



## Mantle Heterogeneity: What is the message from geochemistry?

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Ubiquitous heterogeneity in the Earth's mantle has been documented by numerous chemical and isotopic analyses of oceanic basalts. Despite about four decades of research and the continuously increasing number of data, however, the way in which compositional heterogeneity is manifest in the Earth's mantle, as well as the origin and processes leading to mantle heterogeneity remain fundamental questions. A statistical analysis of the large amount of available isotope data in oceanic basalts shows that two principal compositional vectors capture about 95% of the isotopic variation. Care must be taken, however, to directly equate basalt and mantle isotopic composition, because partial melting, and melt mixing during melt extraction lead to a biased representation and subdued compositional variability in the basalts compared to their mantle sources. This is perhaps best documented by the isotopic disparity between MORB and abyssal peridotites, which are isotopically by far more depleted and variable than MORB. In contrast, enriched isotope signatures in ocean island basalts (OIB) closely represent those of their average enriched mantle source components. The main principal vector of the MORB and OIB isotopic distribution (about two-thirds of the variation) corresponds to the generation and subduction of oceanic plates. Mass exchange between the lower and upper continental crust and the mantle accounts for most of the remaining third of the MORB-OIB isotopic variation. This simple conceptual framework attributes mantle heterogeneity mainly to the large-scale cycling between the Earth's two major lithophile element reservoirs, the mantle and the oceanic and continental crust. Formation and evolution of mantle heterogeneity is therefore a continuous process that is largely governed by plate-tectonic processes, and unlikely to result in just a few large-scale mantle reservoirs, which subsequently interact and mingle during intra-mantle processing. To what extent heterogeneous mantle materials preserve their inherent compositional heterogeneity depends on the physics and fluid dynamics of the mantle. Once formed, by continuous depletion through partial melting (depleted mantle) and by transport into the mantle, heterogeneous materials become stretched, reduced in size and at present, they are more or less statistically distributed. Large-scale statistical differences caused by differences in the relative abundance of the distinct mantle materials may result in large-scale compositional "domains" (e.g. DUPAL or SOPITA). Alternatively these putative domains could be an artifact resulting from different sampling of a similar population of mantle components. At mid-ocean ridges, for example, the observed degree of isotopic variability decreases as the scale of melting, or rate of processing of mantle material (as measured by the spreading rate), increases. This observation also shows that the scale of mantle components is small compared to the maximum dimension over which melts are produced and mixed beneath ridges, i.e. certainly on the kilometer scale of the melting region but perhaps even smaller. Further support for this sub-kilometer scale of mantle heterogeneity comes from theoretical melting models, the depth-dependent sampling of isotopically distinct source materials observed in Icelandic basalts, the isotopic heterogeneity observed in melt inclusions, and the sub-kilometer scale isotopic heterogeneity observed in abyssal peridotites. These observations further show that, despite intra-mantle processing by convective stirring, both enriched and highly depleted isotopic materials survive, i.e. to a large extent they retain their physico-chemical integrity, and escape equilibration with ambient, compositionally distinct material over geologic timescales (> 1 Ga).