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Ophiolite-Related Ultramafic Rocks (Serpentinites) in the Caribbean Region: A Review of their Occurrence, Composition, Origin, Emplacement and Ni-Laterite Soil Formation

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ABSTRACT

Ultramafic rocks, mainly serpentinized peridotites of mantle origin, are mostly associated with the ophiolites of Mesozoic age that occur in belts along three of the margins of the Caribbean plate. The most extensive exposures are in Cuba. The ultramafic-mafic association (ophiolites) were formed and emplaced in several different tectonic environments. Mineralogical studies of the ultramafic rocks and the chemistry of the associated mafic rocks indicate that most of the ultramafic-mafic associations in both the northern and southern margins of the plate were formed in arc-related environments. There is little mantle peridotite exposed in the ophiolitic associations of the west coast of Central America, in the south Caribbean in Curacao and in the Andean belts in Colombia. In these occurrences the chemistry and age of the mafic rocks indicates that this association is mainly part of the 89 Ma Caribbean plateau province. The age of the mantle peridotites and associated ophiolites is probably mainly late Jurassic or Early Cretaceous. Emplacement of the ophiolites possibly began in the Early Cretaceous in Hispaniola and Puerto Rico, but most emplacement took place in the Late Cretaceous to Eocene (e.g. Cuba). Along the northern South America plate margin, in the Caribbean mountain belt, emplacement was by major thrusting and probably was not completed until the Oligocene or even the early Miocene. Caribbean mantle peridotites, before serpentinization, were mainly harzburgites, but dunites and lherzolites are also present. In detail, the mineralogical and chemical composition varies even within one ultramafic body, reflecting melting processes and peridotite/melt interaction in the upper mantle. At least for the northern Caribbean, uplift (post-emplacement tectonics) exposed the ultramafic massifs as a land surface to effective laterization in the beginning of the Miocene. Tectonic factors, determining the uplift, exposing the peridotites to weathering varied. In the northern Caribbean, in Guatemala, Jamaica, and Hispaniola, uplift occurred as a result of transpresional movement along pre-existing major faults. In Cuba, uplift occurred on a regional scale, determined by isostatic adjustment. In the south Caribbean, uplift of the Cordillera de la Costa and Serrania del Interior exposing the peridotites, also appears to be related to strike-slip movement along the El Pilar fault system. In the Caribbean, Ni-laterite deposits are currently being mined in the central Dominican Republic, eastern Cuba, northern Venezuela and northwest Colombia. Although apparently formed over ultramafic rocks of similar composition and under similar climatic conditions, the composition of the lateritic soils varies. Factors that probably determined these differences in laterite composition are geomorphology, topography, drainage and tectonics. According to the mineralogy of principal ore-bearing phases, Dominican Ni-laterite deposits are classified as the hydrous silicate-type. The main Ni-bearing minerals are hydrated Mg-Ni silicates (serpentine and "garnierite") occurring deeper in the profile (saprolite horizon). In contrast, in the deposits of eastern Cuba, the Ni and Co occurs mainly in the limonite zone composed of Fe hydroxides and oxides as the dominant mineralogy in the upper part of the profile, and are classified as the oxide-type.

KEYWORDS | **Peridotite. Serpentinite. Ni-Laterite. Ophiolite. Caribbean**

INTRODUCTION

Ophiolite-related ultramafic rocks, mainly serpentinites, crop out along three of the margins to the Caribbean Plate (Fig. 1). They are most abundant along the northern plate margin, and constitute about 7 per cent (7500 km^2) of the land surface of Cuba. Most of these ultramafic rocks were originally peridotites, formed in the upper mantle, and were then altered to serpentinites, completely or partly, by crustal fluids during their passage to their present tectonic position. When uplifted and exposed to weathering, these partially to completely serpentinized peridotites were altered to form a soil that has a composition determined, not only by the composition of the ultramafic rocks, but by many other factors, the main one of which is climate.

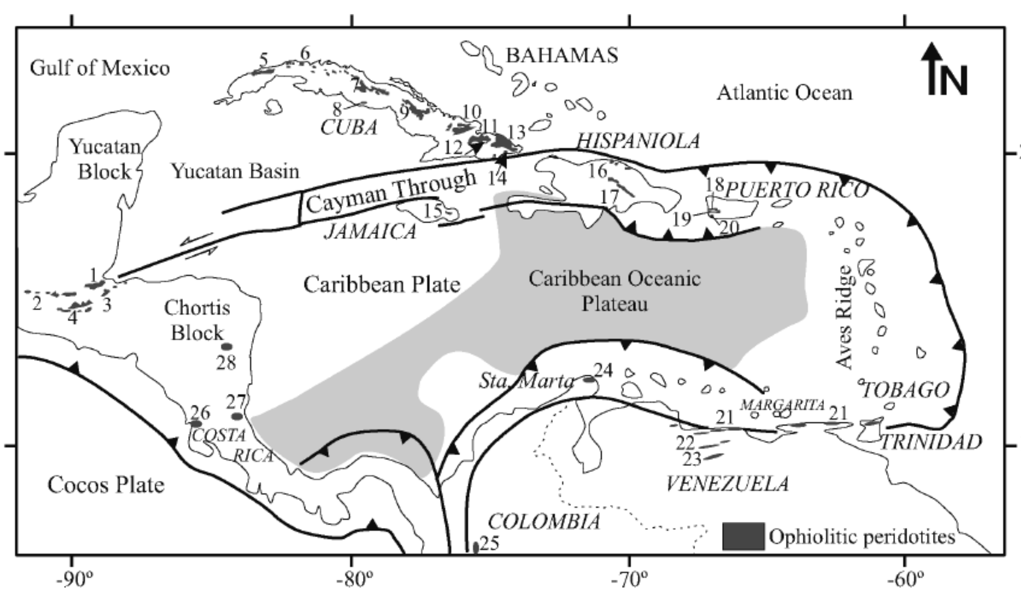

FIGURE 1 | **Distribution of ophiolite-related ultramafic rocks around the margins of the Caribbean Plate: 1: Sierra de Santa Cruz; 2: Baja Verapaz Unit; 3 Juan de Paz; 4: El Tambor Group (South Motagua and North Motagua); 5: Cajálbana; 6: Habana-Matanza; 7: Villa Clara; 8: Escambray; 9: Camagüey; 10: Holguín; 11: Mayarí-Cristal; 12: Alto de La Corea; 13: Moa-Baracoa; 14: Sierra del Convento; 15: Arntully; 16: North Coast Belt; 17: Loma Caribe; 18: Monte del Estado; 19: Río Guanajibo; 20: Bermeja; 21: La Franja Costera; 22: Loma de Hiero; 23: Villa de Cura; 24: Guajira Peninsula (serpentinites of Cabo de la Vela); 25: "Dunita de Medellín" (Aburrá ophiolite); 26: Santa Elena; 27: Rio San Juan; 28: Siuna. Main localities are numbered in italics.**

In the Caribbean, as a result of its tropical climate, thick, nickel-rich laterite soils are developed over the exposures of peridotites and serpentinites. The soils developed are characterized by variable contents of magnesium and iron, with relatively high contents of nickel, chromium and cobalt. Concentrations of nutrient elements calcium, potassium and phosphorus are low. These Ni-laterites are currently being mined in the central Dominican Republic (Loma Caribe), eastern Cuba (Mayari, Nicaro, Moa Bay, Punta Gorda), northern Venezuela (Loma de Níquel) and northwest Colombia (Cerro Matoso). Only the Dominican and eastern Cuban deposits are reviewed in this report.

A characteristic flora is developed on these lateritic soils. Brooks (1987) stated that the Cuban serpentinite flora is the third richest (in number of species) in the world. A wide variety of flora are developed over different areas of serpentinized peridotite in the Caribbean but little has been done to understand the relation between the flora and the composition of the laterite soils.

In this brief report we summarize the present knowledge of the distribution of ultramafic rocks (mainly serpentinites and serpentinized peridotites) the Caribbean, their geological associations, the processes by which they were formed, tectonically emplaced, uplifted and exposed to weathering. Emphasis is placed on the processes of laterite soil formation from the ultramafic rocks. Some geological factors are known better than others, but it is hoped that this review will give a better appreciation of our present knowledge of the processes involved. This is the first overall review of Caribbean serpentinites since those of Dengo (1972) and Wadge et al. (1984).

NATURE AND ORIGIN OF CARIBBEAN OPHIOLITE-RELATED ULTRAMAFIC ROCKS: A SUMMARY

Most of the ultramafic rocks in the Caribbean occur in the Mesozoic orogenic belts along the margins of the Caribbean Plate and are alpine-type peridotites (mantle-tectonites), partly or completely altered to serpentinite. In many of the occurrences, the alpine-type peridotites are closely associated with layered and massive gabbros, basalts, mafic dykes, minor plagiogranites, chromitites and sedimentary rocks, which form the ophiolite association. An idealized cross section of the Moa-Baracoa ophiolite, one of the few more complete ophiolites in the northen Caribbean, is shown in Fig. 2. However, generally, the ophiolites are highly dismembered; not all of the members of the ophiolite suite are present, nor is the ophiolite sequence as defined by the 1972 Penrose Conference (Anonymous, 1972). Although this problem is common in many ophiolitic occurrences in the world, it has led to considerable controversy and misunderstanding of the use of the term ophiolite, and this applies very much to the Caribbean.

Detailed field, petrological and geochemical studies in the past 25 years, on rocks of the ophiolitic associations in many areas, have shown that ophiolites form in a variety of tectonic environments, involving different types of oceanic crust and underlying mantle. Dilek (2003) has developed a classification of ophiolites based more on the tectonic relations, and this classification has been adopted for this review.

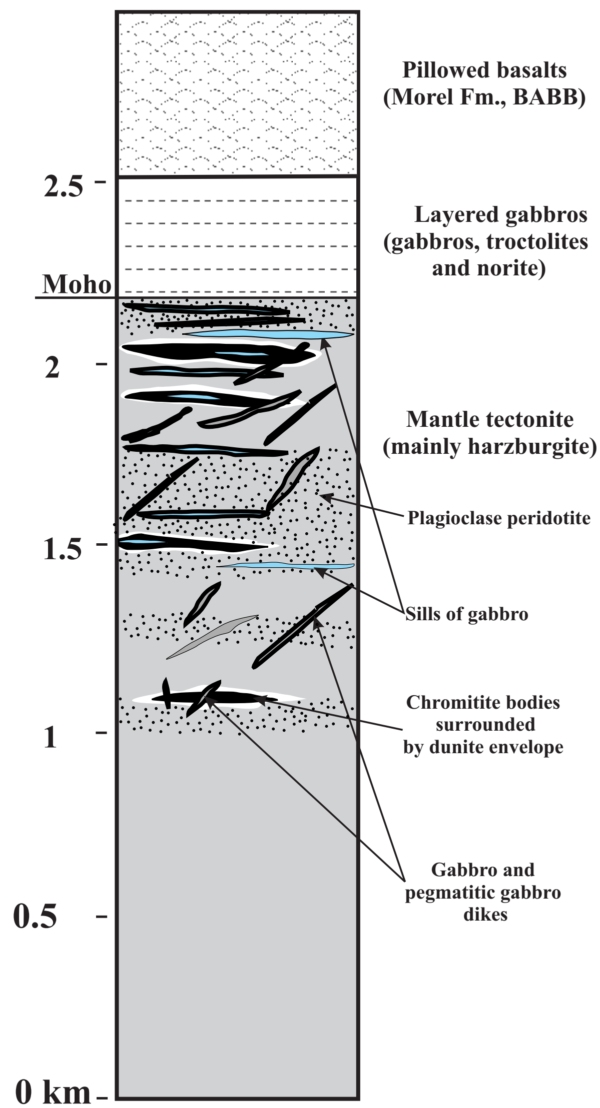

FIGURE 2 **An idealized lithostratigraphic column of Moa-Baracoa ophiolitic massif, which is a representative ophiolite from the northern Caribbean. BABB: back arc basin basalts (Modified from Proenza et al., 2003b; Marchesi et al., in press).**

Based on the field occurrence, the ultramafic rocks of the alpine-type in the Caribbean occupy two important associations that can be matched with similar occurrences in other parts of the world. The first is the occurrence of a tectonised melange of which the essential components are high pressure metamorphic rocks characteristic of subduction zones. These associations form a significant component of the accreting orogenic belts of the Pacific rim and are the San Francisco ophiolites of Dilek (2003). In the Caribbean, examples of this ophiolite type occur in the Motagua Fault Zone, Guatemala, in central Cuba (Villa Clara), the northern Hispaniola coast belt and in the Cordillera de la Costa in Venezuela (Table 1).

The second important type are the more complete, and somewhat less dismembered ophiolites, exposed as subhorizontal sheets, such as those in eastern Cuba. The mantle tectonites are mainly harzburgite and dunite with signicant bodies of chromitite in the upper part of the mantle sequence. High pressure xenoliths or tectonic blocks are absent. These occurrences can be equated with the Mediterranean-type ophiolite of Dilek (2003).

In the Caribbean, the term ophiolite has commonly been applied, in a general way, to include associations of mafic rocks that often do not consist of any ultramafic rocks (or only very little). These associations are often considered to be part of the 89 Ma Caribbean Large Igneous Plateau province (CLIP, Hauff et al., 2000a; Kerr et al., 1997b). Examples are the eastern margin of Central America in Costa Rica, Curacao, western Colombia and the southern Peninsula of Hispaniola in Haiti. Dilek (2003) has considered this type of occurrence to be a particular type of ophiolite association, which he has termed the Caribbean-type ophiolite.

Because of the similarity of ophiolite components with those of the ocean floor, it has long been considered that ophiolites originated at mid-ocean ridges. However, it is now considered more likely that many ophiolites were formed at convergent plate boundaries as part of the island arc structure (see discussion in Shervais, 2001; Robertson, 2002; Dilek 2003; Pearce, 2003). The term supra-subduction zone (SSZ) ophiolites is often used for these ophiolites and they may originate, within the fore-arc, the arc proper, or back-arc spreading area. Based on the composition of the associated basalts and gabbros, and the mineral compositions of both the peridotites and associated chromite deposits, at least some of the Caribbean ophiolites have interpreted as the SSZ type (Beccaluva et al., 1996; Kerr et al., 1999; Proenza et al., 1999a, b, c; Giunta et al., 2002a; Marchesi et al., 2003, 2006; García-Casco et al., 2003).

The composition of the mafic rocks in the ophiolite complexes, including the CLIP complexes, has been fairly extensively studied, in recent years, in order to determine their petro-tectonic affinity. Beccaluva et al. (1995) concluded that mid-ocean ridge (MOR) magmatism is the most widespread represented in the ophiolitic units along the three margins where these occur. They concluded that the oceanic crust was initially generated from multiple spreading centers (LREE depleted MORB compositions in Venezuela, Costa Rica, Guatemala and Hispaniola) and thickened oceanic plateau-related basalts (flat REE MORB), often associated with picrites in Costa Rica, the Southern Peninsula of Haiti, and the Dutch and Venezuelan islands along the southern margin. Island arc magmatism (island arc tholeiites, IAT) have been recognized in several ophiolite complexes in Guatemala, Cuba and Venezuela (Kerr et al., 1999; Giunta et al., 2002a, b; Marchesi et al., 2005). Detailed studies recently made of the chemistry of basaltic (extrusive) rocks from Costa Rica, Colombia and Curaçao as well as ODSP sites from the Caribbean basins (Hauff et al., 2000a) show that these rocks have a strikingly uniform major and trace element and isotopic composition. All these rocks are considered to belong to the Caribbean Plateau or CLIP and have a common mantle-plume source (Sinton et al., 1998). Reliable 40Ar/39Ar ages suggest that the main pulse of magmatism forming the CLIP occurred mainly between 92 and 88Ma, but continued to ~74 Ma (Sinton et al., 1998). Some geophysical evidence suggests the plateau could be as old as 115 Ma (Mauffret and Leroy, 1997) and has been built in several phases.

It should be pointed out that a few of the ultramafic bodies in the Caribbean are not ophiolite-related, have originated in a different way, and belong to a different association. These are peridotites formed by crystallization in a crustal magma chamber and usually exhibit layering as a result of crystal accumulation processes. Those in which the main rock type is websterite and that exhibit zoned structures, are termed zoned ultramafic plutons of the Alaskan-type (e.g. ultramafic rocks of Tobago; Snoke et al., 2001; Scott et al., 1999). The emplacement of these peridotites into the upper crust does not present a difficult problem.

Serpentinized peridotites of mantle origin, along with mafic rocks, have commonly been dredged from submarine scarps on the floor of the Caribbean Sea. Interesting occurrences include the plagioclase-bearing peridotites from the Cayman Trough spreading center (Perfit and Heezen, 1978; Dick and Bullen, 1984) and from the Puerto Rico Trench (Bowin et al., 1966; Perfit et al., 1980). These occurrences indicate that mantle peridotites lie immediately below the oceanic crustal rocks that form most of the Caribbean basin. On the reasonable assumption that the allocthonous ophiolitic bodies of Mesozoic age now found around the Caribbean margins originated as oceanic lithosphere from the area that is now the

Caribbean basin it is important to examine its composition which can be deduced from geophysical studies, dredging and drilling. As reviewed by Mauffret and Leroy (1997) the Caribbean basin is composed of several thick volcanic plateaus (e.g. Beata Ridge) separated by deep basins with thin crust (e.g. Venezuela basin composed of oceanic crust < 5 km thick).

The eastern lower Nicaragua Rise, Beata Ridge and Colombia basin are composed of thickened crust (15-20 km). The upper part of layer 2V is probably mainly basalt sills interlayered with sediment that overlies about 3 km of oceanic crust. The upper part of Layer 3V consists of about 6 km of gabbro that outcrops along scarps on the Beata ridge. The lower part of layer 3V is interpreted to be composed of 10 km of picrite and mafic cumulates rather than a type of modified mantle. The rock types, which are interpreted as cumulates, not alpine-type peridotites, can be matched with the picrite types on Curaçao and Gorgona Islands. Mauffret and Leroy (1997) consider that these crustal features correspond to the Kerguelen and Ontong Java plateaus (Mahoney and Coffin, 1997). Determination of the nature and composition of Layer 3V is important in interpreting the obducted ultramafic rocks around the Caribbean margin and determining how the plateau was formed. Mauffret and Leroy (1997) suggested that the thickening of the Caribbean crust is due largely to underplating.

The question of emplacement of the ophiolitic rocks in the Caribbean, into the upper part of the crust, is a continuing problem, as in other parts of the world. The emplacement of the "Franciscan-type" ophiolites is probably the easiest to comprehend. During subduction, fault bounded slices of ocean crust and some of the underlying mantle, are removed from the descending oceanic lithosphere and are incorporated into the overlying subduction complex that develops at the interface of the descending and over-riding plates, forming serpentinite matrix mélanges (Gerya et al., 2002). The subduction complexes may be developed to considerable depth (at least 30 km), and consequently the part of the ocean crust associated with the peridotites will recrystallize to form high pressure metamorphic rocks such as blueschists and eclogites. Subduction-related, high pressure/low temperature blocks (mainly garnet-bearing amphibolite, eclogites and blueschists) are common in the Caribbean's "Franciscan-type" ophiolite associations (Perfit et al., 1982; Draper and Nagle, 1991; García-Casco et al., 2002, this volume).

Although not yet well investigated, the blocks in the mélanges are probably mainly mid-ocean ridge basalts or gabbro (MORB), from the descending plate. However, in the mélanges of the Rio San Juan complex, in northern Hispaniola, blocks of metabasalt of both MORB and calc-alkaline (?SSZ) affinities are present (Anam, 1994) in addition to rarer blocks of metagranitoids.

The ultimate emplacement or exhumation of these high-pressure "Franciscan-type" ophiolites occurs when a continent-facing arc collides, either directly or obliquely, with a continental margin (Moores, 1982, 1998) or other buoyant crustal mass, island arc, or even an oceanic plateau. Arc-continent collisions of this type seem to be responsible for the final emplacement of the "Franciscan-type" ophiolites in both the northern and southern Caribbean (Pindell and Barrett, 1990; Pindell et al., this volume; García Casco et al., this volume).

The emplacement of coherent "Mediterranian-type" (SSZ or MORB) ophiolites is more problematic. The lower boundary of such ophiolites is thrust faults and like "Franciscan" ophiolites their emplacement must be related to some crustal shortening event. This shortening can be related to collision (as in eastern Cuba), but also to other tectonic events, such as subduction polarity reversal (as in central Hispaniola; Draper et al., 1996). The geometry of the situation, however, has to be one where the ophiolite does not enter a subduction zone, but is thrust onto arc or continental crust at shallow levels.

As the Caribbean has been tectonically active since the early Cretaceous (the last 140 million years), there have been several events at different places, and at different times, that have resulted in the emplacement of alpine peridotites and associated ophiolitic rocks of either the Franciscan or Mediterranean type.

The earliest orogenic event involving ophiolitic rocks seems to have been in mid-Cretaceous times (about 110-120 million years ago) when ophiolitic bodies were emplaced onto the arc crust of Central Hispaniola and western Puerto Rico, perhaps associated with subduction polarity reversal (Mattson, 1973; Mattson and Pessagno, 1979; Draper et al., 1996). In Cuba, also, the earliest event of ophiolite emplacement may have been Aptian-Albian (Kerr et al., 1999; García-Casco et al., 2002), although the details are unclear.

The oceanic plateau that occupies the present central region of the Caribbean sea was formed in the Late Cretaceous about 89 million years ago (Kerr et al., 1997a, b; Sinton et al., 1998) or earlier, somewhere to the west of its present position with respect to the middle America region (Pindell and Barrett, 1990). The eastern, leading edge of this plateau was marked by an island arc system that allowed convergence between the plateau and the American continents. As the Americas moved westward in the Late Cretaceous, parts of the plateau were subducted, but other fragments, along with various Pacific ter-

TABLE 1 | **Main characteristics of ophiolite-related ultramafic rocks in Caribbean region: SSZ = Supra subduction zone ophiolite; MOR = Mid-oceanic ridge.**

	OPHIOLITE UNIT	NUMBER IN FIGURE 1	ULTRAMAFIC ROCKS	CHROMITITES	TECTONIC SETTING	PERIOD OF EMPLACEMENT	Ni LATERITE DEPOSIT	SELECTED REFERENCES
GUATEMALA	Sierra de Santa Cruz	1	Harzburgite		SSZ	Late Cretaceous-	Yes	Beccaluva et al. (1995), Giunta et al. (2002b, c), Valls (2003, 2004)
	Baja Verapaz Unit	2	Harzburgite	Yes	SSZ	Late Cretaceous-Paleogene		Beccaluva et al. (1995), Wadge et al. (1982), Giunta et al. (2002b, c)
	Juan de Paz	3	Harzburgite		SSZ	Late Cretaceous-Paleogene		Beccaluva et al. (1995), Wadge et al. (1982), Giunta et al. (2002b, c)
	El Tambor Group " South " Motagua " North " Motagua	4	Peridotite		MOR (proto-Caribbean)	Late Cretaceous-Paleogene		Beccaluva et al. (1995), Wadge et al. (1982), Giunta et al. (2002a, b)
CUBA	Cajálbana	5	Harzburgite, dunite, lherzolite, pyroxenite	Yes (Cr-rich)	SSZ	Paleocene-Early Middle Eocene (earliest event may be Late Campanian?)	Yes	Fonseca et al. (1985), Murashko and Lavandero (1989), Iturralde-Vinent (1996, 1998), Cobiella-Reguera (2002, 2005)
	Habana-Matanza	6	Harzburgite, Plagioclase-bearing perido-tites, dunite	Yes (Al- and Cr-rich)	SSZ and oceanic plateau?	Paleocene-Early Middle Eocene		Fonseca et al. (1985), Iturralde-Vinent (1996), Llanes et al. (2001)
	Villa Clara	7	Harzburgite	Yes	SSZ and MOR	Late Paleocene-Middle Eocene (earliest event may be Aptian-Albian?)		Iturralde-Vinent (1996, 1998), García-Casco et al. (2002), Cobiella-Reguera (2002,2005)
	Escambray	8	Serpentinite		MOR (Farallón oceanic crust)	Late Cretaceous		Somin et al. (1992), Millán-Trujillo, (1996), Auzende et al. (2002), Scheneider et al. (2004), García-Casco et al. (this volume)
	Camagüey	9	Harzburgite, dunite, websterite websterite	Yes (Al-rich)	SSZ (back arc)	Paleocene-Upper Eocene	Yes	Fonseca et al. (1985) Iturralde-Vinent (1996 1998, 2001) Cobiella-Reguera (2002, 2005)
	Holguín	10	Harzburgite, dunite	Yes	SSZ (fore arc) and MOR	Maastrichtian – Early Middle Eocene (earliest event maybe Aptian-Albian?)		Kozary (1968), Iturralde-Vinent (1996, 1998), Andó et al. (1996), García-Casco et al. (2002), Cobiella-Reguera (2002, 2005)
	Mayarí-Cristal	11	Harzburgite	Yes (Cr- and Al-rich)	SSZ (fore arc)	Maastrichtian-Danian?	Yes	Iturralde-Vinent, (1996), Proenza et al. (1999a, b, 2003), Marchesi et al. (2003, in press), Cobiella-Reguera (2002,2005)
	Alto de La Corea	12	Serpentinite		MOR?	?		Somin et al. (1992), Millán-Trujillo, (1996), García-Casco et al. (this volume)

TABLE 1| **Continued.**

	OPHIOLITE UNIT	NUMBER IN FIGURE 1	ULTRAMAFIC ROCKS	CHROMITITES	TECTONIC SETTING	PERIOD OF EMPLACEMENT	Ni LATERITE DEPOSIT	SELECTED REFERENCES
	Moa-Baracoa	13	Harzburgite	Yes (Al-rich)	SSZ (back arc)	Maastrichtian-Danian?	Yes	Iturralde-Vinent, (1996) Proenza et al. (1999a, b, 2003), Marchesi et al. (2003, in press) Cobiella-Reguera (2002, 2005)
	Sierra del Convento	14	Serpentinite		MOR	Late Cretaceous		Somin et al. (1992), Millán-Trujillo, (1996), García-Casco et al. (this volume)
JAMAICA	Arntully	15	Dunite, harzburgite, lherzolite		MOR	Maestrichtian-Paleocene		Wadge et al. (1982), Scott et al. (1999), Abbott et al. (1999)
HISPANIOLA	North Coast Belt	16	Harzburgite, dunite		MOR and SSZ?	Paleocene		Draper and Nagle (1991), Anam (1994)
	Loma Caribe	17	Harzburgite, lherzolite, dunite	Yes (Cr-rich)	SSZ and/or mantle plume	Late Albian	Yes	Lewis (1981), Lewis and Draper (1990), Draper et al. (1996), Lewis et al. (2003)
PUERTO RICO	Monte del Estado	18	Lherzolite, harzburgite, dunite		SSZ?	?		Evans et al (1997), Jolly et al. (1998a, b)
	Río Guanajibo	19	Lherzolite, harzburgite, dunite		MOR?	?		Jolly et al. (1998b)
	Bermeja	20	Serpentinite		MOR?	Albian?		Mattson (1974), Mattson and Pessagno (1979), Jolly et al. (1998a, b)
VENEZUELA	La Franja Costera	21	Peridotites	Yes	MOR?	Late Cretaceous?. Final thrust emplacement during Eocene-Oligocene		Donovan (1994), Giunta et al. (2002a, c), Ave Lallement (1997)
	Loma de Hiero	22	Peridotites, plagioclase-bearing dunite		MOR (proto-Caribean)	Late Cretaceous?. Final thrust emplacement during Eocene-Oligocen	Yes	Donovan (1994), Giunta et al. (2002a, c), Ave Lallement (1997)
	Villa de Cura	23	Harzburgites		SSZ	Late Cretaceous. Final thrust emplacement during Eocene-Oligocene		Donovan (1994), Giunta et al. (2002a, c), Ave Lallement (1997)
	Guajira Peninsula (serpentinites of Cabo de la Vela)	24	Serpentinte		MOR (proto-Caribbean)	?		Case and Macdonald (1973), Donovan (1994), Sepúlveda et al. (2003)
COLOMBIA	Cordillera Central "Dunita de Medellín" (Aburrá ophiolite)	25	Dunita, harzburgita	Yes (Al-rich)	SSZ (back arc)	Permic-Triasic		Álvarez (1987), Restrepo (2003), Correa and Nilson (2003)
COSTA RICA	Santa Elena	26	Harzburgite, clinopyroxene-poor lherzolite, dunite	Yes	MOR in a mantle plume region and /or SSZ	Late Tertiary		Frisch et al. (1992), Beccaluva et al (1999 Gazel et al. (this volume)
COSTA RICA - NICARAGUA	Río San Juan	27	Serpentinite, lherzolite		MOR?	?		Astorga (1992), Tournon et al. (1995)
NICARAGUA	Siuna	28	Serpentinized, peridotite		MOR?	?		Baumgartner et al. (2004)

ranes were involved in collisions with the western parts of the North and South American continents (Montgomery et al., 1994; Kerr et al., 2003).

In the southern Caribbean boundary, oblique convergence also resulted in the final thrust emplacement of peridotites with Cretaceous high-pressure associations, but in this case the emplacement may have occurred progressively from Eocene times (about 50-55 million years ago) and was not completed until Oligocene or even early Miocene time (15-30 million years ago; Stockhert et al., 1995; Ave-Lallement, 1997).

DISTRIBUTION OF OPHIOLITE-RELATED ULTRAMAFIC ROCKS IN THE CARIBBEAN

The distribution of ophiolite-related ultramafic rocks around the margins of the Caribbean Plate is shown in Fig. 1. The more significant features concerning these rocks are included in Table 1.

Northern Caribbean margin

Guatemala

Ophiolitic rocks exposed along the Motagua Fault Zone in Guatemala include some large bodies of harzburgite such as the Sierra de Santa Cruz and La Gloria massifs (Donnelly et al., 1990). Recently Beccaluva et al. (1995) and Giunta et al. (2002b, c) have recognized four main ophiolite units containing peridotites (Table 1): (1) Sierra de Santa Cruz, (2) Baja Verapaz, (3) Juan de Paz, and (4) El Tambor group (South Motagua and North Motagua).

Sierra de Santa Cruz, Baja Verapaz and Juan de Paz units mainly consist of serpentinized mantle harzburgites, and have been interpreted as SSZ-type ophiolites. In contrast, South Motagua and North Motagua units, which also include serpentinized mantle peridotites, represent remnants of a proto-Caribbean oceanic crust (Beccaluva et al., 1995; Giunta et al., 2002b, c).

It is generally considered that most of these rocks, including the Santa Cruz body, were obducted (overthrust) onto the Maya continental block to the north whereas the South Motagua serpentinites were thrust to the south over the Chortis block. Uplift of these tectonic blocks resulted from sinistral transpressive movement between the Maya and Chortis blocks. The harzburgites contain inclusions of rocks such as jadeite and glaucophane-bearing schists and eclogites, which were formed under high pressure conditions at depths of about 30 kilometers. The harzburgites were probably first exposed to weathering in the Late Eocene at the time of the strike-slip faulting. The larger massifs of Sierra de Santa Cruz have well-developed Ni-laterite soils with a potential for mining (Giunta et al., 2002b; Valls, 2003, 2004).

Cuba

In Cuba, the largest bodies of ophiolite-related ultramafic-rocks (serpentinized peridotites and serpentinites) crop out to the north of the island, along the so-called "northern ophiolite belt" (Iturralde-Vinent, 1994, 1996, 1998). The ophiolites of northern Cuba occur as seven separate "massifs" (ophiolite blocks) or suites exposed along the entire length of the island, from west to east: Cajálbana, Habana-Matanza, Villa Clara, Camagüey, Holguín, Mayarí-Cristal, Moa-Baracoa. All ophiolite massifs contain massive chromitite bodies, a characteristic feature of SSZ ophiolites. The larger serpentinized peridotite massifs that crop out with these ophiolites are identified in Table 1 and Fig. 1.

The available data (Iturralde-Vinent, 1996; 1998; Kerr et al., 1999; Proenza et al., 1999a, 2001; Cobiella-Reguera, 2002, 2005; García-Casco et al., 2002, 2003) suggests that at least two Jurassic-Cretaceous mantle sections exist within the northern ophiolite belt, which underwent two major events: mid-oceanic accretion, and subduction. The northern belt includes both MOR and SSZ-type peridotites. In addition, ultramafic rocks occur as tectonic slabs of serpentinite (commonly associated with high-pressure rocks) embedded in a metasedimentary and/or metabasite matrix in the terranes of Guaniguanico and Escambray, and in the metamorphic complexes of Siera del Convento and La Corea (Somin et al., 1992; Ituralde-Vinent, 1994, 1996; Millán-Trujillo, 1996; Auzende et al., 2002; Schneider et al., 2004; Garcia-Casco et al., this volume).

Ultramafic rocks in western Cuba (the "Bahia Honda ultramafic complex" of Fonseca et al., 1985; Fig. 1, Table 1) are strongly dismembered. Except for the Cajálbana massif, the serpentinite bodies in western Cuba are all small and most have tectonic boundaries against adjacent rock units. In Cajálbana, the ultramafic rocks consist of mainly harzburgite with subordinate dunite, lherzolite, and pyroxenite (Fonseca et al., 1985; Murashko and Lavandero, 1989). These serpentinized peridotites have developed Ni-laterite soils (Ségalen et al., 1980). According to García-Casco et al. (2003), the protoliths of the metabasites from Cajálbana have an island-arc tholeiitic signature (SSZ ophiolite). These authors suggested that Cajálbana ophiolites represent a fragment of the Proto-Caribbean plate incorporated to the Caribbean plate during Aptian-Albian time. Also, in western Cuba, in the

Cordillera de Guaniguanico, blocks of serpentinite with associated eclogitic rocks, occur as olistoliths in the Lower Eocene olistostrome of Manacas Fm (Millán-Trujillo, 1996 and references therein).

In the Habana-Matanza area (Fig. 1), the ultramafic rocks consist of serpentinized harzburgites, minor plagioclase-bearing peridotites, dunite and lherzolite (Fonseca et al., 1985; Llanes et al., 2001). Volcanic rocks, tectonically embedded in deformed serpentinites from the Habana area, have been described as boninites (Fonseca et al., 1989; Kerr et al., 1999). In contrast, basalts from the volcanic-sedimentary sequence of the Margot Fm, that also occur within serpentinite in the Matanza area, have been shown to have an oceanic intraplate affinity (Kerr et al., 1999).

Large bodies of serpentinite and serpentinized peridotites, forming a serpentinized harzburgite mélange (Fonseca et al., 1985), characterize the ophiolitic rocks in the Villa Clara massif (Fig. 1). The ophiolite mélange, as a mass lies over the Bahamas continental margin, and itself is covered tectonically by Cretaceous arc rocks (Iturralde-Vinent, 1996). High-pressure metamorphic rocks are found included within the serpentinite mélange (Millán-Trujillo, 1996; Garcia-Casco et al., 2002). Metabasites from Villa Clara region (Iguará-Perea Complex) have a calc-alkaline magmatic signature, and have been interpreted as formed in a suprasubduction environment during the Late Cretaceous (García-Casco et al., 2003).

Small bodies of serpentinite occur as tectonic slices within the Escambray metamorphic complex to the south of Villa Clara, particularly along its eastern margin (Fig. 1; Somin et al., 1992; Millán-Trujillo, 1996; Auzende et al., 2002; Schneider et al., 2004). Serpentinites form lenses associated with eclogitic metabasites, and are embedded in a metasedimentary matrix. The association of high-pressure rocks in this complex indicates a relatively deep origin for the rocks of the complex including the serpentinized peridotites. According to Schneider et al. (2004), eclogite occurring as exotic blocks within the Escambray serpentinites, originated from a N-MORB type protolith (Farallon oceanic crust). Emplacement of the Escambray complex and the relationship with the ophiolite rocks of the Villa Clara area to the north is one of the most controversial issues of Cuban geology (Iturralde-Vinent, 1994; Millán-Trujillo, 1996; Grafe et al., 2001; Schneider et al., 2004).

The Camagüey massif (Fig. 1) mainly consists of serpentinized harzburgite, dunite, websterite and lherzolite (Fonseca et al., 1985; Iturralde-Vinent, 1989, 1996, 2001). Laterite soils are well-developed and preserved over the San Felipe serpentinite meseta, an erosional remnant near Camagüey city, but in the areas of lower relief the soils over the serpentinite have been washed away into adjacent sedimentary basins. For example, the Magantilla basin contains deposits of sedimentary magnesite and conglomerates with serpentinite pebbles interbedded with shales, often reddish in color. This implies that the serpentinites in the Camagüey area have been continuously uplifted to different levels and exposed to weathering and erosion since the Miocene (Iturralde-Vinent, pers. com., 2001). According to Gleeson et al. (2003) the nickel resource of Meseta de San Felipe is 2-3 Mt with 1.3% Ni.

In the Holguín massif (Fig. 1), the ultramafic rocks form part of a serpentinite mélange. The tectonic mixing and shearing of serpentinite in the Holguín block is higher than in other areas of Cuba (Fonseca et al., 1985). Peridotites consist of mainly harzburgite, with minor dunite (Andó et al., 1996).

The largest area of exposed serpentinized peridotites in Cuba, and in the whole Caribbean, occurs in northeast Cuba in the Mayarí-Cristal and Moa-Baracoa massifs (Fig. 1; Mayarí-Baracoa Ophiolite Belt: MBOB). Recent field and structural data indicate that the western part of Mayarí-Cristal massif (Mayarí zone) is essentially made up of mantle tectonites (>5 km thick) with subordinate gabbro-diabase dikes (Proenza et al., 2003b; Marchesi et al., 2003, in press). Two main domains have been differentiated in this massif: (1) the lower domain, which is composed mainly of porphyroclastic harzburgite tectonites contains pyroxenite veins. Dunites occur as irregular patches and sub-concordand dunite layers (<1 m) in harzburgites and as the wall-rock of chromitite pods; (2) the upper domain is composed of porphyroclastic harzburgite tectonites that are cut by a network of diabase and microgabbro dikes.

The easternmost part of the Mayarí-Cristal massif (Sagua de Tánamo area) includes serpentinized mantle tectonites, volcanic rocks of the Téneme Fm, and ultramafic breccias and chaotic rocks of the Picota Fm. (mélange zone). These ultramafic rocks are mainly composed of harzburgite and minor dunite, and overlie the volcanic and mélange units. Téneme Fm includes rocks ranging from tholeiite with boninitic affinities to typical oceanic island arc tholeiites (Proenza et al., this volume).

In the southeastern part of Mayarí-Cristal massif (Alto de la Corea area; Fig. 1) serpentinite bodies are associated with high-pressure metamorphic rocks. Garnet amphibolites, greenschists, quartzite, and albite-quartz-muscovite pegmatoid veins are abundant in this area (Somin and Millán, 1981; Somin et al., 1992; Millán-Trujillo, 1996; García-Casco et al., this volume).

On the other hand, the Moa-Baracoa massif is comprised of mantle tectonites (>2.2 km thick) topped by a thin crustal section made up of lower gabbros (ca. 300 m thick) and discordant basaltic rocks of the Morel Fm with possible back arc basin affinity (Iturralde-Vinent, this volume; Proenza et al., this volume). Isotropic gabbros and a diabase sheeted dike complex are lacking. In this massif, the Moho Transition Zone (MTZ) is made up of residual harzburgites, minor dunites, and "impregnated peridotites" with plagioclase and clinopyroxene. Concordant and sub-concordant bodies of dunite, sills of gabbro and chromitite bodies with a dunite envelope also occur in this transition zone. The MTZ peridotites are cut by dikes of gabbro, pegmatite gabbro, olivine norite and pyroxenite (Proenza et al., 1999a, b, 2003b; Marchesi et al., 2003, in press).

The MBOB is a SSZ-type ophiolite, that has been interpreted to result from an initial stage of rifting and formation of a "Protocaribbean" oceanic lithosphere followed by the development of a juvenile island-arc in a ?Late Cretaceous SSZ setting and later a back-arc basin (Proenza et al., 1999b, 2001; Marchesi et al., 2003, in press).

The structural/stratigraphic features of the Mayarí-Baracoa ophiolite allocthon are probably the best documented of any in the Caribbean. Ideas as to the mode of emplacement of the ophiolite (Cobiella, 1978) have recently been summarized by Iturralde-Vinent (2003) and Cobiella-Reguera (2005). As in western Cuba the source of the oceanic crust (ophiolite) was from the south but the timing and mechanism of emplacement was apparently different in eastern Cuba. In both areas there was apparently an early thrust event at the end of the Cretaceous. In central Cuba an element of oceanic crust and mantle was emplaced directly over the Bahamian continental borderland and later over segments of the volcanic arc rocks.

In eastern Cuba, the earliest emplacement of oceanic crust over the continental crust is represented by the Guira de Jauco amphibolites. Cretaceous volcano-sedimentary rocks of the Santo Domingo Fm and metavolcanic rocks of the Purial were emplaced over the amphibolites and are interpreted to directly overlie the Bahamian continental platform to the north. The emplacement of the ophiolite was from the south and took place in the Maastrichtian to early Danian with the olistostromes advancing in front of the ophiolite mass and filling the Sagua de Tánamo basin with clastic rocks.

The volume of nickel laterite developed over the Mayarí-Cristal and Moa-Baracoa massifs makes this area the largest known resource of nickel laterite in the world. The Moa-Baracoa laterites were developed over a broad erosion surface, or surfaces, that today vary in height from about 550 m to 1,000 m above sea level. In the lower elevations the serpentinies are covered by sedimentary rocks of Miocene age indicating that the ultramafic rocks were exposed at this time.

The smaller serpentinite massif of the Sierra del Convento, located in the southwest part of the Sierra del Purial, is separate from the Moa-Baracoa massif to the north (Fig. 1). A characteristic feature of the Sierra del Convento serpentinite is that it contains an abundant variety of blocks of high-pressure metamorphic rocks including garnet amphibolites, blueschists, metatrondhjemites and pegmatites suggesting a different origin, probably an uplifted subduction zone (Somin et al., 1992; Millán-Trujillo, 1996; García-Casco et al., this volume.).

Jamaica

A small faulted block of serpentinized peridotite (~0.25 km^2 in area) known as the Arntully sepentinite is located in the southern edge of the Blue Mountains along the Plantain Garden Fault in eastern Jamaica (Wadge et al., 1982; Robinson, 1994; Scott et al., 1992, 1999; Abbott et al., 1999). This body is considered to be related to the Bath Dunrobin complex of basalts and gabbros which would make this an ophiolite association (Wadge et al., 1982, 1984). The Arntully body is composed mainly of serpentinite with a core of partly serpentinized harzburgite, lherzolite, dunite and abundant blocks of rodingite.

Hispaniola

Serpentinized peridotites of apparent ophiolitic affinity occur in two belts across Hispaniola, namely the North Coast belt and the Median Belt in the Cordillera Central (Bowin, 1975; Lewis, 1981; Lewis and Draper, 1990). In both belts there is evidence that these originated separately as parts of ophiolite associations that are now highly dismembered and most of the original features have been destroyed. In the North Coast belt, the serpentinites in the Rio San Juan complex and the two small bodies in the Samana Peninsula are associated with high pressure/low temperature metamorphic rocks (Nagle, 1974; Draper and Nagle, 1991; Joyce, 1991; Abbott et al., 2004). The Rio San Juan complex is interpreted as an uplifted subduction zone complex. The north coast serpentinites are small (only the Punta Gorda body exceeds 5 km across) and there is little soil developed on these.

The main serpentinite belt, the Loma Caribe peridotite, in central Hispaniola in the Median Belt (Bowin, 1966) is about 4-5 km wide and extends for 95 km from La Vega to Cerro Prieta north of Santo Domingo, but the southeastern part of the peridotite is exposed as thin fault slices only. The body extends at depth to the coast where it has been intersected by drilling east of Santo Domingo, Most of the body is serpentinized harzburgite, but dunites, lherzolites and pyroxenites also occur (Lewis et al., 2003). The relationship of the associated basaltic rocks with the peridotite is not clear since all the contacts are faulted, leading to considerable controvery. Draper et al. (1996) have suggested that the Loma Caribe peridotite was emplaced first as early as the late Albian. Ni-laterite is well-developed over the Loma Caribe serpentinized harzburgites. Nickel resources are estimated at 1-2Mt at a grade of 1.2%Ni (Falconbridge Dominicana annual reports).

In addition to the two belts of the ophiolitic association described above, intrusive (magmatic) bodies of serpentinized peridotites also occur in several places along the Cordillera Central of the Dominican Republic and Massif du Nord of Haiti (Lewis, 1980; Lewis and Draper, 1990). These intrusions are composed of massive and layered peridotites and pyroxenites with norites and gabbros of cumulate origin. These ultramafic-mafic complexes are closely associated with the large tonalite intrusive bodies of late Cretaceous age and the metamorphosed mafic rocks of the Duarte Complex (Draper and Lewis, 1989).

Puerto Rico

In southwestern Puerto Rico there are three relatively small serpentinized peridotite bodies, namely Monte del Estado, Rio Guanajibo and the Bermeja in the south. Tectonic relations are not clear but the Bermeja serpentinized peridotite appears to be related to an ophiolite association (Mattson and Pessagno, 1979). Detailed studies show that there is considerable variation in the chemistry and petrography of these bodies (Jolly et al., 1998b). Dunites, harzburgites and lherzolites are all present even over a small area. Whether or not they are all part of the one peridotite mass that has been dismembered is not understood (Schellekens et al., 1989; Schellekens, 1998).

These serpentinized peridotites have features similar to abyssal peridotites (mid-oceanic accretion setting) and were the subject of extensive investigations by Hess and others (Burk, 1964). The Bermeja peridotites and associated amphibolites and metabasalts represent pre-arc oceanic crust and Matson and Pessagno (1979) proposed that the peridotites and crustal rocks were emplaced as a nappe. Jolly and Lidiak (pers. com., 2002) suggest all the peridotite masses appear to be emplaced into the upper crust as diapiric bodies. Jolly et al. (1998a) concluded that the Monte del Estado peridotite was in geochemical equilibrium with sub-arc magma.

Although there is a signicant saprolite zone developed over the Puerto Rico serpentinites, it is unlikely to be become an economic resource for nicked.

Southern Caribbean margin and northern Colombian Andes

Relatively small bodies of serpentinized ultramafic rocks are found along the Caribbean mountain system on the northern coastal region of South America (Fig. 1, Table 1). This mountain system extends discontinuously from the Sierra Nevada de Santa Marta and Guajira Peninsula in Colombia, eastward to the islands of Margarita and Tobago and the Northern Range of Trinidad. Small bodies of serpentinites that occur in the Sierra Nevada de Santa Marta are associated with mafic gneisses and schists of late Paleozoic age (Bellizia and Dengo, 1990). In the Guajira Peninsula, the serpentinites are associated with metagabbros, mafic and pelitic schists, phyllites, metavolcanics and marbles of late Mesozoic to early Tertiary age (Sepúlveda et al., 2003). Some of these serpentinites were considered to be of detrital origin (Lockwood, 1971). In addition, peridotites and associated gabbros occur in the Paraguaná Peninsula, east of Maracaibo (Martin-Bellizia and Arozena, 1972).

The ultramafic-mafic complexes in the Caribbean mountains in cental North Venezuela occur in at least five structural units, or belts, separated by major thrusts. These represent the imbrication of both continental and oceanic crustal units along with slices of mantle rock (Maresch, 1974; Stephan et al., 1980; Avé-Lallement, 1997; Avé-Lallement and Sisson, 2005). The main occurrences of serpentinized peridotites and associated rocks are shown in Fig. 1 and Table 1. Recently Giunta et al. (2002a, c; Table 1) have examined the chemistry of the major complexes and summarized the tectonomagmatic setting of the main ophiolite units. Relationships among rock types are complex and it is apparent that not all of the occurrences are ophiolites.

For example, detailed studies of the Tinaquillo spinel lherzolite, located in the Caucagua-El Tinaco nappe structure in the western part of the Serrania del Interior, have led to the interpretation that it is a piece of continental lithospheric mantle emplaced at the base of, or within, high grade felsic gneisses during the late Cretaceous (Seyler and Mattson 1989, 1993; Seyler et al., 1998). It is one of the few examples of the so-called “orogenic lherzolite” massifs (Menzies and Dupuy, 1991). Ostos et al., 2005 have interpreted the Tinaquillo peridotite complex to be a fragment of Jurassic rift zone.

Small bodies of serpentinized peridotite along the Cordillera de la Costa occur within the ophiolite mélange of the Franja Costera Unit (Fig. 1, Table 1). In this unit, basalt and gabbros show geochemical characteristics with MORB affinity (Giunta et al., 2002a, c).

Serpentinite is found within the complex of high-pressure metamorphic rocks of the island of Margarita north of Venezuela (Stockhert et al., 1995). Giunta et al. (2002a) have suggested that these peridotites bodies (mainly lherzolites) may represent an ultramafic complex equivalent of Tinaquillo.

Serpentinized peridotites (including plagioclase-bearing dunite) along with cumulate gabbros of late Jurassic age occur as part of the Loma de Hierro Unit (Table 1, Fig. 1) within the Serrania del Interior. This is described as an ophiolite association consisting of mainly basaltic rocks and siliceous-carbonate sequences in addition to the gabbros and serpentinized peridotites. The Loma Hierro Unit has been interpreted as a MOR type ophiolite (Giunta et al., 2002a, c). Ni-laterite has been mined from this area since 2000 but there is no published information on this deposit.

Serpentinized mantle peridotites, interpreted as part of subarc mantle and subduction complex, occur in the Villa Cura Group (Giunta et al. 2002a; Fig. 1, Table 1). Although a recent detailed study of the geochemistry of the Villa Cura Goup showed that all the metavolcanic rocks are arc-related (Stiles et al., 1999; Unger et al., 2005), Kerr et al. (2003) considered that at least some of the Villa de Cura volcanic rocks have an oceanic plateau origin similar to the basalts and picrites of Curacao and Aruba.

At least three of the peridotite massifs in the Caribbean mountain range do not belong to the ophiolite association. The ultramafic rocks on the island of Tobago are in the form of a layered intrusion and are interpreted to form the basal part of an island arc complex (Frost and Snoke, 1989; Scott et al., 1999). According to these authors, ultramafic rocks in Tobago are part of a single fractionated plutonic body made up largely of gabbro and diorite with minor tonalite. Snoke et al., (2001) have interpreted the complex as a zoned ultramafic intrusion of the Alaskan-type. Murray (1972) interpreted two of the peridotite intrusions in the Caribbean mountains in Venezuela as zoned ultramafic complexes of the Alaskan type. The largest of these intrusions, about 8 km long by 6 km wide, intrudes the southwestern part of the Villa de Cura Group.

Mafic and ultramafic rock associations of Cretaceous age form north-south trending belts in Colombia. These belts occur in the Cordillera Central, the main belt, the Cordillera Occidental and the Serranía de Baudó along the Pacific Coast discussed below. Many of the ultramafic bodies are thin slices elongated along faults. An example is the Itanguo serpentinite which is 40 km long and only 4000 m wide. In recent years, there has been much controversy on the tectonics and petrogenesis of these mafic-ultramafic associations. Only the northernmost bodies are discussed here.

Álvarez (1983) documented twenty-eight occurrences of ultramafic-mafic rock bodies in the Cordillera Central and Cordillera Occidental in the Colombian Andes. He and others (see Bourgois et al., 1987 review) considered that most of these ultramafic-mafic associations in the Colombian Andes showed ophiolitic affinities. Based on their composition of basaltic lavas around Cali McCourt et al. (1984) and Aspden et al. (1987) advocated a subduction related origin for the basalts. Analyses and age determinations on a larger number of the basaltic rocks led Kerr et al. (1997a, b) to conclude that the basaltic terranes were formed as an oceanic plateau and are most probably part of the mid-Cretaceous Caribbean plateau. Reynaud et al. (1999) have shown that the belt of oceanic plateau basalts, along with Cretaceous arc rocks, extends southward into southern Ecuador. The presence and extent of the Cretacous oceanic plateau in the northern Andes of South America was also based on the dominance of basaltic rocks, the absence of sheeted dike sequences and the occurrence of dunite rather than harzburgite. However, harzburgite is part of many of the mafic-ultramafic complexes and the presence of podiform chromite in some dunites is typical of ophiolite sequences (e.g. the so-called Dunitas de Medellín; Alvarez, 1987; Correa and Nilson, 2003; Restrepo, 2003) exposed in the northernmost part of the Cordillera Central. Most of the bodies are serpentinites and serpentinized dunites, but serpentinized harzburgites also occur. These ultramafic rocks have tectonic contact with orthoamphibolites, and both units are included in the Aburrá Ophiolitic Complex.

Ni-laterite soils are developed on several of the relatively small bodies of serpentinized ultramafics located in the north of Medellin. The largest of these is the Cerro Matoso which is 2 x 1.7 km in area and has a relief of 300 m. The thickness of the laterite varies from a few m to 100 m. The Ni content of the saprolite zone averages 2.5%. A study of the mineralogy and geochemistry of the Cerro Matoso deposit has recently been made by Gleeson et al. (2004).

Western Central America and northwestern Colombia

It is generally considered that the mafic-ultramafic complexes exposed along the west coast of Central America are part of the western most margin of the Caribbean

Plate. These include the well-studied segments of the Nicoya and Santa Elena Peninsulas and Quepos in Costa Rica and the Azuero massif in northwest Panama.

There has been considerable debate as to the origin, age and mode of emplacement of the oceanic crustal segment along the Pacific Coast of Costa Rica and Panama (see Hauff et al., 2000b; Hoernle and Hauff, submitted, for recent reviews). In the past the complexes have been termed ophiolites (Frisch et al., 1992; Beccaluva et al., 1999) but most of the important elements of a typical ophiolite are missing, and peridotite is found only in the north in the Santa Elena exposure (Fig. 1, Table 1). Here, the peridotite bodies consist of harzburgite, dunite and clinopyroxene-poor lherzolite (Frisch et al., 1992; Beccaluva et al., 1999). The 124-109Ma tholeiitic portions of the Santa Elena complex formed in a primitive island arc setting believed to be part of the Chortis subduction zone (Hauff et al., 2000b).

Nicoya complex consists mainly of tholeiitic pillow lavas and sheet flows with gabbroic and plagiogranitic intrusions, and fault bounded sequences of sedimentary rocks. These units are overlain unconformably by a Campanian to Tertiary sedimentary sequence. The Nicoya, Herradura, Golfito, and Burica complexes have been interpreted as part of the Caribbean oceanic plateau and generated as a mantle plume (Sinton et al., 1996; Hauff et al., 1997), or at an oceanic spreading center in a mantle plume region, analogous to the present Galapagos ridge/hot spot system (Beccaluva et al., 1999). Ar/Ar dating has shown that at least part of the Nicoya Complex is the age equivalent (89 Ma) of other magmatic plume basalt centers in the Caribbean-Colombian oceanic basalt plateau (Sinton et al., 1998). However, radiolarian cherts suggest that the lower part of the Nicoya complex might be late Jurassic or earlier in age (Galli-Olivier, 1979; Escalante, 1990). Denyer and Baumgartner (2005) consider that the Jurassic-Cretaceous cherts are sediment blocks disrupted from the original basement by multiple injections of magma. The Quepos segment, composed of tholeiitic pillow lavas overlain by highly vesicular hyaloclastites, breccias and conglomerates, is interpreted as a seamount (Hauff et al., 1997) or ocean island (Hauff et al., 2000b), whereas the Osa segment is considered an oceanic ridge. The structural, textural, and geochemical characteristics of the mafic rocks of Azuero and Sonia Peninsulas in south Panama are typical of CLIP and consistent with an origin from the Galapagos hotspot (Hoernle and Hauff, submitted).

Peridotites and serpentinites are reported from the Serranía de Baudó mafic complex in northwest Colombia (Case et al., 1971; Etayo et al., 1983). Little is known of this complex and that of the Darien area in southeastern Panama, but from limited studies of the mafic rocks both are interpreted as part of the Caribbean-Colombian oceanic basalt plateau (Kerr et al., 1997a; Hoernle and Hauff, submitted).

Small exposures of serpentinized peridotite of apparent mantle origin crop out near the Rio San Juan along the border between Nicaragua and Costa Rica (Vargas and Alfaro, 1992). These rocks were considered by Tournon et al. (1995) to be the remnants of an east-west trending suture zone. Serpentinized peridotites, mafic rocks and radiolarites, which together appear to form part of an ophiolitic association, have been reported from the Siuna area in northeast Nicaragua (Baumgartner et al., 2004). This occurrence is puzzling since it lies within the Chortis block composed of essentially Paleozoic rocks.

FORMATION OF NORTHERN CARIBBEAN Ni-LATERITE DEPOSITS: EASTERN CUBA AND CENTRAL DOMINICAN REPUBLIC

Once exposed to the surface, the serpentinized peridotites and serpentinites readily weather to give laterite soils in which Ni and other elements are distributed and concentrated into vertical zones within the soil (Golightly, 1979, 1981; Brand et al., 1998; Elias, 2002; Gleeson et al., 2003). Lateritization involves the dissolution of the original minerals in the rock and mobilization and precipitation of new chemical species from solution. This process depends largely on the movement of water through the rock and soil, the composition of the water and on the mineral solubilities. The solubility of minerals is known to be affected by lichens and microorganisms such as bacteria. It is probable that bacteria play a significant role in the weathering of rock, the formation of laterites and the migration of ions through the laterite soil (Barker et al., 1997). Lichens, lichen acids and organic acids, particularly oxalic acid, are also considered to be important in the weathering process (Jones, 1988; Drever, 1994; Easton, 1994). However the details of these processes are not yet well understood.

With more complex minerals, such as serpentine minerals, clays, "garnierite" and chlorite, ion exchange reactions occur. It should be mentioned that "garnierite" is not a recognized specific mineral species by the Commission on New Minerals and Mineral Names, but is a term for mixed structure of hydrous Ni-Mg silicates of low crystallinity with affinities to serpentinie, talc and chlorite (Elias, 2002). The most important ion exchange reaction relevant to the weathering of ultramafic rocks is the exchange of Ni for Mg between soil, water and serpentinite. The major overall factor determining the soil profile and element redistribution as a result of weathering is climate and this depends on the altitude at which the rock is weathering. On a large scale the redistribution of the elements by the soil waters is accomplished by the leaching and downward percolation of the elements in solution. The rate and direction of flow of water through the soil and rock substrate depends on the rainfall, the seasonal variation and the location of the water table. Locally the soil profile will be determined by the local drainage conditions which in turn will be determined by the degree of fracturing of the rock. All of these factors are seen in the Ni-laterite profiles in eastern Cuba and central Dominican Republic.The Caribbean has 7% of the world's Ni-laterite resources (distribution by contained nickel) (Dalvi et al., 2004). Most of this resource is in eastern Cuba and Dominican Republic (Loma Caribe).

Composition of protolith

The detailed composition of the ultramafic rocks (alpine-type peridotites) making up eastern Cuba and

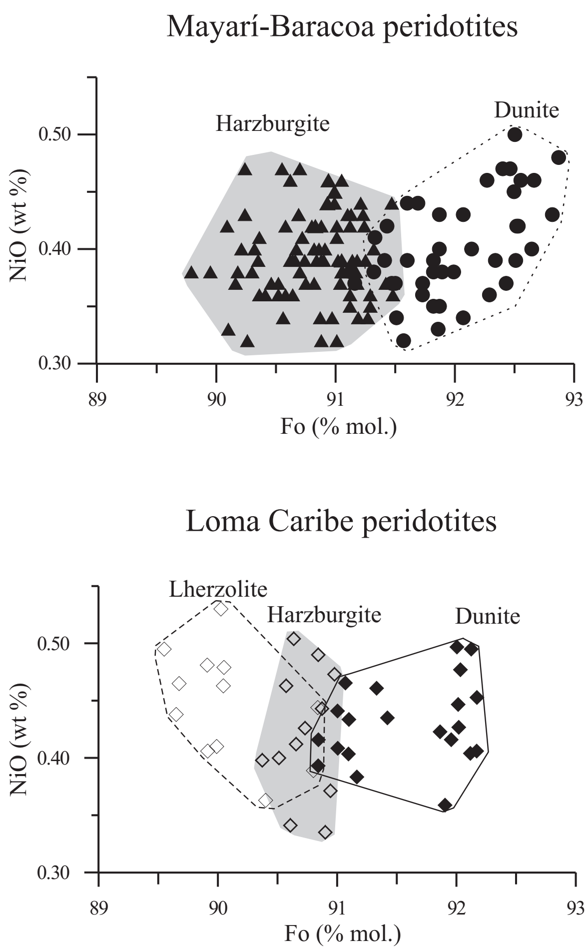

FIGURE 3 | **Ni (wt%) versus Fo content [Mg/(Mg+Fe)] in olivine from Mayarí-Baracoa peridotites (eastern Cuba) and Loma Caribe peridotites (Dominican Republic).**

Dominican Republic will be discussed in a future paper but some representative examples are given here. The compositions of the primary minerals olivine, orthopyroxene, clinopyroxene are very similar in the different rock types and the significance of this with respect to weathering and the composition of the laterites is discussed later. In detail there are small but significant differences in composition within and among the peridotites.

In all peridotite samples analyzed from Mayarí-Baracoa peridotite (eastern Cuba) and Loma Caribe peridotite (Dominican Republic), the olivine in dunite has similar Ni contents but higher Fo number than olivine in harzburgite (Fig. 3). Olivine in lherzolite from Loma Caribe has distinctly lower average Fo-number and similar Ni contents than olivine in dunite and harzburgite (Fig. 3). On the other hand, the Ni content of orthopyroxene and clinopyroxene is very low (NiO < 0.1 wt.%), usually below the detection limit of the electron microprobe.

The chemical and mineral data suggest that the primary source of the Ni-rich laterite is the olivine contained in harzburgite and dunite. These data also exclude orthopyroxene and clinopyroxene as a major source of the Ni contained in the Ni-rich laterite ore.

The Cr# (Cr/Cr+Al) of accessory chromite from harzburgites varies from 0.45 to 0.65 in Moa-Baracoa, whereas in Mayarí-Cristal ranges between 0.56 and 0.69. The Cr# of accessory chromite from dunite varies from 0.44-0.58 in Moa-Baracoa, and between 0.56 and 0.70 in Mayarí-Cristal (Proenza et al., 1999a, b, 2001). According to these authors, peridotites from Mayarí-Baracoa belt are subduction-related.

On the other hand, the Cr# in Cr-spinel from Loma Caribe peridotites vary from 0.30 to 0.88. These large compositional variations indicate the occurrence of peridotites with very different melting histories (Lewis et al., 2003). Relatively fertile peridotites as found in Loma Caribe (e.g. Cr# ~ 0.3) have not been reported in eastern Cuba ophiolites, where they exhibit mostly Cr# > 0.5.

Serpentinization

All the ultramafic rocks around the Caribbean have been serpentinized to at least some degree. Serpentinization is a hydrothermal process that takes place, generally, at crustal levels, and probably at temperatures between 200-500ºC (Moody, 1976; O'Hanley, 1995). The serpentine minerals and the serpentinization process have been little investigated in the Caribbean ultramafic rocks, but it is clear that all three of the main serpentine minerals (antigorite, lizardite

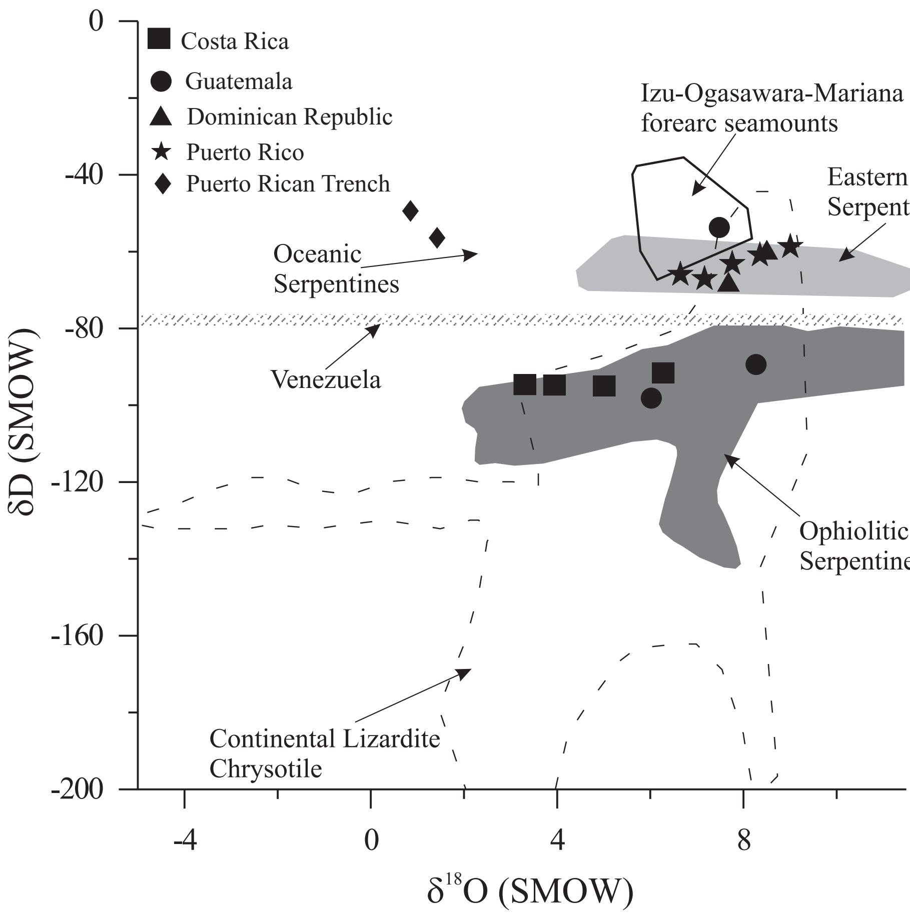

FIGURE 4 **a, δD versus $\delta^{18}O$ plot of Caribbean serpentine. The isotopic values of serpentine from Venezuela, Costa Rica, Guatemala, Dominican Republic, Puerto Rico and Puerto Rican Trench are taken from Wenner and Taylor (1973, 1974). The isotopic domains are from: "oceanic serpentine" and "ophiolite serpentine" (Wenner and Taylor, 1973), "continental serpentine" (Wenner and Taylor, 1974), Izu-Ogasawara-Mariana forearc serpentines (Sakai et al., 1990), eastern Cuba serpentine (Proenza et al., 2003a).**

and chrysotile) can be found in different localities in the Caribbean.

Serpentinite samples from the Dominican Republic, Guatemala, Costa Rica and Puerto Rico were included in the "classic" isotopic studies on serpentinisation of Wenner and Taylor (1971, 1973, 1974). Most of the Central America and Caribbean serpentinite included in the isotopic studies of Wenner and Taylor (1974) consisted predominantly of lizardite-chrysotile, with the only occurrence of antigorite from Guatemala. According to Wenner and Taylor (1974) the isotopic composition of lizardite and chrysotile serpentinite from Dominican Republic and Puerto Rico ranged from $\delta^{18}O$ = +6.7‰ to +8.7‰ and δD = -71‰ to -59‰. Serpentine from Central America (Guatemala and Costa Rica) has $\delta^{18}O$ = +3.3‰ to +8.3‰ and δD = -97 to -78‰.

Serpentinites from Dominican Republic plot within of the eastern Cuba serpentine field (Proenza et al., 2003a), and very close to the suprasubduction domain defined by Sakai et al. (1990). In contrast, isotopic composition of serpentine from Guatemala shows considerable variations in δD, and Costa Rica serpentine shows strong variations in $\delta^{18}O$ values, as well as relatively low and narrow range in δD (-94‰ to -91‰) (Fig. 4).

Based on $\delta^{18}O$ and δD (Fig. 4) values on the serpentine (mainly lizardite) from serpentinized chromitites and dunite from the Mayarí-Baracoa Ophiolitic Belt, eastern Cuba, Proenza et al. (2003a) concluded that serpentinization process took place in the subocean floor scenario at moderate temperatures, and that the Mayarí-Baracoa serpentines represent an example of serpentine formed during interaction with seawater. These authors consider that the serpentinization of the mantle sequence in the Mayarí-Baracoa ophiolite occured pre-obduction, and probably took place in a suprasubduc-

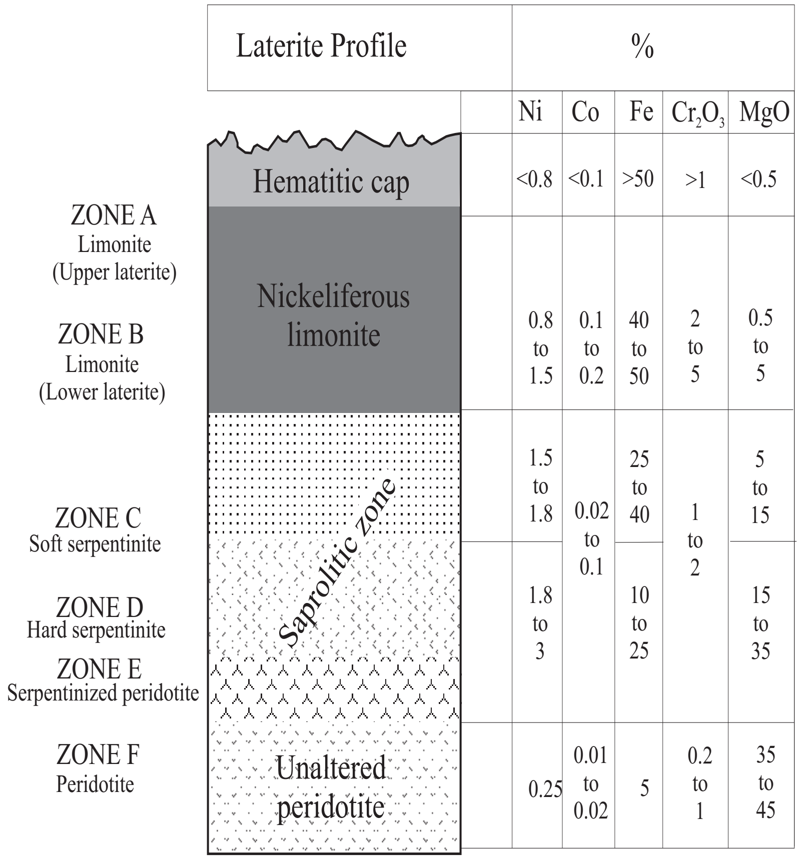

FIGURE 5 **Nickel laterite soil profile showing the zones and variation in chemical composition in each zone. Loma Caribe, Dominican Republic. Courtesy of Falconbridge Dominicana.**

tion setting (forearc environment or spreading axis of a back arc basin).

The laterite profile in central Domincan Republic

The description of the Dominican laterites in Fig. 5 is based on the criteria used by Falconbridge Dominicana in their mining operations (Haldemann et al., 1979). Two main zones (horizons) can be defined: the limonite zone and the saprolite zone. These are further divided into subzones labeled Zones A to F (Fig. 5). It should be noted that the profiles vary laterally (Fig. 6) as well as vertically, and no outcrop profile is identical to another. However, the basic features can be identified and matched throughout the area.

The upper zone (the limonite or laterite zone) is divided into Zone A and Zone B (Fig. 5). Zone A is a chocolate brown limonite which is readily distinguished by its colour and earthy friable texture. The upper part may contain concretions or pisolites of hematite up to 1 cm in diameter but the main constituent is goethite with irregular pockets of gibbsite. A thin zone of ferricrete is often found near the surface. Zone B is ochre-brown limonite and is usually much thicker than Zone A. It is composed of soft clayey material which varies in color from reddish to yellowish brown. It often forms tongues penetrating into the underlying soft or hard serpentinite of Zone C. Its chemical composition is similar to Zone A, but it has less iron and a higher silica content reflecting less goethite and a higher clay content. The saprolite Zone consists of somewhat variably altered bedrock in which most of the original structure and textures in the original bed rock (substrate) is preserved. In the upper part (Zone C of Fig. 5), the material is soft and somewhat clayey and has a wide color range from yellow to brown to reddish-brown with pockets of bright green garnierite. Serpentine is the major crystalline phase occurring with highly variable amounts of goethite and quartz. With increasing proportion of hard serpentine blocks, it grades downward into Zone D of Fig 5. Zone D consists of predominantly hard fragments of serpentinite from 5-25 cm in diameter set in a matrix of soft serpentine minerals. The fragments are a pale yellow ochre or dark grey color and often show concentric alteration zones. The outer skins of the fragments contain up to 3% or more of Ni and there is a gradual decrease in Ni toward the center of the fragment. The iron concentration can increase to about 8 percent with a decrease in the Ni/Fe ratio. This seems to involve leaching of the $Ni_3Si_2O_5(OH)_4$ component of the serpentine and formation of more goethite (Golightly, 1981).

In places where the saprolite is developed on unserpentinized peridotite, a different mineralogy and chemistry is found compared with that developed on completely serpentinized peridotites (Golightly, 1981). Here the blocks of peridotite have a thin crust or skin about 4 cm thick that grades rapidly into saprolite. Olivine decomposes first into amorphous ferrisilicate hydrates or a mixture of smectite and goethite. The saprolite, often penetrated by tongues of limonite, has a coarse blocky appearance. Joints are filled by veins of garnierite and quartz.

Figure 7 gives the concentrations of the key elements for the various zones or horizons through a soil profile on the Loma Caribe peridotite of the Dominican Republic. Iron oxide and MgO are inversely proportional. MgO and SiO_2 remain high through the saprolite and then decrease slowly through the limonite zone. Ni concentrates in the serpentine minerals (lizardite-nepouite) and garnierite, and may show considerable concentration in parts of the saprolitic zone. Concentrations of Ni in the bedrock are consistent at about 0.25%. In some thick saprolitic zones, the concentration of Ni is as high as 3%. Co and Ni concentrate independently. Co does not concentrate into the garnierite mineral structures along with Ni, but migrates and concentrates in Mn oxides (asbolanes) along with Mn at the base of the limonite zone.

There is a certain amount of concentration of Ni in the asbolane zone, but much less than Co. The Ni concentration in the limonite zone varies from about 0.5 to 1.5%. Note that Ni also varies independently from Mg in the weathering zone in contrast to its behaviour in high temperature mafic igneous rocks.

The laterite profile in eastern Cuba

A large province of Ni-laterites, that includes examples of world-class deposits, is formed over the serpentinized peridotites of eastern Cuba. From west to east the mining districts are: Pinares de Mayarí, Nicaro, Moa and Punta Gorda (Linchenat and Shirokova, 1964; Lavaut, 1998). These are mature laterites estimated to be 10-30 million years old, and the minimum reserves have been estimated at 1200 Mt of 1.3 % Ni.

The average thickness of the lateritic crust formed over the peridotite bedrock is 10 m although it can reach 50 m (Lavaut, 1998). The laterite profile of the eastern Cuban deposits has been divided into various zones and subzones. The classification most widely used in the Cuban laterite is that proposed by Lavaut (1998). In general terms one can recognize, in eastern Cuba, the same horizons that have been described in other Ni-laterite deposits of the world (Brand et al., 1998; Gleeson et al., 2003, 2004). The laterite profile is composed of 4 principal horizons. From bottom to top these are: (1) serpentinized peridotite, (2) saprolite, (3) limonite, (4) ferricrete. The lowest part of the profile is represented by tectonized serpentinized peridotite that represents the first stages of weathering. The saprolite zone is characterized by the preservation of the primary fabric, marked reduction in the quantity of primary minerals and the exclusive fm of alteration minerals in the most fractured zones. The boundary between the saprolitic zone and the peridotitic

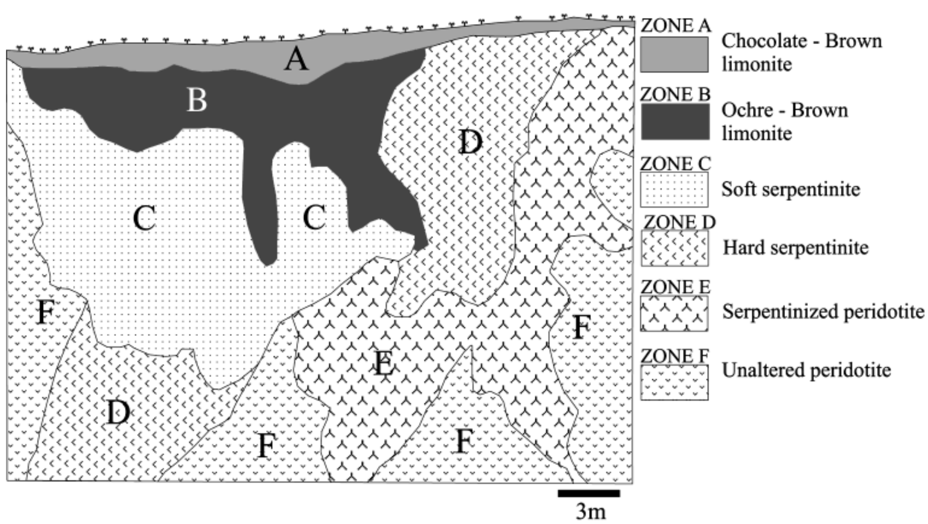

FIGURE 6 | **Generalized profile showing lateral variation in a nickel laterite, Loma Caribe, Dominican Republic. Courtesy of Falconbridge Dominicana.**

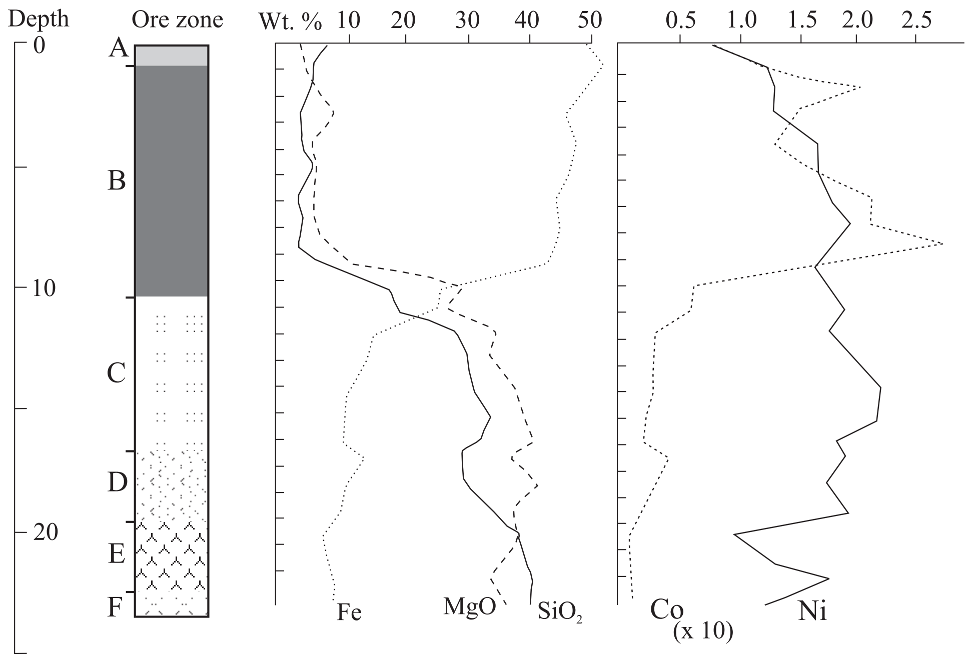

FIGURE 7 **Variation in chemical composition through a nickel laterite from Loma Caribe, Dominican Republic. Courtesy of Falconbridge Dominicana.**

substrate (weathering front) is extremely irregular. The saprolitic zone passes upwards in the section through a leaching zone to a limonite zone (Fig. 8). The limonite zone is defined by its dominant mineralogic composition (goethite and hematite), and two subzones can be defined: lower limonite and upper limonite. Finally, all the zones of the profile can be "protected" from erosion by a ferruginous level of predominantly ferricrete (residual limonite).

Serpentinized peridotite constitutes the major substrate over which the laterites are developed. The principal source of Ni is from olivine (up to 0.4 wt%, Proenza et al., 2003c).

The laterites developed over the Moa-Baracoa peridotites that have associated bodies of gabbro give a different soil profile. These bodies correspond with the presence of abundant dikes and sills of gabbro in the peridotites and are transformed to bauxite. In these soil zones, the content of Ni diminishes abruptly and they are considered "sterile intercalations" that can generate problems in the metallurgical process.

In some of the Ni-laterite deposits (e.g. Punta Gorda district) typical structures characteristic of redeposited laterite are observed (Formell, 1979; Formell and Oro, 1980). The laterites formed on slopes were periodically transported to more depressed zones covering previously formed laterites. Later, lateritic processes modified the layering of the re-deposited laterite and obliterated the primary zoning of the laterite profile.

The principal minerals that contain Ni in the saprolite zone of the Cuban deposits are lizardite-nepouite [$(Mg,Ni)_3Si_2O_5(OH)_4$], along with lesser amounts of clinochlore-nimite [$(Mg,Ni,Al)_6(Si,Al)_4O_{10}(OH)_8$]. In the limonite zone, the Ni is associated principally with goethite and a minor quantity with spinel and oxides and hydroxides of Mn (Rojas-Puron and Orozco, 1994; Oliveira et al., 2001; Rodriguez-Pacheco et al., 2003), whereas Co is associated with Mn minerals (Oliveira et al., 2001).

The Ni-Co laterite deposits of eastern Cuba, in agreement with the classification of Brand et al. (1998) are the oxide type. This classification is based on the mineralogy of the principal Ni-bearing phases. According to Gleeson et al. (2003) the best known example of Ni-laterite deposits of oxide-type are those of Moa (Moa Bay in the English literature).

Comparison of the laterite profiles in eastern Cuba and Central Dominican Republic

Although more units are recognized in the eastern Cuban laterite profiles and the nomenclature used differs (Lavaut, 1998), in general, the main features of the eastern Cuba laterites are very similar to those in the Dominican Republic.

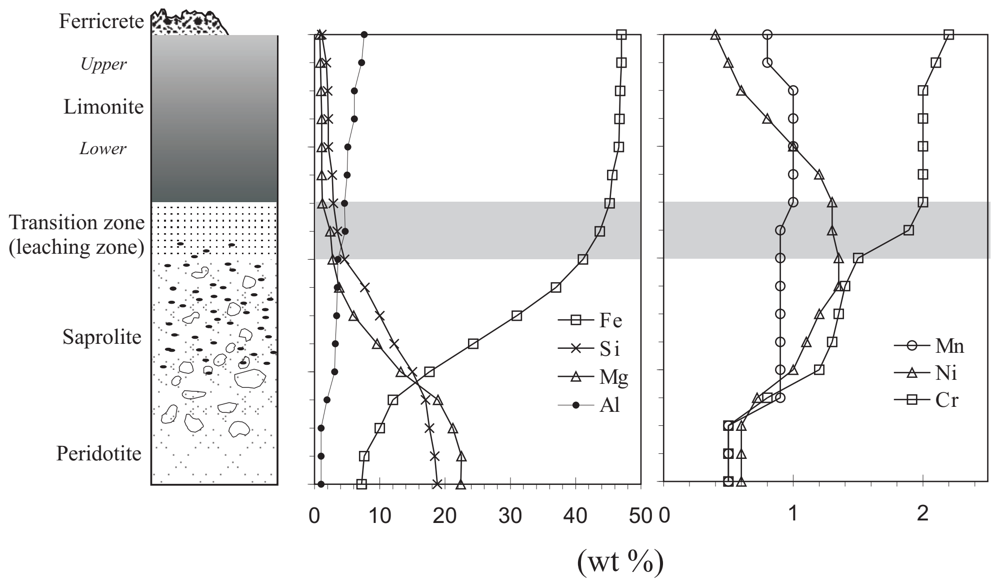

FIGURE 8 **Schematic laterite profile developed on eastern Cuba ultramafic rocks, showing the variation in chemical composition through each zone (from Rodríguez-Pacheco et al., 2003).**

In eastern Cuba, a significant fraction of the nickel is associated with Fe hydroxides and oxides in the upper part of the profile (limonite zone); these deposits are classified as oxide-type (Glesson et al., 2003). In contrast, in the Domincan laterites most of the nickel is found in the saprolite zone and these deposits are classified as the silicate-type deposits (highest-grade Ni laterite deposits). The main ore consists of hydrated Mg-Ni silicates (serpentine and "garnierite") occurring deeper in the profile (zone C to D). These zones account for 40% of the total ore reserves, while zone B (limonite ore) is 25% of the reserve.

The main difference seems to be that Zones C and D, i.e. the saprolitic horizons are less developed in eastern Cuba whereas the limonite horizons are better developed, at least in the Moa Bay area. The reason for this feature has not been properly investigated but could likely be related to the fact that the Moa Bay laterites (oxide type) are developed over a broad plateau with a gentle slope to the coast. Under these topographical conditions, which are unusual according to Golightly (1981), laterite can develop completely down to the water table. Given sufficient time and no rejuvenation a limonite zone will develop without significant saprolite. In contrast, Dominican laterites, as well as other silicate-type laterite, can be formed where there is slow continuos tectonic uplift and the water table is kept low in the profile. In this situation, weathering over long periods can result in development of a thick saprolite horizon (Golightly, 1981; Elias, 2002).

One of the factors that must have influenced the development of soils is the contrast in the tectonic evolution between Cuba and Hispaniola during the Neogene (Lewis and Draper, 1990; Mann et al., 1991). In the Dominican Republic upward movement of the serpentinized peridotites occurred in the late Oligocene and it is generally agreed that the serpentinites along with other older units were exposed to weathering and erosion in the early Miocene. Lateritization began at this time. This Miocene land surface was subsequently broken into blocks by vertical movements associated with transpressional movement along major faults. At least four physiographic cycles can be recognized corresponding to different surface levels (Haldemann et al., 1979). Lateritization still continues today.

In Cuba, the situation is different. The fact that marine sediments of late Eocene and Miocene age overlie the serpentinites unconformably as seen along the northeast coast indicates that the serpentinites were exposed at the surface by this time. The extensive east-west strike-slip faulting that affected most of Hispaniola throughout the Neogene was not developed in Cuba. Hence, although gradual regional uplift occurred which would have aided the lateritization process the peridotite massifs were not broken into smaller blocks that would have undergone differential uplift as a result of strike-slip movement.

CONCLUSIONS

This review shows that major progress has been made in the last 25 years in our understanding as to the role of ophiolite-related ultramafic rocks in the evolution of the Caribbean. However many problems remain. The following comments relate to ultramafic rocks and their significance in the ophiolite concept as applied to the Caribbean.

1) It is important to retain the ophiolite concept in the studies concerning Caribbean ophiolites and consider the rocks (peridotites, gabbros, basalts, sedimentary rocks) not as isolated units, but as an association. For example, in considering melting processes and magma types, the composition of the rocks in the crust-mantle transition zone (mantle peridotites and the intruding dike rocks and chromitites) must be examined together with crustal basalts and gabbros from the same complex. Although the differences are small much can be learned about the compositions of the peridotites through detailed mineralogical and geochemical studies (Proenza et al., 1999b; Lewis et al., 2003; Marchesi et al., in press) and by interpretation of the nature of the mantle at the time of melting and the magma compositions.

2) Although SSZ ophiolites have been identified in a number of localities in the Caribbean, based on the mineralogy of the peridotites or on basalt chemistry, no example has yet been shown to be linked to the development of the axial part of an oceanic arc (Shervais, 2001). With further studies of mélange rock fragments, it should be possible to better determine different types of subduction zones and the polarity of subduction. However, these bodies are often highly dismembered and metamorphosed so there should be caution in the use of these data. Random collections can be misleading.

3) Caribbean ophiolites show many of the features seen in orogenic belts in other parts of the world but the recognition in the Caribbean basin itself of plateaus of thickened basaltic crust formed by major eruptions of basalt over a short period of time is a particularly interesting feature. Parts of the oceanic plateau in western Colombia, western Central America, Southern Peninsula of Haiti and possibly central Hispaniola (Duarte Complex) have been found accreted to the Caribbean margins as expected for buoyant plateau crust, as opposed to normal oceanic crust which should be subducted (Kerr et al., 2003). Dilek (2003) has termed these as ophiolites of the Caribbean-type even though ultramafic rocks are generally absent in these oceanic plateau complexes. This term as used by Dilek maybe confusing to readers not familiar with the area since these plateau (CLIP) rocks are not typical of the major ophiolite bodies in the northern Caribbean such as those of Cuba. The reason for the absence of oceanic plateau crust in Cuba and elsewhere, particularly where mantle peridotites are dominant, may be due to factors of crustal buoyancy, stress geometry or simply other oceanic crust in the area at the time of collision and accretion, but this question should be pursued more vigorously.

4) The Caribbean has the largest resources of Ni-Co laterite in the world formed by the weathering of serpentinized peridotites under special conditions of climate and tectonics of the Caribbean in the Tertiary. Unfortunately, these deposits have been studied in a rudimentary way only and many questions need to be answered. The relation between laterite composition and composition of the serpentinite/peridotite protoliths is not known. There has been no recent study of the mineralogy and geochemistry of the deposits in order to determine and compare quantitatively the variation in chemistry through the soil profiles of different deposits. Such studies are important not only to evaluate the deposits economically, but to investigate how the deposits were formed. In addition a unique flora is found on the Caribbean Ni-laterite soils (Brooks, 1987), but the nature and formation of this flora and its relation to the composition of the soils has been little studied. Such studies should be multi-disciplinary.

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