Dynamical constraints on mantle reservoirs through time

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It is now generally accepted that Earth formed hot, due particularly to a giant, moon-forming impact late in accretion. A resulting magma ocean probably cooled on a geologically short timescale, and may not have left a strongly differentiated mantle, due to vigorous internal mixing, except possibly in the D” region. Loss of excess initial mantle heat would have taken ~0.5 Gyr. Core cooling is controlled by mantle plumes and may always have been slow. Plume activity may have been 2-8 times stronger during the Hadean and early Archean.

The Earth’s surface would have cooled early, soon after the last giant impact (~4.45 Ga?). An active mantle would be expected to produce mafic crust at a substantial rate, and this may have tended to founder episodically, possibly in large bodies. Conceivably some of these persist in D”.

Gravitational settling of foundered or subducted mafic crust could have left the upper mantle strongly depleted, explaining isotopic evidence of stronger early depletion of incompatible elements. This upper mantle would produce only a thin mafic crust, which would facilitate an early start to plate tectonics and efficient cooling of the mantle.

A ‘basalt barrier’ may have formed within the transition zone, yielding a cool upper mantle and a hot lower mantle. Episodic breakdown and overturn of this stratified mantle during the first 1-2 Gyr could have volcanically resurfaced much of the planet.

An accumulation of denser mafic material in D” probably formed early. This persists strongly to the present, though it might not be able to form now. It could retain a record of major melting events from throughout Earth history.

No other mantle stratification is plausible at present. A putative thick layer in the lower mantle should produce mantle plumes several times stronger than what is observed, so it is unlikely.

Lithologic heterogeneity of the mantle probably formed early from foundering differentiated material. Much of the mantle complement of incompatible elements may be carried in hybrid pyroxenite, formed by reaction of melt from mafic inclusions with surrounding peridotite. Noble gases plausibly persist from the early Earth in this material, and the present mantle complement of incompatibles may be 2-3 times previous estimates, whose assumptions make them lower bounds.

Dynamical geochemistry

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Despite progress in reconciling important aspects of mantle chemistry with dynamics, mass balances of key elements and observations of noble gases have remained enigmatic. Resolution may follow from taking fuller account of the lithological heterogeneity of the mantle [1].

The Hofmann-White-Christensen reconciliation of refractory trace elements and their isotopes with the dynamical mantle has been strengthened by work over the past decade. The apparent age of lead isotopes and the broad refractory-element differences among and between ocean island basalts (OIBs) and mid-ocean ridge basalts (MORBs) can now be quantitatively accounted for with some assurance.

Noble gases may reside in a so-called *hybrid pyroxenite* assemblage that is the result of melt from fusible pods reacting with surrounding refractory peridotite and refreezing. Hybrid pyroxenite that rises off-axis may not remelt and erupt at MORs, so its volatile constituents would recirculate within the mantle. Hybrid pyroxenite is likely to be denser than average mantle, and thus some would tend to settle in the D” zone at the base of the mantle, along with some old subducted oceanic crust. Residence times in D” are longer, so the hybrid pyroxenite there would be less degassed. Plumes would sample both the degassed, enriched old oceanic crust and the gassy, moderately enriched hybrid pyroxenite and deliver them to OIBs. This model can account quantitatively for the main He, Ne and Ar isotopic observations, and for the poor correlation of unradiogenic gases with refractory-element enrichment in OIBs.

The difficulty with mass balances can be traced to the common inference that the MORB source is strongly depleted of incompatible elements. However conventional estimates focus on an ill-defined “depleted” mantle component while neglecting less common enriched components. Recent estimates have also been tied to the composition of peridotites, but these probably do not reflect the full complement of incompatible elements in the heterogeneous mantle. New estimates that account for enriched mantle components can satisfy mass balance requirements, although some additional uncertainties apply to argon. The result is that the MORB source is depleted by only about a factor of 2, relative to the primitive Earth.

[1] G. F. Davies, (2011) *Dynamical geochemistry of the mantle, Solid Earth Discuss.*, **3**, 249-333, www.solid-earth-discuss.net/3/249/2011/