Growth and mixing dynamics of mantle wedge plumes

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ABSTRACT

Recent work suggests that hydrated partially molten thermal-chemical plumes that originate from subducted slab as a consequence of Rayleigh-Taylor instability are responsible for the heterogeneous composition of the mantle wedge. We use a two-dimensional ultrahigh-resolution numerical simulation involving 10×10^9 active markers to anticipate the detailed evolution of the internal structure of natural plumes beneath volcanic arcs in intraoceanic subduction settings. The plumes consist of partially molten hydrated peridotite, dry solid mantle, and subducted oceanic crust, which may compose as much as 12% of the plume. As plumes grow and mature these materials mix chaotically, resulting in attenuation and duplication of the original layering on scales of 1–1000 m. Comparison of numerical results with geological observations from the Horoman ultramafic complex in Japan suggests that mixing and differentiation processes related to development of partially molten plumes above slabs may be responsible for the strongly layered lithologically mixed (marble cake) structure of asthenospheric mantle wedges.

Keywords: numerical modeling, subduction, volcanic arcs, mantle wedge structure, subducted crust melting.

INTRODUCTION

It is widely accepted that dehydration of slab minerals and hydration of overlying rocks is one of the driving forces for melting processes in the mantle wedge (Stern, 2002; van Keken et al., 2002), and the phenomenon has been investigated from geophysical (Fluck et al., 2003; Zhao, 2001), numerical (Arcay et al., 2005; Gerya et al., 2006), analog (Poli and Schmidt, 1995), and geochemical (Ito and Stern, 1986; Schiano et al., 2000) perspectives. Despite progress in understanding mantle wedge processes, dynamics of magma production and transport above the slab are not well understood. Of particular interest are mantle mixing processes (van Keken et al., 2002) in the asthenospheric wedge involving partially molten rocks, as evidenced by exhumed fragments of strongly layered wedge mantle composed of alternating mafic and ultramafic lithologies and possibly representing results of magmatic differentiation and mixing within a molten plume (Obata and Takazawa, 2004). This hypothesis is consistent with numerical models of subduction predicting partially molten thermal-chemical plumes above subducting slabs (e.g., Gerya et al., 2006, 2004; Gerya and Yuen, 2003b; Manea et al., 2005) that form as a consequence of slab dehydration and wedge melting. However, no detailed comparison of numerically modeled structures with natural cases has been made. To this end, we have developed an ultrahigh-resolution numerical model of subduction and the associated slab dehydration and melting processes to resolve plume features on the scale of observation comparable to field studies (~1 m). This approach permits studying the influence of large-scale subduction processes on small-scale mantle mixing processes. The high increase in model resolution allows for comparison of the results with an exposed ultramafic complex, the Horoman Complex, located in Japan.

We have performed high-resolution two-dimensional experiments containing 10×10^9 randomly distributed markers using the new parallel code I2OMP developed from the I2VIS (Gerya and Yuen, 2003a). Effective resolution (240,000 × 120,000 pixels) of the numerical lithological field is ~2 m (one pixel corresponds to 1.663 × 1.663 m) (Fig. 1). The experiment performed with this technique is a part of the series of lower resolution ($0.5–10 \times 10^6$ markers) coupled petrological-thermomechanical numerical simulations (described in detail in Gorczyk et al., 2006) investigating the behavior of molten material in the mantle wedge for intraoceanic subduction setting. Full descriptions of numerical approach, initial configuration, and thermomechanical and petrological techniques can be found in Gerya et al. (2006) and Gorczyk et al. (2006). The purpose of this paper is to present the detailed dynamic chemical evolution of partially molten upwelling rising from the slab (Gerya and Yuen, 2003b), especially mixing and layering processes between plume components.

DESCRIPTION OF THE PLUME GROWTH

In our numerical experiment, a large composite partially molten plume (Figs. 1 and 2) grows at sublithospheric depth as the result of individual diapiric upwellings rising from the slab. In accordance with our previous results (Gerya et al., 2006), there are two distinct types of upwellings: (1) lithologically unmixed (homogeneous) structures composed of mantle material only, and (2) lithologically mixed (heterogeneous) structures composed of both mantle and crustal material. We have chosen the starting time for our measurements as 11.2 m.y. (time from the onset of the simulation) to show the development of the homogeneous plume prior to the contribution of crustal material, which occurs 0.6 m.y. later. At 11.2 m.y. the plume head has a volume of 143 km^2 (km^3/km trench length). The subsequent period of 2.2 m.y. (Fig. 2) is characterized by rapid growth of plume due to injections of molten peridotite (on an average ~97.13 km^2/m.y.). The molten peridotite injections are not distributed evenly; rapid increase in volume of molten peridotite is triggered by attachment of smaller plumes to the major one. The next period of 4.1 m.y. is characterized by a slow rate of the plume's growth (on an average 9.76 km²/m.y.). After this period we observe a slight increase in the growth rate due to the increasing contribution of molten sediments and molten gabbro. Crustal material is introduced at 11.8 m.y. The dominant component of the plume is hydrated, partially molten mantle wedge; the crustal components mostly contribute to the plume composition by 12%, and upper oceanic crust is a dominating source for mafic material (Fig. 2C).

MIXING AND LAYERING PROCESSES

We have analyzed model results from eight time steps for the frequency of appearance of specific thicknesses of various rock layers composing the plume head (Fig. 3). Measurements were taken every 50th column of pixels, taking into account the local layer orientation. Test calculations made at higher resolution verified that the results are representative. Our measurements (Fig. 3) suggest that the frequency of crustal layers is always at least one order of magnitude less than that of mantle layers of the same thickness. Moreover, the frequency distribution of all rock layers, dry mantle excepted, becomes steeper with time: the amount of thick (>1000 m) layers

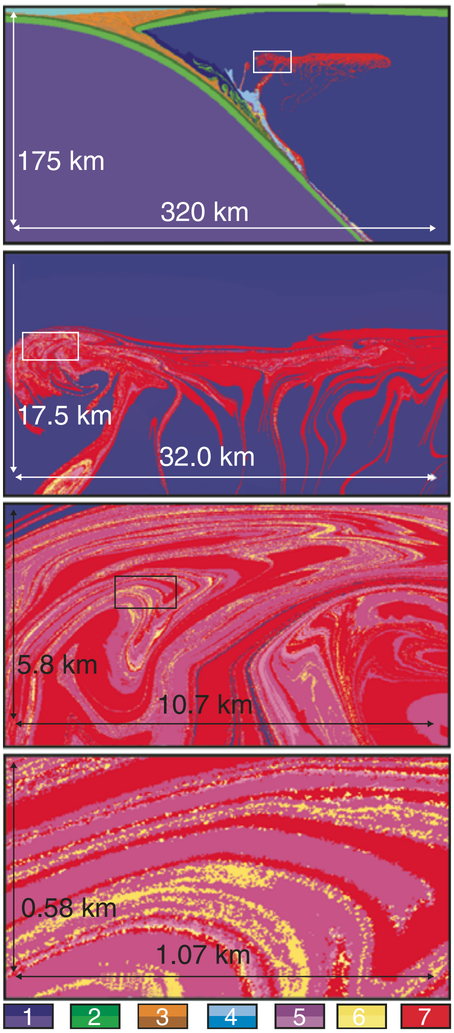

Figure 1. Plume at time of 15.733 m.y. shown at different scales. At this time plume head reaches its mature stage, and expresses complexity of structure. 1—dry mantle; 2—oceanic crust; 3—sediments; 4—hydrated mantle; 5—molten oceanic crust; 6—molten sediments; 7—molten peridotite.

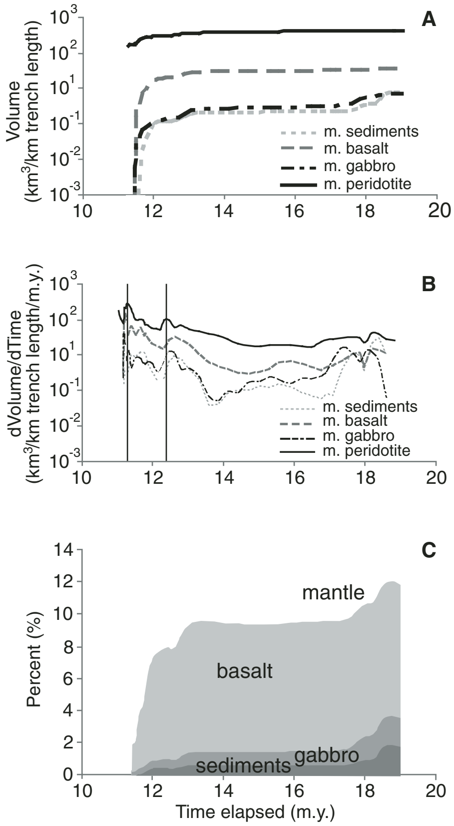

Figure 2. A: Dynamic volume change of plume's components. B: Dynamic changes of plume components in time; vertical lines indicate time when smaller plumes have contributed to major plume head. C: Relative percent contribution of plume's components.

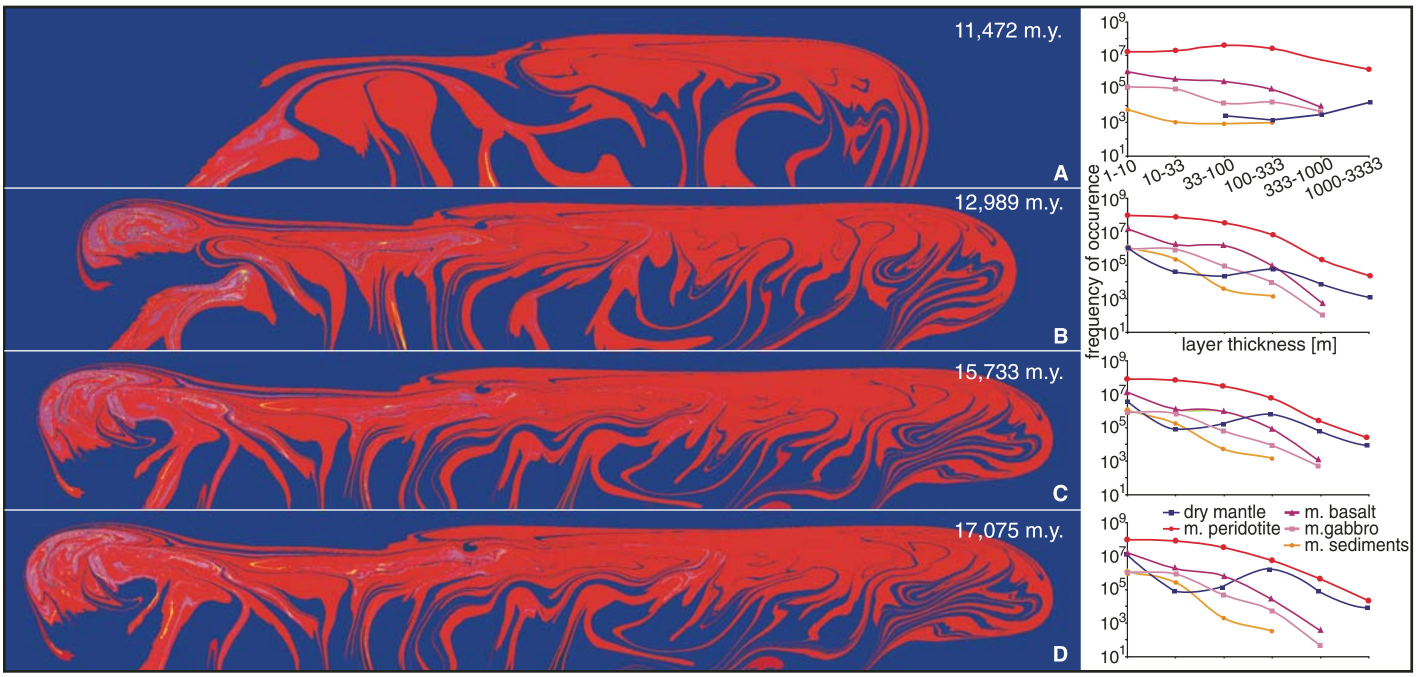

Figure 3. Geometrical evolution of mantle wedge plume (left column) and related variations in frequency of appearance for specific thicknesses of various rock layers composing plume head (right column).

decreases by two orders of magnitude with time, while that of thin (<10 m) layers increases by one order of magnitude. This increase is caused by plume mixing and subsequent layer stretching and duplication. At the later stages of plume growth, new material injections are composed of intensely mixed thin layers of both crustal and mantle rocks representing tectonic mélange derived from the hydrated subduction channel (Gerya et al., 2002). This mixing is reflected, for example, by changes in frequency of gabbroic and sedimentary rocks: as the amount of these rocks increases (Fig. 2C), a rapid increase in the proportion of thinnest layers is obtained (Fig. 3). The uneven growth of the plume head and intensive mixing within the plume lead to dry hot asthenospheric mantle wedge rocks entering the plume structure. Dry mantle wedge rocks become surrounded by molten material and are included in mixing and layering processes. This process verifies the marble cake theory (Allegre and Turcotte, 1986), and suggests that the hot asthenospheric mantle wedge has a heterogeneous strongly layered lithologically mixed (marble cake) structure. Due to different processes responsible for introducing dry and partially molten components into the plume, the frequency patterns for these components is also notably different (Fig. 3).

DISCUSSION AND CONCLUSIONS

The plume structure obtained in high-resolution numerical models is similar in geometry and lithology to the Horoman ultramafic complex (Japan) (Fig. 4), an upper mantle peridotite characterized by prominent layering, and host peridotite is interlayered by mafic layers that are parallel to the whole rock foliation (Niida, 1974; Obata and Nagahara, 1987; Frey et al., 1991).Whole-rock composition consists of lherzolite, plagioclase-lherzolite, harzburgite, dunite, and mafic rocks with abrupt discontinuities between lithologies in which layering ranges from several millimeters to hundreds of meters (Takazawa et al., 1999, 2000). In the numerical model, these lithologies correspond to dry mantle, molten peridotite, hydrated mantle, and molten crustal components. Three main models have been proposed to explain the layered structure of the Horoman Complex. Two of them require partial melting and segregation of partial melt (Obata and Nagahara, 1987; Obata and Takazawa, 2004), and the third invokes streamlined mixing of partial melt (Toramaru et al., 2001). Toramaru et al. (2001) explained the structure by mechanical chaotic mixing (Ottino, 1990) of plume material that also influences layer stretching and duplication processes.

For comparison, we have digitalized the geological map in Takazawa et al. (1996) to measure the frequency of layers of variable thickness (the thickness of layers presented in the Horoman

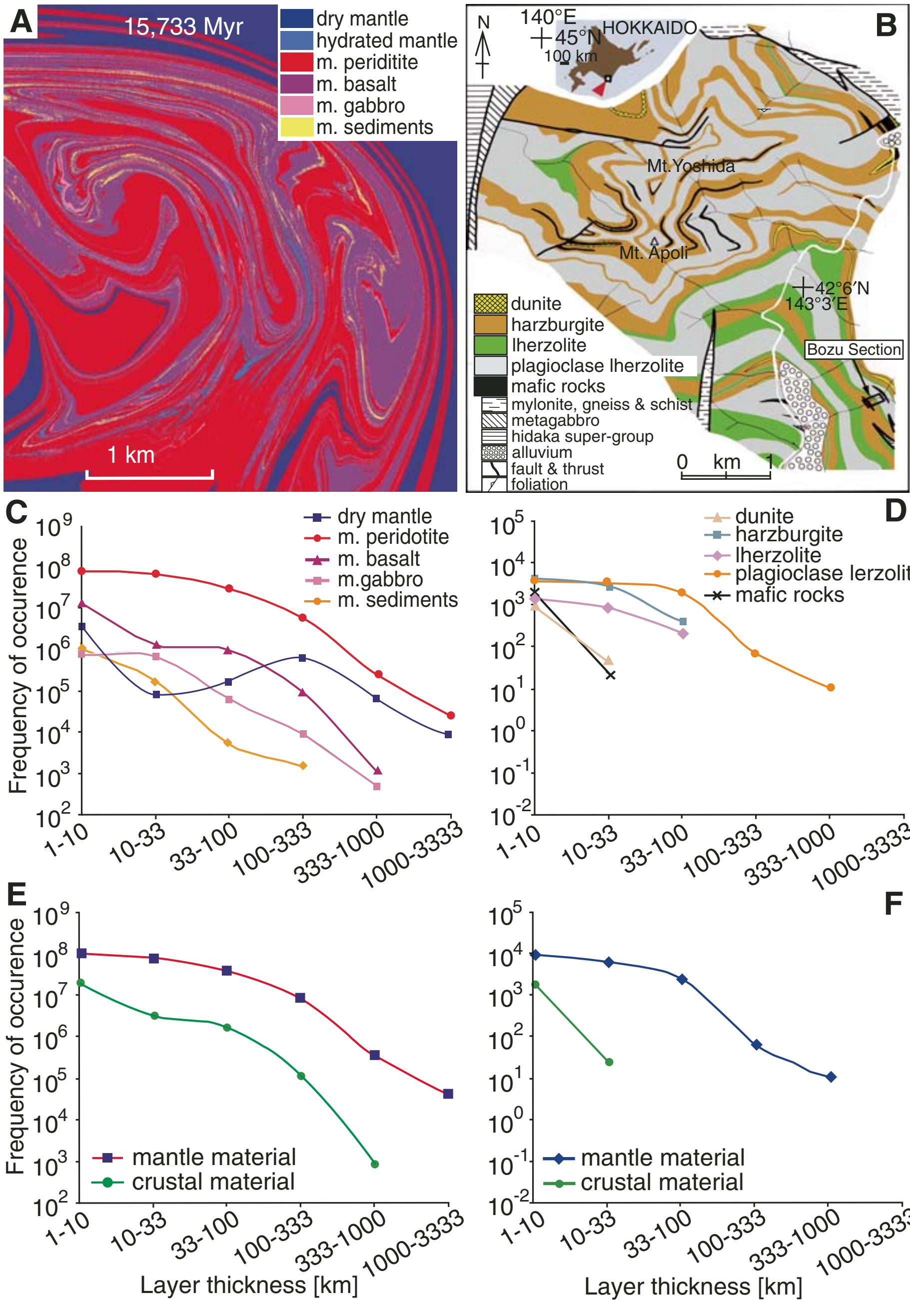

Figure 4. Comparison of numerical results computed at 15.73 m.y. after beginning of subduction (A, C, E) with data obtained for Horoman Complex, Japan (B, D, F). A, B: Layered pattern and composition (geological map of Horoman Complex is after Takazawa et al., 1996). C, D: Frequencies of different layer thickness for various rocks. E, F: Total frequencies of different layer thickness for crustal (mafic and sedimentary compositions) and mantle (ultramafic compositions) rocks.

map is relative). The same trends are observed on diagrams depicting the Horoman Complex (Figs. 4D, 4F) and plume material (Figs. 4C, 4E): (1) one order of magnitude difference in frequency of thin (<10 m) mantle and crustal layers, and (2) three orders of magnitude difference between frequencies of thin (<10 m) and thick (>1000 m) mantle layers. There are some discrepancies between the model and the geologic data: (1) no layers with the composition possibly corresponding to molten sediments have been identified in the Horoman Complex; (2) our model does not take into account magma segregation and extraction that can be essential for layering (e.g., according to Sawaguchi, 2004; Takahashi, 1992). Despite these discrepancies we conclude that the Horoman Complex may represent part of a partially molten, strongly mixed upwelling generated above a subducting slab. Our experiment suggests that the complex layered structure of the plume is not a direct effect of segregation and extraction of magma, but an effect of uneven injections and mechanical mixing of slab and wedge materials. This complex mixing process causes abrupt changes between lithologies and irregular distribution of plume components; thus the lack of sediments in the Horoman Complex does not exclude the concept of a slab upwelling origin.

In addition to the Horoman Complex, other ultramafic complexes may represent exhumed plume material, notably the Ronda (Spain) peridotite or Beni Bousera (Morocco) peridotite, which consists of lherzolite and harzburgite with subordinate amounts of dunite and <5% mafic layers that are intercalated concordantly in the peridotite (Crespo et al., 2006).

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