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Delivery of deep-sourced, volatile-rich plume material to the global ridge system

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ABSTRACT

The global mid-ocean ridge (MOR) system represents a major site for outgassing of volatiles from Earth's mantle. The amount of H_2O released via eruption of mid-ocean ridge basalts varies along the global ridge system and greatest at sites of interaction with mantle plumes. These deep-sourced thermal anomalies affect approximately one-third of all MORs – as reflected in enrichment of incompatible trace elements, isotope signatures and elevated ridge topography (excess melting) – but the physical mechanisms involved are controversial. The "standard model" involves solid-state flow interaction, wherein an actively upwelling plume influences the divergent upwelling generated by a mid-ocean ridge so that melting occurs at higher pressures and in greater amounts than at a normal spreading ridge. This model does not explain, however, certain enigmatic features including linear volcanic ridges radiating from the active plume to the nearby MOR. Examples of these are the Wolf–Darwin lineament (Galápagos), Rodrigues Ridge (La Réunion), Discovery Ridge (Discovery), and numerous smaller ridge-like structures associated with the Azores and Easter–Salas y Gómez hot spots. An important observation from our study is that fractionation-corrected MORB with exceptionally-high H_2O contents (up to 1.3 wt.%) are found in close proximity to intersections of long-lived plume-related volcanic lineaments with spreading centres.

New algorithms in the rare-earth element inversion melting (INVMEL) program allow us to simulate plume–ridge interactions by mixing the compositions of volatile-bearing melts generated during both active upwelling and passively-driven corner-flow. Our findings from these empirical models suggest that at sites of plume–ridge interaction, moderately-enriched MORBs (with 0.2–0.4 wt.% H_2O) result from mixing of melts formed by: (i) active upwelling of plume material to minimum depths of $\sim$35 km; and (ii) those generated by passive melting at shallower depths beneath the ridge. The most volatile-rich MORB (0.4–1.3 wt.% H_2O) may form by the further addition of up to 25% of "deep" small-fraction plume stem melts that contain >3 wt.% H_2O. We propose that these volatile-rich melts are transported directly to nearby MOR segments via pressure-induced, highly-channelised flow embedded within a broader "puddle" of mostly solid-state plume material, spreading beneath the plate as a gravity flow. This accounts for the short wavelength variability (over 10s of km) in geochemistry and bathymetry that is superimposed on the much larger (many 100s of km) "waist width" of plume-influenced ridge.

Melt channels may constitute a primary delivery mechanism for volatiles from plume stems to nearby MORs and, in some instances, be expressed at the surface as volcanic lineaments and ridges. The delivery of small-fraction hydrous melts from plume stems to ridges via a two-phase (melt-matrix) regime implies that a parallel, bimodal transport system is involved at sites of plume–ridge interaction. We estimate that the rate of emplacement of deep-sourced volatile-rich melts in channels beneath the volcanic lineaments is high and involves 10s of thousands of km^3/Ma. Since mantle plumes account for more than half of the melt production at MORs our findings have important implications for our understanding of deep Earth volatile cycling.

1. Introduction

The eruption of basalts along the global mid-ocean ridge (MOR) system represents a major avenue for outgassing of volatiles (e.g. CO_2, H_2O) from the mantle (Dixon et al., 2002, 2017;

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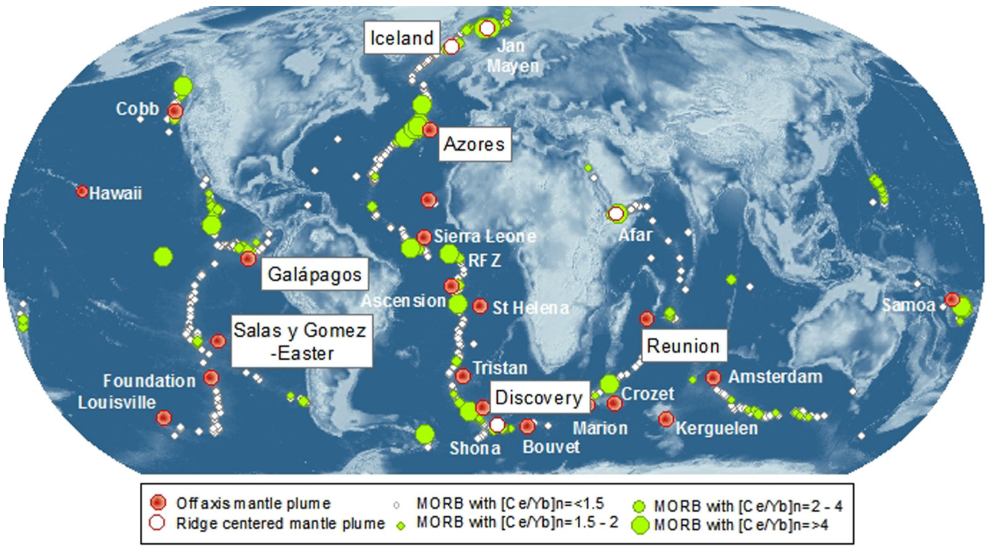

Fig. 1. Global distribution of MORB with elevated chondrite normalised Ce/Yb ratios. Many of the ridge segments with enriched MORB are in the vicinity of mantle plumes. Ce/Yb ratios exhibit a positive correlation with H_2O but the precise relationship varies for different sites of plume–ridge interaction (see Fig. 2). The locations of hotspots discussed in the text are shown in boxes. MORB data are from Gale et al. (2013a) and Jenner and O'Neill (2012). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Saal et al., 2002; Simons et al., 2002; Le Voyer et al., 2015; Michael and Graham, 2015). Melt production and geochemical enrichment along MORs is not, however, uniform and varies over distances of 10s of km, e.g. Ito et al. (2003), Jenner and O'Neill (2012), Gale et al. (2011, 2013b) (Fig. 1). Some of the most convincing evidence that this variation is linked, at least in part, to melt contributions from deep-sourced mantle plume material is provided by the occurrence of high $^3He/^4He$ basalts on spatially-confined sections of the global ridge system (Poreda et al., 1993; Sarda et al., 2000; Graham, 2002; Graham et al., 2014). Melting of this enriched plume material significantly affects bathymetry and basalt geochemistry along approximately 30% of the global mid-ocean ridge system (Ito et al., 2003); for hotspots such as Tristan, Azores, Easter–Salas y Gómez, Iceland and Galápagos (Fig. 1) the average flux of deep-sourced, volatile-rich material to the adjacent MOR is considerable ($\sim 2.2 \times km^3/a$) and amounts to almost half of global ridge melt production (Ito and Lin, 1995). This plume–ridge interaction may be sustained over 10s if not 100s of millions of years but the physical mechanisms that allow the supply of volatile-rich melts to ridges to be maintained over long time scales are poorly understood.

Most oceanic hotspots are connected to spreading centres via lateral flow of plume material, albeit sometimes with separation distances extending over 1000 km, and this may play an important role in modulating the migration of MORs (Gibson et al., 2015). In conventional models, plumes affect MORs via straightforward solid-state flow interactions of the sheet-like, mantle-upwelling flow induced by plate spreading along a ridge, and the upwelling of the plume itself (e.g. Feighner and Richards, 1995; Ito and Lin, 1995; Ribe, 1996). For some mantle plumes the maximum horizontal spreading of enriched plume material (i.e. the waist width) extends for almost 1000 km, e.g. the Azores, Galápagos and Iceland. While model parameters such as plume–ridge separation distance, MOR spreading rate, and plume buoyancy flux all act to control this waist width in fairly obvious ways (e.g. Feighner and Richards, 1995; Ribe, 1996; Schilling, 1991), the conventional solid-state models do not, however, explain variable amounts of trace element and isotopic enrichment along sections of plume-influenced ridge. Modifications to these solid-state models have therefore included the hypothesis that the plume source material may contain streaks of enriched peridotite or pyroxenite, which undergo partial melting at lower temperatures and higher pressures (Ito and Mahoney, 2005; Gale et al., 2013b).

An alternative to purely solid-state flow interaction models involves the lateral transport of "enriched" melts toward ridges (Stroncik et al., 2008; Stroncik and Devey, 2011; Gibson et al., 2015; Mittal and Richards, 2017). The model proposed by Gibson et al. (2015) and expanded in Mittal and Richards (2017) involves pressure-induced transport at least partially via two-phase flow along a channelised network of volatile-rich melts at sub-lithospheric depths, embedded in the plume itself, or along the base of the lithosphere, away from the plume. Evidence cited in these studies includes the correspondence of volcanic "lineaments" connecting mantle plume stems with spatially-confined enriched MORB, such as the Wolf–Darwin lineament in Galápagos.

The conceptual models that relate volcanic lineament formation between the plume and ridge to volatile-rich melt channels at sub-lithospheric depths contrast with those that invoke passive melting due to upwelling flow beneath linear lithospheric extensional structures, e.g., Sinton (2003). These extensional models are, however, inconsistent with a broad range of geophysical and geological observations. For Galápagos this evidence includes the following arguments: (1) Mapped fault orientations do not correspond to the orientations of the volcanic lineaments (Mittelstaedt et al., 2012). (2) The dominant extensional feature in the region, the Galápagos Transform Fault, shows no evidence of associated volcanism (Mittal and Richards, 2017). (3) Numerical calculations of passive upwelling suggest insufficient melt production to explain the lineament volumes (Mittelstaedt et al., 2012). (4) Gravity analysis does not indicate pervasive intrusion associated with the pattern of extension in the region (Mittal and Richards, 2017). (5) Regional seismicity is not related to the locations of the lineaments, suggesting that they do not represent primary faulting structures (Mittal and Richards, 2017). As we illustrate in detail below, enigmatic volcanic lineament structures also link other hotspots (Azores, Salas y Gómez, La Réunion and Discovery) with global spreading centres.

In this work, we examine recently published datasets for volatiles (H_2O) in quenched basaltic glasses and melts trapped in olivine phenocrysts (inclusions) at archetypal regions of plume–ridge interaction. While the amount of volatile data is limited, we have been able to establish an empirical relationship between $[Ce/Yb]_n$ and H_2O that we use to examine spatial variability in