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Short communication

Low-viscosity mantle blobs are sampled preferentially at regions of surface divergence and stirred rapidly into the mantle

Michael Manga *

Department of Earth and Planetary Science, University of California, Berkeley, Berkeley, CA 94720, USA

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ABSTRACT

The persistence of mantle heterogeneity depends on its density and viscosity and as well as the characteristics of the convecting mantle, such as the vigour and possible stratification of convection. Low-viscosity regions stretch and deform more rapidly than their high-viscosity counterparts. Low-viscosity regions are also drawn into, and hence preferentially sampled at, regions of surface divergence such as mid-ocean ridges and plume-fed hotspots. Low-viscosity heterogeneities in the form of blobs are thus more rapidly stirred into a convecting mantle. Discrete blobs of primitive or enriched mantle are unlikely to persist for billions of years.

1. Introduction

Differentiation in the early Earth, and ongoing processes of subduction and mantle melting, create compositional heterogeneity in the mantle. Fig. 1 is a schematic illustration of some of the large-scale distinct regions known to exist, or hypothesized to exist, within Earth's mantle. Many similar conceptual illustrations have been generated in an attempt to integrate constraints from geochemical measurements on igneous rocks, seismological images and properties, and geodynamic models of mantle convection (see Tackley, 2000; Albarède and Van der Hilst, 1999 for compilations of conceptual models). Here I focus exclusively on the dynamics of the blobs shown in Fig. 1, in particular the role of the viscosity of these blobs on their preservation.

The important role of viscosity-stratification on mantle mixing has been well established (e.g., Davies, 1990; van Keken and Ballentine, 1998; Naliboff and Kellogg, 2007). The effect of viscosity differences associated with compositionally distinct regions has also been considered for several cases: the compositionally distinct region is a continuous layer (e.g., Le Bars and Davaille, 2004; Gonnermann et al., 2002), a discontinuous layer sampled by plumes (e.g., Jellinek and Manga, 2002), or exists as discrete blobs (Allègre et al., 1984; Davies, 1984; du Vignaux and Fleitout, 2001). I address only this latter case, and consider the interaction of blobs with regions of surface divergence – plume-fed hotspots and mid-ocean ridges – where compositional heterogeneity is both sampled by igneous processes and destroyed by melting.

2. Model

As a model problem I consider a two-dimensional region representing the entire mantle in which flow is driven by moving plates, as shown in Fig. 2a. Mantle density and viscosity are uniform. The upper boundary condition for the flow is one of constant speed U; side boundary conditions are reflecting; the bottom is a free-slip surface. Fig. 2a shows the velocity and streamlines for this flow when no blob is present.

The blob is modeled as an initially circular (in cross section) region with the same density as the surrounding mantle, but with a different viscosity. Neutrally buoyant blobs are considered because large buoyant blobs will segregate to the top or bottom of the mantle. Circular initial shapes are assumed, recognizing that this is not a realistic geometry for many sources of heterogeneity, though high-viscosity blobs tend to aggregate and segregate into quasi-circular regions (Manga, 1996b). The viscosity of the blob divided by that of the mantle is λ, i.e.,

$$\lambda = \frac{\text{blob viscosity}}{\text{mantle viscosity}} \tag{1}$$

The motion and deformation of the interface that defines the blob are calculated using a boundary integral method to solve the Stokes equations (Manga, 1996a). Time is normalized by the advection time-scale H/U where H is the depth of the mantle.

* Tel.: +1 510 643 8532; fax: +1 510 643 9980.
E-mail address: manga@seismo.berkeley.edu.

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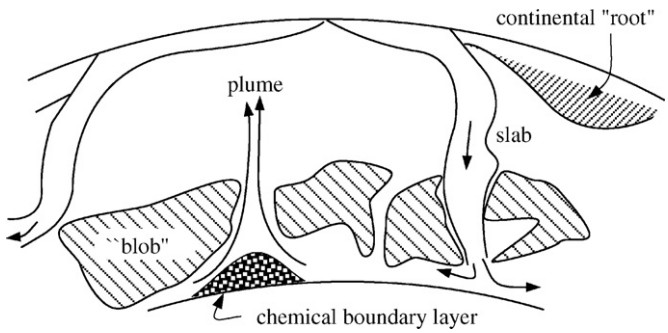

Fig. 1. Cartoon idealization of large compositionally distinct regions in the mantle. The present discussion addresses the preferential sampling and preservation of blobs.

The adopted computational method keeps track of the moving and deforming blob and the influence of the blob on the surrounding flow. While there is no interfacial tension, there is also no diffusion between the blob and its surroundings and hence there is no true mixing. We thus cannot keep track of geochemical and isotopic evolution (e.g., Kellogg et al., 2002) only motion and stretching of the blob. The method also does not permit a quantitative assessment of preferential sampling of the blobs by melting at the ridge, as the flow is isothermal and driven only by the moving plates.

3. Results

Fig. 2 shows snapshots of the blob shape at four times for two cases: $\lambda = 0.1$ and $\lambda = 10$. All other parameters are otherwise the same. There are three features of the example comparison in Fig. 2 that are generic and relevant for the evolution and preservation of mantle heterogeneity in the form of blobs.

First, as has been well established in previous studies, high-viscosity blobs deform more slowly than their low-viscosity counterparts. Manga (1996a), for example, showed that deformation rate is approximately proportional to $1/(1+\lambda)$; blobs with viscosity ratios $\lambda > O(10)$ can persist with largely undeformed cores for >1 Ga. Low-viscosity blobs, in contrast, are stirred into the mantle faster than passive tracers.

Second, most of the stretching and deformation of blobs occur near the region of surface divergence—this is where the flow is dominated by pure shear. As has been noted before in the context of mantle mixing (e.g., Olson et al., 1984; Gurnis, 1986a), pure-shear leads to stretching that is exponential in time whereas simple shear leads to stretching that is linear in time and hence much slower.

Third, and of greatest importance for the preservation of mantle heterogeneity in blobs, the low-viscosity blob is drawn towards the ridge. This occurs because of the blob's influence on the large-scale flow—the blobs in Fig. 2 are not passive tracers but instead interact dynamically with the flow. Fig. 3 illustrates how the blob influences the flow. For the case of a low-viscosity blob, its surface approximates a free-slip surface so that the plate-driven flow in Fig. 2 draws in more mantle from the right side of the box and from around the blob. The opposite is true for the high-viscosity blob. Instead, mantle from the left can flow more easily towards the ridge. As a consequence, there is a migration of blobs within convecting fluids, and high-viscosity blobs tend to aggregate near the center of convection cells (Manga, 1996b). The migration of the low-viscosity blob towards the ridge is similar to the dynamics observed in studies of the interaction between ridges and off-axis plumes, though buoyancy of the plume (Ribe, 1996; Ito et al., 1997) and in some cases the presence of a sloping lithosphere (Kincaid et al., 1996, 2002) enhance the lateral migration of plume material towards the ridge.

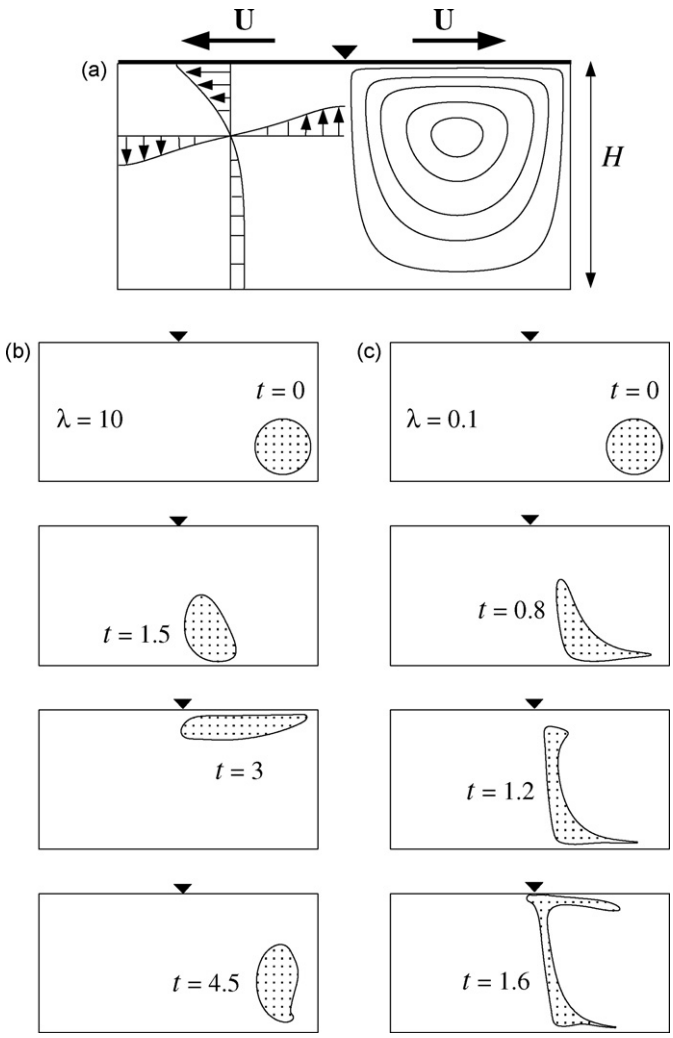

Fig. 2. (a) Geometry of the model problem. Velocity on the upper surface, U, is specified. The left and right side boundary conditions are reflecting. Bottom is free-slip. A minimum of 80 boundary elements define the blob, and 320 elements define the mantle boundary. The flow inside this box is changed by the blob—the blob is an active, not passive, tracer. Snapshots of blob shape and position for blobs (b) 10 and (c) 0.1 times more viscous than the surrounding mantle. Blobs are neutrally buoyant. Initial positions in (b) and (c) are identical. Notice in (c) that the blob is drawn towards the left and part of it crosses to the circulation cell on the left.

The cross-streamline migration of blobs does not violate the basic kinematic reversibility of Stokes flows in this case because the blobs deform in response to the flow and influence the flow as well. An even more striking difference between the evolution of

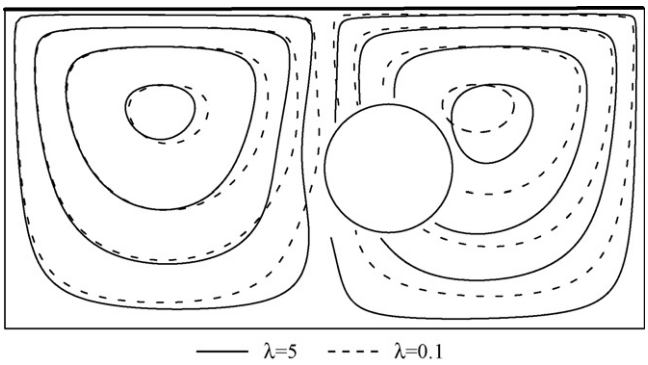

Fig. 3. Calculated streamlines for a blob five times more viscous (solid curves) and 10 times less viscous (dashed curves) that their surroundings. Notice that flow is drawn towards the low-viscosity blob but is diverted around the more viscous blob.

high- and low-viscosity blobs is that part of the low-viscosity blob actually migrates from the circulation cell on the right to the one on the left (Fig. 2c at $t = 1.6$). Cross-cell migration is key for rapid mixing (e.g., Ferrachat and Ricard, 1998). In Earth's mantle, the migration of ridges and evolution of plate geometry probably dominate mixing in the upper mantle (O'Connell, personal communication).

4. Discussion

The viscosity of mantle heterogeneities depends on their temperature and composition. Regions enriched in incompatible heat-producing elements, e.g. leftovers from a basal magma ocean (e.g., Labrosse et al., 2007) or subducted crust, may be warmer and hence less viscous than the surrounding mantle. The viscosity ratios considered in Fig. 2 can arise for temperature anomalies of 100–200 K. Regions that have been depleted or melted multiple times are likely to have a higher viscosity because their melting temperature is higher (making the reasonable assumption that viscosity depends on homologous temperature) and they are depleted in water. The effects of multiphase mixtures (Jin et al., 2001) and grain-size, however, complicate this simple characterization of viscosity (e.g., Solomatov and Reese, 2008).

With these caveats about the viscosity of different mantle regions, three classes of mantle heterogeneities may have lower viscosities than the depleted upper mantle and hence should be preferentially sampled at hot spots fed by plumes or at mid-ocean ridges, if this heterogeneity exists in the form of blobs dispersed in the mantle. First are regions enriched in subducted crust, e.g. an eclogite-enriched reservoir often invoked to explain isotope and trace element systematics in ocean island basalts (e.g., Hofmann and White, 1982) and high melt productivity of plumes (e.g., Cordery et al., 1997). A low viscosity is expected because of a low homologous temperature and additionally requires that the effect of high strength garnet is more than compensated by weak pyroxene (e.g., see Jin et al., 2001). Second are products of a basal magma ocean because they are enriched in incompatible elements and have lower melting temperatures, at least at lower mantle conditions. Third are blobs of primitive mantle, at least their cores, which will be less viscous than their surroundings (Becker et al., 1999).

Blobs of low-viscosity mantle should be effectively sampled at Earth's surface and will also become well stirred into the mantle within a few mantle overturn times (e.g., Huber et al., 2009), unless they can settle to the base of the mantle to form a stably stratified layer (Farnetani and Samuel, 2003; Brandenburg and van Kaken, 2007). Thus, old blobs are not likely to be the source of the distinctive features of ocean island basalts (OIB). Instead, if features of OIB require the presence of a discrete source region, a dense and stably stratified (possibly discontinuous) layer, or an active process to continually create new blobs, is required.

The effect of viscosity on the sampling of mantle heterogeneity by ridges also means that the spatial geochemical variability mapped along ridges (e.g., Gurnis, 1986b; Jellinek et al., 2003; Agranier et al., 2005) is not necessarily a faithful image of the deeper mantle structure. This sampling bias is a dynamic one, an additional effect beyond differences in melting temperature and productivity (e.g., Sleep, 1984; Korenaga and Keleman, 2000; Anderson, 2006). The same basic dynamics apply to smaller blobs sampled at plume-fed hotspots: small, low-viscosity blobs will become highly stretched, as are passive tracers (e.g, Farnetani and Hofmann, 2009), and will be preferentially sampled. High-viscosity blobs, however, with viscosity ratios $\lambda > 4$ (Taylor, 1932), however, will remain relatively undeformed in the rising plume. It has also been proposed that high-viscosity material within plumes can induce toroidal motions (Blichert-Toft and Albarède, 2009). While the simulations presented here are for a two-dimensional Cartesian geometry and hence cannot quantify this effect, the distortion of streamlines shown in Fig. 3 should be a generic feature of high-viscosity blobs and should promote azimuthal flow and mixing within plumes.

5. Conclusion

Low-viscosity blobs become highly deformed within one mantle overturn time. They are preferentially sampled, compared with high-viscosity blobs, at mid-ocean ridges and plume-fed hot spots. Isolated, discrete blobs of primitive or enriched mantle are unlikely to persist for billions of years.

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