Can progressive melt extraction from a plum-pudding mantle explain the 'Pb-κ' and Os-isotope paradoxes in MORB?

W. J. Morgan Dept. of Geological Sciences, Princeton University, Princeton, NJ, USA

J. P. Morgan IGPP, Scripps Institution of Oceanography, La Jolla, CA, USA

We explore a geochemical model for mantle evolution where a sequence of hotspot and ridge upwelling has melted the mantle to make hotspot and mid-ocean ridge basalts and their residues, and plate subduction has re-cycled and stirred all of these differentiation products back into the mantle. After billions of years this process has mixed various 'plums' of incompatible-element rich veins within a matrix made from the residues of melting that have been depleted in incompatible elements (Polve and Allegre, 1980). We propose that the mantle experiences progressive melt-extraction as flows upward and melts first deep beneath a hotspot, later more shallowly beneath a mid-ocean ridge. During the first stage, plume upwelling and melting creates an enriched ocean island basalt by extracting a low degree melt (~1–4%) from the rising mantle mixture. Ascent and melting typically stops at the relatively large depth (~70 km) of off-axis oceanic lithosphere. The plums are easier to melt, so proportionally more of the incompatible elements are extracted from these components. After melt extraction, the mixture of leftovers is depleted in composition, even though it still contains ~96–99% of the mass of the original plume upwelling. These depleted leftovers are hot and buoyant so they pond beneath the lithosphere as an asthenosphere layer. When they rise and melt later on beneath a mid-ocean ridge, a depleted mid-ocean ridge basalt is extracted. The now extremely depleted leftovers, ~85% of the mass of the original plume upwelling, accrete to oceanic lithosphere which eventually subducts to recycle leftovers, eroded continental crust, and basaltic plums back into the mantle. In this recipe the two-stage melting process does not change through time, but the rate of mantle overturn slows over time in proportion to the decrease in radioactive heat production.

To make a MORB the veins must be stripped of most of their incompatible elements. Such depletion naturally arises if the MORB source is residual to a recent melting event. In this scenario the OIB source is typical mantle, and the MORB source is derived from typical mantle by a process which effectively subtracts vein components from the mantle. This subtractive derivation of the MORB source from typical mantle contrasts with the conventional scenario, wherein the MORB source is the typical upper mantle, and the OIB source is created by the addition of isotopic heterogeneity to the MORB source through upwelling plumes of typical lower mantle.

The MORB Pb-κ Paradox

The residual origin of the MORB source provides a simple explanation (Gast, 1968) for the long-standing 'Pb-κ-paradox' in MORB (Galer and O'Nions, 1985). The Th/U ratio (κ) measured in MORB is ~2.5, while $^{208}Pb/^{206}Pb$ in MORB implies that the long-term ratio of Th/U in the MORB source was close to the OIB-source ratio of ~4. Since Th and U are both highly incompatible during melting, their ratio in a melt phase closely matches that of the source that melted. Thus the apparent paradox: by the direct Th/U measure, the MORB source has a Th/U ratio of ~2.5, while by the indirect $^{208}Pb/^{206}Pb$ measure, the MORB source appears to have had a long-term Th/U ratio of ~4. However, even though they are highly incompatible elements, the ratio of Th/U in the residues of melt extraction remains sensitive to slight differences between the melt-mineral partition coefficients for Th and U. By most measures, Th is more incompatible than U during melting of garnet or clinopyroxene. Thus, while hotspot melt extraction will strongly deplete both Th and U in the leftovers from melt-extraction, it will deplete Th more than U (Gast, 1968). In contrast, as long as Pb is compatible enough for significant amounts of Pb to survive OIB melt extraction, then $^{208}Pb/^{206}Pb_{MORB}$ will be similar to $^{208}Pb/^{206}Pb_{OIB}$, even though Th/U_{MORB} is much less than Th/U_{OIB}. This decoupling of Th/U and $^{208/206}Pb$ in MORB is a natural consequence of deriving the MORB source as residues of melt-extraction from typical mantle.

Hiding compatible Os within a plum-pudding mantle

Compatible elements can 'hide' within a plum-pudding mantle – while they can be found in abyssal outcrops of highly depleted peridotite, highly depleted restites may never further melt to contribute to OIB or MORB. This may be an important effect in isotopic systems where one element of a radio-isotope pair is compatible and the other element incompatible during melt-extraction. Over Earth evolution, the compatible element will remain in depleted peridotite residues from melt extraction while the incompatible element will be concentrated into recycled plum components. If the most depleted residues undergo pressure release melting during neither plume nor ridge ascent, they contribute to neither OIB nor MORB melts, so their elements are essentially hidden from the melting process.

In a plum-pudding mantle ^{187}Re, an incompatible isotope, is now concentrated in recycled plum components created during previous mid-ocean ridge melting (Since Re is only a moderately incompatible element during pressure-release melting, it is not concentrated into low-degree OIB melts.) The ^{187}Re decays to ^{187}Os, a highly compatible isotope now concentrated in the peridotite residues to ancient (mostly Archaean) prior melt extraction. The OIB has a ~hundred-fold higher Re/Os ratio than its mantle sources, and current results indicate the presence of higher-than-primitive ^{187}Os/^{188}Os in many OIBs (Reisberg *et al.*, 1993; Roy-Barman and Allegre, 1995). Mantle xenoliths from ancient subcontinental lithosphere have consistently lower-than-primitive ^{187}Os/^{188}Os values (Pearson *et al.*, 1995). Such low ^{187}Os/^{188}Os values have never been found in oceanic basalts (Reisberg *et al.*, 1993; Roy-Barman and Allegre, 1995). Our model suggests that they may never be found in oceanic basalts, but they are present in ophiolites, alpine peridotites, and abyssal peridotites. In a plum-pudding mantle, low Re/Os and ^{187}Os/^{188}Os values typify the large volume of MRES that is residual to mantle differentiation. This provides a simple explanation to the mg#-Os isotope trend found in mantle peridotites, where the degree of depletion of the rock (defined by its mg# or fraction Al_2O_3) strongly correlates with the Os-isotopic 'depletion'. However, being the most residual and most refractory material with the highest Mg# and lowest Os-isotopic values, this MRES may have such a high-temperature solidus that it never melts to participate in modern oceanic basalt genesis. This more depleted fraction of MRES would be a large, silent, volume of the mantle, only seen by its absence, through apparent higher-than-primitive ratios of moderately incompatible to highly compatible elements in the OIB and MORB sources.

References

Galer, S.J.G. and O'Nions, R.K. (1985) Residence time of thorium, uranium, and lead in the mantle with implications for mantle convection. *Nature*, **316**, 778–82.

Gast, P.W. ((1968) Trace element fractionation and the origin of tholeiitic and alkaline magma types. *Geochim. Cosmochim. Acta*, **32**, 1057–86.

Pearson, D.G., Carlson, R.W., Shirey, S.B., Boyd, F.R. and Nixon, P.H. (1995) Stabilisation of Archaean lithospheric mantle: A Re-Os isotope study of peridotite xenoliths from the Kaapvaal craton. *Earth Planet. Sci. Lett.*, **134**, 341–57.

Polve, M. and Allegre, C.J. (1980) Orogenic lherzolite complexes studies by 87Rb-87Sr: A clue to understand the mantle convection processes? *Earth Planet. Sci. Lett.*, **51**, 71–93.

Reisberg, L., Zindler, A., Marcantonio, F., White, W., Wyman, D. and Weaver, B. (1993) Os isotope systematics in ocean island basalts. *Earth Planet. Sci. Lett.*, **120**, 149–67.

Roy-Barman, M., and Allegre, C.J. (1995) 187Os/186Os in oceanic island basalts: tracing oceanic crust recycling in the mantle, *Earth Planet. Sci. Lett.*, **129**, 145–61.