

Major element heterogeneity in the mantle: constraints from a general model for basalt petrogenesis

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Basalts provide a useful constraint on mantle heterogeneity because they sample the mantle on the scale of a melting regime. Although this scale is not precisely known, it is probably on the order of cubic kilometers or more. This is a useful scale, because it is far larger than the few cubic centimeters of ultramafic nodules, and far smaller than the thousands of kilometers currently sampled on average by most geophysical methods. The system of ocean ridges is particularly useful in this regard, because it circumnavigates the globe and gives a high resolution reading of the composition of the oceanic upper mantle.

Young basalts from ocean ridges, ocean islands and convergent margins provide a remarkably coherent model of magma generation and mantle composition. It has been known among igneous petrologists for decades that melting occurs by decompression of the mantle (e.g. Carmichael *et al.*, 1974; Cawthorn, 1975) and that the compositions of melts should and could be calculated along adiabatic decompression paths (Langmuir and Hanson, 1980). Combination of this long-standing, simple concept with the tectonic setting produces a unified view of basalt petrogenesis that is able to explain most of the global variations of basalt compositions. Beneath ocean ridges the base of the melting regime is controlled by mantle temperature, and the top by the thickness of the crust, except at very slow spreading rates, where surface cooling causes there to be a thicker lithosphere. Basalt chemistry correlates with axial depth and crustal thickness (Klein and Langmuir, 1987). This view is also consistent with observations from abyssal peridotites (Dick *et al.*, 1984; Michael *et al.*, 1985). At ocean islands, the base of the melting regime is still controlled by mantle temperature, but the top varies substantially due to variations in the thickness of the lithosphere. Basalt chemistry correlates with the combination of buoyancy flux (e.g. Sleep, 1990) and the age of the lithosphere (Langmuir, 1991). At convergent margins, the base of the melting regime is ultimately controlled by the top of the slab,

though the actual initiation of mantle melting is probably somewhat shallower. The top of the melting regime is ultimately constrained by the base of the crust. The large variations in crustal thickness impose changes on the melting regime. Of course, exactly how melting occurs in the complex environment of temperature and mantle flow within the mantle wedge is still subject to debate (e.g. Davies and Stevenson, 1992), but it is clear that crustal thickness imposes the first order constraint on how much melting can occur. Indeed, basalt compositions correlate with crustal thickness, and show the same sense of variation as at ocean ridges (Plank and Langmuir, 1988).

These global relationships are all for average compositions, from a hundred kilometers of ridge length, or an entire island arc, or a chain of ocean islands. Within each of these tectonic settings, there are also local variations, which have a different set of controlling parameters. At ocean islands and slow-spreading ridges, local variations seem to be controlled by from where in the melting regime the basalt is derived—small degree melts from deep, and larger degree melts from shallow (Langmuir and Hanson, 1980; Klein and Langmuir, 1989; Langmuir, 1989; Langmuir, Klein and Plank, 1992). At fast-spreading ridges, however, the local variations seem to be influenced by small scale heterogeneity in the mantle (e.g. Batiza and Vanko, 1984; Zindler *et al.*, 1985; Langmuir, Klein and Plank, 1992). At convergent margins, fluids have an important influence in controlling the local variability among volcanos. A greater fluid input increases the source abundances of elements that are carried by the fluid, and at the same time leads to a greater extent of melting because of the lowering of the melting temperature of the mantle (Miller *et al.*, 1990; 1992; Luhr, 1992; Stolper and Newman, 1994).

The variations in composition of the basalts can be modeled quantitatively at ocean ridges and ocean islands, and are broadly consistent with mantle of uniform major element composition. Furthermore, basalts at convergent margins show

a remarkable coherence with those from ocean ridges, despite the very different tectonic settings and the likely great importance of water in the convergent margin setting. Therefore to first order, and in an average sense, basalts can be modeled successfully from a homogeneous mantle source.

In detail, however, there is clear evidence for modest heterogeneity in all settings. The different ocean basins are subtly distinct from one another. For example, Pacific basalts are high in TiO_2 . When ocean ridges traverse regions influenced by hot spots, the gradients in chemistry provide a high resolution signal of mantle composition. In some cases, such as the Galapagos and Azores hot spots, it is clear that the mantle composition changes at the hot spot. In these two cases, the mantle appears to be depleted in terms of its $\text{Mg}/(\text{Mg} + \text{Fe})$ ratio, but have higher Na_2O contents than normal ridges (Langmuir and Hanson, 1980). In a traverse across Iceland, there is evidence for slightly elevated Na_2O contents in the mantle. Basalts and nodules from Hawaii provide diverse evidence for a more fertile mantle source—the combination of high FeO contents in both melts and ultramafic nodules from beneath the islands, high SiO_2 contents that are not consistent with quantitative melting models, and anomalous Mg-Ni relationships. At convergent margins, deviations from the simple global model outlined above seem to result in part from the existence in some places of a depleted mantle composition in the wedge, as suggested, for example, by Woodhead *et al.*, (1993).

The evaluation of data from a single region in the context of the global systematics for all three tectonic settings can elucidate in much greater detail the existence and nature of the mantle heterogeneity in major elements.

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