Tutorial on Geochemical Constraints on mantle evolution and plume structure

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Geochemists sample the mantle by analyzing peridotite outcrops, mantle xenoliths in erupted rocks, and melts produced in the mantle. The latter approach, although it has the disadvantage that we must understand the melting process before we can say something meaningful about the mantle, has the enormous advantage that melts sample the mantle very extensively along ocean ridges, on ocean islands and seamounts, as well as on continental rifts and above subduction zones. This tutorial will concentrate on the data and interpretation obtained from basalts erupted along ocean ridges (MORB) and ocean islands (OIB), primarily in order to avoid the complications arising from crustal contamination common in subduction and many continental settings.

Global chemical evolution of the Earth

Accretion from primitive meteoritic (chondritic) material starting 4.57 Ga ago required several tens of millions of years. Therefore, the "age of the Earth" cannot be sharply defined, but is now often taken to be the age of the "giant impact" of a Mars-sized impactor, which melted and partly volatilized the proto-Earth, produced the moon and completed terrestrial core formation approximately 4.53 Ga ago. Subsequently, the silicate portion of the Earth (the "primitive mantle") was further differentiated by melting, which formed various types of crust through segregation and upward movement of low-density partial melts. It is possible that at the base of the mantle, silicate melt may be denser than its residue. In that case, a dense and (at least initially) partially molten layer may have formed at the base of the mantle, now known as D''.

Crust-mantle budget

Continental crust is thicker and less dense than oceanic crust. Its formation probably requires the presence of water liberated from subducted lithosphere. The mean age of the preserved continental crust is 2 to 3 Ga, several times greater than the mean age of preserved oceanic crust. Separation of the continental crust (about 0.5 % of the total silicate mass) had no measurable effect on the major- element (SiO_2, Al_2O_3, CaO, FeO, MgO) composition of the mantle, but it did change the abundances of the so-called incompatible trace elements (e.g. Th, U, Cs, Rb, Nb, Ta, La etc.) in the mantle dramatically, because roughly half the total terrestrial budget of Th and U resides in the present-day continental crust. This leaves the residual mantle severely depleted in these elements. The magnitude of this effect depends on the bulk partition coefficient between mantle minerals and melt, which in turn depends on the ionic properties (radius and charge) of the various elements, which determine their "goodness of fit" in the silicate minerals. Quantitative modeling shows that the incompatible-element budgets of mantle and crust are approximately, though not perfectly, complementary (Hofmann, 1988; Hofmann, 2003).

Mantle reservoirs

The above relationships also explain the complementary parent-daughter ratios of radioactive decay systems found in continental crust and mantle, i.e. high Rb/Sr and Re/Os, and low Sm/Nd and Lu/Hf, leading to high ^{87}Sr/^{86}Sr, ^{187}Os/^{188}Os, and low ^{143}Nd/^{144}Nd, ^{177}Hf/^{176}Hf in the crust, with the respective opposite ratios in the mantle. Since the isotope ratios in mantle- derived basalts reflect the respective ratios in the source region of these melts, they also indicate the degree of incompatible-element depletion (or enrichment) in the source region of these basalts.

For noble gases, the radiogenic species are alpha-particles (^{4}He) from the decay of U and Th, and ^{21}Ne from nuclear reactions of neutrons and alpha-particles with Mg and O. The relative compatibilities of He and Ne compared with U and Th are controversial. Nevertheless, mid-ocean ridge basalts (MORB), representing the most depleted mantle reservoir, have higher ^{4}He/^{3}He and ^{21}Ne/^{22}Ne ratios than most OIB. This is consistent with the interpretation that the MORB-source portion of the mantle has been degassed at some time in the past, leading to high (Th,U)/(He,Ne) and thus causing the ^{4}He/^{3}He and ^{21}Ne/^{22}Ne ratios to increase with time. In addition, the complex systematics of Xe isotopes requires the existence of at least two Xe reservoirs in the mantle.

Mantle heterogeneity

The above trace element and isotope systematics is the basis of most of mantle geochemistry. Beyond this, one of the main questions is: What is the cause and the spatial distribution of the many isotopic and trace element heterogeneities observed in mantle-derived basalts? It is a wide-spread misconception that mid-ocean ridge basalts (MORB) represent isotopically and chemically homogeneous source regions, whereas ocean island basalts (OIB) represent much more heterogeneous mantle sources. Although it is true that MORB are on average more depleted with a somewhat lower variability than OIB, it is not clear to what extent the lower variability of MORB is the result of mixing in magma chambers rather than a greater homogeneity of the MORB sources. Such a mixing mechanism is indicated by the study of microscopic melt inclusions in magmatic olivines, which invariably show much greater variability than do the host basalts. A much better understanding of the true nature of mantle heterogeneity, as well as higher resolution of convection studies, will be needed to relate the two types of studies and understand the true nature of the scales and spatial distribution of convective stirring and magmatic redifferentiation in the mantle.

Reservoir sizes and locations

An important specific question is which portion of the mantle is occupied by the above-mentioned depleted reservoir. Classical geochemical thinking postulated two primarily (though not perfectly) isolated mantle reservoirs with a chemical boundary at 660 km depth. Recent geophysical evidence increasingly favors vertical transport through this boundary, creating an apparent conflict with geochemical constraints, which continue to require preservation of a relatively primitive mantle reservoir *somewhere*. Tolstikhin and Hofmann (2005) have proposed that the D'' layer at the base of the mantle is sufficiently large to satisfy the geochemical constraints for a reservoir containing primitive noble gases and a significant portion of terrestrial heat production, and they proposed that this reservoir was generated by subduction of a primordial mafic crust shortly after solidification of the early magma ocean. Boyet and Carlson (2005) have provided dramatic new evidence for mantle reservoir containing very ancient mafic crust. They showed that the relative abundance of ^{142}Nd in nearly all terrestrial rocks is about 20 ppm higher than in chondritic meteorites. ^{142}Nd is produced by decay of the extinct nuclide ^{146}Nd ($t_{1/2} = 100 \times 10^6$ yrs). This requires the existence of a very ancient, hidden reservoir with a Sm/Nd ratio lower than the chondritic value, in other words, a reservoir of ancient hidden crust, since crustal rocks invariably have lower Sm/Nd ratios than the mantle rocks from which they originate.

Sources and anatomy of plumes

Another question of great interest to mantle geochemists concerns the origin and internal compositional variation of mantle plumes. Such plumes are compositionally heterogeneous, and because melting is the dominant mechanism for creating chemical heterogeneity, the idea that plumes contain significant amounts of recycled crustal or lithospheric material has gained wide acceptance. Even the alternative, so-called “metasomatic”, hypotheses call on melt migration to generate geochemically enriched lithosphere, which is thought to be subducted and preferentially recycled in mantle plumes. The specific isotopic “flavors” found in various plume-derived OIB (usually called HIMU, EM-1, and EM-2; Zindler and Hart, 1986) are all thought to be created by such crustal or lithospheric material, including the possibility of (generally minor amounts of) continental material. Questions of interest to the geophysical “mantle community” include the mechanism for segregating and storing such crustal material for sufficiently long periods of time in the mantle, spatial scale and evolution of heterogeneities introduced by subduction in response to convective stirring, and the internal structure of plumes including the role of entrainment by plume heads and plume stems. Entrainment by the plume stem is expected to lead to a concentric compositional structure of plumes, and evidence for such variations has been suggested in the literature on the Hawaiian plume. However, recent results from high-resolution Pb isotopic studies of the Hawaiian plume indicate a very different plume structure, which is consistent with the transport of laminar, stretched, large-scale and small- scale heterogeneities from the base of the plume through its conduit, without any evidence for concentric zoning (Abouchami et al., 2005). This is consistent with the most recent numerical results of Farnetani and Samuel (2005) and tank experiments of Kerr and Mériaux (2004). Such results are to be expected if the outer, entrained zones of mantle plume stems are too cool to undergo melting beneath the thick, N-Pacific lithosphere. Consequently, these outer zones are likely to remain “invisible”. These results are also consistent with the observation that erupted melts sample the Hawaiian plume only over a radius of about 50 km, although the total plume radius is expected to be considerably greater.

Melting process and melt extraction

There remains the question how melts are actually sampling mantle compositions, both in ridge and in plume settings. Are the melts being formed in the mantle actually in chemical and isotopic equilibrium with the source rocks? Is the melting process fractional in nature? Are melts extracted by mechanisms of porous flow, or do they quickly collect in fractures and are thus prevented from chemically interacting with the solid phases? Answers to these questions require experimental studies of diffusion and reaction kinetics, solid-melt interface properties, and theoretical work on melt extraction. New insights have come from the study of microscopic melt inclusions in magmatic crystals, particularly olivines. These melt inclusions often show extreme compositional heterogeneities. Originally, these were believed to be caused by fractional melting processes, where successive melt parcels progressively deplete the residue in all incompatible trace elements. However, it is now clear that much of this heterogeneity actually reflects the heterogeneity of the source rocks. This raises new questions, e.g. how such compositional heterogeneity can be introduced into single olivine crystals, which sometimes contain melt inclusions of grossly different compositions, even though these olivines crystallized in relatively shallow magma chambers. Sorting out these problems leaves many theoretical and experimental problems for future research.

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