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The mantle's fabric

The analysis of mantle-derived rocks on increasingly smaller scales and advances in geodynamic modelling are providing new insights into the nature of mantle heterogeneity and magmatic processes.

It is unlikely that the Earth's mantle — the layer beneath the crust and above the core — was completely homogeneous when it initially formed. Over time, cooling-induced convection as well as partial melting have subsequently played a pivotal role in generating additional chemical heterogeneities in this vast reservoir.

Formation of continental and oceanic crust depletes the convecting mantle in certain elements, but some of these elements are returned to the mantle when the oceanic lithosphere sinks at subduction zones. The mantle can, rarely, be sampled directly, as in the study discussed in the News & Views article on page 215 of this issue. But its composition can also be inferred from basaltic rocks in the oceanic or continental crust, or from chunks of mantle rock that were caught up in the crust.

A compositionally heterogeneous mantle at all length scales has long been postulated by the geodynamics community. The emphasis of most researchers was initially on recognizing and understanding the origin of large-scale heterogeneities, on the order of hundreds of kilometres. However, the focus has gradually shifted towards documenting heterogeneity at much smaller scales and understanding its geodynamic implications. Technological improvements over the past 15 years or so have allowed the acquisition of high-quality data for a whole suite of radiogenic and stable isotopes, such as those of osmium, hafnium, oxygen and lithium. It has also become possible to analyse individual minerals constituting the basalts as well as melt inclusions trapped within the minerals.

Armed with these tools, researchers now study basalts at an unprecedented range of scales, from a fist-sized sample to a tiny melt inclusion. Rocks that were thought to have little compositional variability now appear in an entirely different light. As a result, it is no longer the norm to consider a single sample as representative of a particular basaltic deposit. Researchers are now analysing multiple samples at multiple scales, even for products of single eruptions or intrusions.

Such work has shown that basalts from volcanoes only a few kilometres apart, as well as from within a single volcano, exhibit an amazing level of compositional diversity. The range in compositions at such small spatial scales often encompasses the entire range ascribed to large mantle reservoirs. Not only that, but the same pattern is observed at the scale of individual minerals and melt inclusions.

It is no wonder then that traditional notions regarding the length scale of mantle heterogeneity are being re-evaluated.

Some of this diversity is due to secondary processes, such as assimilation of compositionally distinct material by the basaltic magma. However, there is little doubt that part of the heterogeneity is inherited from the mantle source of the basalts. It is no wonder, then, that traditional notions regarding the length scale of mantle heterogeneity and the mantle's fabric are being re-evaluated. Although such a 'plum-pudding' mantle — one consisting of blobs of one composition dispersed in a matrix of another — has been invoked previously, the data assembled over the past few years provide concrete evidence for its existence. Studies such as the one discussed on page 215 suggest that the mantle is more heterogeneous than previously considered.

These results have important implications for our understanding of the nature of mantle convection, degree of partial melting and extent of magma mixing. Sophisticated geophysical models suggest that convection is an inefficient process — although it is able to stir and disaggregate larger heterogeneities such as subducted slabs, it may be unable to destroy the compositional distinctiveness of the smaller chunks or blobs. The recent geochemical evidence for small-scale heterogeneity provides an important corroboration of these modelling results.

The final product of volcanic eruptions had long been assumed to be homogeneous in terms of its chemical and isotopic composition, owing to rapid diffusion in zones of partial melting, and to mixing during transport or in magma chambers. This is no longer a tenable assumption in view of recent work implying that inefficient mixing of small, compositionally distinct batches of magma is common. Moreover, the existence of imprints of small-scale mantle heterogeneity in basalts from diverse environments suggests that diffusion during partial melting in the source as well as subsequent mixing through the Earth's mantle and crust are insufficient to destroy its signatures.

Basalts have traditionally not been subjected to geochemical studies at a fine scale, unlike their more silicic counterparts such as rhyolites. The fact that this has begun to change bodes well for acquiring better information regarding the exact disposition of heterogeneities in the mantle. Geochemical data are invaluable for this research, but viewed in isolation they are sometimes insufficient to discriminate between signatures derived from mantle sources as opposed to those imprinted by processes such as assimilation of crustal material. Geochemical data should therefore always be carefully evaluated in the context of field relationships and ages.