GEOPHYSICAL RESEARCH LETTERS, VOL. 34, L21309, doi:10.1029/2007GL031059, 2007

Asthenospheric upwelling, oceanic slab retreat, and exhumation of UHP mantle rocks: Insights from Greater Antilles

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Received 22 June 2007; revised 29 August 2007; accepted 14 September 2007; published 14 November 2007.

[1] Exhumation of garnet-bearing peridotites has been associated with low density continental rocks. This association does not explain the occurrence of garnet-bearing peridotites in the oceanic subduction zone of the Greater Antilles in Hispaniola. We use numerical models of intra-oceanic subduction to explain exhumation of garnet peridotites without involvement of buoyant continental crust. We demonstrate that rheological weakening of the mantle wedge takes place due to its strong hydration during subduction of serpentinized slow spreading ridge. This weakening triggers upwelling of the hydrated peridotites and partially molten peridotites followed by upwelling of hot asthenosphere and subsequent retreat of the subducting slab. According to numerical modelling of P-T paths this process can explain exhumation of UHP (4GPa) rocks in an intra-oceanic setting. **Citation:** Gorczyk, W., S. Guillot, T. V. Gerya, and K. Hattori (2007), Asthenospheric upwelling, oceanic slab retreat, and exhumation of UHP mantle rocks: Insights from Greater Antilles, *Geophys. Res. Lett.*, *34*, L21309, doi:10.1029/2007GL031059.

1. Introduction

[2] Garnet peridotites have been described in many ultrahigh-pressure metamorphic (UHP) terranes in Phanerozoic continent-continent collisional zones, including the Dabie-Sulu terrane in China, the Kokchetav massif in Kazakhstan, the Western Gneiss Region in Norway, the Alpe Arami in Switzerland and the Palaeozoic belt of Europe [e.g., *Medaris*, 1999]. They have been interpreted in two ways [e.g., *Brueckner and Medaris*, 2000; *Zhang et al.*, 2000]: (1) peridotites originating from mantle wedges and tectonically incorporated within subducting slab; (2) cumulate ultramafic rocks intruded into the continental crust prior to the subduction. In both cases, garnet peridotites are associated with low density continental rocks. Their exhumation is explained by decoupling of the continental slice from the descending slab due to the positive buoyancy of sialic continental rocks within the subduction channel [*Ernst*, 1999, 2005; *Van den Beukel*, 1992]. These interpretations are not suitable for garnet-bearing peridotites in the oceanic subduction zone of the Greater Antilles in Hispaniola [*Abbott et al.*, 2006; *Abbott et al.*, 2005]. Field observations show that the garnet-bearing peridotites occur as intrusive layers within the retrogressed Cuaba eclogitic units, which was intensively recrystallized under amphibolite facies conditions. To the north, a gabbroic intrusion is observed; this intrusion separates the Cuaba eclogites from a high pressure (HP) and low temperature (LT) serpentinite mélange. These three units are in a fore-arc position with respect to the Cretaceous arc (Figure 1). To evaluate the exhumation mechanism of such garnet-bearing peridotites, we performed a two-dimensional simulation of intra-oceanic subduction using available petrological-thermomechanical rock properties and the modified I2VIS computer program [*Gerya and Yuen*, 2003].

[3] The simulations test the dynamic processes of HP-LT rocks exhumation during the subduction of slow-spreading ridges.

2. Geological Setting

[4] The Northern Serpentinite Mélange (Figure 1) forms a 1000 km belt along the northern margin of Cuba and Hispaniola islands [e.g., *Lewis et al.*, 2006]. It was formed during subduction of the Proto-Caribbean oceanic plate under the intra-oceanic Greater Antilles arc from mid-Cretaceous to mid-Eocene before arc's docking with the North American plate [e.g., *Pindell et al.*, 2005]. This mélange includes meter to decimetre long lenses of various HP-LT metamorphic rocks [*Garcia-Casco et al.*, 2002; *Krebs et al.*, 2007] of oceanic crustal origin [*Garcia-Casco et al.*, 2002; *Lewis et al.*, 2006]. *Lewis et al.* [2006] proposed that the majority of serpentinites in the belt has originated from the subducting slab. However, serpentinites of mantle wedge origin are also observed [*Hattori and Guillot*, 2007; *Saumur et al.*, 2007].

[5] The Rio San Juan (RSJ) complex is the largest exposure (700 km^2) of the Greater Antilles fore-arc in Hispaniola (Figure 1). The northern half of the RSJ complex consists of a serpentinite mélange containing eclogite and blueschist lenses (Figure 1); these fragments are dated at 104 Ma and 80 to 62 Ma respectively [*Krebs et al.*, 2007]. The southern half consists of the Cuaba gneiss and the Rio Boba intrusive complex (Figure 1). The central part of the Cuaba gneiss (45 km^2) consists of vertically foliated garnet-bearing metagabbros that are interpreted as Late Cretaceous eclogites, of oceanic crustal origin [*Draper and Nagle*, 1991], recrystallized under amphibolite facies conditions [*Abbott et al.*, 2005]. The Rio Boba Complex is a Late Cretaceous dioritic to gabbroic pluton of calc-alkaline affinity [*Draper and Nagle*, 1991]. Its southern part intruded into the Cuaba gneiss causing amphibolitic foliation. Syntectonic emplacement of the Rio Boba intrusion along the sinistral strike-slip Septentrional Fault has been suggested (Figure 1). Garnet peridotites and garnet clino-

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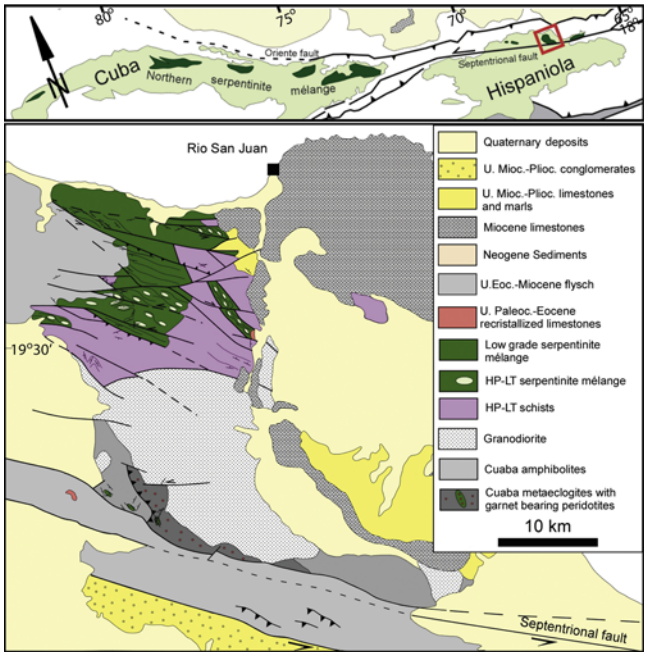

Figure 1. Geological map of Rio San Juan Complex (Dominican Republic, Hispaniola island), belonging to the Northern Serpentinite Mélange (modified after *Draper and Nagle* [1991]).

pyroxenites occur as stream metric boulders mainly in the Rio El Cuevas eroded out of the retrogressed eclogites [*Abbott et al.*, 2005]. The boulders outcrop in a narrow restricted NW-SE elongated zone (<100 m large, <1000 m long) surrounded by the foliated retrogressed eclogites. This observation suggest that the ultramafic rocks initially formed small lenses (<100 m long) embedded in the eclogites.

[6] According to *Abbott et al.* [2005] the clinopyroxene-spinel-corundum-garnet mineral association is in textural equilibrium. This suggests that garnet-bearing peridotites and associated corundum-bearing garnet clinopyroxenite formed from melt at ~4 GPa in the mantle wedge. Their exhumation was controlled by their incorporation within the eclogitized subducting oceanic slab and marked by the secondary crystallization of hornblende and serpentine. According to P-T estimates [*Abbott et al.*, 2006], The exhumation path is characterized by an isobaric cooling from ~1550°C to ~850°C followed by a cooling decompression path down to crustal conditions (Figure 2).

3. Numerical Model

[7] To simulate oceanic crust formed at slow spreading ridge, we assume an oceanic lithosphere containing blocks of 1.0 × 1.5 km of basaltic (upper 2 rows) and gabbroic (lower row) layers, within a serpentinite matrix at every 0.5 km (Figure 3). Free slip conditions are placed at all boundaries except for the lower boundary, which is open in both downward and upward directions. The plate velocity is assumed to be constant at 2 cm/a (Figure 3). Thus, initial bending of the slab is geometrically set, during the run the slab bending is not prescribed what allows the evolution of unrestricted slab movement. The dip angle of the subducting plate is mainly controlled by the rheology and density of subducting slab and the mechanical interactions with the surrounding mantle peridotites. The momentum, continuity and thermal equations for the two-dimensional creeping-flow, accounting for thermal and chemical buoyancy, are solved using the modified I2VIS–program [*Gerya and Yuen*, 2003] based on finite differences combined with a non diffusive-marker-in-cell technique. The effective creep viscosities of solid rocks are represented as a function of temperature and stress by experimentally determined flow laws [*Ranalli*, 1995]. The stable mineralogy of each lithology is evaluated at various pressures and temperatures using the thermodynamic data as described by *Gerya et al.* [2006]. Water migration released from the slab is simulated. When aqueous fluid is released due to dehydration reactions at a given depth, it percolates upward with prescribed velocity until it starts to react with rocks forming new hydrous minerals and/or melt. This numerical simulation allows free slab bending and retreat as well as self-organizing hydration and melting processes in the mantle wedge.

[8] In the Caribbean domain, the proto-Caribbean ocean opened during the Oxfordian to the upper Kimmeridgian times (about 145 Ma ago) and started to subduct southward, as a result the Greater Antilles arc was formed on the northern margin of Caribbean plate at about 120 Ma. The subduction rate of about 2 cm/a [*Meschede and Frisch*, 1998] suggests that a total length of 1200 km oceanic crust had been subducted by 60 Ma. A subducting slab, formed at such a slow-spreading ridge, is characterized by a heterogeneous and relatively thin (<5 to 7 km) crust and exposure of partially hydrated peridotites [*Cannat*, 1993; *Cannat et*

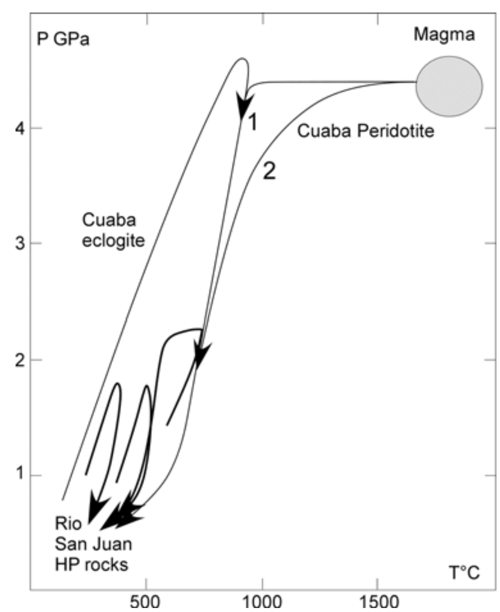

Figure 2. Proposed P-T paths for Cuaba garnet-bearing ultramafic rocks and associated eclogites (modified from *Abbott et al.* [2006]). Path 1: incorporation of the Cuaba peridotites into the oceanic eclogitic unit at UHP conditions. Path 2: incorporation of the Cuaba peridotites into the oceanic eclogitic unit at HP conditions. The P-T paths of the low pressure eclogites and associated blueschists (HP rocks) observed in the Northern Serpentinite Mélange are also reported (after *Krebs et al.* [2007]).

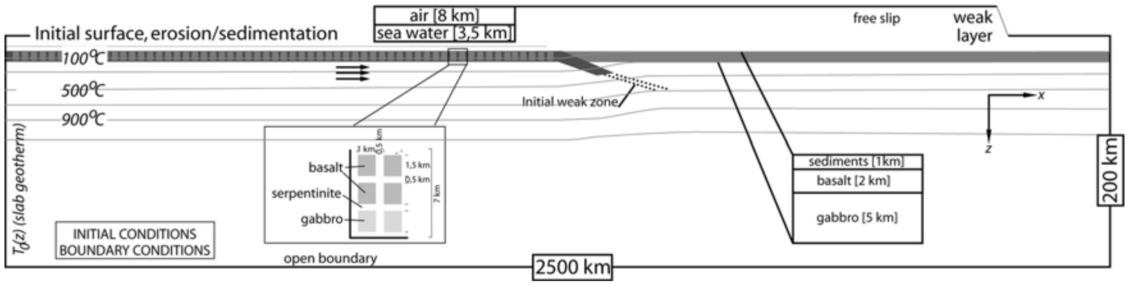

Figure 3. Two-dimensional numerical setting employed in this study showing initial distribution of different rock lithologies. The low-spreading oceanic crust (7 km thick) is composed by blocks of basalt and gabbro (1 km × 0.5 km) embedded in a serpentinite matrix. The upper mantle is composed of dry peridotites. The upper plate is composed of a classical oceanic crust (sediment, basalt, and gabbro) above an initial dry peridotitic mantle. Initial temperature field (isotherms in °C) and boundary conditions are from *Gorczyk et al.* [2007]. Numerical grid steps: 2 km in the area of interest, 10 km outside area of interest. See text for detailed explanations.

al., 1995] at the ridge and beneath the abyssal sediments far from the ridge [*Carlson*, 2001].

[9] The numerical model shows that subduction of oceanic lithosphere formed at a slow-spreading ridge produces a wide subduction channel composed of serpentinites, metabasalts, metagabbros and minor metasediments. The numerical model predicts two kinds of serpentinites: (1) incoming hydrated abyssal peridotites and (2) hydrated, fore-arc mantle peridotites (Figure 4). The maximum depth of circulating material in the serpentinite subduction channel reaches a depth of 60 km (~2 GPa) due to antigorite P-T stability field. As antigorite present a negative-sloped reaction boundary in the P-T field, antigorite is no more stable at temperature superior than 600-700°C [*Bromiley and Pawley*, 2003] or 720–740°C [*Ulmer and Trommsdorff*, 1999] at ~2 GPa and started to dehydrate.

[10] During the steady state subduction, no garnet-bearing peridotites are exhumed. Progressive hydration of the mantle wedge weakens its rheology allowing the upwelling of the asthenospheric mantle wedge and subsequent retreat of the subducting slab. Studies show that the slab retreat would occur if the dimensionless ratio (R_{H2O}) between plate convergence rate and upward water propagation velocity is higher than 4 [*Gorczyk et al.*, 2007]. The slab retreat would induce exhumation of a deep-seated melange from a depth of 100–150 km that consists of UHP mafic rocks (subducted oceanic lithosphere), anhydrous peridotites, hydrated and partially molten peridotites of the mantle wedge. This deep-seated mélange does not reach the surface but stops at about 20 km depth beneath the already exhumed serpentinite mélange.

4. Discussion

[11] The lithology of the Northern Serpentinite Mélange is similar to that predicted in the numerical model. Furthermore, the maximum pressure and temperature of the modelled subduction channel is similar to those recorded from the Northern Serpentinite Mélange. The oldest eclogites in the serpentinite mélange record anti-clockwise P-T path [*Krebs et al.*, 2007], typical for the initial phase of subduction as the mantle wedge cools gradually with progressive descending slab [*Gerya et al.*, 2002]. In the model the blue P-T (Figure 4) path is adequate for oldest eclogites form the Northern Serpentinite Mélange. However, the blueschists established for the natural rocks were exhumed farther from the trench (in internal part of the serpentinite mélange) than in the model (Figure 4, red P-T path). Also, the exhumation of blueschists in the model is later than the exhumation age observed in the field. This late exhumation of blueschists seems to be controlled by the rapid uprising of the deep part of the partially hydrated and molten mantle wedge that push the serpentinites and associated blueschist blocks to the surface (Figure 4). The final exhumation of the blueschists is accompanied by extension at shallow surface level similar to that what has already been described in the eastern part of the Dominican Republic [*Goncalvez et al.*, 2000].

[12] The end of the exhumation is not simulated, but the location of the Cuaba unit and its intense vertical foliation formed by metamorphic minerals of amphibolite facies clearly suggests that the surface exposure of the deepest rocks was controlled by local vertical motion along the Septentrional Fault.

[13] *Abbott et al.* [2006] estimated that the Cuaba garnet-bearing peridotites and clinopyroxenite equilibrated at the highest P-T conditions, about 1550°C and 4 GPa, followed by cooling and rapid decompression (Figure 3). The model shows a similar P-T path.

[14] Our model is in contrast to the previously proposed model involving the incorporation of garnet-bearing peridotites in a slice of continental crust at great depth [*Brueckner and Medaris*, 2000; *Ernst*, 1999] before their exhumation driven by buoyancy forces [*Ernst*, 1999, 2005]. The absence of UHP continental rocks in the area studied and the intimate association of the Cuaba garnet-bearing peridotites with dense eclogitized oceanic crust require an alternative explanation. The exhumed garnet peridotites are not incorporated within a UHP oceanic crustal slice, but were incorporated at a shallower level when the deep-seated melange "collided" with the Northern Serpentinite Mélange as observed in the numerical model (Figure 4). This interpretation is compatible with the fact that the Cuaba eclogites associated with UHP rocks do not show any evidence of UHP metamorphism, the maximum P-T estimates being 1.8 GPa at 730°C [*Abbott et al.*, 2006].

[15] Although some difference exists with the exhumation model proposed for UHP continental unit, the common

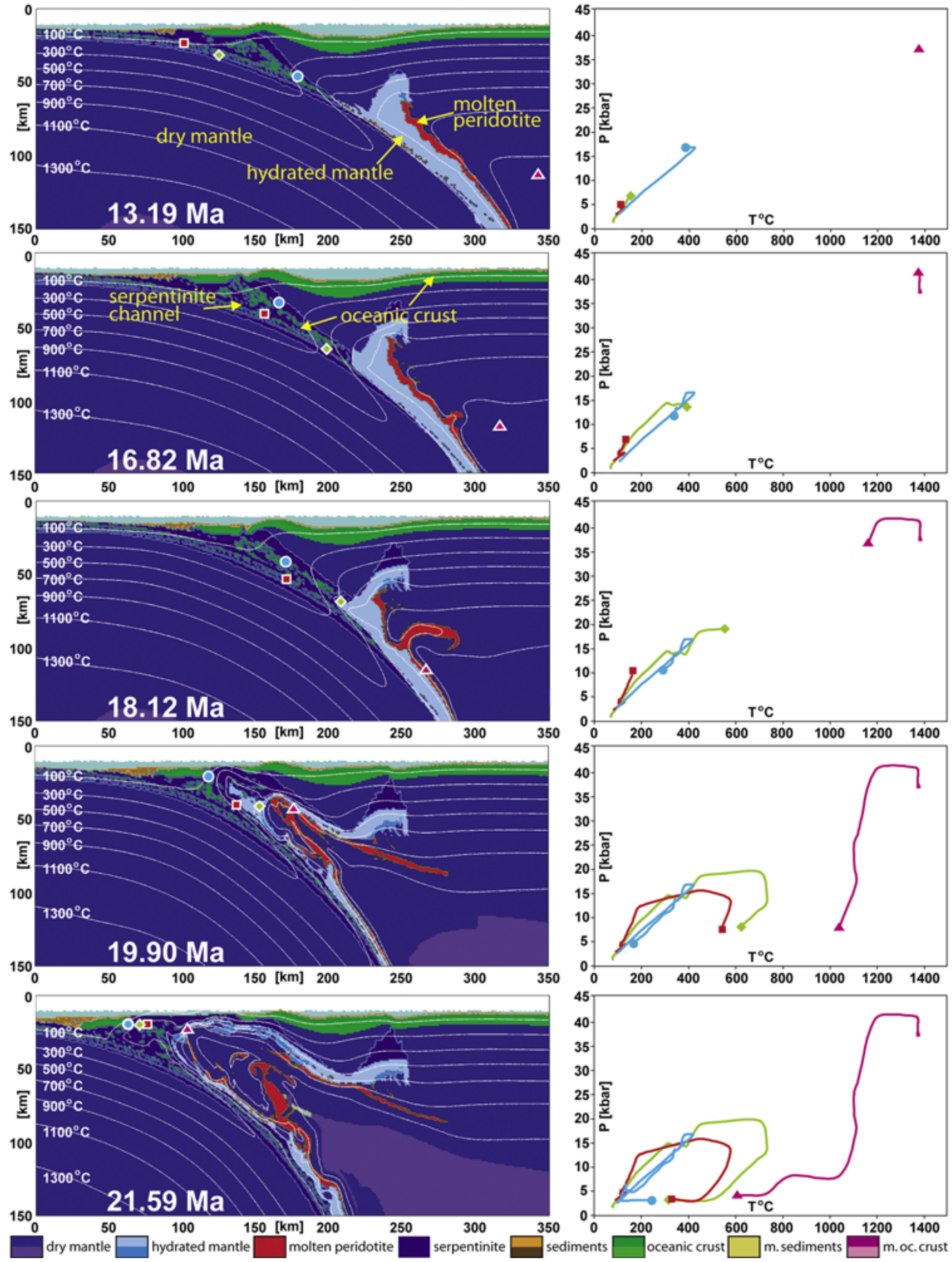

Figure 4. Final evolution of the 2-D model of the subduction of a slow spreading ridge in five time-step (total duration: 22 Ma). The colors of the geometrical shapes refer to the diagram with P-T paths and do not correspond to rock type. In the color code description "m." stands for partially molten. The model reproduces the occurrence in the Rio San Juan complex of HP rocks in the front of the Northern Serpentinite Mélange and garnet bearing peridotites at its rear. The model predicts that the exhumation of HP rocks occurred within the serpentinite channel coming from the subducted oceanic lithosphere. The garnet bearing peridotite derived from the mantle wedge and exhumed when the buoyant partially hydrated mantle (composed of partially dehydrated oceanic serpentinite and partially hydrated mantle wedge) is pushed toward the surface when the slab retreat and the asthenosphere upraise. Notice the occurrence of molten peridotite that could correspond to the observed Rio Boba intrusive (Figure 1).

point is that the driving force for the exhumation remains the buoyancy. The buoyancy forces developed by the contrast between the dry mantle peridotites and the partially hydrated peridotites allow the deep seated mélange to rise quickly in extension zones induced by the slab retreat. The numerical model may be compared with exhumation of garnet-bearing peridotites involving continental rocks worldwide.

5. Conclusion

[16] The numerical model shows that garnet-bearing peridotites may be exhumed within oceanic subduction

without involvement of buoyant continental crust. Subduction of oceanic lithosphere formed at a slow spreading ridge produces a wide serpentinite subduction channel, in which the transient exhumation of HP eclogites occurred at the onset of subduction while transient exhumation of blueschists started when the deep-seated subduction melange reached shallow crustal levels in an extensional context. In the deeper part, of the subduction zone, (>60 km) the progressive hydration of mantle peridotites modifies the rheology of the mantle wedge and triggers the upwelling of the hydrated peridotites and partially molten peridotites followed by upwelling of hot asthenosphere. The buoyant deep-seated melange rises quickly (5 cm/yr) in the extension zone induced by the slab retreat and exhumes along a cooling or near adiabatic decompression path up to intermediate crustal level. In nature the final exhumation, is controlled by local vertical motion along major strike-slip fault what was not modelled.

[17] The proposed model explains the observations of the Northern Serpentinite Mélange in Cuba and Hispaniola and it is an alternative to the classical model [e.g., *Medaris*, 1999] of exhumation of UHP continental units.

[18] **Acknowledgments.** This work was financially supported by ETH research grants TH-12/04-1, TH-12/05-3, SNF research grant 200021-113672/1 (WG, TVG) and the CNRS INSU program DYETI (SG). We would like to thank Diane Seward for correcting English. Constructive review by L. Dobrzhinetskaya is greatly appreciated.

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