Earth and Planetary Science Letters 499 (2018) 74–82

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Dynamics of rheological heterogeneities in mantle plumes

Cinzia G. Farnetani [a,*], Albrecht W. Hofmann [b,c], Thomas Duvernay [a,1], Angela Limare [a]

[a] *Institut de Physique du Globe de Paris, Sorbonne Paris Cité, Université Paris Diderot, UMR 7154, 75005 Paris, France*
[b] *Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY 10964, USA*
[c] *Max-Planck-Institut für Chemie, Hahn-Meitner-Weg 1, 55128 Mainz, Germany*

ARTICLE INFO

Article history:
Received 23 March 2018
Received in revised form 9 July 2018
Accepted 17 July 2018
Available online xxxx
Editor: J. Brodholt

Keywords:
rheology
mixing
mantle plume
dynamics
heterogeneity

ABSTRACT

The geochemical record of Hawaiian basalts has been interpreted to reflect vertically stretched, partly filament-like heterogeneities in the Hawaiian plume, but one alternative interpretation has been that this record reflects intra-conduit mixing, caused by rheological contrasts across the conduit. Here we present numerical simulations of a mantle plume carrying rheological heterogeneities λ times more viscous than the surrounding fluid. Our first objective is to quantify how the heterogeneity deforms during upwelling. We find a full spectrum of shapes, from stretched filaments to nearly undeformed blobs, and we map the respective stability domain as a function of the viscosity ratio λ and of the flow characteristics, including the plume buoyancy flux. Our second objective is to test the hypothesis that a rheological heterogeneity can cause intra-conduit mixing. Although horizontal velocities do appear across the plume conduit, we have not found any toroidal "doughnut-shaped swirl" mode. Instead we show that perturbations of the flow trajectories are a local phenomenon, unable to cause permanent mixing. Our third objective is to determine over which time-scales a rheological heterogeneity crosses the magma capture zone (MCZ) beneath a hotspot volcano. For a blob-like heterogeneity of radius 30–40 km and viscosity ratio 15–20, the crossing time-scale is less than 1 Myr. Contrary to a stretched filament, a blob can entirely fill the MCZ, thereby representing the unique source rock of partial melts feeding a volcano. If the heterogeneity has a distinct isotopic fingerprint (or a distinct fertility), surface lavas will then record an isotopic fluctuation (or a fluctuation in melt productivity) lasting 0.5–0.8 Myr. Our simulations predict that such fluctuations should occur preferentially in low buoyancy flux hotspots, where blob-like rheological heterogeneities are more easily preserved than in the vigorous Hawaiian plume.

1. Introduction

Most geodynamic studies, from Becker et al. (1999) to Ballmer et al. (2017), share the idea that rheological heterogeneities in the Earth's mantle have large dimensions, with a radius ranging from several hundred to a thousand kilometers. A key issue is then to determine under which conditions the heterogeneous volumes can "survive" in the large scale mantle flow and whether they might represent long-lasting geochemical reservoirs. Here we change perspective and focus on small scale (30–50 km radius) rheological heterogeneities deformed by the three-dimensional flow of a thermal plume. A heterogeneity initially embedded in the basal thermal boundary layer, source region of plumes, has a complex deformation history which includes pure shear, while converging to the plume stem, and simple shear once in the conduit (Farnetani and Hofmann, 2009). It is also noteworthy that strain rates vary non-linearly across the plume conduit and their values are up to two orders of magnitude higher than in the convecting mantle (Cordier et al., 2012). Previous studies on the deformations of rheological heterogeneities did not consider these specific aspects of the plume flow, either because they analyzed pure shear and simple shear separately (Cox, 1969; Spence et al., 1988; du Merveilleux and Fleitout, 2001) or because they used two-dimensional kinematically-driven models (Manga, 1996). Clearly, results obtained with large-scale circulation models cannot be extrapolated to the plume flow, as illustrated by the case of a heterogeneity with viscosity ratio $\lambda = \eta_h/\eta = 1$, where η_h is the viscosity of the heterogeneity and η the viscosity of the surrounding fluid. In a large-scale circulation model a $\lambda = 1$ heterogeneity is moderately deformed, even after a complete mantle overturn (Manga, 1996), whereas a passive heterogeneity rising into a plume

---

[*] Corresponding author.
E-mail addresses: cinzia@ipgp.fr (C.G. Farnetani), albrecht.hofmann@mpic.de (A.W. Hofmann), thomas.duvernay@anu.edu.au (T. Duvernay), limare@ipgp.fr (A. Limare).

[1] Now at Research School of Earth Sciences, The Australian National University, Canberra, ACT, 2601, Australia.

https://doi.org/10.1016/j.epsl.2018.07.022
0012-821X/© 2018 Elsevier B.V. All rights reserved.

is stretched into a filament (Farnetani and Hofmann, 2009). It is thus relevant to ask if such a contrasting behavior persists for heterogeneities which are intrinsically more viscous ($\lambda > 1$) than the surrounding fluid.

Pioneering laboratory experiments by Taylor (1934) showed that pure shear leads to exponential stretching, independently of the viscosity ratio, whereas for simple shear Manga (1996) defined a "threshold value": if $\lambda < 4$ the heterogeneity is linearly stretched, if $\lambda > 4$ the heterogeneity rotates with minor deformation. In order to test whether this "threshold value" applies to the plume flow, we conducted numerical simulations where we calculate the deformation of rheological heterogeneities for a wide range of viscosity ratios and flow characteristics.

Besides the deformation of the heterogeneity, we study to which extent a rheological heterogeneity perturbs the flow of the surrounding fluid, because lateral viscosity variations can induce a toroidal flow component within a poloidal flow (O'Connell et al., 1991; Bercovici et al., 2000). Just as a reminder, the toroidal flow is associated with rotations in a horizontal plane, whereas the poloidal, buoyancy driven, flow is associated with upwellings and downwellings. Using mantle circulation models driven by surface motion, Ferrachat and Ricard (1998) concluded that mantle mixing is enhanced when both poloidal and toroidal components are present. Although the plume flow is clearly poloidal, rheological contrasts across the conduit could favor the appearance of a toroidal flow component which would cause intra-conduit mixing, as argued by Blichert-Toft and Albarède (2009). A quantitative understanding of intra-conduit mixing is fundamental to interpret the spatio-temporal isotopic variability observed in hotspot lavas. For example, the bilateral zonation of Hawaiian volcanoes, forming the Kea- and Loa-trends, has been interpreted to reflect isotopically distinct areas in the deep-mantle (Abouchami et al., 2005; Weis et al., 2011; Huang et al., 2011). The idea that the isotopic zonation in the plume conduit preserves a "memory" of the large-scale zonation in the source region implies insignificant intra-conduit mixing. This requirement is satisfied for thermal plumes advecting passive heterogeneities (Farnetani et al., 2012), but is not satisfied for thermo-chemical plumes, since compositionally denser material rises preferentially at the plume axis (Jones et al., 2016).

A complex aspect of intrinsic viscosity contrasts (i.e., those not due to temperature differences) is that the rheology of mantle rocks depends on several parameters. Plastic deformation of rocks occurs either by dislocation creep (i.e., motion of dislocations) or by diffusion creep (i.e., diffusive transport of atoms). For diffusion creep, which dominates in most of the lower mantle, viscosity is directly related to the diffusion coefficients. Because silicon is one of the slowest diffusing species (Yamazaki et al., 2000), a Si increase likely leads to a viscosity increase, as supported by early studies on the activation energies (Weertman, 1970) and on melting temperatures of perovskite and periclase (Zerr and Boehler, 1994). Viscosity also increases with the square of the mineral grain size (Ammann et al., 2010) and it varies with water content (Katayama and Karato, 2008; Karato, 2010), thus rocks that experienced an efficient fluid removal should be more viscous than the surrounding peridotites (Hirth and Kohlstedt, 1996). Last but not least, for a mineral assemblage of a weak and a strong component, the bulk viscosity depends on the volume fraction and on the geometry of the weak component (Takeda, 1998). More specifically, when the weak MgO periclase (Cordier et al., 2012) forms isolated grains the bulk viscosity is 10–1000 times higher than when MgO periclase forms a continuous film (Yamazaki and Karato, 2001). In our work, we model rheological heterogeneities without specifying their mineral assemblage, bulk composition, grain size and fluid content; only in the Discussion we hypothesize that rheological heterogeneities might carry a distinct isotopic signature or have a distinct fertility to melt production. This hypothesis will enable us to predict time-scale of isotopic variability, or of fluctuation in melt productivity, caused by a rheological heterogeneity crossing the melting zone beneath a hotspot volcano.

2. Model setup

The geodynamic code Stag3D (Tackley, 1998) solves the equations governing conservation of mass, momentum and energy for an incompressible viscous fluid at infinite Prandtl number. The size of the cartesian domain in the X:Y:Z directions is 2200:2200:2900 km, and the grid size ranges from 8 to 10 km/cell. The physical parameters used to calculate the Rayleigh number

$$Ra = \frac{\rho g \alpha \Delta T d^3}{\eta_m \kappa} \tag{1}$$

are the mantle density $\rho = 4000\ \mathrm{kg\,m^{-3}}$, the thermal expansion coefficient $\alpha = 3 \times 10^{-5}\ \mathrm{K^{-1}}$, the maximum potential temperature contrast $\Delta T = 1950$ K, the depth $d = 2900$ km, the mantle viscosity $\eta_m = 10^{22}$ Pa s and the thermal diffusivity $\kappa = 10^{-6}\ \mathrm{m^2\,s^{-1}}$. Similar to van Keken et al. (2013), a thermal plume is generated at the bottom of the model domain over a heated patch of radius $r_p = 500$ km and maximum excess potential temperature $\delta T_p = 600\,^\circ$C. Viscosity is temperature dependent:

$$\eta(T) = \eta_m \exp\left[\frac{E}{R}\left(\frac{T_m - T}{T_m T}\right)\right], \tag{2}$$

where $T_m = 1350\,^\circ$C the mantle potential temperature, R the gas constant, E the activation energy. For the reference model $E = 220\ \mathrm{kJ\,mol^{-1}}$, but we vary the activation energy over a range going from 140 $\mathrm{kJ\,mol^{-1}}$ to 300 $\mathrm{kJ\,mol^{-1}}$. A rheological heterogeneity λ times more viscous than the surrounding fluid is simulated using 7×10^6 tracers. The heterogeneity is at an initial distance of 100 km form the plume axis, this distance is kept constant because it guarantees minimum temperature gradients across the heterogeneity, thereby avoiding to have a temperature-dependent viscosity variation superimposed on the intrinsic viscosity increase λ. At each time step the code calculates the number of tracers present in each grid cell, modifies the cell viscosity and calculates the resulting velocity field, which is then used to advect the tracers. As discussed by du Merveilleux and Fleitout (2001), a numerical method based on grid cells cannot accurately resolve a sharp viscosity interface. In view of this limitation, we conducted a series of tests to verify that the grid resolution is sufficiently accurate to resolve heterogeneities with an initial radius $R_i \geq 30$ km.

3. Results

Fig. 1 shows the evolving shape of an initial sphere ($R_i = 40$ km) as it rises in the plume conduit. The passive heterogeneity ($\lambda = 1$) is stretched into a filament (Fig. 1a), in agreement with Farnetani and Hofmann (2009). For viscosity ratio $\lambda = 10$ (Fig. 1b) we find a transitional shape resembling a "tadpole" with a blob-shaped lower part and an elongated, progressively stretched upper "tail". Finally, for viscosity ratio $\lambda = 20$ (Fig. 1c) the heterogeneity maintains a blob-like shape. In the following we focus on the flow field within and around the viscous heterogeneity, in order to understand the dynamic interaction between the heterogeneity and the surrounding flow. For the reference case without viscous heterogeneity the radial dependence of the vertical velocity (Fig. 2a, green dashed line) fits Olson et al. (1993) exponential law $v_z(r) = v_z^{axis} \exp(-Cr^2)$, where the value of the constant C depends on the activation energy and on the plume's temperature contrast. (Note that the radial distance from the plume axis