eocene sedimentary matrix (Pszczólkowski, 1978; Somin and Millán, 1981; Somin et al., 1992; Millán, 1996a, 1997a; Bralower and Iturralde-Vinent, 1997). The metamorphosed blocks consist of serpentinite-matrix mélanges containing HP exotic blocks. Available age data from the HP metamorphic blocks range form 128 to 58 Ma, with recurrence of 110±10 Ma ages (Somin and Millán, 1981; Somin et al., 1992; Iturralde-Vinent et al., 1996) as in central Cuba (see above). The coincidence of age data of HP blocks from western and central Cuba suggests that the occurrence of HP ophiolitic rocks within Lower Eocene sedimentary matrix in western Cuba is a peculiarity of this region related to the late stages of Tertiary orogenic evolution and not to the primary evolution of the subduction system where the HP blocks originated. Additionally, the Early Cretaceous radiometric ages in western and central Cuba mélanges suggest that HP metamorphism developed in the same subduction system.

That the Early Cretaceous subduction system of central Cuba extended to western Cuba is also indicated by the petrologic features of HP bocks from serpentinite mélanges of the Guaniguanico terrane. Here we describe a garnet amphibolite block (SRO1A) collected from a Paleogene olistostromic deposit located ca. 8 km to the south of the village of Bahía Honda (Fig. 4B). Figure 5 depicts the relevant textural and mineral composition information of this sample (see also the phase diagram of Fig. 3 for further information). The amphibolite is fine-grained, composed of garnet, calcic to sodic-calcic amphibole (actinolite-magnesiohornblende-barroisite-magnesiokatophorite), clinozoisite/epidote, rutile, sphene, albite, chlorite and glaucophane. Of these, amphibole, epidote and chlorite are oriented along the foliation. Glaucophane appears as scarce xenomorphic blasts set in the matrix of calcic to sodic-calcic amphibole and is interpreted as relict. Garnet porphyroblasts (≈500 μm in width) contain inclusions of glaucophane, calcic amphibole, epidote, albite and sphene. Albite is fine to medium grained, locally porphyroblastic, and has non-oriented inclusions of all the phases (including garnet) with which it is in textural equilibrium. However, garnets appear slightly corroded by the matrix assemblage, particularly actinolitic amphibole, epidote and chlorite. The absence of omphacite and the coexistence of garnet+albite indicates this block was metamorphosed at lower pressure and temperature than eclogites from central Cuba described above, within the albite-epidote amphibolite facies, while relict glaucophane suggests the prograde path evolved through the blueschist facies. The retrograde assemblage (actinolite+epidote+chlorite+albite) denotes greenschist facies overprint.

Although sample SRO1A formed at a distinct shallower level in the subduction system compared with the eclogites from central Cuba, their metamorphic evolutions prove to be similar. This interpretation is confirmed by prograde growth zoning of garnet from this W-Cuba sample, which is disturbed by several euhedral concentric oscillations in Mn, Mg, Ca and Fe (Fig. 5). These oscillations developed in the course of prograde metamorphism towards peak albite-epidote amphibolite facies conditions

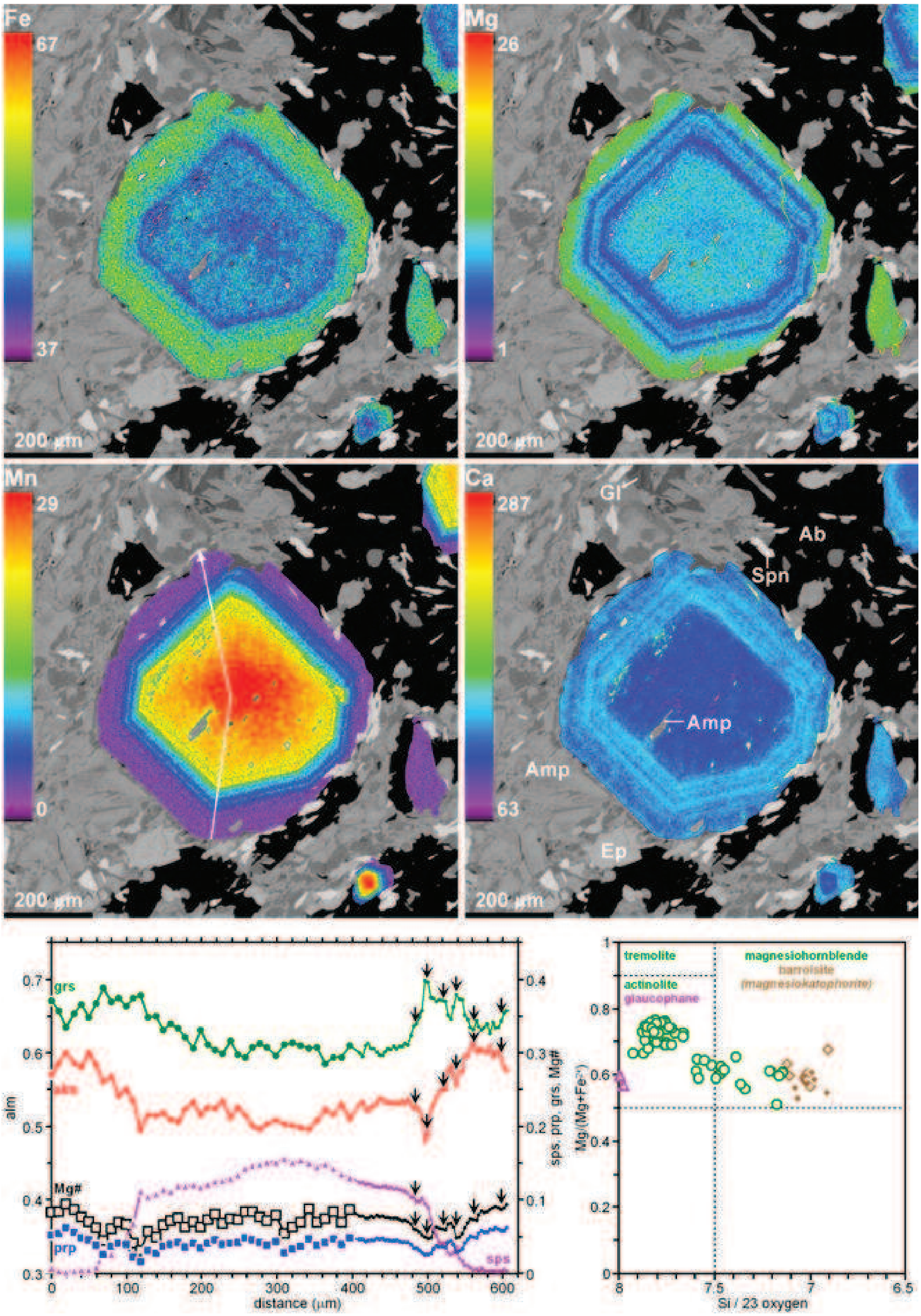

FIGURE 5 | **Key textural and mineral composition data of sample SR01A. The synthetic XR images were generated with Imager software (Torres-Roldán and García-Casco, unpublished) and consist of the XR signals for Kα lines of Fe, Mn, Mg, and Ca in garnet (color coded counts/nA/sec) corrected for 3.5 μs deadtime; voids, polish defects, and all other mineral phases masked out), overlaid onto a gray-scale base-layer that contains the basic textural information calculated with the expression Σ(counts/nA/s)$_i$·A$_i$], A=Atomic number, i= Fe, Mn, Mg, Ca. Acceleration potential: 20 kV. Beam current: 151 nA. Step (pixel) size: 2 μm. Counting time: 30 ms. The compositional profile of garnet (Step size: 10 μm -left hand side of the profile-, and 4 μm -right hand side) is indicated in the XR image of Mn. The arrows indicate the location of Mg# reversals in the detailed profile. The composition of amphibole is plotted within the classification scheme of Leake et al. (1997). The green, brown and magenta symbols and labels correspond to calcic, sodic-calcic and sodic amphiboles, respectively. The empty symbols and normal typeface labels correspond to compositions with Sum(A) < 0.5. The filled symbols and italic typeface labels correspond to compositions with Sum(A) > 0.5.**

(Fig. 3). The distribution of the elements define relatively homogeneous cores that have high Mn (that slightly decreases outward) and low Ca and Mg# contents, and overgrowths poorer in Mn and richer in Ca but only slightly richer in Mg# where the oscillations take place. In terms of Mg (and Mg#), the overgrowths display two major reversals (resolved in the detailed right-hand side section of the profile of Fig. 5) that match upturns in Mn and Ca, in addition to other reversals of lower intensity. As in the eclogites of central Cuba, the increase in Mn and decrease in Mg# at the reversed layers indicate formation upon recurrent prograde-retrograde episodes taking place in the course of subduction. Matrix amphibole shows a distinctively irregular patchy zoning in many grains (Fig. 5). When concentric zoning is developed the cores are actinolitic and the overgrowths are magnesiohornblende to barroisite-magnesiokatophorite, indicating prograde growth. The outermost rims are retrograde as they trend backwards to magnesiohornblende and actinolite with increasing Mg# relative to peak sodic-calcic amphibole. The inclusions of amphibole within garnet cores are similar to the actinolitic cores of matrix amphibole. Consequently, the prograde zoning of matrix amphibole correlates, at least in part, with the oscillatory zoning of garnet. Indeed, the preservation of prograde patchy zoning in this sample is consistent with the adjustment of amphibole composition to recurrent changes in pressure and/or temperature in the course of subduction-related metamorphism. Glaucophane has intermediate Mg# (ca. 0.6) contents, slightly higher than prograde barroisitic amphibole and lower than calcic amphibole. Chlorite has Mg# = 0.54-0.52.

Metamorphic temperatures and pressures were estimated using Thermocalc (Holland and Powell, 1998, version 3.21). Calculations using different combinations of the composition of the phases have large errors, probably due to equilibrium problems and the poorly-known activity-composition relations of complex amphibole and chlorite solid solutions. The calculated pre-peak and peak P-T conditions are 444 ± 82 ºC, 6.4 ± 2.4 kbar, and 556 ± 107 ºC, 11.5 ± 3.1 kbar, respectively. Relative to the eclogites of central Cuba (Fig. 3), these figures are in accordance with the Mg#-poorer composition of garnet rims and the lack of omphacite in sample SRO1A. A range of 400-500ºC was calculated using the Fe-Mg exchange equilibrium among relict glaucophane and garnet cores, although the pressure calculations using glaucophane in combination with other phases were rather imprecise. Consequently, the shape of the prograde path towards peak conditions depicted in Fig. 3 is uncertain. A similar range of temperature and 2-4 kbar was calculated using combinations of chlorite, garnet rims with lower Mg#, and retrograde amphibole, albite and epidote. The P-T path depicted in Fig. 3 is clockwise with a) P-T oscillations (that account for the Mg and Mn reversals in garnet) during the prograde subduction-related path and b) decompression-dominated retrogression. It should be noted that the P-T oscillations of the path suggest tectonic instability of the down-going slab, and that the Alpine-type retrograde portion of the path implies rapid exhumation and a relatively steep geothermal gradient, in all aspects similar to paths followed by eclogite blocks of central Cuba. These features strongly suggest the serpentinite-mélanges of western and central Cuba formed at the same Early Cretaceous subduction system that extended for a distance of about 800 km (present geographic coordinates), and that this system suffered a generalized (Aptian-Albian) tectonic event that terminated subduction.

Eastern Cuba

Eastern Cuba extends towards the East from the Nipe fault (Fig. 1B). The huge Mayarí-Cristal and Moa-Baracoa ophiolite bodies of this region have been classically viewed as the eastern counterpart of the northern ophio-

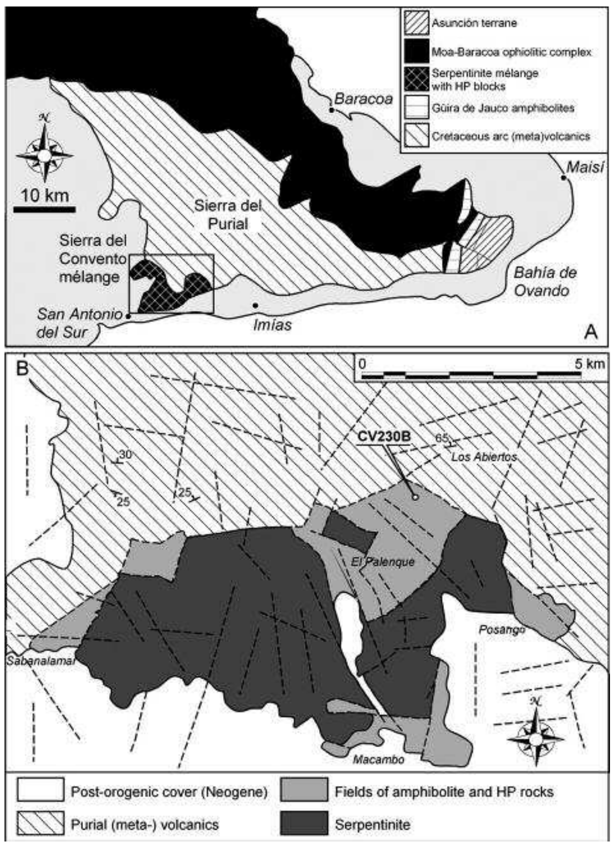

FIGURE 6 | **A) Basic geologic features of eastern Cuba (Iturralde-Vinent, 1996a). The inset corresponds to the location of the studied area shown in 6B. B) Geologic map of the Sierra del Convento mélange (Kulachkov and Leyva, 1990) with indication of sample locality CV2130B.**

lite belt, but Iturralde-Vinent et al. (this volume) have characterized them as "eastern ophiolites". These bodies have been considered as suprasubduction ophiolite that underwent widespread infiltration by melts of island arc tholeiitic and boninitic composition that interacted with the ultramafic rocks (Proenza et al., 1998, 1999; Gervilla et al., 2005). The region contains a number of volcanic arc formations having distinct island arc tholeiitic, boninitic and calc-alkaline signatures, though in most cases they appear to be of Upper Cretaceous age (Iturralde-Vinent et al., this volume; Proenza et al., this volume). Whether these geochemically distinct arc volcanics formed within a single or different subduction zones is uncertain. The Purial volcanic complex, south of the ophiolitic bodies (Fig. 6A), includes island arc tholeiitic and calc-alkaline signatures and has been classically considered the eastern prolongation of the Cretaceous arc belt of western-central Cuba (Iturralde-Vinent, 1996c). However, important geological contrasts with other parts of Cuba are that this Cretaceous volcanic arc terrane is a) tectonically overridden by the ophiolitic complexes and b) metamorphosed to the greenschist and blueschist facies (Boiteau et al., 1972; Cobiella et al., 1977; Somin and Millán, 1981; Millán et al., 1985). Importantly, metamorphism in this complex is dated as late Upper Cretaceous by Somin et al. (1992; 75 ± 5 Ma K-Ar whole-rock) and Iturralde-Vinent et al. (this volume; 75-72 Ma based on paleontological dating). The Mesozoic North American margin (Florida-Bahamas platform) is likely represented in this region by the sedimentary sequences of the Asunción terrane, though an exotic origin cannot be excluded. This complex is metamorphosed to high-P low-T conditions (Millán et al., 1985). Regionally, the ophiolite bodies override the Asunción metasediments. The major displacements appear to be NE to NW-directed thrusts (Cobiella et al., 1984; Quintas, 1987, 1988; Nuñez Cambra et al., 2004). However, the structure of the region is complex and has not been studied in detail.

The ophiolitic bodies of eastern Cuba include serpentinite-matrix mélanges containing high-pressure blocks. The largest complexes are La Corea and Sierra del Convento mélanges, both having similar lithological assemblages (Millán, 1996a). La Corea mélange is located in Sierra de Cristal and is associated with the Mayarí-Cristal ophiolitic body (Fig. 1B). The Sierra del Convento mélange, located southward (Figs. 1B and 6), overrides the Purial metavolcanics. The nature of the metamorphic blocks is varied but, in contrast with other mélanges from central and western Cuba, high temperature epidote±garnet amphibolites bearing small bodies of leucocratic (mostly trondhjemitic) material dominate. Other types of block are blueschist, greenschist, quartzite, metagreywacke and metapelite, while eclogite is rare (Cobiella et al., 1977; Somin and Millán, 1981; Kulachkov and Leyva, 1990; Hernández and Canedo, 1995; Leyva, 1996; Millán, 1996a). Available age data for HP rocks range from 125 to 66 Ma in La Corea and 116-82 Ma in Sierra del Convento (Adamovich and Chejovich, 1964; Somin and Millán, 1981; Somin et al., 1992; Iturralde-Vinent et al., 1996; Millán, 1996a). As in central and western Cuba, the recurrence of Early Cretaceous ages indicates Early Cretaceous subduction. However, the geological singularities of eastern Cuba make the correlation of the associated subduction systems doubtful. These doubts are strengthened by the petrologic differences of the metamorphic blocks from both regions, as described below.

The most typical rock type of eastern Cuba mélanges is epidote-amphibolite, commonly bearing garnet. We shall describe here a representative garnet amphibolite sample (CV230b) of Sierra del Convento complex collected from the area of El Palenque (Fig. 6B). Figure 7 depicts the relevant textural and mineral composition information of this sample (see also the phase diagram of Fig. 3). The prograde assemblage consists of calcic (pargasitic) amphibole, epidote, garnet, sphene, rutile and apatite. Prograde plagioclase is lacking, as in most metabasite samples metamorphosed to the epidote-amphibolite facies of the Sierra del Convento mélange, suggesting relatively high pressure of formation. Retrograde overprints in the studied sample are faint and consist of albite, actinolite, glaucophane, chlorite and pumpellyite. Similar overprints are common in other samples, though the extent of retrogression is highly variable. Pargasitic amphibole comprises most of the matrix and is oriented parallel to the foliation. Individual crystals have a smooth core-to-rim prograde zoning (minimum Si = 6.38 atoms pfu; max. NaB= 0.33; max. SumA= 0.68; max. Ti = 0.11; min. Mg# = 0.62). The rims are commonly partly replaced by actinolite, glaucophane, chlorite and albite. Epidote displays a faint patchy zoning (Fe^{3+} = 0.12-0.17 atoms pfu). Garnet forms large porphyroblasts (up to >1.5 cm in diameter) that include pargasitic amphibole, epidote, rutile and sphene, and is slightly replaced at the rims and along fractures by pargasite-magnesiohornblende-actinolite, chlorite, pumpellyite and albite. Its composition is rich in almandine and grossular (X_{alm}= 0.45; X_{grs}=0.35-0.40), and the grains bear a smooth prograde growth zoning with decreasing Mn (down to 0.06 atoms pfu) and increasing Mg# (up to 0.24) towards the rims. The outermost 200-300 μm of the grains display reverse diffusive zoning (noted by upturns in Mg# and Mn; Fig. 7) formed during retrograde exchange with the matrix. This type of zoning indicates relatively high temperature at the onset of retrogression. Importantly, oscillatory zoning has not been observed in garnet from this and other samples of amphibolite from the Sierra del Convento mélange.

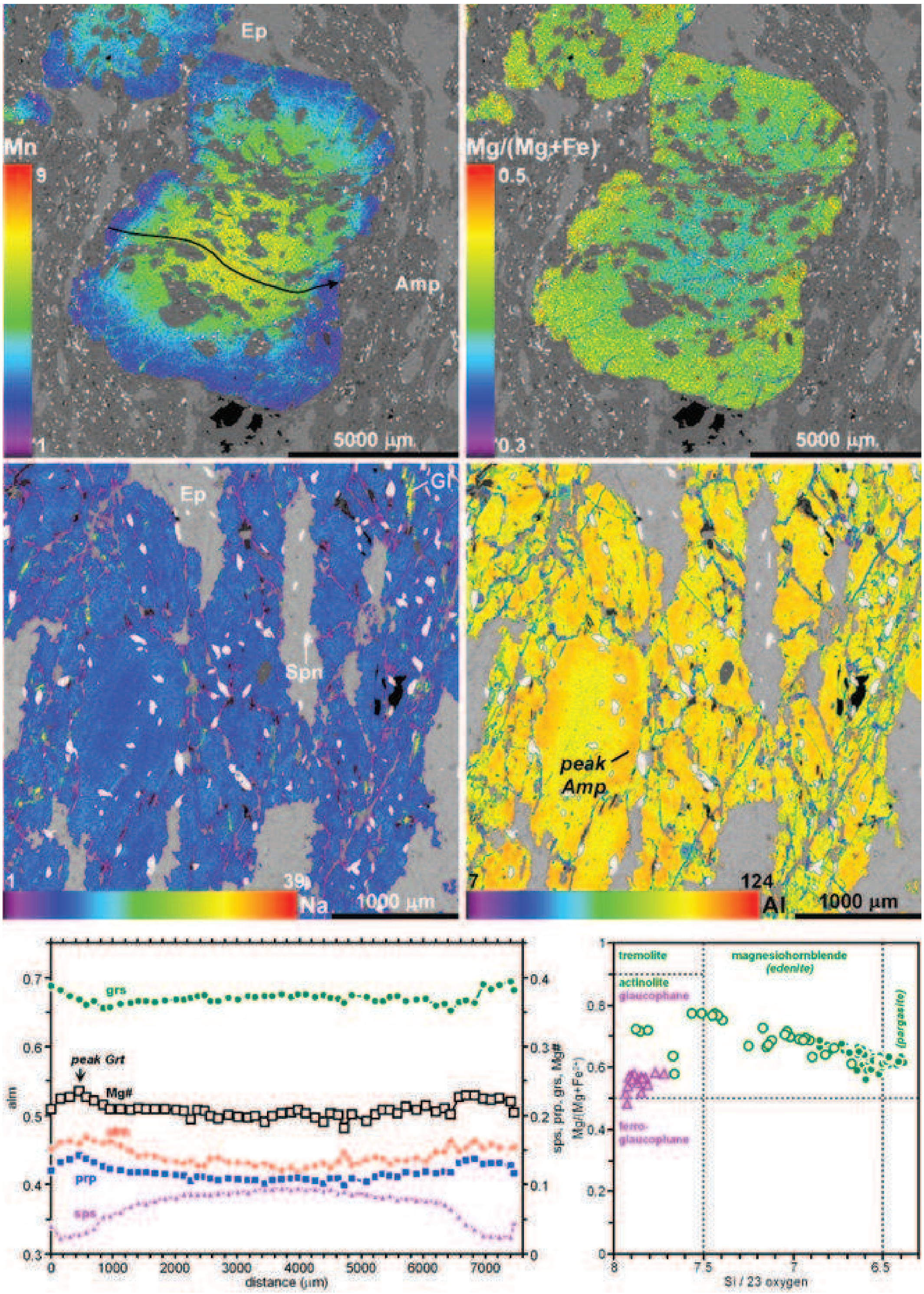

FIGURE 7 | **Key textural and mineral composition data of sample CV230B. The top synthetic XR images correspond to Mn(Kα) and Mg(Kα)/(Fe(Kα)+Mg(Kα)) of garnet (beam current: 292 nA; step size: 26 μm; counting time: 50 ms (Na, Mn, Ti, Mg) and 25 ms (Si, Al, Fe, Ca); all other operating conditions and procedures as in figure 5, except that the gray-scale base is calculated with the expression Σ(counts/nA/s)$_i$·A$_i$], A=Atomic number, i= Si, Ti, Al, Fe, Mn, Mg, Ca, and Na). The bottom synthetic XR images (step size: 7 μm; all other operating conditions and procedures as above) correspond to Na(Kα) and Al(Kα) of amphibole (sodic and calcic; in the Na image, prograde pargasite-edenite-magnesiohornblende compositions appear with shades of blue, retrograde glaucophane is green-yellow, and retrograde actinolite is magenta). The compositional profile of garnet is indicated in the XR image of Mn. The composition of amphibole is plotted within the classification scheme of Leake et al. (1997), with symbols and labels as in figure 5.**

Metamorphic conditions were estimated using Thermocalc (version 3.21). As for sample SRO1A, the results have a large uncertainty. In addition, errors are increased by the high-variance of the peak assemblage garnet-pargasite-epidote (Fig. 3). Using different combinations of the composition of inclusions within garnet and of the rims of garnet (not affected by retrograde diffusion) and matrix pargasite, the conditions of the pre-peak and peak assemblages were estimated at 600-650ºC and 14-16 kbar, and 750-800ºC and 15-18 kbar respectively. The conditions of retrogression could not be estimated with certainty, though the growth of retrograde glaucophane indicates cooling at relatively high pressure. The P-T path is counterclockwise, with high-grade conditions attained during subduction and blueschist conditions attained during accretion and exhumation.

Similar P-T conditions and counterclockwise paths can be inferred from other samples of amphibolite from the Sierra del Convento and La Corea mélanges. These findings, which indicate hot subduction and cold exhumation for the amphibolite blocks of eastern Cuba mélanges, contrast with P-T conditions and paths observed in blocks from mélanges in western-central Cuba. Thus, the Early Cretaceous subduction systems of the two regions either were different or were associated with different geodynamic scenarios. Indeed, hot-subduction can be rationalized within the framework of either a) initiation of subduction or b) subduction of young oceanic lithosphere or an active oceanic ridge (Oh and Liou, 1990; Wakabayashi, 1990, 2004; Gerya et al., 2002; Willner et al., 2004). In the first case, the mélanges of eastern Cuba document initiation of a new subduction system during the mid-Cretaceous simultaneously with termination of subduction in central and western Cuba. In the second case, the mélanges of western-central and eastern Cuba were generated within the same Early Cretaceous subduction system, but a triple junction interaction (ridge-trench-transform or trench-transform-transform, Wakabayashi, 2004) should have occurred at its eastern branch. An important constraint that may contribute to solving this problem is the progressively refrigerated system implied by the observed retrograde paths in the high-grade blocks from eastern Cuba mélanges, which is consistent with continued subduction during incorporation of the blocks into the associated overlying subduction channel. This mechanism is not consistent with the mid-Cretaceous arrest of subduction inferred for western-central Cuba, favoring the "initiation of subduction scenario" for eastern Cuba and, consequently, the lack of correlation between the subduction systems of both regions.

ESCAMBRAY TERRANE

The Escambray terrane crops out south of central Cuba within the Cretaceous volcanic arc belt, in a tectonic window below the metamorphosed arc-related Mabujina complex (Figs. 1B and 8). It is composed of an ensemble of strongly deformed tectonic slices that comprise continental margin metasediments and metaophiolites (Somin and Millán, 1981; Millán and Somin, 1985; Millán, 1997b; Stanek et al., this volume). Millán (1997b) subdivided the massif into four major tectonic units (I to IV, numbered from bottom to top in the pile; Fig. 8), each of which comprises a number of smaller tectonic units. The lithological sequences

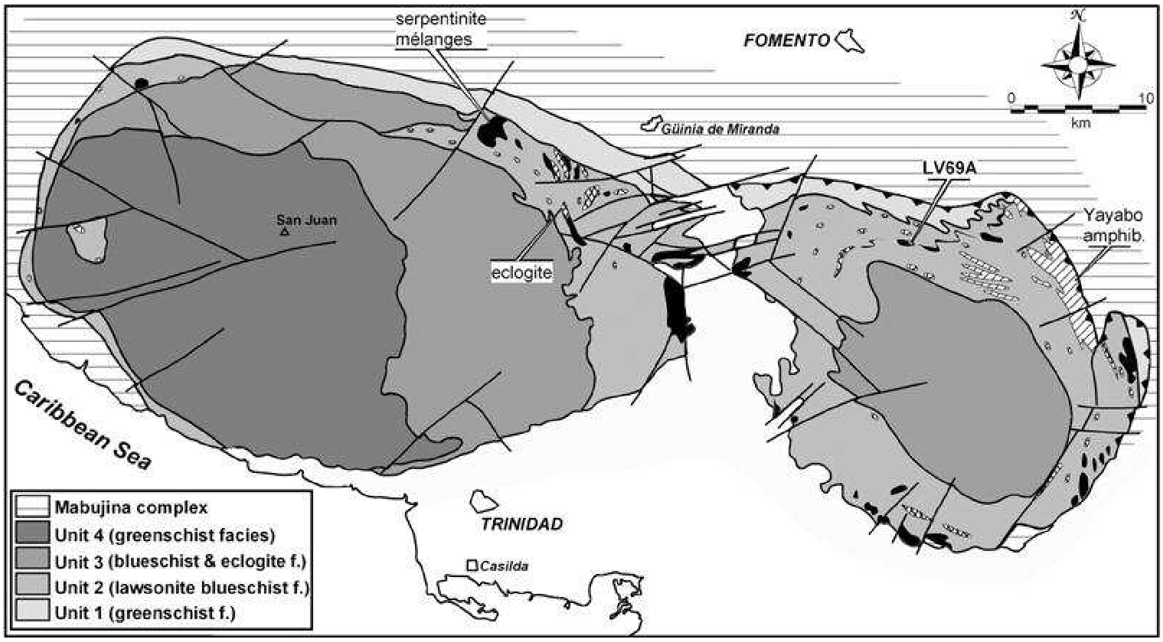

FIGURE 8 | **Geologic map of the Escambray (Millán, 1997b and unpublished data) with indication of major tectonic units, serpentinite mélanges and amphibolite and eclogite bodies within unit 3, and sample locality LV69A. See location in Figs. 1 and 2A.**

consist of metacarbonatic and metapsammopelitic rocks, with local metabasite intercalations. These rocks have been correlated with non-metamorphosed Jurassic-Cretaceous continental margin sequences in the Guaniguanico terrane of western Cuba, which formed part of the borderland of the Maya block (Millán, 1997a, b; Iturralde-Vinent, 1996a; Pszczólkowski, 1999). However, other reconstructions locate the terrane farther southwest in the borderland of the Chortis block (Pindell and Kennan, 2001).

P-T conditions during metamorphism in the Escambray were variable (Millán, 1997b; Stanek et al., this volume; Fig. 8), ranging from low grade at intermediate-P (greenschist facies) and high-P (blueschist facies) to medium grade at high-P (eclogite facies). The internal deformation is intense and complex, with numerous tectonic-metamorphic inversions. The massif has an inverted metamorphic zoning, with greenschist facies at the base in unit I, greenschist and lawsonite blueschist facies in unit II, and epidote-blueschist and eclogite facies at the top in unit III. The uppermost unit IV in contact with the overlying Mabujina complex diverges from this pattern (greenschist-blueschist facies). High pressure conditions indicate subduction of the continental margin. Subduction of oceanic lithosphere is also documented by serpentinite-matrix mélanges bearing high-pressure exotic blocks (Fig. 8). Available age data range from Upper Jurassic (U-Pb age of zircon in eclogite, Maresch et al., 2003) through mid-Cretaceous (U-Pb: 106-100 Ma; Hatten et al., 1988, 1989) to Upper Cretaceous (K-Ar: 85-68 Ma; $^{40}Ar/^{39}Ar$: 71-68 Ma; Rb/Sr: 65-69 Ma; Somin and Millán, 1981; Hatten et al., 1988; Somin et al., 1992; Iturralde et al., 1996; Schneider et al., 2004). Except for the Upper Jurassic age (discussed below), these ages are consistent with subduction in the course of the Upper Cretaceous and exhumation during the late Upper Cretaceous. This suggests that the associated subduction system may be independent of the Lower Cretaceous subduction system recorded in the HP blocks of mélanges from the northern ophiolite belt in western and central Cuba. Petrologic evidence presented below also support this view.

Millán (1997b) reported that eclogite facies rocks of tectonic unit III underwent blueschist facies retrogression, and related this overprinting to the low-grade high-pressure metamorphism of unit II. This type of blueschist retrogression is not common in the HP exotic blocks of the northern ophiolite belt from western-central Cuba, a fact that may relate to tectonic processes exclusive of the Upper Cretaceous subduction system where the Escambray complex impinged. Millán (1997b) and Schneider et al. (2004) identified blueschist retrogression as a result of syn-subduction exhumation during the late Upper Cretaceous. These authors also noted that the prograde metamorphic evolution of coherent eclogite samples present in the metasedimentary formations is more complex than that of the eclogite blocks of the tectonically intercalated strips of serpentinite-mélanges, but that their peak eclogite conditions and retrograde evolutions are similar, the latter characterized by substantial cooling upon exhumation. Since subduction of buoyant continental crust should have lead to tectonic-thermal processes different from those triggered by subduction of normal oceanic lithosphere, we concentrate here on the metamorphic evolution of the HP exotic blocks within serpentinite-mélanges representing oceanic material present in unit III, using one sample of an eclogite block (LV69A) located towards the NE of the massif (Fig. 8). This sample was studied in detail by Schneider et al. (2004), though we shall give here additional petrologic evidence pertaining to its retrograde metamorphic evolution. The age data provided by Schneider et al. (2004) are $^{40}Ar/^{39}Ar$ (phengite): 69.3±0.6, $^{40}Ar/^{39}Ar$ (barroisite): 69.1±1.3 and Rb/Sr (whole-rock-phengite-barroisite): 66.0±1.7 Ma, and were interpreted as cooling ages close to thermal peak.

Figure 9 illustrates textural and mineral composition data from sample LV69A (see also Fig. 3 and Schneider et al., 2004). The peak mineral association is composed of almandinic (type-C) garnet, sodic-calcic (barroisite) amphibole, omphacite, epidote, phengite, quartz, rutile and apatite, which is typical of amphibole-eclogites. Amphibole, omphacite, epidote, phengite, quartz and rutile comprise the matrix, though omphacite develops porphyroblasts up to 2 mm in length. Garnet is porphyroblastic, 1-2 mm in diameter, and includes epidote, sphene, rutile and, occasionally, amphibole, omphacite and quartz. These inclusions are oriented along an internal foliation oblique to the external foliation. The primary assemblage is irregularly replaced by a post-kinematic retrograde assemblage consisting of actinolite, glaucophane, albite, (clino)zoisite and chlorite, indicative of blueschist facies conditions.

Garnet zoning is concentric, typical of prograde growth, with cores richer in Fe, Mn and Ca, and rims richer in Mg and Mg#. This zoning pattern is disturbed by mechanical rupture of grains during deformation and, locally, by weak diffusional readjustments of Fe-Mn-Mg along fractures and rims of the grains and along the garnet-inclusions and garnet-garnet interfaces (Fig. 9). The mechanical rupture of the grains took place before attainment of the metamorphic peak, as indicated by broken grain boundaries overgrown by rims rich in Mg and Mg# and poor in Mn. The diffusional process took place close to the thermal peak since the modified composition of the garnet interiors trends towards high Mg#. The composition of omphacite is almost homogeneous, though subtle variations in Al, Na, Ca, Fe, Mg and Mg# occur in patches. At places where omphacite is replaced by retrograde albite, the associated patches are poorer in Al and Na (i.e., lower jadeite content). Grains of omphacite included

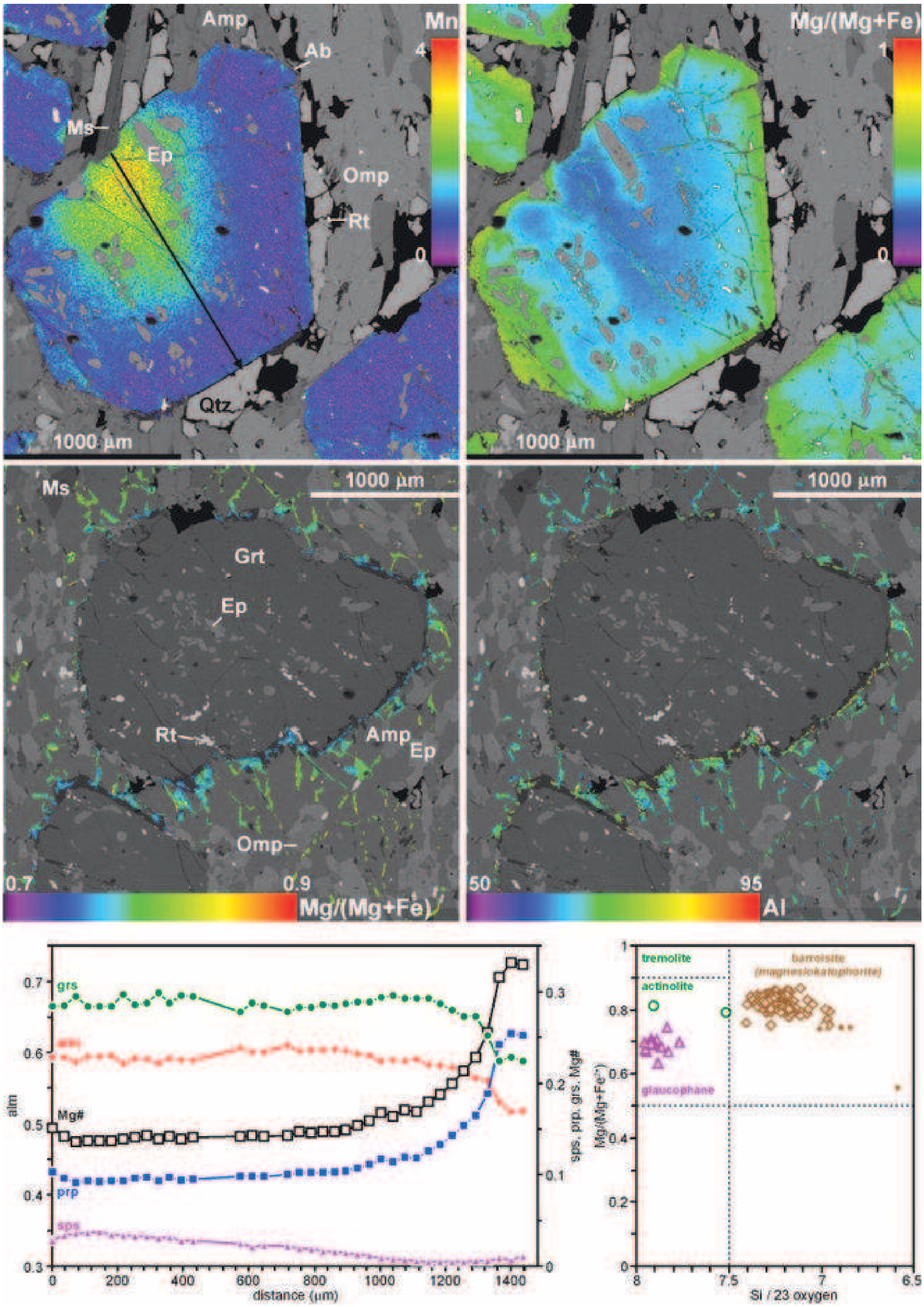

FIGURE 9 | **Key textural and mineral composition data of sample LV69A. The top synthetic XR images (beam current: 251 nA; step size: 5 µm; counting time: 50 ms; all other operating conditions and procedures as in Fig. 7) correspond to Mn(Kα) and Mg(Kα)/(Fe(Kα)+Mg(Kα)) of garnet. Note that the grain in the center of the images is fractured. The bottom synthetic XR images (step size: 6 µm; counting time: 50 ms (Na, Mn, Ti, Si) and 35 ms (Al, Fe, Mg, Ca; all other operating conditions and procedures as above and Fig. 7) correspond to Al(Kα) and Mg(Kα)/(Fe(Kα)+Mg(Kα)) of retrograde glaucophane. The compositional profile of garnet is indicated in the XR image of Mn. The composition of amphibole is plotted within the classification scheme of Leake et al. (1997), with symbols and labels as in Fig. 5.**

within garnet have lower Mg# than those of the matrix and porphyroblasts, though the jadeite contents are similar. Thus, the composition of peak omphacite corresponds with high Al, Na and Mg# contents. Amphibole in the matrix and enclosed within omphacite and garnet is sodic-calcic (barroisite, locally magnesiokatophorite). The compositional zoning is faint and concentric, with rims richer in Ti, Al, Fe and Na+K(A) indicative of prograde growth. The amounts of Na(B) decrease slightly towards the rims. Locally, amphibole rims are calcic (magnesiohornblende-actinolite), with a composition similar to that of retrograde grains associated with chlorite, albite and glaucophane. Inclusions of epidote within garnet have the Al-richest composition, the grains of the matrix show a faint zoning with cores richer in Al and rims richer in Fe^{3+} and some grains associated with retrograde overprints have lower Fe^{3+}, all indicating positive correlation of Fe^{3+} with temperature. Phengite shows a faint concentric zoning with cores richer in Si and Mg and rims richer in Al and Ti. This pattern is consistent with prograde growth at high pressure. Small grains of glaucophane overprint prograde barroisite, omphacite and garnet. At sites where omphacite grew adjacent to garnet, its composition is richer in Fe and Al, while it is richer in Mg at sites dominated by amphibole and/or omphacite. This is clearly shown in Fig. 9, where grains of Al-Fe-richer glaucophane grown at the rims of garnet become richer in Mg as they intrude the matrix formed by barroisite +omphacite. Since garnet is rich in Al and Fe, and barroisite and glaucophane are poorer in Al and richer in Mg, this texture indicates that the heterogeneous composition of glaucophane is the result of diffusion problems during retrogression and not because of different stages of growth. Similarly, retrograde chlorite occurs adjacent to garnet and within the barroisite+omphacite matrix, and its composition mimics the site of growth with higher Fe contents in the former and higher Mg contents in the latter (not shown) indicating equilibrium problems.

Metamorphic conditions have been estimated using Thermocalc (version 3.21). With the new data outlined above, we refined the calculations of Schneider et al. (2004) with identical results within error. Conditions calculated for the pre-peak inclusion assemblage and the peak assemblage are 573 ± 66 º C and 14.6 ± 2.8 kbar, and 657 ± 47ºC and 15 ± 2.1 kbar, respectively. Conditions calculated for the retrograde assemblage are 460 ± 87ºC and 8.8 ± 1.7 kbar, though these figures are uncertain because of equilibrium problems of glaucophane and chlorite mentioned above. The resulting P-T path describes a prograde section within the eclogite field followed by strong cooling during decompression. That the retrograde P-T path involves substantial cooling, as is typical for Franciscan-type paths, is indicative of a low geothermal (i.e., refrigerated) gradient during exhumation, implying that subduction did not stop during mélange formation and exhumation. This situation resembles that inferred for eastern Cuba, but is the reverse from that inferred for the mélanges of western-central Cuba.

PLATE-TECTONIC IMPLICATIONS

Alternative plate-tectonic models have been proposed for the Caribbean region (Morris et al., 1990; Pindell, 1994; Meschede and Frisch, 1998 for reviews, and the IGCP 433 “Origin of the Caribbean Plate” site http://www.ig.utexas.edu/CaribPlate/CaribPlate.html). However, most authors agree in a) formation of an oceanic inter-Americas gap (i.e., Proto-Caribbean) during Jurassic break-up of Pangea and Cretaceous drift of North and South America, b) progressive consumption of the Proto-Caribbean during the Cretaceous-Tertiary in one or several subduction zones, c) insertion of the Pacific-derived Caribbean plate into the inter-Americas gap and d) collision of the Caribbean plate with the North and South American plate margins during the uppermost Cretaceous and Tertiary (Wilson, 1966; Malfait and Dinkelman, 1972; Mattson, 1979; Pindell and Dewey, 1982; Burke et al., 1984; Duncan and Hargraves; 1984; Burke, 1988; Pindell and Barrett, 1990; Pindell, 1985, 1994; Iturralde-Vinent, 1998; Kerr et al., 1998, 1999; Mann, 1999; Pindell and Kennan, 2001). This process may have been accompanied by a change in polarity of subduction, from eastward-dipping subduction of the Pacific below the Proto-Caribbean to westward-dipping subduction of the Proto-Caribbean below the Pacific (Caribbean), but the age and tectonic scenario of the flip is debated.

Burke (1988), Duncan and Hargraves (1984) and Kerr et al. (1998) have argued for an Upper Cretaceous flip of subduction, while Mattson (1979), Pindell and Dewey (1982), Pindell (1994) and Pindell and Kennan (2001) have proposed an Aptian age. Mid-Cretaceous unconformities recorded in volcanic arc sequences along the Antilles and Venezuela have been related to an important mid-Cretaceous orogenic event by Pindell and Kennan (2001), but the unconformity is absent in Puerto Rico (Schellekens, 1998; Jolly et al., 2001) and Virgin Islands (Rankin, 2002). In La Habana, Villa Clara and Camagüey regions of central Cuba, unconformities and conglomerates of Albian age locally separate the tholeiitic and calc-alkaline island arc suites of the Cretaceous volcanic belt of central Cuba (i.e., pre-Camujiro/Los Pasos and Camujiro/Mataguá formations, respectively), but conglomerates and unconformities of Coniacian-Santonian age are also present within this volcanic belt (Iturralde-Vinent, 1996c; Diaz de Villalvilla, 1997; Piñero Pérez et al., 1997). Lebron and Perfit (1993, 1994) argued for a mid-Cretaceous flip based on an abrupt change from IAT to CA affinity in volcanic arc rocks, but this argument has been disputed by Kerr et al. (1999), Jolly et al. (2001) and Iturralde-Vinent et al. (this volume) based on evidence from Cuba and Puerto Rico. Mid-Cretaceous reversal of subduction has been related to northward overthrusting of the arc by oceanic crust in the Cordillera Central of Hispaniola (Draper et al., 1996, Lewis et al., 1999, 2002), but according to Lapierre et al. (1997, 1999) this tectonic event took place in Upper Cretaceous times. Our data and interpretations add to this debate.

Mid-Cretaceous arrest of subduction (western-central Cuba)

The P-T path and age data from high pressure blocks within serpentinite mélanges of the northern ophiolite belt in western and central Cuba provide evidence for pre-Aptian (pre-118 Ma) subduction, Aptian tectonic instability of the subduction system and Aptian-Albian arrest of subduction and mélange formation and exhumation. This mélange-forming event may relate to Aptian collision between Chortis and western Mexican blocks documented in exotic blocks of eclogite within serpentinite mélanges south of the Motagua fault zone in Guatemala (Harlow et al., 2004). If correlation exists, the lack of evidence for ocean basin closure and continent-continent collision in Cuba indicates prolongation of the continent-continent collision belt of Guatemala into a southern intra-oceanic belt.

The possible Cuban prolongation of mid-Cretaceous Guatemalan collision can be integrated into the tectonic model of Kerr et al. (1999). This model diverges from others proposed for the Caribbean region in postulating two simultaneous subduction systems during the Lower Cretaceous, the western one involving NE-directed consumption of the Pacific and associated with the formation of the tholeiitic island arc and the eastern one involving SW-directed consumption of the Proto-Caribbean and associated with the formation of a boninitic arc. Based on the extinction of the boninitic arc, the model incorporates termination of the subduction of the Proto-Caribbean and an orogenic event during the Aptian-Albian that formed an intra-oceanic suture. Thus, correlation of mid-Cretaceous sutures in Cuba and Guatemala is possible. Because the suture is located within the northern ophiolite belt, between the Cretaceous volcanic arc belt (to the South) and the Bahamas Platform (to the North) in central Cuba, the associated subduction zone likely involved subduction of the Proto-Caribbean, as suggested by Kerr et al. (1999). However, Harlow et al. (2004) suggested NE dipping subduction of the Pacific (Farallon) plate in Guatemala. To clarify this problem, age data of the boninitic rocks from Cuba are needed.

Alternatively, the mid-Cretaceous event of arrest of subduction and mélange formation in western-central Cuba may represent arrest of subduction of Pacific lithosphere related to Aptian flip of subduction as proposed by Pindell (1994) and Pindell and Kennan (2001). However, the model of Aptian flip of subduction predicts formation of western-central Cuba mélanges to the southwest (pre-Aptian scenario) of the volcanic arc. This prediction conflicts with the structural arrangement of central Cuba, where the Cretaceous volcanic arc belt overrides the northern ophiolite belt and associated mélanges along N-directed thrusts. Though this structure formed during the uppermost Late Cretaceous to Paleogene collision, the reconstruction of the relative position of the complexes during pre-Upper Cretaceous times places the mélanges northeast of the arc. The conflict is resolved if the mélanges are of Upper Cretaceous age, as proposed, for example, by Andó et al. (1996). But, while an additional Upper Cretaceous event of mélange formation is not excluded, the metamorphic data from the high-pressure blocks in the Holguín region indicate subduction during the Lower Cretaceous. Thus, model of Aptian flip of subduction can only accommodate our inferences concerning metamorphism in western-central Cuba mélanges if a fragment of the pre-Aptian fore-arc (located in the Pacific side of the arc) was tectonically incorporated to the post-Aptian fore-arc (located in the Proto-Caribbean side of the arc) during the flip of subduction, perhaps as a result of important sinistral strike-slip movements traversing the magmatic arc.

Mid-Cretaceous onset of subduction (eastern Cuba)

High-grade metamorphism in amphibolite blocks from eastern Cuba mélanges indicates formation in a hot subduction environment suggesting initiation of subduction. Initiation of subduction in the Caribbean realm has been proposed for parts of the Cordillera de la Costa accretionary prism, Venezuela (Smith et al., 1999). However, these authors dated the onset of subduction as Upper Cretaceous, while it is probably of Aptian-Albian age in eastern Cuba. Consequently, rocks from eastern Cuba support models of flip of subduction during the Aptian. This type of model predicts the birth of a new SW-dipping subduction system that consumed hot oceanic lithosphere of the Proto-Caribbean basin, which was opening at that time and subduction of a ridge was possible, as suggested by Pindell and Kennan (2001) who depict subduction of the Proto-Caribbean ridge in their model. Furthermore, continued subduction and, consequently, refrigeration of the subduction system during the Upper Cretaceous is consistent with counterclockwise P-T paths of eastern Cuba amphibolite blocks.

Upper Cretaceous subduction of the Purial volcanic arc

Though a sound structural analysis of eastern Cuba has not been undertaken, the basic structural arrangement of the region is dominated by NE-directed thrusts of (meta)ophiolitic material over the (meta)volcanic arc terrane of the Purial complex. This arrangement implies that the ophiolitic material and associated serpentinite mélanges were located to the SW of the Cretaceous volcanic arc belt previous to thrusting, conflicting with the predictions of models of Aptian flip of subduction. In this type of model, the mélanges should have been accreted to the fore-arc of the Caribbean plate and, consequently, should have been located to the NE of the volcanic arc. In addition, it should be noted that this model does not satisfactorily explain Late Campanian metamorphism of the Purial volcanic arc. This metamorphism was developed during collision of the Cretaceous volcanic arc belt with a subduction zone, as indicated by the attainment of high-pressure metamorphism and associated intense ductile deformation. In order to explain this orogenic process during the late Upper Cretaceous and the structural arrangement of eastern Cuba, it appears that two subduction zones are required as depicted in Fig. 10. This two-fold configuration explains a) volcanic arc sequences of Upper Cretaceous age with contrasted geochemical signatures including boninitic and tholeiitic in the eastern ophiolites and (mostly) calc-alkaline in the Cretaceous volcanic arc belt of the Purial complex, b) high-pressure metamorphism of oceanic material in La Corea and Sierra del Convento mélanges associated with the eastern ophiolites, c) high-pressure metamorphism of Cretaceous volcanic arc belt (Purial complex) and continental-margin sequences (Asunción), and d) thrusting of the ophiolitic bodies over the Cretaceous volcanic arc belt (Purial complex). The proposed arrangement of subduction during the Upper Cretaceous for eastern Cuba strengthens our view that mélanges of eastern and western-central Cuba are not correlated.

Upper Cretaceous subduction of the Escambray

Before our data and interpretations are discussed, the Late Jurassic (140-160 Ma) U-Pb ages of zircon of eclogites from the Escambray merits comment. This age is enigmatic and may represent either the magmatic crystallization of the precursor gabbro or an early (pre-Caribbean) metamorphic event (Maresch et al., 2003). Pindell and Kennan (2001) considered that this age correlates with Late Jurassic high pressure rocks from Baja California and suggested that the continental rocks of the Escambray (and Isle of Pines) may be located south of Chortis block during the late Jurassic. Furthermore, these authors depict the continental part of the Escambray massif to the SW of the Proto-Caribbean subduction zone during the Upper Cretaceous, implying that it was not subducted during this stage. This configuration is inconsistent with our interpretation of on-going subduction of oceanic and continental material during the late Upper Cretaceous and with independent studies that suggest correlation of a) the dragged basement of the eastern margin of the Yucatan peninsula with the Guaniguanico terrane (Pyle et al., 1973) and b) the latter with the Escambray and Isle of Pines terranes (Iturralde-Vinent, 1996a; Millán, 1997a, b; Pszczólkowski, 1999, and references therein). Further geochronological work is needed to solve this problem.

Assuming the continental portion of the Escambray ensemble forming part of the margin of the Maya block during the Mesozoic, subducted ophiolitic material within the complex (i.e. serpentinite-mélanges containing HP blocks) should correspond to Proto-Caribbean oceanic crust. K-Ar, $^{40}Ar/^{39}Ar$ and Rb/Sr ages of metasediments from the margin and of subducted oceanic crust (e.g. eclogite block LV69A) suggest subduction during the Upper Cretaceous and exhumation during the late Upper Cretaceous. This configuration is consistent

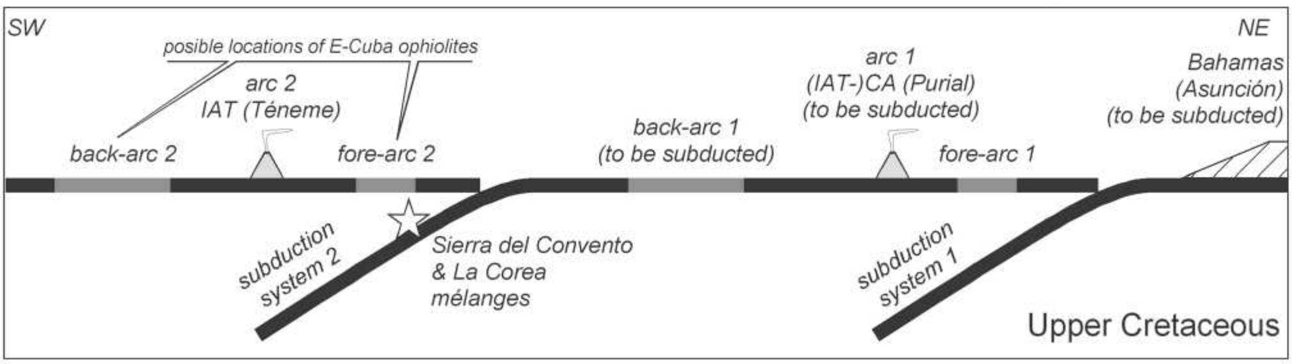

FIGURE 10 | **Model of the tectonic configuration of eastern Cuba during the Upper Cretaceous. Oceanic and suprasubduction volcanisms are indicated in black and grey, respectively. The Sierra del Convento and La Corea amphibolites (star) would have been formed upon the (Aptian) onset of subduction system 2, and the Purial complex (volcanic arc 1) would collide with this subduction system in the Late Campanian. The age of collision of the Asunción terrane (Bahamas?) with subduction system 2 is uncertain. Possible locations of eastern Cuba ophiolites and associated volcanics (suprasubduction system 2) are also indicated.**

with models that incorporate flip of subduction either during the Upper Cretaceous or the Aptian, though pre-100 Ma U-Pb ages constitute a problem of the former type of models. In the latter type of model, the 100-106 Ma U-Pb ages of zircons (Hatten et al., 1988, 1989) of eclogite blocks within serpentinite mélanges are explained as earlier subducted Proto-Caribbean crust (Millán, 1996a).

CONCLUDING REMARKS

The metamorphic evolution of subducted ophiolitic material from Cuba and the geologic setting of the different complexes do not support a single subduction system in the region during the Cretaceous. We propose that:

a) High-pressure blocks from the northern ophiolite belt in western and central Cuba formed in a pre-Aptian subduction zone that arrested during the Aptian-Albian due to an intra-oceanic collision event related to either Early Cretaceous continent-continent collision event in Guatemala or Aptian flip of subduction,

b) high-pressure high-temperature amphibolite blocks from the eastern Cuba ophiolites formed in a new Aptian (SW-dipping) hot subduction zone which evolved to mature subduction during the Upper Cretaceous and arrested during the Late Campanian when the Purial segment of the Cretaceous volcanic arc belt impinged into the subduction zone (Fig. 10), and

c) high-pressure rocks from the Escambray complex formed in a mature (SW-dipping) subduction zone of Upper Cretaceous age which consumed Proto-Caribbean oceanic crust and arrested during the late Upper Cretaceous, when the margin of the Maya block impinged into the subduction zone.

These conclusions suggest a variety of tectonic arrangements that may record space and time complexity in a dynamic plate-tectonic scenario strongly influenced by adjacent continental masses of North and South America. It may be no coincidence that the inferred Aptian-Albian subduction arrest of in western and central Cuba and initiation of hot subduction in eastern Cuba is synchronous with the onset of opening of Equatorial-South Atlantic and the westward drift of South America during mid-Cretaceous times. This was a global event that may have had significant consequences for the plate-tectonic evolution of the Caribbean region, such as the demise and birth of subduction systems, subduction polarity reversals, intraoceanic collision, closure of small oceanic basins flanking continental blocks, and changes in location and geochemical signature of arcs and of ocean-basin magmatic activity. The time overlap of these events and of the episodes of subduction-related metamorphism and serpentinite-matrix mélange formation in Cuba makes conceivable that the latter had shared the same origin. This could mean that a number of independent subduction zones evolved in the Caribbean-eastern Pacific region during the Cretaceous. Plate tectonic models that incorporate Aptian flip of subduction better accommodate our data and interpretations, though some adaptations of the models are needed. In particular, the Early Cretaceous Cuban-Guatemalan subduction-collision event and two simultaneous Upper Cretaceous subduction zones should be considered. Thus, the subduction zone where the blocks from the northern ophiolite belt of western-central Cuba were formed document a Lower Cretaceous subduction system different from that of eastern Cuba and the Escambray, and the subduction zones where the HP rocks of the latter two regions formed do not necessarily represent different parts (separated along strike) of a single Upper Cretaceous subduction system.

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