MANTLE GEOCHEMISTRY

Small-scale stirrings

Rapid plate motions at fast-spreading ocean ridges mix the mantle, yet homogeneous lavas erupted at slow-spreading ocean ridges imply a well-mixed mantle there, too. Numerical modelling suggests that small-scale convection efficiently stirs the mantle beneath slow-moving plates.

David Graham

Variations in the composition of Earth's mantle can provide clues to the evolution of our planet. The extraction of magma from the mantle and the subduction of tectonic plates produce spatial heterogeneity in mantle chemistry. In contrast, convection associated with large-scale plate flow helps homogenize the mantle, so the mantle is expected to be well mixed beneath rapidly moving tectonic plates and more poorly mixed beneath slower-moving plates. However, the geochemical variations observed in basaltic lavas erupted at mid-ocean ridges — which provide a measure of mantle heterogeneity because they originate from partial melting of the uppermost mantle — cannot be easily explained by the regional and global differences in the convective mixing efficiency of the mantle that are expected from known plate motions. Writing in *Nature Geoscience*, Samuel and King[1] show that small-scale convective motions in the mantle have an important and widespread role in reducing chemical heterogeneity in locations where plate-scale motions are inefficient at mixing.

Earth's mantle contains a variety of materials including the residues of partial melting, tectonically recycled oceanic crust, fluid- and melt-altered continental lithosphere, and remnants of primitive mantle that have been left largely untouched since Earth's formation[2]. Mantle convection stretches and folds these materials, leading to a local isotopic composition that is mainly governed by the mantle flow field[3]. Stretching increases the interfacial area between mantle parcels, convective stirring causes transport of those elements within the mantle and folding brings distant parcels closer together. This multiplicative stretching and folding controls the time scales for mixing mantle heterogeneities. Large-scale mantle convection is linked to plate motions, so the variance in the isotopic composition of basalts at mid-ocean ridges is expected to vary with plate spreading rate[4,5]. That is, where the oceanic plates spread apart rapidly, for example, along the East Pacific Rise in the Pacific Ocean, the underlying mantle is efficiently mixed. In these regions, mid-ocean ridge basalts, or MORBs, are quite homogeneous. However, variance in the isotope ratio of helium-3 to helium-4 ($^3He/^4He$) does not follow the simple expectation for MORBs globally[6]. For example, the low variance of $^3He/^4He$ for MORBs sampled from slow-spreading ridges, such as the Southwest Indian Ridge in the Indian Ocean, implies that the mantle there is also well mixed.

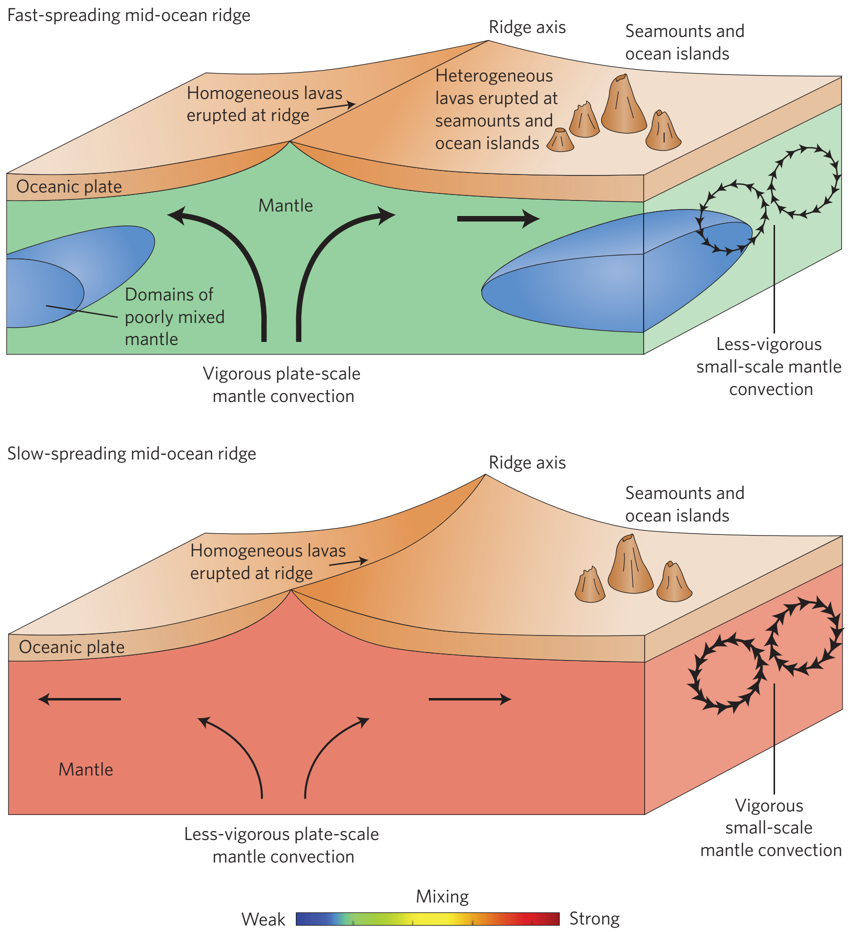

Figure 1 | Schematic illustration of mantle mixing beneath mid-ocean ridges. Lavas erupted at fast-spreading mid-ocean ridges are thought to have a fairly homogeneous geochemical signature because the rapid plate motions help to mix the underlying mantle from which the lavas are sourced. Yet, lavas erupted at slow-spreading mid-ocean ridges are also homogeneous. Samuel and King[1] used a numerical model to show that small-scale mantle convection, which is inhibited beneath fast-moving plates, efficiently mixes the mantle beneath slow-spreading mid-ocean ridges. The variation between mantle mixing efficiency and seafloor spreading rate is thus due to the combined effects of plate-scale and small-scale mantle convection.

Samuel and King[1] used a numerical model to simulate the mixing beneath mid-ocean ridges that spread at different rates. The model combines large-scale mantle flow and plate movements with the small-scale mantle convection that progressively develops beneath a thickening tectonic plate as it ages and loses heat. The model shows that the mantle is most efficiently mixed beneath large tectonic plates that move at slow to moderate rates because small-scale convection becomes well developed. In contrast, beneath smaller and faster-spreading plates, small-scale convection is inhibited and mantle mixing is less efficient (Fig. 1). The results imply that although the plate-scale flow leads to homogeneous lavas erupted at fast-spreading mid-ocean ridges, small-scale mantle convection leads to homogeneous lavas erupted at slow-spreading ridges. In particular, the model reproduces the observed relationship between $^{3}He/^{4}He$ variance and plate speed for mid-ocean ridges around the globe.

The model results also suggest that mixing efficiency is low at distances far from the mid-ocean ridge beneath faster-moving plates. This is surprising, because rapid plate motions were thought to efficiently mix the mantle, irrespective of distance from the ridge. Yet, for plates spreading apart faster than 80 mm per year, small-scale convection is absent and the mantle is mixed only by large-scale plate motions, and the model results indicate that this leads to large, weakly mixed mantle domains beneath some mid-plate regions. This result has far-reaching implications. For example, lavas erupted in the middle of tectonic plates as ocean island basalts, or OIBs, are geochemically heterogeneous. These lavas are thought to be derived from plumes that upwell from the deeper mantle and the geochemical heterogeneity of the lavas is commonly assumed to reflect heterogeneity in the mantle plume. However, the modelling results imply that the geochemical heterogeneity of OIBs should not be solely ascribed to mantle plume heterogeneity and may instead be partly derived from these poorly mixed domains in the shallow mantle.

In the future, small-scale mantle convection should be incorporated into models that simulate the origin and dispersal of heterogeneities throughout the whole mantle[3], or with models for the behaviour of different mantle materials as they ascend into the melting region beneath mid-ocean ridges[7]. One obstacle to an accurate description of the mantle through such comprehensive models is an incomplete understanding of the transport pathways of key elements, such as the noble gases. For example, analyses of xenon isotopes imply that the source regions for OIBs and MORBs have been isolated from each other for more than 4.4 billion years[8]. If true, this seems to preclude mantle plumes as a source of ^{3}He to the upper mantle and makes the origin of the primordial ^{3}He in MORBs unclear.

Samuel and King[1] have developed a numerical model to show that small-scale mantle convection provides an efficient mechanism to mix the mantle beneath slowly moving plates. Such small-scale mixing can therefore explain observations of homogeneous lavas erupted at slow-spreading mid-ocean ridges, such as the Southwest Indian Ridge in the Indian Ocean. The challenge now is to understand how stirring of the mantle over different length scales contributes to mantle composition and evolution globally. ❐

David Graham is at the College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, Oregon 97331, USA.
e-mail: dgraham@coas.oregonstate.edu

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