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Possible Causes of Trace-Element Stratification in the Mantle

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It is a straightforward inference that the mantle is stratified in trace element and isotope characteristics, since MORBs, sampling the shallow mantle, are different from OIBs, sampling deeper mantle via plumes. A continuing question is whether there is an accompanying stratification in major element composition and intrinsic density. It is also not clear whether the trace-element "stratification" is in the form of continuous variation with depth or in layers with sharply defined boundaries. Seismic tomography and other geophysical evidence for a substantial mass flux through the 660-km seismic discontinuity has been widely accepted as implying that this is not a major compositional boundary. Interest has now focussed on what physical changes in the deeper mantle might account for the trace-element stratification of the mantle. The three main possibilities are (1) vertical variation in viscosity, (2) lateral variation in rheology, and (3) stratification of intrinsic (compositional) density.

There is long-standing evidence that the viscosity of the deep mantle is higher than in the shallow mantle by 1-3 orders of magnitude, with some of the increase concentrated at 660km. The evidence comes from studies of post-glacial rebound and from the geoid signature of subduction zones. Numerical models show that subducted lithosphere descending into higher viscosities at depth buckles in a manner reminiscent of seismic tomography features that have been interpreted as descending lithosphere. Therefore seismic tomography does not, by itself, require a separate layer in the bottom third of the mantle, as some have suggested.

Mass balances of trace elements, including the heat source elements K, U and Th, imply that the deep mantle is less depleted on average than the MORB source, but it is not clear how to reconcile these chemical constraints with thermal constraints. A distinct layer of enriched material in the deep mantle could satisfy the geochemical constraints, but it would imply that plumes would rise from above this layer and would carry 50% or more of the earth's heat budget, whereas the sizes of hotspot swells imply that plumes carry no more than 10% of the earth's heat budget. A gradational enrichment with depth would not violate the plume constraint, but we do not know at present whether the enriched mantle would remain at depth, or would rise buoyantly because of its higher internal heating.

Current geochemical data suggest that the chemical differences between the MORB source and the OIB source may be smaller than has been previously thought. Recently discerned systematics imply that the concentrations of helium in the MORB source and OIB sources differ by less than an order of magnitude. Radiogenic isotopic ratios of helium, neon and argon in MORBs and OIBs also differ by factors of only 2-5. The range of OIB isotopic ratios in the Nd, Sr and Pb systems is only 2-3 times the range in MORBs.

The only clear exception to this pattern comes from the traditional version of the earth's argon-40 budget. This has recently been questioned because it implies that the concentration of argon-40 in the lower mantle would be a factor of 50-100 greater than in the upper mantle, which seems to be inconsistent with the geophysical constraints on the vertical mass flux. Possible resolutions are that the earth's potassium content has been over-estimated, or that argon has been lost from the earth entirely, or both. Recent indications of distinct peaks of impact bombardments of the Moon at 3.2Ga and in the Phanerozoic suggest that a significant fraction of the atmosphere might have been blasted away in the course of earth history.

Numerical modelling now in progress suggests that much of the required moderate differences between the top and the bottom of the mantle might be generated by viscosity stratification, without recourse to compositional layering. Although previous models have shown little effect due to a viscosity jump by a factor of 30 across the transition zone, we find that models in which the viscosity continues to increase exponentially with depth by another factor of 30 or more through the lower mantle develop substantial vertical differences in the proportion of mantle that has been processed through a shallow melting zone. However some deep compositional stratification cannot be excluded, and the exploration of models continues.