

Earth's mantle: Old concepts change yielding place to new

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Studies and debates on the earth's mantle, its composition, structure and dynamics, conducted during the last 25 years, have rather added more grist to the mill of conflicting perceptions than in achieving a model satisfying all geochemical and geophysical constraints. During the 1960s, on the basis of distinctly different chemistry shown by the two major classes of mantle-derived basalts – MORBs and OIBs (the latter with more primitive composition), and also from data on noble gas and isotope abundance, it was conjectured that the earth's mantle is divided into an upper layer depleted in composition (source for MORBs) relative to that of early bulk silicate earth (BSE) and a lower layer (source for the OIBs), close to BSE composition with C-1 chondritic high He^3/He^4 ratios, quite unlike those of the MORBs. A seismic discontinuity present at a depth of 670 km, was considered a barrier separating the two independently convecting regions.

Accumulating new data, in the decades following 1960s, disputed these ideas about independently convecting mantle layers and prompted revisions to its structure and geochemistry. For example, they suggested that the claimed unique isotopic composition of Nb, U, Ce, Pb observed for oceanic mantle could as well have evolved by mixing of depleted MORB mantle and enriched components¹. Also, studies on U/Th ratio from Pb and Th isotopes as well as non-primitive trace element ratios for Nb/Th, Nb/U, Ce/Pb and Sn/Sm, all pointed to some mass exchange between the upper and lower mantle contrary to the established notions favouring an isolated pristine lower mantle. In the last ten years alone, studies on samples from the deep mantle have shown how fractionation processes indeed had operated in lower mantle reservoirs, even in early earth times and hence survival of a reservoir with primitive composition is unlikely²⁻⁴. Rejecting the argument that He-ratios for the OIBs are exclusive and primitive, a statistical appraisal of several of the new datasets has indicated that these ratios in lower mantle-derived OIBs are not exceptionally higher than those in the MORBs⁵. Some also pointed out how conclusions from noble gas geochemistry had in the past ignored

that their concentrations in rocks and minerals are highly site-dependent, being controlled by physico-chemical parameters operating during magmatic processes at that site. Since these parameters will not be the same at all places, inferences based on noble gas abundance from one site cannot be generalized and applied universally⁶.

Several improved geophysical data from high-pressure phase-transition experiments, seismic tomography and geodynamic studies based on geoid, gravity and viscosity have also doubted the layered mantle concept. The 670 km discontinuity, well established as an effective chemical barrier between the upper and lower mantles, has ceased to be so. Instead, this junction is supposed to represent a mineral phase change – from a less dense upper mantle spinel structure to a denser, lower mantle perovskite structure (a density difference of 10%), as well as a change to a more viscous lower mantle⁷. Conclusions from global tomography interpreting the observed seismically fast areas as images of subducting slabs, some extending up to the core/mantle boundary (CMB) and spreading laterally, were taken to imply mantle mixing. The resulting distortions in convection are believed to give rise to magma upwellings having anomalous chemistry⁸.

The process of subduction of mafic crustal slabs could introduce mantle contamination and compositional heterogeneity and this is now well brought out through reliable geochemical indicators⁹ such as the isotopic systems of Hf, Os, O and Ne. Besides, several studies have identified low-pressure mineral inclusions (e.g. in diamond, garnet, etc.) testifying to the slab's sojourn in the deep mantle. At the same time, some geochemists, while endorsing the presence of seismically fast areas, have pointed out that temperature effects at high-pressures are small and that these thermally fast areas seen in the deep mantle tomography instead of representing penetrating slabs can as well signify areas of chemical and mineralogical contrasts, possibly presence of geochemical reservoirs of composition different from surrounding mantle or in other words, denoting existence of chemical heterogeneity^{10,11}.

Today, many of these findings seem to point to whole-mantle mixing and they question the existence of an isolated primitive lower mantle. However, the issue plaguing the concept of whole-mantle mixing is the persistence of heterogeneity in the mantle even after 4.5 billion years of earth's evolution, for which explanations by either geochemistry or geophysics have not been wholly satisfactory. Recognizing the existing impasse between geochemical and geophysical conclusions, a recent review² has stressed that geochemical models to be viable cannot disregard the dynamic geophysical parameters controlling mantle chemistry. Likewise, geophysical models have to take note of mass balance constraints and also satisfy geochemical findings. Besides, there also exists another fundamental difference in data acquired by the two methods. Whereas all geochemical data pertain to the mantle at specific periods of geological evolution, geophysical data relate only to the state of the present earth. Appropriately therefore, several of the new conclusions arrived from recent investigations have integrated physical, chemical and temporal controls over mantle evolution and have offered explanations for the observed long-lived heterogeneity².

One of the early explanations¹² visualized a two-layered independently convecting mantle initially, at which time the lower mantle remained pristine. However, this changed drastically 500 m.y. ago due to breakdown of the 670 km barrier, this event triggered by the changed Raleigh number of the mantle causing catastrophic sinking of subducted slabs (slab avalanching) piled up at the 670 km discontinuity¹³. Based on xenon and Pb isotope data from the MORB source region in the upper mantle and measurement of stirring time, this model suggested a division of the upper mantle, one above the 400 km discontinuity (asthenosphere) with rapid mixing and another between 400 and 600 km with sluggish mixing¹². However, critics have questioned how such a break-up of the layered system could be achieved and why such a drastic change in convection mechanism had not left any record in surface geology².

Another view has attributed mantle heterogeneity to the presence of large-sized

lumps or blobs (> 800 km radius) of primitive material in the lower mantle. Because of their high viscosity, these blobs could survive 4 billion years of convection and probably they are also the source for several plumes rising from the lower mantle¹⁴. Investigations based on dynamical, thermal (density–buoyancy effects), geochemical and rheological effects of the blob model have supported such a state, which could also explain some of the disagreements between geochemical and geophysical data¹⁴. Detection of a strong discontinuity in the lower mantle at about 1600 km depth, has led to another version of mantle structure. It is considered that this depth marked the junction between a heterogeneous upper mantle and a pristine lower mantle retaining substantial heat-producing radioactive elements, which would explain the anomalous heat flow and rare gas isotope anomalies. The upper zone carrying the subducted material mixed with depleted and enriched mantle, could then resolve the complex geochemistry of oceanic basalts¹⁵.

A new report on deep mantle mineralogy has recently pointed out that a 200–300 km thick region at the base of the lower mantle, just above the CMB, has a different high-pressure crystalline phase – a newly discovered phase termed post-perovskite structure¹⁶. It is believed that this phase change could considerably influence rheology of the lowermost mantle and introduce unusual geochemical trends like accommodation of elements like Na, K, U and Th, suggesting deep mantle layering and a global heterogeneity. It is also speculated that earth's core may be a source for the anomalous excess heat flow flux, high ³He/⁴He ratios and possibly

also for the primitive noble gas abundance¹⁶. Considerable amount of radiogenic K is believed to have partitioned into the core¹⁷ during core formation. Similarly, U and Th are thought to have been extracted from the early magma ocean, as FeS alloy, into the core in amounts enough to initiate a 'georeactor' that could account for the extra heat flow flux and ³He excess¹⁸.

Results from a large volume of geochemical and geophysical investigations, particularly over the last couple of decades, have undoubtedly shown how the layered mantle concept is difficult to accept. They have proved co-existence of both homogeneity and heterogeneity in the mantle; the latter, perhaps less dominant. Interesting reports on core–mantle exchanges, appearing lately, seem promising in overcoming many of the observed anomalies about the earth's mantle and perhaps a synthesis of data expected from many on-going multidisciplinary approaches may be able to provide a unified model about mantle structure and composition.

1. Hofmann, A. W., *Nature*, 1997, **385**, 219–228.
2. Van Keken, P. E., Hauri, E. H. and Balentine, C. J., *Annu. Rev. Earth Planet. Sci.*, 2002, **30**, 493–525.
3. Jochum, K. P., Arndt, N. T. and Hofmann, A. W., *Earth Planet. Sci. Lett.*, 1991, **107**, 272–285.
4. Srivastava, R. K., *DCS Newsl.*, 2005, **15**, 1–6.
5. Anderson, D. L., *Int. Geol. Rev.*, 2000, **42**, 289–311.
6. Kaneoka, I., Goldschmidt Conference, Abstr., Award Lecture, Japan, 2003.
7. Ito, E. and Takahashi, E., *J. Geophys. Res.*, 1989, **94**, 10637–10646.
8. Van der Hilst, R. D., Widiyantoro, S. and Engdahl, E. R., *Nature*, 1997, **386**, 578–584; Grand, S. P., Van der Hilst, R. D., and Widiyantoro, S., *GSA Today*, 1997, **7**, 1–6.
9. Hauri, E. H., *Philos. Trans. R. Soc. London Ser. A*, 2002, **360**, 2371–2382.
10. Anderson, D. L., AGU Meeting, Carnegie Institution of Washington (Abstracts), 2003.
11. Trampert, J., Deschamps, F., Resovsky, J. and Yuen, D., *Science*, 2004, **306**, 853–856.
12. Allègre, C. J., *Earth Planet. Sci. Lett.*, 1997, **150**, 1–6; *Philos. Trans. R. Soc. London, Ser. A*, 2002, 2411–2421.
13. Stein, M. and Hofmann, A. W., *Nature*, 1994, **372**, 63–68; Condie, K. C., *Tectonophysics*, 2000, **322**, 153–162.
14. Becker, T. W., Kellogg, J. E. and O'Connell, R. J., *Earth Planet. Sci. Lett.*, 1999, **171**, 351–365.
15. Kellogg, L. H., Hager, B. H. and Van der Hilst, R. D., *Science*, 1999, **283**, 1881–1884.
16. Iitaka, T., Hirose, K., Kawamura, K. and Murakami, M., *Nature*, 2004, **430**, 442–445; Oganov, A. R. and Ono, S., *Nature*, 2004, **430**, 445–448; Ono, S., Ohishi, Y. and Mibe, K., *Am. Mineral.*, 2004, **89**, 1480–1485.
17. Lee, K. K. M. and Jeanloz, R., *Geophys. Res. Lett.*, 2002, **30**, 2212; Gessmann, C. K. and Wood, B. J., *Earth Planet. Sci. Lett.*, 2002, **200**, 63–78.
18. Hollenbach, D. F. and Herndon, A. N., *Proc. Natl. Acad. Sci. USA*, 2001, **98**, 11085–11090; Porcelli, D. and Halliday, A. N., *Earth Planet. Sci. Lett.*, 2001, **192**, 45–56.

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