Earth and Planetary Science Letters 434 (2016) 10–17

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

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Do mantle plumes preserve the heterogeneous structure of their deep-mantle source?

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ARTICLE INFO

Article history:
Received 16 May 2015
Received in revised form 16 October 2015
Accepted 11 November 2015
Available online 28 November 2015
Editor: B. Buffett

Keywords:
mantle plumes
hotspot volcanism
LLSVPs
Hawaii
mantle structure and dynamics
thermochemical convection

ABSTRACT

It has been proposed that the spatial variations recorded in the geochemistry of hotspot lavas, such as the bilateral asymmetry recorded at Hawaii, can be directly mapped as the heterogeneous structure and composition of their deep-mantle source. This would imply that source-region heterogeneities are transported into, and preserved within, a plume conduit, as the plume rises from the deep-mantle to Earth's surface. Previous laboratory and numerical studies, which neglect density and rheological variations between different chemical components, support this view. However, in this paper, we demonstrate that this interpretation cannot be extended to distinct chemical domains that differ from surrounding mantle in their density and viscosity. By numerically simulating thermo-chemical mantle plumes across a broad parameter space, in 2-D and 3-D, we identify two conduit structures: (i) bilaterally asymmetric conduits, which occur exclusively for cases where the chemical effect on buoyancy is negligible, in which the spatial distribution of deep-mantle heterogeneities is preserved during plume ascent; and (ii) concentric conduits, which occur for all other cases, with dense material preferentially sampled within the conduit's centre. In the latter regime, the spatial distribution of geochemical domains in the lowermost mantle is not preserved during plume ascent. Our results imply that the heterogeneous structure and composition of Earth's lowermost mantle can only be mapped from geochemical observations at Earth's surface if chemical heterogeneity is a passive component of lowermost mantle dynamics (i.e. its effect on density is outweighed by, or is secondary to, the effect of temperature). The implications of our results for: (i) why oceanic crust should be the prevalent component of ocean island basalts; and (ii) how we interpret the geochemical evolution of Earth's deep-mantle are also discussed.

1. Introduction

Mantle plumes are buoyant upwellings that bring hot material from Earth's deep-mantle to its surface, generating large igneous provinces (LIPs) and volcanic island chains, such as the Siberian Traps and the Hawaiian–Emperor chain, respectively (e.g. Morgan, 1972; Richards et al., 1989; Campbell and Griffiths, 1990; Griffiths and Campbell, 1991; Davies, 1992; Farnetani and Richards, 1994, 1995; Leitch and Davies, 2001; Davies and Davies, 2009; Davies et al., 2015b, 2015c). Although mantle plumes represent the only source of volcanism on Earth that directly samples the lowermost mantle, it remains unclear how their variable geochemical expression at Earth's surface (i.e. the geochemical variations recorded in volcanic hotspot lavas) relates to the heterogeneous structure of their deep-mantle source (e.g. Dupré and Allègre, 1983; Allègre et al., 1996; Tackley, 1998; Hofmann, 2003). For example, the most recent 2–3 Myr of volcanism along the Hawaiian–Emperor chain is defined by two parallel volcanic island tracks, the Loa- and Kea-tracks (Jackson et al., 1975), which exhibit distinct geochemical signatures (e.g. Tatsumoto, 1978; Abouchami et al., 2005). Southern Loa-track volcanoes are generally less depleted, displaying systematically higher $^{208}Pb/^{204}Pb$ at a given $^{206}Pb/^{204}Pb$, as well as higher $^{87}Sr/^{86}Sr$ and lower $^{143}Nd/^{144}Nd$, when compared to the Northern Kea-track volcanoes (e.g. Abouchami et al., 2005). While several hypotheses have been proposed to explain such systematic variations (e.g. Bianco et al., 2008, 2011; Ballmer et al., 2011, 2013, 2015), the most prominent attributes them to internal zonation within the underlying mantle plume conduit, which may relate directly to large-scale geochemical domains in the lowermost mantle (e.g. Abouchami et al., 2005; Weis et al., 2011;

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http://dx.doi.org/10.1016/j.epsl.2015.11.016

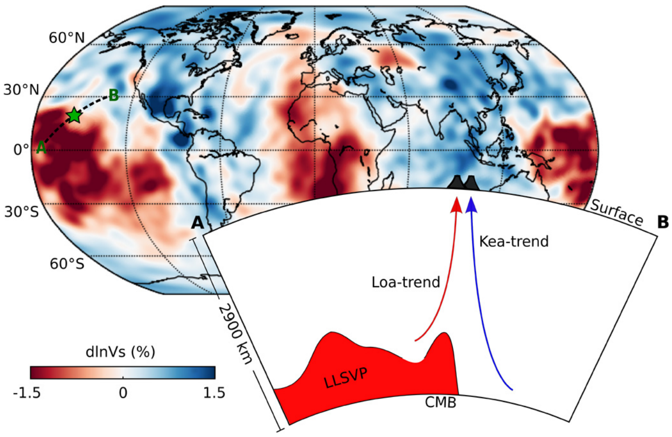

Fig. 1. The Hawaiian hotspot (green star), plotted above the shear-wave tomography model S40RTS (Ritsema et al., 2011) at 2800 km depth, illustrating that Hawaii overlies the boundary between a large region of low shear-wave velocities – the Pacific LLSVP – and surrounding mantle. Under the assumption that the Pacific LLSVP represents a chemically distinct body, Weis et al. (2011) hypothesise that geochemical differences between the Kea and Loa trends reflect preferential sampling of these two distinct sources of deep mantle material.

Huang et al., 2011; Farnetani et al., 2012; Hofmann and Farnetani, 2013; Payne et al., 2013; Harpp et al., 2014).

Weis et al. (2011) and Farnetani et al. (2012) hypothesise that the observed variations at Hawaii occur because the southern side of the Hawaiian plume preferentially samples less depleted material, from a distinct, large-scale geochemical reservoir in the deep-mantle: the Pacific large low shear-wave velocity province (LLSVP: see Fig. 1), a feature that is consistently imaged by seismological studies of the deep Pacific mantle (e.g. Houser et al., 2008; He and Wen, 2009; Ritsema et al., 2011). This hypothesis makes two central assumptions: (i) that the Pacific LLSVP represents a long-lived chemically distinct structure, termed a thermo-chemical pile (e.g. Tackley, 1998; McNamara and Zhong, 2005; Garnero and McNamara, 2008; Bower et al., 2013); and (ii) that source-region heterogeneities are transported into and preserved within a plume conduit (i.e. not stirred), as the plume rises from the deep-mantle to Earth's surface. Although the Pacific LLSVP's thermo-chemical structure is strongly debated (e.g. Garnero and McNamara, 2008; Simmons et al., 2009; Schuberth et al., 2009, 2012; Davies et al., 2012, 2015a), and it is unclear whether or not mantle plumes can preserve the heterogeneous structure of their boundary-layer source region during plume ascent, the interpretation of Weis et al. (2011) and Farnetani et al. (2012) has been extended to several other volcanic island chains in the Pacific, namely Marquesas, Samoa, Society, Galápagos and Easter (e.g. Huang et al., 2011; Payne et al., 2013; Harpp et al., 2014; Jackson et al., 2014). However, observations from the Samoan hotspot appear inconsistent with this hypothesis. Samoa lies on the southern margin of the Pacific LLSVP and, accordingly, the northern side of the Samoan plume would be expected to preferentially sample isotopically enriched material: the opposite trend is observed, with the Malu (southern) track exhibiting more enriched compositions, when compared to the Vai (northern) track (Huang et al., 2011).

There is no doubt that plumes carry a message from Earth's lowermost mantle. However, as illustrated by conflicting observations for Samoa and Hawaii, deciphering this message is challenging. The most systematic laboratory and computational studies undertaken, thus far, have focused on geochemical domains that are passive: that is, they lack any physical property contrast from surrounding mantle (e.g. Kerr and Mériaux, 2004; Farnetani and Hofmann, 2010; Farnetani et al., 2012). However, it has been recognised, in both numerical simulations and laboratory experiments, that the incorporation of active compositional heterogeneity (i.e. heterogeneity that differs from ambient mantle in its material properties) strongly influences the dynamics of upwelling mantle plumes (e.g. Tackley, 1998; Jellinek and Manga, 2002; Farnetani and Samuel, 2005; Lin and van Keken, 2006a, 2006b; Davies et al., 2012; Steinberger and Torsvik, 2012).

In this study we use the computational modelling framework Fluidity (e.g. Davies et al., 2011; Kramer et al., 2012; Le Voci et al., 2014; Garel et al., 2014) to explore the parameter space over which the spatial distribution of geochemical domains in the lowermost mantle is preserved in plume conduits during plume ascent, in 2-D and 3-D. Specifically, we build on and complement earlier studies by, for example, Kerr and Mériaux (2004), Farnetani and Hofmann (2010) and Farnetani et al. (2012), and examine the effects of density and rheological variations between initially distinct and separate source components on plume stability, source entrainment and the stirring of these components. Included in our parameter search is the density and viscosity range predicted for LLSVPs as possible long-lived, thermo-chemical piles (e.g. Tackley, 1998; McNamara and Zhong, 2005; Deschamps and Tackley, 2008, 2009; Cobden et al., 2009). Our goal is to further test the hypothesis of Weis et al. (2011) and Farnetani et al. (2012) in the presence of chemical density and viscosity contrasts between different chemical domains.

2. Methods

We solve the Stokes and energy equations relevant to mantle convection using Fluidity, a finite-element, control-volume model with several state-of-the-art features (e.g. Davies et al., 2011; Kramer et al., 2012). We also solve for a volume fraction field that tracks the presence of a chemically distinct reservoir (Wilson, 2009). Fluidity: (i) uses an unstructured mesh, which enables the straightforward representation of complex geometries; (ii) dynamically optimizes this mesh, providing increased resolution in areas of dynamic importance, thus allowing for accurate simulations across a range of length-scales, within a single model; (iii) enhances mesh optimization using anisotropic elements; (iv) is optimized to run on parallel processors and has the ability to perform parallel mesh adaptivity; (v) utilises the highly-scalable parallel linear system solvers available in PETSc (Balay et al., 1997), that can handle sharp, orders of magnitude variations in viscosity; and (vi) has a novel interface-preservation scheme, which conserves material volume fractions, and allows for the incorporation of distinct chemical components (Wilson, 2009; Garel et al., 2014). In this study, Fluidity's adaptive mesh capabilities are utilised to provide a local resolution of 1 km in regions of dynamic significance (i.e. at the interface between materials and in regions of strong temperature, velocity and viscosity contrasts), with a coarser resolution of up to 100 km elsewhere.

Key model parameters are provided in Table 1. Simulations are undertaken in 2-D square and 3-D cubic domains of dimension 2900 km. Boundary conditions for temperature are $T = 273$ K at the surface, $T = 2073$ K at the base, with insulating (homogeneous Neumann) sidewalls. Velocity boundary conditions are free-slip and no normal flow at all boundaries. The material volume fraction, ϕ, is 1 inside the chemically distinct reservoir and 0 elsewhere. A 100-km thick stiff lithosphere is imposed at the top of the model, with a linear temperature profile between surface and underlying mantle. A temperature dependent viscosity is utilised, following the relation:

$$\eta(T^*) = \eta_0 \exp^{-bT^*} \tag{1}$$

where $T^* = (T - T_{Surf})/(T_{CMB} - T_{Surf})$ is the non-dimensionalised mantle temperature. The reference viscosity, η_0, is multiplied by $\hat{\eta}_{lith}$ above 100 km depth and $\hat{\eta}_{660}$ below 660 km depth. Within