

# UHP metamorphism in garnet peridotite, Cuaba unit, Rio San Juan Complex, Dominican Republic

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**ABSTRACT.** Spinel-bearing garnet peridotite (olivine + diopside + enstatite? + garnet + spinel + late magnesiohornblende + late serpentine) and a corundum-bearing variant are associated with hornblende gneiss and schist (hornblende + plagioclase + quartz + rutile +/- garnet +/- biotite +/- epidote) and retrograded eclogite (hornblende + symplectic diopside-plagioclase + garnet + quartz +/- epidote) in the Cuaba amphibolite unit of the Cretaceous Rio San Juan complex. The occurrence is unusual because the garnet peridotite was exhumed at an ocean-ocean convergent plate boundary.

Four attributes suggest low-P/T (UHT) conditions: (1) Sequence of mineral assemblages, (2) nature of associated rocks, (3) Cr-in-clinopyroxene, Mg<sub>2</sub>Si<sub>2</sub>O<sub>6</sub>-in-clinopyroxene thermobarometry (>1.8 Gpa, >900 °C), and (4) tectonic setting. However, the thermobarometry is questionable because of low Cr in clinopyroxene. On the other hand, CFMAS equilibria involving components in olivine, garnet, clinopyroxene, spinel, and corundum suggest pressures from 2.8 Gpa (810 °C) to 3.5 Gpa (740 °C). These high-P/T (UHP) conditions are at odds with other indications (1, 2, 4, above) for low-P/T conditions. The contradiction highlights the unusual character of the rocks, but may be consistent with emplacement and uplift at an ocean-ocean convergent plate boundary.

Elsewhere, Alpine-type garnet peridotite is associated with what had been deep subducted continental rock, and ascent was presumably driven by the buoyancy of the continental material. In the present case, the buoyant force is not obvious. Indications of initially very high temperature at a modest depth in the mantle (~55 km) argue for the involvement of hot upwelling mantle. We offer alternative models wherein the garnet peridotite originates (1) in the mantle wedge above the subduction zone or (2) in the mantle beneath the subduction zone. In the first instance, the process may be related to extension in the forearc. In the second instance, the process may be related to subduction of an ocean ridge or mantle plume.

## 1. INTRODUCTION

The subject of this paper is Alpine-type garnet peridotite and a corundum-bearing variant, recently discovered in the Dominican Republic (Abbott *et al.*, 2001a, b; Draper *et al.*, 2002). While peridotite is relatively common in orogenic belts, garnet-bearing varieties are very rare and only associated with ultra high pressure (UHP) or high pressure – ultra high temperature (HP-UHT) metamorphic terranes (Medaris, 1999). Such rare rocks yield valuable insight into convergent plate-boundary tectonics, especially with regard to extreme conditions in a subduction zone, deep subduction of crust, the transfer of mantle rock to deep-subducted crust, and the mechanism by which such rocks are delivered to the surface. To the best of our knowledge, the discovery in the Dominican Republic is the second of its kind in the Americas. The first example described in the Americas is from the Seward Peninsula of Alaska (Lieberman and Till, 1987; Till, 1981).

## 2. GEOLOGIC SETTING

Hispaniola is one of the four large islands of the Greater Antilles (Fig. 1). Three of the islands (Jamaica, Hispaniola and Puerto Rico) lie just south of the northern edge of the Caribbean plate. The fourth and largest island (Cuba) lies just north of the plate boundary, on the North American plate. The cores of the islands were created as an intra-oceanic

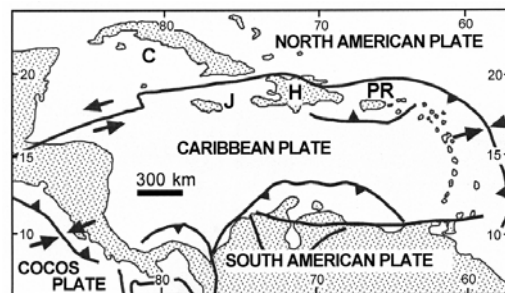


Figure 1. Geologic provinces of the Caribbean. Islands of the Greater Antilles: C = Cuba; H = Hispaniola; J = Jamaica; PR = Puerto Rico.

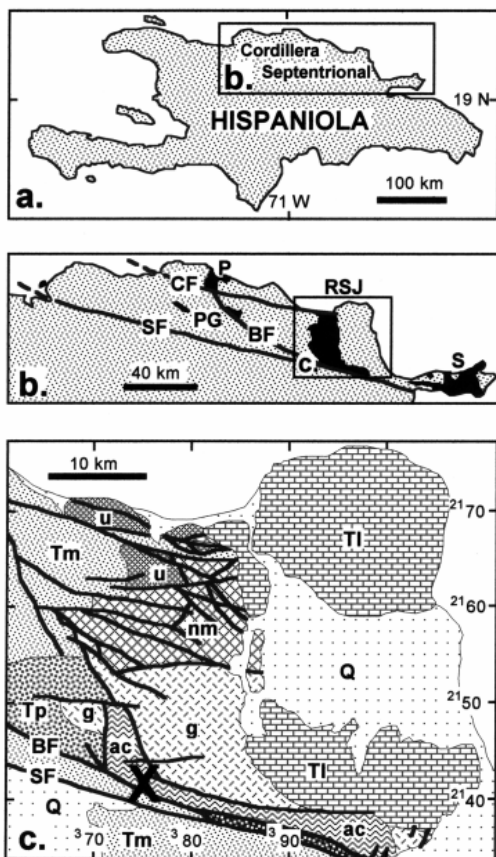


Figure 2. Location and geology. a. Hispaniola, Cordillera Septentrional-Samana morphotectonic terrane. b. Major inliers (black) of pre-Middle Eocene rocks: Rio San Juan (RSJ), Samana (S), Puerta Plata (P), Pedro Garcia (PG). CF = Camu Fault, BF = Bajabonico Fault, SF = Septentrional Fault. c. Simplified geologic map of the RSJ complex (Draper and Nagle, 1991). Northern part of the inlier: serpentinite (u), blueschist/eclogite metamorphic rocks (nm). Southern part of the inlier: Cuaba unit (ac), Rio Bobo Intrusive Suite (g). Location of garnet peridotite in the Cuaba unit is indicated by the “X.” Sediments and sedimentary rocks: Late Eocene to Oligocene clastic sedimentary rocks (Tm), Neogene limestone (TI), Tertiary conglomerate (Tp), Quaternary alluvium and reef deposits (Q).

island arc, which resulted from the subduction of the North American plate beneath the northern edge of the Caribbean plate (Pindell and Barrett, 1990). Subduction began in the Early Cretaceous and continued into Eocene time. The original island arc system has since been modified by E-W, left-lateral, transcurrent tectonics that began in the middle Eocene and continues today.

In northern Hispaniola (Fig. 2a), the Cretaceous to middle Eocene basement underlies the Cordillera Septentrional (Fig. 2b), which is the northernmost range on the island (Draper *et al.*, 1994; Draper and

Nagle, 1991). The basement is generally covered by Upper Eocene to lower Miocene siliciclastic sedimentary rocks and younger carbonate rocks. Where this cover has been eroded away, the basement is exposed in a number of stratigraphic windows (or “inliers”). The largest inlier exposes the Rio San Juan Complex.

The Rio San Juan Complex (Fig. 2c) is divided into distinct northern and southern parts, which were juxtaposed by faulting in the Paleogene (Draper and Nagle, 1991). The northern half consists of serpentinite, blueschist-eclogite melange with serpentine matrix and coherent greenschist-blueschist facies rocks. The southern half consists of hornblende gneiss and schist of the Cuaba unit. This was intruded by the Rio Boba gabbro complex. The Cuaba unit contains eclogite (Abbott and Draper, 1998, 2002) and the garnet peridotite (Abbott *et al.*, 2001a, b; Draper *et al.*, 2002). The ‘X’ marks the location of the garnet peridotite.

### 3. GARNET PERIDOTITE

Garnet peridotite was discovered as well-rounded boulders up to 4 metres in diameter in Rio Cuevas. The coarse garnet peridotite is homogeneous in a given boulder and from one boulder to another. The distribution of the boulders and reconnaissance of bedrock geology restrict the source to an area of about 0.25 km<sup>2</sup> on the slope east of Rio Cuevas. So far, efforts to find in situ exposures have failed because of the terrain and vegetation. But, because other rock types are exposed nearly continuously in bedrock along relevant parts of Rio Cuevas, its tributaries and in dry gullies, we do not think that the boulders came from a single, large body. More likely, the boulders came from many, small bodies of about the sizes of the boulders themselves.

In hand specimen and in thin section, pink garnet porphyroblasts, up to 2 cm in diameter, are the most conspicuous feature. The garnet contains fine inclusions of transparent, emerald-green spinel. Magnesiohornblende forms irregular, light grey-green rims on the garnet porphyroblasts, and also forms deep embayments in the garnet. Close to the garnet, spinel occurs as fine, mainly intragranular grains and clusters of grains in the hornblende. The hornblende also forms rims on rounded grains of diopside. Partially serpentinized olivine forms a continuous, black matrix. Minor minerals include magnetite, pyrite, spinel, and corundum.

Textural relationships suggest that the rock passed through four metamorphic facies. Starting with the earliest, these are: (1) Spinel peridotite facies, involving olivine, diopside, enstatite(?), spinel, and corundum, (2) Garnet peridotite facies,

**Table 1. Mineral Analyses**

No. Analyses	ASU <sup>1</sup>			FCAEM <sup>2</sup>			
	Garnet 10	Spinel 7	Corundum 2	Garnet 4	Olivine 5	Diopside 22	Hornblende 5
	Wt. %			Wt. %			
Na <sub>2</sub> O	na <sup>3</sup>	na	na	0.00	0.03	0.12	1.49
MgO	13.30	20.46	na	9.47	40.12	15.49	16.48
Al <sub>2</sub> O <sub>3</sub>	23.29	68.40	99.73	22.57	0.03	2.47	11.40
SiO <sub>2</sub>	41.17	na	na	38.86	37.62	50.90	46.95
K <sub>2</sub> O	na	na	na	0.00	0.01	0.00	0.01
CaO	11.09	na	na	8.57	0.01	23.05	12.48
TiO <sub>2</sub>	0.02	0.10	na	0.01	0.00	0.19	0.48
Cr <sub>2</sub> O <sub>3</sub>	0.09	0.09	0.03	0.00	0.02	0.10	0.56
MnO	0.47	0.18	na	0.81	0.23	0.15	0.05
FeO <sup>4</sup>	10.59	10.78	na	21.10	23.21	5.29	7.09
Fe <sub>2</sub> O <sub>3</sub> <sup>5</sup>	na	na	0.24	na	na	na	na
Total	100.00	100.00	100.00	101.40	101.27	97.76	96.99
	Cations p.f.u.			Cations p.f.u.			
Na	-	-	-	0.00	0.00	0.01	0.41
Mg	1.45	0.76	-	1.05	1.53	0.87	3.51
Al	2.00	2.01	1.996	1.99	0.00	0.11	1.92
Si	3.01	-	-	2.90	0.96	1.91	6.72
K	-	-	-	0.00	0.00	0.00	0.00
Ca	0.87	-	-	0.69	0.00	0.93	1.91
Ti	0.00	0.00	-	0.00	0.00	0.01	0.05
Cr	0.00	0.00	0.000	0.00	0.00	0.00	0.06
Mn	0.03	0.00	-	0.05	0.00	0.00	0.01
Fe <sup>2+</sup>	0.65	0.23	-	1.11	0.42	0.10	0.85
Fe <sup>3+</sup>	-	-	0.003	0.21	0.07	0.07	0.00
Total cations	8.00	3.00	1.999	8.00	3.00	4.00	15.45
Total O	12.01	4.00	3.000	12.00	4.00	6.00	23.00
Mg#	0.69	0.77	-	0.49	0.78	0.90	0.81
pyr	0.48			0.36			
grs	0.29			0.24			
sps	0.01			0.02			
alm	0.21			0.38			
			fo		0.78		
			fa		0.22		
			wo			0.49	
			en			0.46	
			fs			0.05	

1 - Electron microscope facility, Appalachian State University

2 - Florida Center for Analytical Electron Microscopy, Florida International University

3 - na = not analyzed

4 - Total Fe as FeO

5 - Total Fe as Fe<sub>2</sub>O<sub>3</sub>

involving the same minerals plus garnet, (3) Amphibolite facies, involving the growth of magnesiohornblende, and (4), Greenschist facies, associated with serpentinization.

New observations on parts of the rock where olivine is locally missing reveal the assemblage, diopside + garnet + spinel + corundum (+ late magnesiohornblende + late chlorite). Small aggregates of spinel and corundum occur as inclusions in the garnet. Individual, anhedral grains of spinel and corundum range up to 0.5 mm in size. While the association garnet + spinel + corundum can be anticipated on theoretical and experimental grounds (Ackermann *et al.*, 1975), we believe this is the first report of a natural occurrence. The association is important because it can form only at high pressures (>2.2 Gpa, Ackermann *et al.*, 1975), outside the field of stability for sapphirine. Elsewhere, in particular the Ronda peridotite (Tomoaki *et al.*, 2001) and closely related Beni Bousera peridotite (Kornprobst *et al.*, 1990), the reported equilibrium association is corundum + sapphirine + garnet, and the spinel (associated with plagioclase) is interpreted as a later product of retrograde reequilibration.

#### 4. MINERAL ANALYSES

Preliminary chemical analyses of garnet, olivine, diopside, spinel, corundum, and magnesiohornblende represent core-compositions, away from cracks and grain boundaries (Table 1). In this context, each of the minerals is relatively homogeneous. Mineral analyses under the heading of “FCAEM” were performed at the Florida Centre for Analytical Electron Microscopy at Florida International University. The analyses involved natural and synthetic standards and are ZAF-corrected. Analyses of garnet pertain to the assemblages, olivine + garnet + diopside + spinel. Mineral analyses under the heading of “ASU” were performed on a new electron microscope (ESEM-EDX) at Appalachian State University. The garnet analyses pertain to the assemblage, garnet + diopside + spinel + corundum. The “ASU” analyses are ZAF-corrected, but no standards were used. This seemed to work satisfactorily (i.e., stoichiometries look good) for major elements in the anhydrous minerals, under the constraint that the oxide components sum to 100%.

When compared with other Alpine-type garnet peridotites, the garnet is unusually rich in Ca and has a low Mg#. The Mg# is approximately 0.7 for garnet associated with diopside + spinel + corundum and approximately 0.5 for garnet associated with olivine + diopside + spinel. The

olivine also has a low Mg#, about 0.78. The diopside and magnesiohornblende are unremarkable. While bulk rock analyses are not yet available, the low Mg#'s for the minerals and low Cr#'s suggest that the rock represents unusually fertile mantle. The spinel (Mg# ~ 0.77) is typical of spinels in other high P, Alpine-type peridotites (Barnes and Roeder, 2001).

#### 5. P-T CONDITIONS

Figure 3 shows the assemblages used in P-T calculations, projected from diopside onto the plane MgO-Si<sub>1/2</sub>O-Al<sub>2/3</sub>O, so all compositions are normalized to one oxygen. The assemblages are (1) olivine + garnet + diopside + spinel, and (2) garnet + diopside + spinel + corundum.

Conditions of P and T were estimated by means of multiple-equilibrium analysis (Gordon, 1999). Starting with the mineral analyses, the activities of “end member” components were calculated using the program AX, written by Holland and Powell (2000). The activities were converted to single-site mixing models and then entered, online, into the program WEBINVEQ, developed by Gordon (1999). WEBINVEQ determines the equilibrium conditions for all possible equilibria involving the mineral components. Each such equilibrium describes a line in P-T space. Ideally the lines for all such equilibria would intersect at the P-T conditions satisfying all of the equilibria. Typically the equilibria do not intersect at a well-defined point, in which case a search is conducted for the set

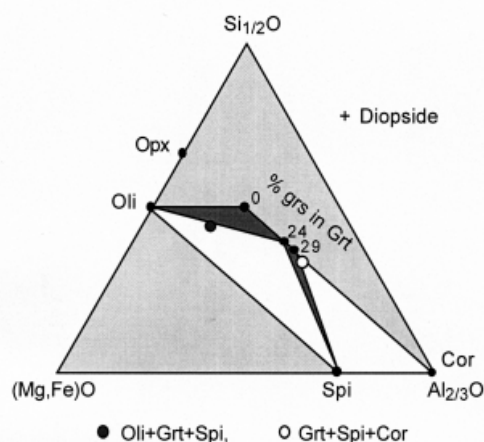


Figure 3. MAS projection from diopside. M = (Mg,Fe)O, A = Al<sub>2/3</sub>O, S = Si<sub>1/2</sub>O, such that all compositions sum to one oxygen. Because the projected minerals are all based on close-packings of oxygen atoms, the projection preserves modal proportions approximately.

of activities that gives the best solution. The results provide for error analysis, and assessment of uncertainty in the estimated conditions.

Results of the calculations are presented in Figure 4. P-T conditions for the equilibrium involving olivine, garnet, diopside, and spinel are 3.5 Gpa and 740 °C. For the equilibrium involving garnet, diopside, spinel and corundum, the best estimates are 2.8 Gpa and 810 °C. The estimated pressures are consistent with depths from 85 to over 105 km.

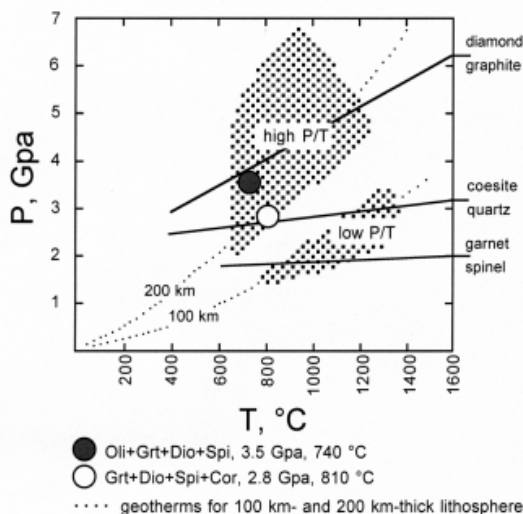
In his 1999 review article, Medaris showed that Alpine garnet peridotites fall into two groups, “high-P/T” and “low-P/T.” In our example, the sequence of mineral assemblages, nature of associated rocks, and tectonic setting are consistent with the low-P/T group. Earlier estimates of the conditions (>900 °C, >1.8 Gpa, Abbott *et al.*, 2001a, b) based on Cr-in-Cpx and En-in-Cpx (Nimis and Taylor, 2000) are consistent with this. However, the thermobarometry is questionable because of the low Cr in the diopside. We consider the new WEBINVEQ estimates to be much better because they involve many components in four minerals. The new estimates fall clearly in the high P/T, UHP regime. Conditions for the olivine + garnet + diopside + spinel assemblage reach almost into the diamond field. Laboratory experiments (Ackermann *et al.*, 1975) show that the association garnet + spinel + corundum cannot form (in equilibrium) at pressures less than about 2.2 Gpa.

Formulations for Fe-Mg exchange in the pairs, garnet-hornblende, garnet-clinopyroxene, and garnet-olivine, give temperatures from 660 °C down to 400 °C (Abbott *et al.*, 2001a). We take this to mean that the Fe-Mg ratios in these minerals were frozen when the rock passed through the amphibolite facies.

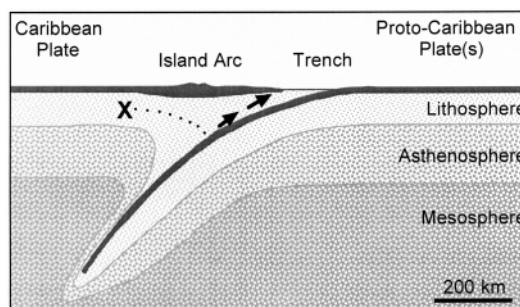
## 6. TECTONIC MODEL

Subduction of oceanic crust beneath northern Hispaniola began in the Early Cretaceous and continued into the Eocene (Pindell and Barrett, 1990; Draper *et al.*, 1994; Draper and Nagle, 1991). Presumably, at a great depth in the subduction zone, on the order of 85 to 105 km, garnet peridotite or its precursor was emplaced into the descending oceanic crust that would become the Cuaba unit. Figures 5 and 6 illustrate two working hypotheses, differing

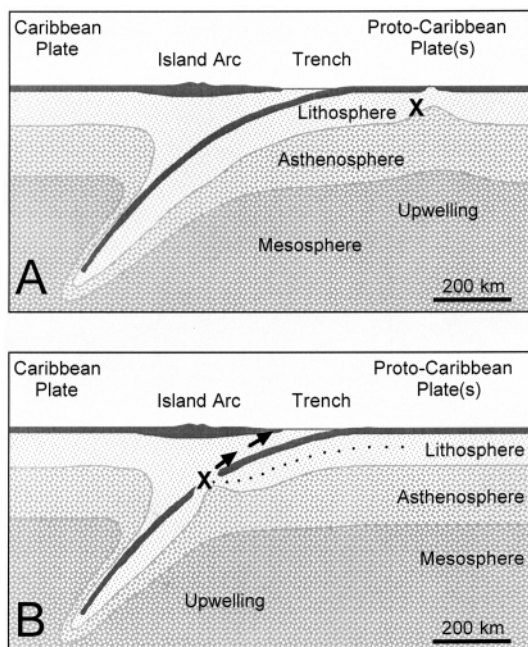
with regard to the source of the original peridotite: (1) in the mantle above the subduction zone (hanging wall or mantle wedge model, Fig. 5), or (2) in the mantle beneath the subduction zone (footwall model, Fig. 6).



**Figure 4.** P-T conditions for the olivine + garnet + diopside + spinel assemblage (filled circle) and the garnet + diopside + spinel + corundum assemblage (open circle). Stippled fields represent the ranges of conditions for high-P/T and low P/T Eurasian garnet peridotites (modified from Medaris, 1999; Brueckner and Medaris, 2000). The low-P/T field is defined by metamorphic conditions reported by Medaris (1999) for garnet peridotites from the Southern Carpathians; Gfohl Nappe, Bohemian Massif; Gory Sowie, Poland; Sulawesi, Indonesia; Nonsberg, Austridic Alps; and Ronda, Spain; and for reconstructed spinel peridotite protoliths from Nonsberg, Austridic Alps; and Ronda, Spain. Geotherms (dotted curves) are for 200 km and 100 km thick lithosphere, respectively. Diamond-graphite equilibrium (Bohlen and Boettcher, 1982), and Coesite-quartz equilibrium. Garnet peridotite-spinel peridotite equilibrium in CMASH and NCMASH systems (Schmadicke, 2000).



**Figure 5.** Tectonic model - source of the peridotite in the mantle wedge of the Caribbean plate. ‘X’ marks a hypothetical location for the original garnet-free, spinel peridotite. Path (dotted) followed by the peridotite to the subduction zone, and subsequent trajectory of uplift (arrows).



**Figure 6. Tectonic model - source of the peridotite near an upwelling of asthenosphere in the subducting, Proto-Caribbean plate. A. 'X' marks a location for the original garnet-free, spinel peridotite. B. Path (dotted) followed by the peridotite to the subduction zone, and subsequent trajectory of uplift (arrows).**

The garnet peridotite may have originated in the mantle wedge (Fig. 5), where induced convection (e.g., Roselle *et al.*, 2002) coupled with erosion of the hanging wall delivered the peridotite to the subduction zone. There the peridotite was incorporated into deep-subducted oceanic crust of the Cuaba unit. Once cooled in the subduction zone, the Cuaba unit was uplifted along reverse faults (e.g., Roselle and Engi, 2002). Uplift may have been assisted by extension in the forearc (Draper *et al.*, 1994; Draper and Nagle, 1991). While the model has the advantage of simplicity, it may not adequately account for early high temperatures greater than the 900 °C indicated by the clinopyroxene thermobarometry. Temperatures at the requisite depth of approximately 55 km would normally be too cool in the mantle wedge (Brueckner and Medaris, 2000). However, according to thermal modeling by Roselle and Engi (2002), the temperature at a depth of 55 km in the mantle wedge, well away from the subduction zone, would be close to 900 °C. Given the uncertainty in the clinopyroxene thermobarometry at very low Cr concentrations, a source in the mantle wedge certainly cannot be discounted.

Accepting the clinopyroxene thermobarometry, the peridotite originated at a very high temperature

at a modest depth, as spinel peridotite in the low P/T regime. Observations on other such spinel peridotites argue for the involvement of hot, upwelling asthenosphere in the down going plate (Brueckner and Medaris, 2000). The peridotite may have originated near an asthenospheric upwelling associated with a mantle plume or divergent plate boundary (Fig. 6a). Once overridden by the mantle wedge (Fig. 6b), diapiric intrusion of anomalously hot mantle material (asthenospheric or otherwise) through the subduction zone and even into the mantle wedge would be a natural adjustment to isostatic disequilibrium. The model provides a ready mechanism (diapirism) for delivering the peridotite to the subduction zone. Once cooled in the subduction zone, the Cuaba unit was transferred to the hanging wall, and uplifted along reverse faults.

## 7. CONCLUSIONS

Alpine-type garnet peridotite represents a valuable, if not unique, source of information regarding tectonic processes deep within a subduction zone (Medaris, 1999). The discovery in the Dominican Republic is the second of its kind in the Americas. The example is special because it contains the only natural occurrence of the UHP mineral association of garnet + spinel + corundum.

Thermobarometry, sequence of mineral assemblages, tectonic setting, and current plate tectonic models suggest the following history,

- (1) an initially hot protolith at modest depth in the lithosphere, ~55 km (>1.8 Gpa, >900 °C),
- (2) descent to a depth of 85 to 105 km (2.8 Gpa, 810 °C to 3.5 Gpa, 740 °C),
- (3) incorporation into subducted oceanic crust,
- (4) cooling during initial ascent, and intrusion by gabbro,
- (5) Lower Tertiary transensional tectonics,
- (6) ascent to present position as a result of Upper Tertiary to recent transpressional tectonics.

Our present understanding is not adequate to discriminate unambiguously between possible sources for the peridotite. We offer alternative models for the source, (1) in the mantle wedge (Fig. 5, hanging wall), or (2) near a mantle upwelling in the down going plate (Fig. 6, footwall). Continuing efforts focus on resolving the issues through detailed mapping, geochemistry, and petrography of the garnet peridotite and associated eclogites.

**NOTE.** Recent observations (Abbott *et al.*, 2003) on garnet clinopyroxenite and corundum-bearing garnet clinopyroxenite, associated with the garnet peridotite, show evidence for UHP magmatic fractionation. The evidence is textural, and involves

orthocumulate clinopyroxene with interstitial garnet. One of the magmatic assemblages (garnet + clinopyroxene + spinel + corundum + melt) is only possible at  $P > 3.4$  Gpa and  $T > 1550$  °C (Abbott et al., 2003). Therefore, P-T conditions presented in this report are presumed to reflect subsolidus reequilibration. The new evidence suggests more or less isobaric cooling ( $P > 3.4$  Gpa) from  $T > 1550$  °C (magmatic) to  $T \sim 740-810$  °C (subsolidus, this report). Steps 1 and 2 in our proposed history (see Conclusions) may be revised accordingly.

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