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Geochemical variations at ridge-centered hotspots caused by variable melting of a veined mantle plume

Todd Anthony Bianco [a,*], Garrett Ito [b], Jeroen van Hunen [c], John J. Mahoney [b,1], Maxim D. Ballmer [b]

[a] Geological Society of America—United States Geological Survey Congressional Science Fellow, Washington, DC, USA
[b] Department of Geology and Geophysics, SOEST, University of Hawaii Manoa, Honolulu, HI 96822, USA
[c] Department of Earth Sciences, Durham University, Durham DH1 3LE, United Kingdom

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ABSTRACT

We model the dynamics and melting of a ridge-centered mantle plume, and predict the geochemical composition of magma at the surface. The mantle source is a fine-scale mixture of a small fraction of hydrous peridotite that is relatively enriched in incompatible elements ("EC") and is embedded in a drier peridotite ("DC") matrix. We assume all magma erupts at the ridge and calculate the contribution of EC and DC to the pooled composition along the ridge. If viscosity increases as melting dehydrates the mantle, EC contributes more to the pooled magma at the hotspot center than anywhere else along the ridge. The magnitude of this EC anomaly increases with Rayleigh number, and the along-axis distance to normal ridge composition increases with Rayleigh number, plume radius, and thermal buoyancy flux. A subset of model calculations designed to simulate the Iceland hotspot and Mid-Atlantic Ridge predict variations in crustal thickness, $^{87}Sr/^{86}Sr$, and La/Sm with magnitudes and widths along the ridge that are comparable to, but less than, those observed. Improved fits to the observations require the innermost plume mantle to be compositionally distinct from the ambient asthenosphere; for example, by having a slightly higher mass fraction of EC (13–16%), or with DC having slightly higher $^{87}Sr/^{86}Sr$ and La/Sm. The inferred bulk plume $^{87}Sr/^{86}Sr$ composition, however, is within the predicted range of the source of normal mid-ocean ridge basalts worldwide. The broader implication is that the source of the Iceland plume is more similar in composition to the ambient upper mantle than previously thought, as a large part of the variation in ridge basalt composition can be attributed to the dynamics of mantle flow and melting.

1. Introduction

The largest variations in the composition and thickness of crust along mid-ocean ridges are often attributed to the interactions of ridges with mantle plumes (e.g., Hart et al., 1973; Ito et al., 2003; Morgan, 1972; Schilling, 1973; Vogt, 1971; Wilson, 1963). For example, Iceland has an extremely thick crust (up to ~40 km, Darbyshire et al., 1998) and the thickness decreases with distance to the north and to the south along the Mid-Atlantic Ridge (MAR) (e.g., Hooft et al., 2006; Menke, 1999; Smallwood et al., 1995; Weir et al., 2001) to values (~7 km) that are within the range found at ridges not influenced by mantle plumes (e.g., Dick et al., 2003; White et al., 1992). Local seismic tomography studies have imaged the Iceland mantle plume as a columnar-shaped body with low seismic wave speeds in the upper mantle beneath Iceland (e.g., Allen et al., 2002; Hung et al., 2004; Wolfe et al., 1997), and geodynamic models have shown how a plume with a diameter comparable to that (~200 km) of the seismic velocity anomaly can successfully explain the variations in crustal thickness observed at Iceland and along the MAR (Ito et al., 1999). Geochemical studies have shown evidence for anomalously rapid upwelling beneath Iceland (Maclennan et al., 2001; Peate et al., 2001), in further support of a buoyantly rising mantle plume.

Accompanying the anomaly in crustal thickness are anomalously high $^{206}Pb/^{204}Pb$, $^{87}Sr/^{86}Sr$, $^{3}He/^{4}He$, and La/Sm and low $^{143}Nd/^{144}Nd$, as well as additional compositional anomalies, which change gradually with distance from Iceland (e.g., Cohen and O'Nions, 1982; Hanan and Schilling, 1997; Hart et al., 1973; Hemond et al., 1988; Mertz et al., 1991; O'Nions et al., 1973; Schilling, 1973; Schilling et al., 1999; Wood et al., 1979; Zindler et al., 1979). Like crustal thickness, the geochemical anomalies are largest on Iceland and diminish with distance north and south along the MAR to values more typical of normal mid-ocean ridges.

A common interpretation of the geochemical variations is that they reveal an Iceland mantle plume that is compositionally

* Corresponding author.
E-mail address: toddanthonybianco@gmail.com (T.A. Bianco).
[1] Deceased.

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distinct from, and is becoming more diluted as it mixes with the ambient mantle with distance away from Iceland (e.g., Schilling, 1973, 1991). The main difficulty with this interpretation is that previous geodynamic models of a mantle plume rising beneath a mid-ocean ridge fail to predict significant mixing between material native to the plume and material native to the ambient upper mantle (Ito et al., 1999). Thus, rather than along-axis gradients in composition, previous numerical models have predicted a more-or-less uniform composition along the whole section of the ridge influenced by the plume, and a step-like change to normal ridge compositions outside of this section (Ito et al., 1999). Alternatively, the Iceland mantle plume may have some form of radial zoning in composition on the regional scale, for example, due to the entrainment of ambient mantle as it rises from the lower mantle (e.g., Hauri et al., 1994). However, geodynamic models that simulate such a process predict little or no mixing between the hot center of a plume and the surrounding, entrained material (Farnetani and Richards, 1995). This prediction complicates an explanation for the gradual changes in compositions with distance away from central Iceland.

A possible solution may be related to how different mantle materials are extracted by melting in response to variations in mantle flow. One key concept is that upwelling and decompression melting in a mantle plume tends to be faster near the base of the melting zone than near the top, and this leads to melt compositions heavily concentrated in incompatible elements (Maclennan et al., 2001), i.e., those elements that are extracted near base of the melting zone. But in addition, if the mantle is composed of a mixture of enriched material that is more fusible than accompanying depleted material, the rapid deep upwelling of plumes can lead to a greater concentration of the enriched components in the melts than in starting mantle source (Ito and Mahoney, 2005a, 2005b). A number of studies have argued that both "enriched" materials (e.g., high $^{87}Sr/^{86}Sr$) as well as "depleted" materials (e.g., low $^{87}Sr/^{86}Sr$) are intrinsic to the Iceland plume (e.g., Breddam, 2002; Hards et al., 1995; Fitton et al., 1997; Thirlwall et al., 2004) (although this point is still debated (Hanan et al., 2000; Mertz and Haase, 1997; Stracke et al., 2003)). Geodynamic models that assume such compositional heterogeneity is present at the fine scale ($\leq\sim 10^{\circ}$ km, e.g., a "veined" mantle) in plumes at intraplate (Bianco et al., 2005, 2008, 2011) as well as near-ridge settings (Ingle et al., 2010; Ito and Bianco, in press) have demonstrated that spatial variations in upwelling and melting rates can give rise to gradients in magma composition at the surface. Such a process may be occurring beneath the MAR near Iceland.

Here we test the hypothesis of variable melt extraction from a veined mantle using geodynamic models that simulate 3D upper mantle flow, heat transfer and melting of a ridge-centered plume. Our overarching goal is to quantify, generally, the degree to which flow and melting of a heterogeneous mantle can influence the variability in magma composition along a plume-influenced ridge axis. The effects of temperature- versus compositionally-dependent mantle rheology, radius of the plume thermal anomaly, and reference viscosity of the mantle are quantified. Finally, we compare predictions to observations of $^{87}Sr/^{86}Sr$, the incompatible element ratio La/Sm, and crustal thickness along the Iceland–MAR system.

2. Methods

We simulate upper mantle convection of an incompressible, infinite-Prandtl-number fluid with CITCOM, a Cartesian coordinate finite-element code (Moresi and Gurnis, 1996; van Hunen et al., 2005; Zhong et al., 2000). For the energy equation, we use the extended Boussinesq approximation and account for cooling due to latent heat of melting and adiabatic decompression (see Appendix 1 of Bianco et al. (2011)). Melting is handled by using passive tracers to advect melt depletion and by using parameterizations of hydrous peridotite melting (Katz et al., 2003). The mantle in these models is uniformly heterogeneous (veined), and the heterogeneities are assumed to be in thermal equilibrium. For simplicity, chemical interaction between melt and solid are ignored, which is appropriate for fractional melting (e.g., Johnson et al., 1990; Kelemen et al., 1997; McKenzie, 2000; Rubin et al., 2005; Stracke et al., 2006; Zhu et al., 2011). More generally (e.g., if there is some melt–solid interaction), our treatment applies to a situation in which magmas from different components reach the surface in approximately the same relative proportion as they were formed by decompression melting. More details of the method are in Bianco et al. (2008, 2011). Unless otherwise noted in Supplementary Tables S1 and S2, melting parameters are the same as in Bianco et al. (2008, 2011) and Table 2 of Katz et al. (2003). The following section discusses the main adaptations for the current study.

2.1. Model setup, boundary, and initial conditions

The general model setup is shown in Fig. 1. All models include the upper 400 km of mantle (z-dimension), and $\geq$1600 km of ridge axis (y-dimension) and $\geq$800 km in the direction of plate motion (x-axis). Vertical resolution is 5 km at depths above 225 km, which provides adequate resolution in the melting zone; vertical resolution is $\leq$9 km below 225 km, and horizontal resolution is 6.25 km everywhere. To ensure a steady state, calculations were run for $\sim$100 Myr of model time.

As in the previous work (Bianco et al., 2008, 2011), the initial temperature condition is set using a half-space cooling model (Davis and Lister, 1974), and in all cases the initial thermal age at the ridge ($x=0$) is set to 0.01 kyr to allow the axial lithosphere to start with a finite thickness. A plume is imposed as a steady, hot circular patch at the base of the model (e.g., Bianco et al., 2008, 2011; Ribe et al., 1995). The anomaly is greatest at the center ($T_{plume}=200$ °C, at $(x,y)=(0,0)$ km) and decays as Gaussian function of radial distance. The radius r_{plume} is the distance at which the thermal anomaly has decayed by a factor of $1/e$. The rest of the model base is kept at the simulated ambient potential temperature of 1300 °C (we include an adiabatic gradient). This potential temperature is near the lower bound of recent estimates for normal upper mantle (e.g., Putirka, 2005; Herzberg et al., 2007; Lee et al., 2009) and leads to predicted crustal thicknesses (4–5 km) in models without a plume—at the low end of the range observed at the relevant half spreading rate (10 km/Myr) (Brown and White, 1994; White et al., 1992; Dick et al., 2003). The main reason for using this temperature is computational advantages; the shallower solidus allows for higher resolution in the melting zone at a given computational expense.

Plate motion is simulated with a horizontal velocity in the x direction of 10 km/Myr (i.e., approximately the half-spreading rate near Iceland (DeMets et al., 2010)) imposed on the top of the model space. The vertical walls beneath the ridge ($x=0$) and slicing through the center of the hotspot ($y=0$) are reflecting, insulating boundaries, and are thus planes of symmetry. All other boundaries are open to material flow with zero conductive heat flow. Thus, the symmetry of the problem allows us to simulate one quarter of the full volume of a ridge-centered plume system.

2.2. Rheology

Viscosity η is controlled by temperature-dependent Newtonian rheology with an additional term to simulate the stiffening of the