Heterogeneity in the lower mantle: Constraints from numerical models and chemical geodynamics

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Numerical simulation of convection in the mantle, combined with observational and model constraints from heat flow, cosmochemistry, and geochemistry, is used to investigate models of possible compositional heterogeneity in the lower mantle. Geochemical and heat flow observations appear to require long-lived heterogeneity in the mantle. A variety of models have been proposed, including isolation of ancient subducted crust in the D’’ layer at the base of the mantle, or a dense layer in the lowermost 1000 km of the mantle, or viscous “blobs” in the lower mantle. These models are intended to reconcile diverse inferences about mantle dynamics and structure from geochemical and geophysical observations. Noble gas signatures from mid-ocean ridge basalts, oceanic island basalts, and the atmosphere imply that the mantle is incompletely outgassed. The global heat flow budget, in addition, requires a reservoir of mantle containing a higher concentration of heat-producing elements than the depleted mantle source of MORB. Numerical models of convection using homogeneous bulk composition exhibit rapid mixing, although models that include recycling of depleted lithosphere can yield streaks of mantle with apparently primordial helium isotopic signatures. The most straightforward explanation of all the observations is a compositionally heterogeneous lower mantle. A difference between the composition of the MORB source and the composition of the deep mantle is also consistent with recent estimates of the properties of perovskite at high pressures and temperatures. A transition to a different average composition in the middle of the lower mantle is also supported by recent seismic studies of lower mantle structure. Heterogeneity in the lower mantle may take the form of a hot abyssal layer of variable thickness starting at the mid-mantle or in the lowermost mantle (i.e. D”) or may consist of “blobs” in the lower mantle. We prefer the hot abyssal layer model over the blob model, because hot, neutrally buoyant blobs are unlikely to persist for the long times required by chemical geodynamics. Chemical geodynamics and heat production put bounds on the volume of any dense layer and suggest that the transition to a dense layer should occur between about 1500-2000 km depth. The resulting layer would have to be enriched in heat producing elements compared to the depleted source of MORB. The D” region is unlikely to be the sole repository of any compositional variation; its volume is so small that excessive heat production would be required. Nevertheless, D” cannot be entirely ruled out as a source. Whatever its depth, a hot abyssal layer is likely substantially, but not entirely, isolated from the overlying depleted mantle.

Relating mixing in the mantle to Nd, Sr, and Pb ratios in oceanic basalts

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We present an extension of the conventional geochemical reservoir model for the evolution of the Earth's crust-mantle system in which we calculate not only the mean isotopic ratios, but also the distribution of those ratios within the reservoirs. Owing to low chemical diffusion rates, sub-reservoirs created by mass transport into and out of the mantle effectively exist as distinct geochemical entities for all time. By tracking these sub-reservoirs, we obtain a model of the full range of isotopic values represented in the mantle. Using results from numerical calculations of mixing, we also track the length scales associated with each sub-reservoir. Applying simple statistics, we obtain the distribution of expected measurements as a function of the stirring time, effective melt fraction, sampling volume, and mass transport history. These models allow us to connect isotope geochemistry with mantle dynamics without conducting full-blown thermo-chemical convection calculations.

We first present calculations of isotopic heterogeneity for two simple mantle evolution models and explore the sensitivity of geochemical observables to the variables mentioned. We focus on the Rb-Sr and Sm-Nd systems and are able to reproduce much of the observed complexity of oceanic basalts. Mixing time scales of ~500 Myr, in accordance with dynamical calculations of mixing rates, and sampling length scales of ~100 km yield distributions consistent with observation. We conclude that the differences between isotopic data from mid-ocean ridge basalts and ocean island basalts cannot simply be due to differences in sampling volume, but must also reflect differences in the source reservoirs and/or melting processes. Increasing the size of the ocean island basalt source region by 45% with respect to the mid-ocean ridge basalt source region reproduces the offset between the two distributions, but still fails to explain the more isotopically extreme measurements. Our results show that the argument suggesting that the absence of samples with a primitive isotopic signature indicates that no primitive material remains in the mantle is not valid.

The behavior of the U-Th-Pb system requires that we appeal to more complicated models. For example, we employ a two-layer crust to explain the observation that both the upper crust and depleted mantle appear to have “future” Pb compositions. We show that the ^{207}Pb-^{206}Pb “isochron” as well as the (de)coupling of Pb with the other isotopic systems arise naturally within a continuously convecting and differentiating system.