# Geochemical reservoirs and whole-mantle convection

A. W. Hofmann

Max-Planck-Institut für Chemie, Postfach 3060, 55020 Mainz,
Germany and Laboratoire des Sciences de la Terre, Ecole Normale
Supérieure de Lyon, 69364 Lyon, France

There are currently four rather separate approaches to study the evolution and present state of mantle dynamics, (1) geochemical characterization of mantle reservoirs by studying isotopes and trace elements in mantle rocks and mantle-derived melts, (2) high-pressure mineralogy, (3) numerical simulation of mantle convection, and (4) seismic tomography. Relevant geochemical data have been accumulating over the past 30 years, but quantity, quality and isotopic variety of geochemical data have increased dramatically within the past ten years. Similarly, increasingly rapid progress has been made in the fields of high pressure mineralogy and convection studies, but the most dramatic advance, at least from the point of view of an 'outsider', has come from seismic tomography during the past four years (Grand, 1994; van der Hilst *et al.*, 1997). The detailed delineation, by independent methods, of high-velocity 'slabs' reaching through the 660 km seismic discontinuity and into the deep mantle is widely accepted as prima-facie evidence for deep subduction and, by implication, for whole-mantle convection. High-pressure mineralogy has shown that the 660 km discontinuity corresponds to a major mineralogical phase transition from ringwoodite (= γ-phase olivine) to a Mg-perovskite-magnesiowüstite assemblage in the deep mantle. Most workers in that field now agree that no difference in bulk major-element composition between upper and lower mantle is required to satisfy mineralogical and geophysical constraints. However, whole-mantle circulation could still be inhibited by a dramatic shift in viscosity or by a strongly negative slope ('Clapeyron slope') of the ringwoodite-perovskite transition. Numerical modelers of mantle convection, perhaps partly as a result of the seismic evidence, are also increasingly concerned with whole mantle circulation, and they have been developing models whereby the 660 km seismic discontinuity may retard or temporarily stall vertical movement, rather than inhibiting circulation between upper and lower mantle altogether. To be sure, there are holdouts and heretics in the fields of geophysics and mineralogy who stick to (compositionally and convectively) strongly layered mantle models, but the majority of workers in these fields are now worshipping at the altar of whole-mantle convection.

Geochemists, in contrast, have been spoiling the fun of uninhibited whole-mantle convection by pointing to the evidence from noble gas and other (no less noble) isotopes, which require the long-term persistence of separate geochemical reservoirs, and are most easily explained if the upper and lower mantle layers convect separately. This isolation may be disturbed by leaks through the 660 km boundary, but these leaks must be small enough to keep the upper and lower mantle reservoirs from being homogenized. In short, the 1new paradigm' explaining how Earth really works still eludes us, as Dev. L. Advocate (1998) has reminded us.

What does geochemical evidence tell us? To start with, geochemistry *per se* provides no evidence for layering. Only in conjunction with other observations and their interpretation can geochemical evidence be interpreted in terms of Earth models. For example, we do not know from geochemistry that the source reservoir of mid-ocean ridge basalts is located in the upper mantle. Rather, we infer this from the observation that the lateral movements of spreading ridges appear to be controlled by plate geometry and movements, in other words by near-surface phenomena. Ridges respond passively to these controls, and common sense seems to dictate that they tap the asthenosphere lying directly beneath the plates. In contrast, hotspots or plumes, whether they are stationary of not, are strongly decoupled from plate movements. The common-sense inference is therefore that they are derived from deeper levels. In any case, it should be remembered that none of this is dictated by geochemistry. What geochemical evidence does tell us is that (1) sources of hot spot magmatism are different from those of mid-ocean ridge basalts; (2) the source reservoirs have in most cases been kept separate for several hundred million years, in some cases for as much as 1.5 to 2 Ga (Austral-Cook and St. Helena hotspot sources); (3) not all of the mantle is as depleted in incompatible trace elements as the MORB source, and the remainder is not made up entirely of hot-spot sources, but a significant portion is either still 'primitive' or in any case less depleted than the MORB-source reservoir. The validity of this last constraint depends, however, on the approximate correctness of the chondrite model for the bulk composition of the Earth, because it is obtained by a simple mass-balance calculation. Best estimates, using geochemical parameters as different as Nd isotopes, Nb/U ratios, the amount of radiogenic argon accumulated in the atmosphere, or the imbalance between the (nearly negligible) heat production in the MORB-source mantle and heat flow in the oceanic crust, all lead to the conclusion that only about 50% of the mantle has been depleted as a result of the production of continental crust. An undepleted or less depleted remainder is still 'down there' with enough Th, U and K to produce heat and radiogenic argon, enough other incompatible trace elements to balance the chondritic Earth budget for Nd isotopes and trace element ratios such as Nb/U, and enough primordial noble gas to account for the 'solar-type' He and Ne isotopes found in some but not all of the hotspots.

The combined weight of the geochemical evidence mentioned above favours mantle evolution and circulation models that provide for some, but very limited exchange of material between the upper and lower mantle. If subducted oceanic lithosphere were to enter the lower mantle routinely, the equally massive counterflow from the lower to the upper mantle would replace the upper mantle with lower-mantle material within a few hundred million years. Strontium isotopes in the MORB reservoir provide possibly the strongest constraint relevant to this scenario. The $^{87}$Sr/$^{86}$Sr ratio of any primitive mantle reservoir increased from 0.699 (4.5 Ga ago) to 0.7025, the value of ordinary depleted Pacific and Atlantic MORB, about 2 Ga ago, and its present values is about 0.7048. If large amounts of this lower-mantle material had routinely entered the upper mantle since 2 Ga ago, the $^{87}$Sr/$^{86}$Sr ratios of the upper mantle would have irreversibly increased above 0.7025. Subsequent redepletion processes in the upper mantle could not undo the poisoning effect of the introduction of such high-$^{87}$Sr/$^{86}$Sr material. Such irreversible poisoning has indeed taken place in the upper mantle beneath the Indian Ocean, but it came from the continental crust or subcrustal lithosphere, not the lower mantle. In contrast, the Pacific upper mantle has remained virtually free of geochemically detectable contamination either from the crust or the lower mantle for the past 2 Ga or so.

The validity of the above arguments depends on our knowledge of the approximate composition of the silicate Earth. It also depends on the assumption that material introduced into the upper mantle is mixed into this reservoir relatively rapidly by convection. Clearly, if the contaminating material can somehow escape the convective mixmaster in the upper mantle, it could conceivably be removed before it becomes involved (and therefore 'visible') in MORB melting. Again, there are no specifically geochemical constraints to prevent this, but current understanding of convective mixing and melt extraction cannot be said to favour such a scenario.

Can we have our cake and eat it too? Perhaps. It is important to remember that seismic tomography gives an instantaneous image of the Earth's interior today, and today only. In contrast, isotope geochemistry records the time-integrated evolution of the various reservoirs over 4.5 Ga of Earth history. This evidence dictates that whole-mantle convective mixing has not taken place during the last 1–2 Ga. We therefore need to think of mechanisms, in which deep subduction does not automatically lead to whole-mantle mixing or rapid replacement of the depleted upper mantle by less depleted lower mantle. Perhaps, deep subduction and concomitant deep-mantle upwelling are episodic and rare (Stein and Hofmann, 1994) or exclusively recent (Allègre, 1997) phenomena. In this context is also important to know which form the upwelling from the deep mantle takes. Do present-day mantle plumes originate at the core-mantle boundary or at the 660 km boundary or both? Can we distinguish deep-mantle plumes from shallow-mantle plumes by their isotopic composition? Clearly, these are important areas for future collaborative research where new, high-resolution seismic tomography can help to interpret the existing, large volume of geochemical data from mantle-derived rocks and vice versa.

## References

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