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New Mantle Convection Model May Reconcile Conflicting Evidence

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Recently, a new model for mantle convection was proposed that may be more realistic than previous standard models. Exciting questions remain, of course, but we believe it can be used to reconcile otherwise conflicting evidence from different research fields and thus provide a new framework for further studies of convection.

Drawing on some of our own recent work [Albarède, 1998] and that of others we further explore the model proposed by Kellogg et al. [1999] and Van der Hilst and Kárason [1999]. The new view considers that a deep layer, chemically distinct from the overlying layers, occupies roughly the lower third of the mantle. Such a deep layer would host a substantial fraction of the terrestrial heat producing elements and help close the budget of some critical isotopic systems. The subtle trade-off between chemical and thermal density variations produces significant dynamic topography, which complicates its seismic detection but facilitates downwelling slabs to pierce through it. Thermal plumes would form at the transition between the boundary layer and the overlying part of the convective mantle. Severing the tie between thedepleted and less depleted and outgassed reservoirs and the seismologically identified upper and lower mantle, separated by the 660-km discontinuity, seems to go a long way toward reconciling the otherwise conflicting pieces of evidence.

The Controversy

In the past half century, the nature and scale of mantle convection has been one of the big puzzles in Earth sciences. A major challenge has been to understand, evaluate, and reconcile the range of observations and constraints provided by different scientific disciplines.

On the one hand, the geochemical signature of ocean floor basalts and Earth's heat budget (the balance between heat production and heat loss) suggest that distinct mantle reservoirs have retained a separate identity for 2 billion years or more. The morphology of and depth to these reservoirs is not constrained, but the heat and mass balances indicate that they must comprise a significant fraction of the mantle, and a major reservoir boundary is typically placed 660 km deep. On the other hand, although subducting plates seem to be occasionally deflected by the 660-km discontinuity, seismic tomography evidence for substantial amounts of cold material breaking the limit and reaching the core-mantle boundary (CMB) seems overwhelming.In addition, computer simulations of mantle flow show that long-term segregation at the upper-to-lower mantle interface is actually difficult to achieve, unless the lower mantle is intrinsically more dense than (and thus compositionally distinct from) the upper mantle. But this is not supported by geophysical and petrological evidence.

Some important concepts and constraints have emerged from the latest developments in the geochemistry of oceanic basalts, computational geodynamics, and high-resolution mantle tomography. Yet reexamination is needed of even the most implicit assumptions of the antagonistic models of whole-mantle (Figure 1.1) and layered convection (Figure 1.2) in order to identify precisely where each fails and how the combined geophysical and geochemical evidence can be pieced together into new classes of convection models.

Issue of Composition

The geochemist's view of mantle convection is deeply intertwined with the issue of the composition of the deep mantle. With the exception of rare inclusions in diamond, geological processes fail to deliver unprocessed samples from the mantle below the 660-km discontinuity to the surface.

Short of prima facie geochemical evidence, an indirect approach must therefore be employed. Geochemical observations contribute to the debate on mantle convection through first principle arguments of mass balance and radioactive decay. Some of the most relevant elements of discussion follow.

- The heterogeneities in physical properties that are imaged by seismology and modeled numerically largely reflect variations in pressure, temperature, and major element mantle composition. The mantle sources of mid-oceanridge basalts (MORB) and ocean island basalts unambiguously differ by their distribution of lithophile trace elements and their isotopic composition of refractory radiogenic elements, and also to some extent by their major element compositions.
- Virtually unprocessed after planetary accretion, ordi-

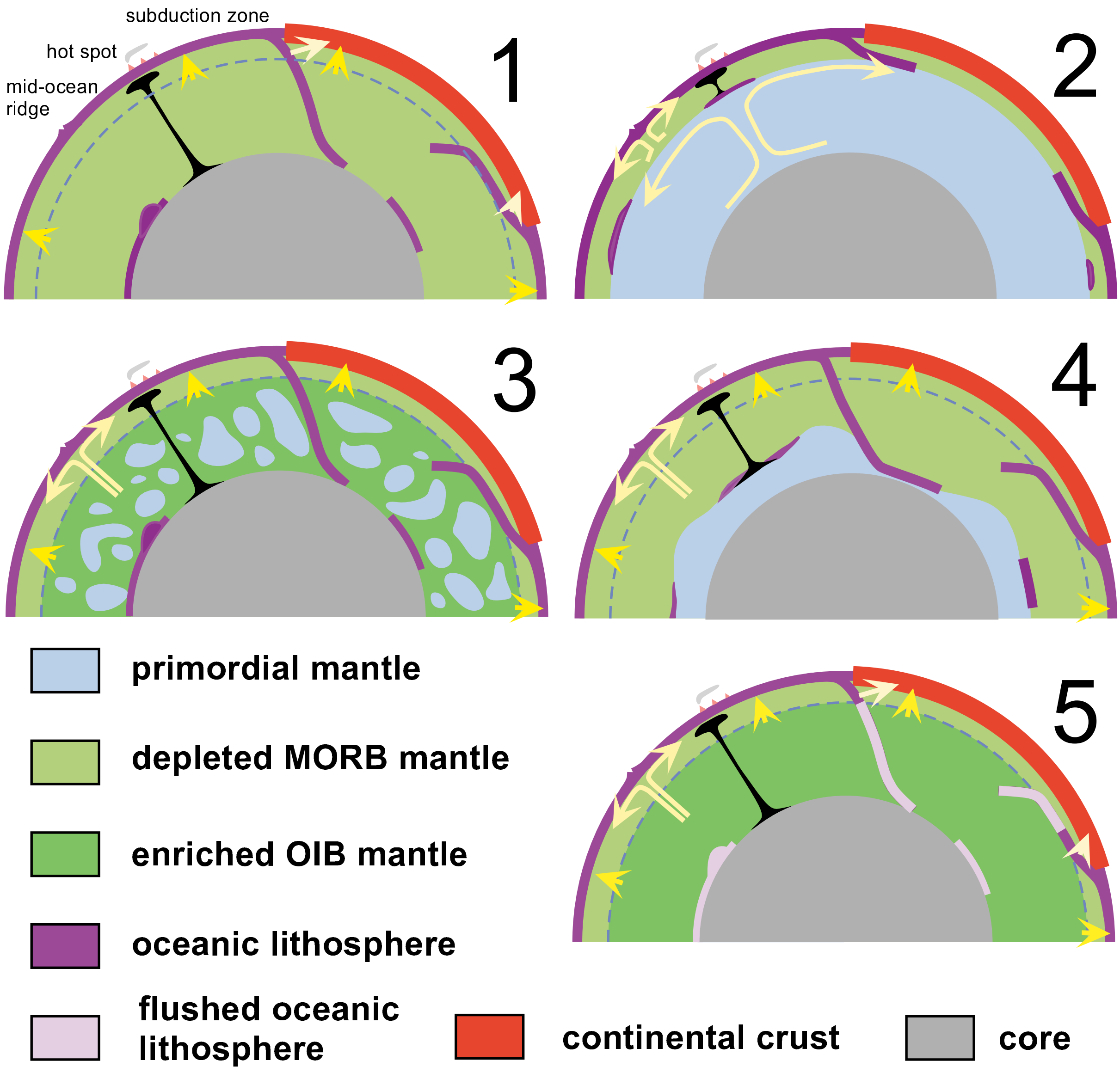

Figure 1. Summary of mantle convection models. 1) Whole mantle convection: plates break through the transition zone. 2) Layered mantle convection: plates are confined to the upper mantle. 3) Whole mantle convection with deep blobs of primordial mantle. 4) Layered mantle convection with a deep layer of primordial mantle. 5) Whole mantle convection with plate depletion at subduction zone.

nary chondrites should provide, at least for the least volatile elements, a compositional analog of terrestrial planets more closely than any igneous material.

- The part of the mantle that is sampled by MORB is both outgassed and thoroughly depleted in lithophile elements– those elements, such as Rb, Ba, the rare-Earth elements, and the radioactive elements, K, U, and Th, that are concentrated in the continental crust.

- At least some part of the deep mantle is apparently undegassed. The "argon argument," as most clearly formulated by Allègre et al. [1996], contends that about 50% of the radiogenic ^{40}Ar produced through geological time by the decay of ^{40}K is still sequestered in an undegassed lower mantle. From the 20 ppb and a K/U ratio of 12,000 in the bulk silicate Earth, the argon budget is easily obtained from the radioactive ingrowth over 4.56 Gyr. The relatively unradiogenic character (high ^{3}He/^{4}He) of the helium tr apped with CO_2 bubbles in olivine crystals from the Loihi seamount off Hawaii and other hot spot basalts also seems to indicate that the mantle source of oceanic island basalts (OIB) has lost far less of the stable 3He and therefore is far less degassed than that of MORB. Association of a mantle region enriched in heat producing elements with the source of ^{3}He/^{4}He is problematic and this aspect of models such as that of Kellogg et al. [1999] requires further study.

- Isotopic evidence indicates that, although they carry the mostprimitive ^{3}He/^{4}He signal, OIB come from a source dominated by components derived from the recycled oceanic lithosphere. The essential igneous and sedimentary parts of the recycled oceanic crust have now been isotopically fingerprinted in the mantle source of OIB [see, e.g., Hauri and Hart, 1993, Hofmann, 1997]. The conflict between the signals sent by rare gas and by lithophile isoto pes has, however, received surprisingly marginal attention in the geochemical literature. It requires either that the nature of recycled material does not affect the relatively primordial He signal of the deep mantle [Albarède, 1998] or that plumes originate from the boundary between an undegassed reservoir hidden at the bottom of the mantle and the overlying lumps of recycled lithosphere [Kellogg et al., 1999].

Against Whole-Mantle Convection

A simple assessment of replacement times shows that, as long as mater ial is transported across the 660-km discontinuity at a rate similar to the rate of plate subduction, compositional differences between the upper and lower mantle would fade out in a few hundred million years. The chondritic paradigm, the noble gas record, and the replacement time argument gave rise to the canonical model of layered mantle convection in which the upper part of the mantle (the MORB mantle), both thoroughly outgassed and depleted in lithophile el ements, overlies a mantle layer relatively primordial and undegassed. As a corollary, this lower layer should have remained unspoiled by the addition of subducted slabs and therefore its refractory elements should be present in nearly chondritic proportions.

The complementary distribution of many nonvolatile elements, such as the rare-Earth elements, in the continental crust and the MORB mantle didappear for a while to support a chondritic composition for the mantle below the 660-km discontinuity. The isotopic balance of a variety of elements such as Pb, Os, Hf, Nd (see, e.g., Blichert-Toft and Albarède [1997]) among MORB and OIB actually requires that the refractory element composition of this "invisible" mantle is not chondritic, and to make it a suitable source of nonradiogenic rare gas isotopes, that it should never have reached the depth of degassing (approximately a few tens of kilometers). These conditions could be met by dense high-pressure phases accumulated in a magma ocean shortly after the Earth's accretion, but they exclude ancient lithospheric material.

The terrestrial heat flow-heat production balance also argues against whole-mantle convection. The sum of the heat produced by the continental crust and by a MORB mantle that would extend down to the CMB would only account for a small fraction of the present-day terrestrial heat flow. Such a deficit of heat-producing radioactive elements would therefore require that the terrestrial thermal regime is still transient and that the Archean mantle was very hot.

For these reasons, a hidden reservoir with higher concentrations of heat-producing elements U, Th, and K and other incompatible elements than in the MORB mantle is a required feature of convection models. Some U, Th, and K could be stored in the bottom boundary layer (D") layer but the mantle volume encompassed by this region is too small to account for all missing heat production [Kellogg et al., 1999].

Against Layering at 660 km Depth

The geochemical data constrain neither the morphology of the MORB mantle nor the depth to the undegassed mantle. But in conventional models of layered convection, it has long been convenient to identify the MORB mantle with the upper mantle and the undegassed mantle with the lower mantle, with little or no mass flux across the boundary at about 660 km deep (Figure 1.2). This interface coincides with a discontinuity in elastic properties produced by phase transformations in the mantle silicates.

Near cold downwellings, some of these phase transformations occur deeper than in ambient mantle; if deep enough, the positive buoyancy associated with this depression could indeed prevent slabs from penetrating into the lowermantle. However, mineral physics experiments and seismological observations indicate that the Clapeyron slope of the phase transition and the related variation in depth to the discontinuity are too small to cause long-term stratification.

Layering would also occur if the intrinsic density of lower mantle material is at least 2% larger than that of the upper mantle. But there is no evidence 66rom mantle mineralogy and seismology for the implied change in composition. Moreover, seismological evidence that–in the past 200 Myr–many slabs of former tectonic plates have sunk into the lower mantle demonstrates that the density contrast, if any, is too small to prevent significant mass exchange across this interface.

No evidence exists for a thermal boundary layer (TBL) at 660 km depth, which would develop if the upper and lower mantles are convectively isolated. The low viscosity implied by a hot lower mantle also is at odds with inferences 66rom geoid modeling and data on postglacial rebound.

Tomographic images indicate that flow trajectories can severely deform in the upper mantle transition zone, but analog and numerical flow simulations have demonstrated that this does not require long term stratification of convective flow. Local and transient layering can result from interplay between relative plate motion (lateral trench migration) and changes in the morphologyof slabs when they encounter resistance (such as higher viscosity or an endothermic phase change). Structural complexity probably persists down to 1000 km [e.g., Van der Hilst and Kárason, 1999], but the significance of this depth is not yet known, and many slabs sink even deeper.

Collectively, geophysical evidence thus rules out present-day stratification 660 km deep. It has been proposed that, at some time in the Earth's history, the convection regime switched from layered to whole-mantle convection. The tomographic snap-shots could then still be reconciled with the canonical model of layering at 660 km depth. However, geological and geochemical evidence for such a major transition in the geological record is at best undocumented, and in our view unsupported.

Incomplete Mixing of the Mantle?

If isolated ”reservoirs” still exist, they are likely to reside deeper than 660 km. Various mechanisms have been proposed for preserving distinctdomains in a convecting mantle. One class of model assumes that convective isolation is controlled by variations in viscosity and mixing timescales, with no need for variations in major element composition. Another explains segregation by means of gravitational stabilization of intrinsically dense material,with viscosity playing a less pivotal role. Of course, a combination of these is possible.

The timescale for mixing in the high-viscosity lower mantle is probably larger than in the upper mantle, and mantle-wide homogenization may simply not have occurred yet. Primordial material may have survived in the low strain-rate centers of the convection cells or may be contained in high viscosity”blobs” (Figure 1.3), which, by virtue of their rheology, do not mix with thesource of mid-ocean ridge basalts. Such reservoirs would be virtually invisible seismologically.

The fundamental dilemma for segregation solely by means of high viscosity is that enhanced internal heat production of the enriched material quickly lowers the viscosity and increases the positive buoyancy. This, for instance, also diminishes the probability for blobs to remain convectively isolated.Indeed, computer simulations indicate that viscosity variations alone cannot prevent the mantle from homogenizing in a relatively short period of geological time. But the outcome of these calculations may be different if the distinct rheology of tectonic plates is accounted for.

Long-term isolation of enriched reservoirs seems feasible only by means of gravitational segregation. The positive thermal buoyancy caused by internal heating is then offset by an increase in intrinsic density [Kellogg et al., 1999] (Figure 1.4). In fact, the current blob models require the blobs to be intrinsically more dense in order to prevent them from rising to shallower depth [Becker et al., 1999]. The problem with mechanisms based on variations in intrinsic density is that there is more evidence from mantle mineralogy for a homogeneous mantle than for the required differences in major element composition. Several phase transitions have been suggested to occur in the pressure range of interest (65-135 GPa). Some of them would help produce and preserve a dense, iron-rich assemblage at high temperatures [Van der Hilst and Kárason, 1999] but this is still a controversial topic.

Dilution of Lithospheric Material

The sources of MORB and OIB are compositionally distinct. Although we have argued that seismological evidence does not support substantial differences in major element chemistry between the upper mantle and the lower mantle, geochemistry requires that the asthenospheric source of MORB is more depleted in incompatible lithophile elements than the source of OIB. This strong restriction requires that, for those elements that differ in content and isotopic compositions, their transport across the boundary between these two mantle reservoirs cannot be unimpeded.

One possibility is the subduction filter. Continental crust is extracted from the oceanic lithosphere and piggyback oceanic plateaus. It is widely agreed that upon dehydration and melting, the subducted lithosphere is largely stripped from its most lithophile elements. The lithospheric materialexported to the deep mantle must therefore be far more diluted in the radioactive elements U, Th, and K than the shallow mantle itself, which allows helium and argon in most of the deep mantle to keep a relatively unradiogenic isotopic composition. The radiogenic (Sr, Nd, Hf, Pb, Os) and stable (O, C) el ements that survive extraction into the continental crust and flushing into the lower mantle are nevertheless expected to preserve the isotopic memory of their source, conspicuously the oceanic and continental crust components that modern isotope geochemistry identifies in the source of plume basalts.

At least part of the deep mantle is enriched in lithophile elements with respect to the asthenospheric mantle. This seems so because, for one, lithophile elements are far more concentrated in OIB than in MORB, which most current models ascribe to OIB being derived by a smaller degree of melting 66rom a source enriched in lithophile elements. Second, the long-term values of the parent/daughter ratios in the source of MORB and OIB deduced fromthe isotope systematics of Sr, Nd, Hf, Pb, and Os require that the ratio of more lithophile to less lithophile elements (notably Re/Os) is higher in the OIB source. It is usually understood as well that the depletion of the MO RB source is ancient. A third reason for deep mantle enrichment is that hidden heat sources are required to account for the terrestrial heat flow [Kellogg et al., 1999].

It is commonly thought that K and U are not fractionated by magmatic processes so that the terrestrial K/U ratio can be deduced from the 12,000 ratio of fresh MORB and OIB. This point may not be as robust as expected. In the youngest, and therefore unweathered, basaltic flows from the Piton dela Fournaise volcano on Reunion Island, the values of K/U actually vary by more than 30% and correlate with their K content. A. W. Hofmann (personal communication, 1999) made very similar observations on recent Hawaiian basalts.

For MORB, the K/U ratio is virtually out of control. The terrestrial K/U ratio and, consequently, the size of the undegassed reservoir are thereforeonly loosely constrained by the ^{40}Ar budget of the Earth.

The New Model: Two Domains Identified

A mantle convection scenario slightly modified from Van der Hilst and Kárason [1999] and Kellogg et al. [1999] (Figure 1.4) and incorporating some features of the whole-mantle convection of Albarède [1988] (Figure 1.5) is onein which we envisage–apart from the upper and lower boundary layers (lithosphere and D”, respectively)–two domains that differ in their major element compositions but we identify three dynamic regimes.

To a depth of approximately 2000 km the mantle may have a relatively uniform major element composition and may largely represent the depleted and outgassed reservoir. The upper mantle transition zone (400-1000 km deep) divides this compositional domain into two dynamic regimes, each with different timescales for mixing. The shallow part–the asthenospheric mantle–is well mixed and is sampled directly by MORB. Mixing in the deep part (1000-2000 km) is much slower. The transition zone distorts the trajectories of mantle flow because of the viscosity stratification, effects of isochemical phase transformations in the mantle silicates, and the direct interaction with relative motion of plate boundaries at Earth’s surface.

The deepest part of the depleted reservoir may differ from the shallow, asthenospheric part by the extraction of continental crust material, but they are relatively similar in major elements composition and, therefore, in their physical properties.

The bottom 1000 km of the mantle has a higher intrinsic density and contains undegassed material enriched in heat-producing elements and formed very early in the history of the planet. The home of the OIB source is on top orin the boundary layer of this deep domain, the graveyard of lithospheric plates, which are largely depleted in lithophile elements by the subduction zone processes and known to be poorly mixed [Hofmann, 1997].

The interface between the depleted and enriched mantle domains could be close to isopycnic; in other words, the compositional and thermal effects on buoyancy are in balance [Kellogg et al., 1999]. The excess density isexpected to be small so that significant dynamic topography can develop. This would strongly reduce the visibility of this interface by classical seismicimaging. The layer would be severely deformed by large-scale convective flow. It would be thin, or absent, beneath cold downwellings and thick far away fromthem. The coldest downwellings can sink all the way to the CMB, but the D” region may not be the ultimate graveyard of slabs since many may equilibratein the middle of the lower mantle.

Upwellings could still arise from the TBL above the CMB but most are expected to originate in the pronounced TBL near the top of the amorphous layer within the junkyard of old crustal material, thus giving OIB the observed signature of recycled material.

This model thus recognizes the existence of reservoirs with different levels of depletion and simply suggests that the interface between them can be located at much greater depth than the base of the upper mantle transition zone.

Other Constraints

The model, with heterogeneity in the bottom 1000 km of the mantle, wa s inspired by the need for chemically distinct reservoirs and is supported–but not yet well constrained–by a range of geophysical observations.

That the bottom 300 km of the mantle, the so-called D" region, involves variations in composition has been known for over a decade. But several lines of geophysical evidence are now beginning to suggest that the chemical heterogeneity may extend up to 1000 km or more above the CMB. In the upper and mid-mantle, lateral variations in P and S wavespeed are highly correlated [van der Hilst et al., 1997; Grand et al., 1997] and are predicted successfully by computer simulations of thermal convection and the Mesozoic-to-present plate motion and subduction of oceanic lithosphere. However, the subduction-related features disintegrate in the bottom 1000 km of the mantle, with only some fragments of them connecting to D" heterogeneity, for instance beneath eastern Asia and Central America. This could be a reflection of the transient nature of convection.

For the same depth range, P and S body wave travel times and anomalous shifts of normal mode frequencies provide increasing evidence for large-scale decorrelation of wavespeed variations and perhaps density. This behavior and the large magnitude of the wavespeed variations in some places in thedeep mantle cannot be explained by temperature variations alone [cf. Van der Hilst and Kárason, 1999].

In the deep mantle, seismic wave propagation is very slow over large geographical regions, for instance beneath southern Africa and the Pa cific. Without gravitational stabilization, a thermal boundary layer would probably develop convective instabilities if the lateral temperature variations exceed several hundred K, unless thermal expansion is very low.

At these large pressures such a thermal anomaly would produce only a small wavespeed perturbation. This would also explain why it is difficult to produce the large and seismically slow megaplumes by numerical calculations of purely thermal mantle convection. Therefore neither the morphology nor the magnitude of the wavespeed variations are consistent with a thermal origin.

Even though it is not yet well constrained, it has also been argued that the temperatures in the bottom 1000 km of the mantle are higher than expected from adiabatic compression in a compositionally homogeneous mantle. High temperatures would indeed be the logical result of an internally heated but gravitationally stabilized layer in the deep mantle [cf. Van der Hilst and Kárason, 1999].

The existence of compositional heterogeneity in the bottom 1000 km was also inferred from high frequency scattering of seismic waves. But it has not yet been established how the spatial distribution of such scatterers relates to the large-scale pattern of mantle flow. Moreover, observed scatteringof seismic waves near 1500 km deep in regions away from present-day downwellings may be the smoking gun for old oceanic crust piled atop the distorted interface in the mid-lower mantle.

The ensemble of geochemical and geophysical evidence is thus consistent with the existence of compositionally distinct, gravitationally stabilizeddomains in the deep mantle. Of course, many questions remain to be answered, which poses a tremendous challenge for interdisciplinary research. For example, the nature of the domains remains a question. The two domains may coincide with the thermodynamic stability of mantle silicates (at lowpressure and temperature) and the compounding oxides (at high pressure and temperature), but at those pressures the major element mineralogy and phase chemistry are still uncertain.

Also, isotopic heterogeneities inherited from the Earth's early ages would fingerprint the survival of such a primordial mantle domain and this is one way of interpreting the existence of solar neon in the mantle. However, the search for isotopic anomalies produced by the decay of extinct nuclides (especially 146Sm and 182Hf), which was so successful in identifying early differentiation processes in Mars and the Moon, has so far been unproductive on Earth.

Moreover, seismic imaging (wavespeed ratios, wavespeed-density relationships, anisotropy, scattering) needs to be improved in order to confirm or refute the existence of compositional domains in the deep mantle. But a concerted effort will no doubt shed light on a part of the mantle that until recently has largely been overlooked because of research emphasis on the conventional upper-lower mantle division and the D" region.

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