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Review article

Earth's heterogeneous mantle: A product of convection-driven interaction between crust and mantle

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ABSTRACT

Ubiquitous heterogeneity in the Earth's mantle has been documented by numerous chemical and isotopic analyses of oceanic basalts. Despite the ever-increasing amount of data, the way in which compositional heterogeneity is manifest in the Earth's mantle, as well as the processes leading to mantle heterogeneity remain fundamental questions. The large amount of available isotope data in oceanic basalts shows that, statistically, only two principal compositional vectors capture the essential features of the data. Care must be taken, however, when estimating the isotopic composition of mantle from basalt samples. This is because partial melting, and melt mixing during melt extraction leads to a biased representation and subdued compositional variability in the basalts relative to their mantle sources. In both ridge and ocean island settings, for example, erupted lavas are expected to be isotopically less depleted than the most depleted source components. Abyssal peridotites indeed range to much more depleted isotope compositions than mid ocean ridge basalts (MORB). The extent of heterogeneity of the MORB mantle source, the depleted mantle, therefore depends on the proportion, as well as differences in composition, age, and sampling of its various depleted and enriched source components. While MORB data thus do not reflect the full extent of mantle heterogeneity, the large amount of trace element and isotope data in ocean island basalts (OIB) suggests that enriched isotope signatures in OIB closely correspond to those of their average enriched mantle components. OIB can therefore be used to trace the geologic reservoirs that exchange mass with the mantle and to identify the geological processes that introduce enriched material into the Earth's mantle. The generation and subduction of oceanic plates into the deeper mantle, together with small amounts of lower and upper continental crust, appears to be the main process for mantle enrichment. Thereby, erosion and subduction of the lower continental crust accounts for a large part of the enriched isotope signatures in oceanic basalts. Recycling of the upper continental crust, on the other hand, is inferred to be only a minor process, but required to explain the entire spectrum of enriched OIB signatures. Hence a first order geologic process – the generation and subduction of oceanic plates – accounts for the first-order heterogeneity of the Earth's mantle. Moreover, one of the main processes for establishing the composition of the continental crust – erosion and recycling of the lower continental crust – is also one of the main processes for the generation of mantle heterogeneity. Overall, large-scale chemical cycling between Earth's two major lithophile element reservoirs, the mantle and the oceanic and continental crust, is responsible for mantle enrichment. Once introduced into the mantle, the heterogeneous materials become stretched, reduced in size and distributed by mantle convection. The isotopic heterogeneity observed in melt inclusions and abyssal peridotites suggests that eventually, the heterogeneity of the mantle sources of oceanic basalts will exist at relatively small scales, certainly on the kilometer scale of the melting region but perhaps even smaller. The way in which mantle heterogeneity is manifest in the source of oceanic basalts is therefore directly related to the fluid dynamics of mantle convection, whereas the timing, nature, and extent of crust–mantle interaction govern the differentiation and compositional evolution of the silicate Earth.

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1. Introduction

The main driving force for the chemical differentiation of the silicate Earth is partial melting of the Earth's upper mantle. This process generates the oceanic, but ultimately also the continental crust, and Earth's atmosphere (Gast et al., 1964; Allègre et al., 1987b; Hofmann, 1988). Left behind is a residual mantle that is preferentially depleted in those elements that make up the crust and atmosphere, the so-called incompatible elements which are difficult to incorporate into the mineral structure of common mantle minerals (e.g., Hofmann, 1988). This depleted mantle is, however, continuously re-enriched in incompatible elements and the chemical composition and overall heterogeneity of the Earth's mantle have evolved progressively, possibly from the earliest stages of the Earth ~4.5 Ga ago to the present day (e.g., Harper and Jacobsen, 1992; Caro et al., 2003; Boyet and Carlson, 2005; Harrison et al., 2005).

As of yet, no consensus has been reached about what the most important processes for re-enrichment of the mantle are. Among the great diversity of persisting models, the most often invoked are recycling of oceanic and continental crust (Hawkesworth et al., 1979; White and Hofmann, 1982; Zindler and Hart, 1986; Weaver, 1991; Chauvel et al., 1992; Stracke et al., 2003a; Willbold and Stracke, 2006, 2010), delamination and foundering of the subcontinental lithosphere (e.g., McKenzie and O'Nions, 1983; Mahoney et al., 1989, 1996; Milner and LeRoex, 1996; Douglass et al., 1999; Douglass and Schilling, 2000; Lustrino et al., 2000; Doucelance et al., 2003; Hanan et al., 2004), and various types of mantle metasomatism (e.g., Zindler et al., 1979; Roden et al., 1984; Hart, 1988; Niu and O'Hara, 2003; Donnelly et al., 2004; Workman et al., 2004; Pilet et al., 2005; Salters and Sachi-Kocher, 2010).

The degree to which these processes influence the compositional evolution of the silicate Earth remains a matter of active debate. It has become clear, however, that with the possible exception of intra-mantle metasomatism, re-enrichment of the mantle principally occurs by large-scale chemical cycling between different silicate reservoirs on Earth: the continental and oceanic crust and associated lithospheres, and the Earth's mantle. Element cycling between these different global reservoirs links the continuing compositional evolution of the Earth's mantle to the global differentiation and compositional evolution of our planet. Understanding the driving forces responsible for the current state of mantle heterogeneity is therefore key for improving our basic understanding of Earth's workings.

Owing to the paucity of direct mantle samples, the composition of the mantle is mostly studied through basalts erupted on the ocean floor. Oceanic basalts are large-scale partial melts from the Earth's mantle that escape contamination by the continental crust and hence indirectly record mantle composition. Numerous isotope and trace element studies of oceanic basalts show that the Earth's mantle is heterogeneous (e.g., Gast et al., 1964; Tatsumoto et al., 1965; Hedge, 1966; Tatsumoto, 1966; Hart et al., 1973; White and Schilling, 1978; Allègre, 1982; White, 1985; Zindler and Hart, 1986; Hofmann, 1997; Stracke et al., 2005) and that most mantle sources consist of complex assemblages of two or more components with isolated long-term chemical evolution, on both global and local scales. Traditionally, the observed range of isotopic compositions in oceanic basalts is assumed to directly reflect those of the underlying mantle. A long-prevailing view is that the Earth's mantle consists of a restricted number of large-scale reservoirs: a depleted mantle and about 3–4 enriched reservoirs that mix to produce the isotopic variability observed in oceanic basalts (e.g., Zindler and Hart, 1986).

Recent studies show, however, that isotopic heterogeneity in oceanic basalts is observed even at the μm-scale of melt inclusions (Saal et al., 1998; Shimizu et al., 1998; Saal et al., 2005; Jackson and Hart, 2006; Maclennan, 2008b; Paul et al., 2011; Sobolev et al., 2011). This small-scale heterogeneity is evidence for a highly heterogeneous mantle, perhaps even on a sub kilometer scale. Furthermore, comparison of melt inclusions with erupted basalts shows that the elemental and isotopic heterogeneity in the melt inclusions is greater than in the erupted basalts (see references above and below). This observation indicates that melts are mixed to different extents during the melting and melt aggregation process. Erupted melts are therefore generally incomplete mixtures of small degree partial melts produced at variable depths in the melting region (Sobolev and Shimizu, 1993; Nielsen et al., 1995; Shimizu, 1998; Morgan and Morgan, 1999; Sours-Page et al., 1999; Slater et al., 2001; Maclennan et al., 2003a,b; Stracke et al., 2003b; Ito and Mahoney, 2005; Laubier et al., 2007; Maclennan, 2008a,b; Stracke and Bourdon, 2009; Shorttle and Maclennan, 2011; Waters et al., 2011; Koornneef et al., 2012).

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