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

Weronika Gorczyk,¹ Stéphane Guillot,² Taras V. Gerya,¹ and Kéiko Hattori³

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 ultra-high-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 Serpentine 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 km²) 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 km²) 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-

¹ETH Zürich, Zurich, Switzerland.

²Laboratoire de Géodynamique des Chaînes Alpines, CNRS, University of Grenoble, Grenoble, France.

³Ottawa-Carleton Geoscience Centre and Department of Earth Sciences, University of Ottawa, Ottawa, Ontario, Canada.

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 suggests 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 subduct-

ing 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 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 Serpentine 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 exhumed 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. Dobrzynetskaya is greatly appreciated.

References

- Abbott, R. N., G. Draper, and S. Keshav (2005), UHP magma paragenesis, garnet peridotite, and garnet clinopyroxenite: An example from the Dominican Republic, *Int. Geol. Rev.*, **47**, 233–247.
- Abbott, R. N., G. Draper, and B. N. Broman (2006), P-T path for ultrahigh-pressure garnet ultramafic rocks of the Cuaba Gneiss, Rio San Juan complex, Dominican Republic, *Int. Geol. Rev.*, **48**, 778–790.
- Bromiley, G. D., and A. R. Pawley (2003), The stability of antigorite in the systems $\text{MgO-SiO}_2\text{-H}_2\text{O}$ (MSH) and $\text{MgO-Al}_2\text{O}_3\text{-SiO}_2\text{-H}_2\text{O}$ (MASH): The effects of Al^{3+} substitution on high-pressure stability, *Am. Mineral.*, **88**, 99–108.
- Brueckner, H. K., and L. G. Medaris (2000), A general model for the intrusion and evolution of 'mantle' garnet peridotites in high-pressure and ultra-high-pressure metamorphic terranes, *J. Metamorph. Geol.*, **18**, 123–133.
- Cannat, M. (1993), Emplacement of mantle rocks in the sea-floor at mid-ocean ridges, *J. Geophys. Res.*, **98**, 4163–4172.
- Cannat, M., et al. (1995), Thin crust, ultramafic exposures, and rugged faulting patterns at Mid-Atlantic Ridge (22°–24°N), *Geology*, **23**, 49–52.
- Carlson, R. L. (2001), Lower crustal water contents, P-wave velocities, and modal mineralogy of oceanic diabase and gabbro, *Eos Trans. AGU*, **82**, 1154.
- Draper, G., and F. Nagle (1991), Geology, structure and tectonic development of the Rio San Juan Complex, northern Dominican Republic, *Spec. Pap. Geol. Soc. Am.*, **262**, 77–95.
- Ernst, W. G. (1999), Metamorphism, partial preservation, and exhumation of ultrahigh-pressure belts, *Isl. Arc*, **8**, 125–153.
- Ernst, W. G. (2005), Alpine and Pacific styles of Phanerozoic mountain building: Subduction-zone petrogenesis of continental crust, *Terra Nova*, **17**, 165–188.
- García-Casco, A., R. L. Torres-Roldán, G. Millán, P. Monie, and J. Schneider (2002), Oscillatory zoning in eclogitic garnet and amphibole, Northern Serpentinite Melange, Cuba: A record of tectonic instability during subduction?, *J. Metamorph. Geol.*, **20**, 581–598.
- Gerya, T. V., and D. A. Yuen (2003), Characteristics-based marker-in-cell method with conservative finite-differences schemes for modeling geological flows with strongly variable transport properties, *Phys. Earth Planet. Inter.*, **140**, 295–320.
- Gerya, T. V., B. Stöckhert, and A. L. Perchuk (2002), Exhumation of high-pressure metamorphic rocks in a subduction channel: A numerical simulation, *Tectonics*, **21**(6), 1056, doi:10.1029/2002TC001406.
- Gerya, T. V., J. A. D. Connolly, D. A. Yuen, W. Górczyk, and A. M. Capel (2006), Seismic implications of mantle wedge plumes, *Phys. Earth Planet. Inter.*, **156**, 59–74.
- Goncalvez, P., S. Guillot, C. Nicollet, and J. M. Lardeaux (2000), Thrusting and sinistral wrenching in a pre-Eocene Caribbean accretionary wedge (Samana peninsula -Dominican Republic), *Geodin. Acta*, **13**, 119–132.
- Górczyk, W., A. P. Willner, T. V. Gerya, J. A. D. Connolly, and J.-P. Burg (2007), Physical controls of magmatic productivity at Pacific-type convergent margins: Numerical modeling, *Phys. Earth Planet. Int.*, **163**(1-4), 209–232, doi:10.1016/j.pepi.2007.05.010.
- Hattori, K. H., and S. Guillot (2007), Geochemical character of serpentinites associated with high-to ultrahigh-pressure metamorphic rocks in the Alps, Cuba, and the Himalayas: Recycling of elements in subduction zones, *Geochem. Geophys. Geosyst.*, **8**, Q09010, doi:10.1029/2007GC001594.
- Krebs, M., W. V. Maresch, H.-P. Schertl, A. Baumann, G. Draper, B. Ildeman, C. Münker, and E. Trapp (2007), The dynamics of intra-oceanic subduction zones: A direct comparison between fossil petrological evidence (Rio San Juan Complex, Dominican Republic) and numerical simulation, *Lithos*, doi:10.1016/j.lithos.2007.09.003.
- Lewis, J. F., G. Draper, J. A. Proenza, J. Espaillet, and J. Jiménez (2006), Ophiolite-related ultramafic rocks (serpentinites) in the Caribbean region: A review of their occurrence, composition, origin, emplacement and Ni-laterite soil formation, *Geol. Acta*, **4**, 237–263.
- Medaris, L. G. (1999), Garnet peridotites in Eurasian high-pressure and ultrahigh-pressure terranes: A diversity of origins and thermal histories, *Int. Geol. Rev.*, **41**, 799–815.
- Meschede, M., and W. Frisch (1998), A plate-tectonic model for the Mesozoic and Early Cenozoic history of the Caribbean plate, *Tectonophysics*, **296**, 269–291.
- Pindell, J., L. Kennan, W. V. Maresch, K. P. Stanek, G. Draper, and R. Higgs (2005), Plate-kinematics and crustal dynamics of circum-Caribbean arc-continent interactions: Tectonic controls on basin development in Proto-Caribbean margins, *Spec. Pap. Geol. Soc. Am.*, **394**, 7–52.
- Ranalli, G. (1995), *Rheology of the Earth*, 413 pp., Chapman and Hall, London.
- Saumur, B. M., K. H. Hattori, and S. Guillot (2007), Protrusion of fore-arc mantle serpentinites together with HP and UHP rocks along major strike-slip faults in the northern subduction complex of Dominican Republic, paper presented at Subduction Zone Geodynamics Conference, Geosci. Montpellier Res. Group, Montpellier, France, 4–7 June.
- Ulmer, P., and V. Trommsdorff (1999), Phase relations of hydrous mantle subducting to 300 km, in *Mantle Petrology: Field Observations and High-Pressure Experimentation*, edited by Y. Fei, C. M. Bertka, and B. Mysen, *Spec. Publ. Geochem. Soc.*, **6**, 259–281.
- Van den Beukel, J. (1992), Some thermomechanical aspects of the subduction of continental lithosphere, *Tectonics*, **11**, 316–329.
- Zhang, R. Y., J. G. Liou, J. S. Yang, and T. F. Yui (2000), Petrochemical constraints for dual origin of garnet peridotites from the Dabie-Sulu UHP terrane, eastern-central China, *J. Metamorph. Geol.*, **18**, 149–166.

T. V. Gerya, ETH Zürich, ETH Hönggerberg, HPP, CH-8093 Zürich, Switzerland.

W. Górczyk, ETH Zürich, LEB, Leonhädstrasse 19, CH-8092 Zürich, Switzerland. (weronika.gorczyk@erdw.ethz.ch)

S. Guillot, Laboratoire de Géodynamique des Chaînes Alpines, CNRS, University of Grenoble, 1381 rue de la Piscine, BP53, F-3841 Grenoble, France.

K. Hattori, Department of Earth Sciences, University of Ottawa, 140 Louis Pasteur, Ottawa, ON, Canada K1N 6N5.