TOMOGRAPHIC EVIDENCE FOR COMPOSITIONAL HETEROGENEITY DEEP IN EARTH'S MANTLE

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Abstract

In the past decade, tomographic imaging has revealed that trajectories of mantle convection are more complex than expected from end-member models of unhindered whole mantle circulation or layered convection with an interface at 660 km depth. In the context of recently proposed mantle flow models, we discuss evidence for compositional heterogeneity in the deepest 1000 km of the mantle, and describe how this could survive in a system of thermo-chemical convection.

Introduction: developing views on mantle convection

In recent years, several models of mantle convection have been proposed to reconcile geophysical, geological, and geochemical constraints. These models need not provide the best fit to particular data sets but should be permissible within their uncertainty. Here we discuss some results of our research on wavespeed ratios and body wave scattering in the framework provided by the model by *Kellogg et al.* [1999], hereinafter KHH99.

KHH99 recognized (1) the complexity of flow trajectories as inferred from seismic tomography (there is evidence for slab deformation and stagnation in the upper mantle transition zone and for subduction to larger depth, sometimes perhaps to near the core mantle boundary (CMB) [e.g., *Van der Hilst et al.*, 1991; *Fukao et al.*, 1992; *Van der Hilst et al.*, 1997; *Grand et al*., 1997; *Fukao et al.*, 2001] and (2) the need for compositional heterogeneity (to explain the seismologically inferred relative variations in compressional-, shear-, and bulksound speed and account for the missing inventory of some elements required by the isotopic planetary budget, including heat producers such as uranium). The KHH99 model has an upper mantle transition, where most of the slab complexity is observed, loosely from ~400 to ~1000 km (like Bullen's region 'C'; see *Van der Hilst and Kárason* [1999]) and both compositional and rheological stratification. The depleted mantle extends across the transition zone, locally perhaps to near the CMB, but on average perhaps to some 1700 km depth, whereas the geochemically enriched domains are thought to reside mostly in the bottom 1000 km or so of the mantle. Gravitational stabilization of these domains produces the long residence times required by geochemical analyses. Slabs would not all sink to the very base of the mantle and many or most would recycle above the deep "layer".

The rheological stratification implied by KHH99 can be explained by the pressure and temperature dependence of viscosity, and there may be an additional effect of slab accumulation near the base of the transition zone. With increasing depth the viscosity increases due to increasing pressures and the diverging geotherm and solidus, but it decreases in a thermal boundary or hot basal layer. The change from the one regime to the other produces a viscosity maximum at a depth that is model dependent [*Van Keken et al.*, 1994] but constrained by *Forte & Mitrovica* [2001] to be near 2000 km depth (which is consistent with KHH99, their Fig. 2B). The characteristic time scales for mixing increase with depth in what KHH99 considered the depleted mantle. Against this backdrop, the accumulation of deflected slabs could increase the viscosity toward the base of 'Layer C' (i.e., near 1000 km depth). This viscosity profile (increasing toward 1000 km, decreasing below 2000 km) could produce a reduction in the radial correlation of mantle structure near these depths [*Van der Hilst & Kárason*, 1999; *Forte & Mitrovica*, 2001].

The KHH99 model can reconcile a range of different observations and constraints, but the seismological evidence for compositional layering has been indirect and ambiguous and the search for waveform effects due to a mid-mantle interface has mostly yielded negative results. In the following we summarize some of our research pertinent to these issues.

Compositional heterogeneity?

In recent years, much seismological research has focused on determining the relative variations in density, compressional-, shear-, and bulk sound speed (see *Masters et al.* [2000] for a recent review). The ratio of relative variations in shear vs. compressional wavespeed, often expressed as $R=\mathrm{dln}V_S/\mathrm{dln}V_P$, increases with depth, in particular near the base of the mantle. It is not yet well known what value of R necessarily implies compositional variations, but there is growing consensus that values less then about 2.5, which is much of the radial R profile, can be ascribed to a thermal origin.

However, a focus on the radial dependence of R can be misleading and aspherical variations may be significant [*Masters et al.*, 2000]. From the analysis of EHB travel time data [*Engdahl et al.*, 1998], *Saltzer et al.* (2001) demonstrated that R increases more rapidly with depth (to values exceeding 2.5) away from regions of recent subduction than beneath the major convergent margins where R remains less than ~2.0. This suggests that the R values diagnostic for compositional heterogeneity are primarily associated with the regions away from downwellings, which are mostly characterized by lower than average V_P and, in particular, V_S. This notion is consistent with Earth's free oscillations data, which indicate that bulk sound speed and density are negatively correlated with shear speed in the lowermost mantle beneath central Pacific and Africa [*Ishii & Tromp*, 1999]. Some of the low shear speeds in the deep mantle may thus be due to higher intrinsic density, for instance due to iron enrichment [*Van der Hilst & Kárason*, 1999]. The morphology of anomalous domains or their extent above the CMB has remained enigmatic. The most anomalous values probably occur near the base of the mantle [*Masters et al.*, 2000], but the R profiles for regions near and away from major downwellings begin to diverge near 1500 km depth [*Saltzer et al.*, 2001] suggesting that compositional differences may extend far above the CMB.

For the determination of R from travel times of seismic waves V_P and V_S must be determined with comparable accuracy. Uneven data coverage and, in particular, differences between *P* and *S* sampling complicate the analysis. *Saltzer et al.* [2001] selected from the global EHB catalog *P* and *S* data with comparable data coverage, but the quality and quantity of *S* data are inferior to *P* and global tomography can leave large regions without a meaningful value of R or V_P and V_S correlation.

In a subsequent regional study, *Saltzer et al.* [2002] determined variations in elastic parameters from Earth's surface to CMB along a transect from Japan, across Alaska, to North America. They selected *P* and *S* (and *PcP* and *ScS*) waveforms (from IRIS DMS) and determined differential travel times by waveform cross correlation. High data quality allowed the determination of the Poisson's ratio, σ, and relative variations in V_P, V_S, and bulk sound speed as a function of depth. Also here the data coverage is uneven, but by selection it is similar for *P* and *S*, which reduces uncertainties in the derived values of R and $\mathrm{dln}\sigma$.

Using wavespeed-to-temperature derivatives and equations of state from a variety of sources, *Saltzer et al.* [2002] estimated the range of temperatures required to explain $\mathrm{dln}\sigma$ and the relative variations in V_S and bulk sound speed. Surprisingly, we found that the range in temperature implied by our results for bulk sound speed is about twice as large as the range inferred from dlnV_S. This could indicate that the derivatives used are incorrect or that anelastic effects on incompressibility are larger than commonly believed (in fact, we ignored it in our analysis). Moreover, interpreting the inferred variations in wavespeed and σ without invoking effects of composition (either iron enrichment or a variable proportion of perovskite (pv) and magnesiowüstite (mw)) required lateral variations in temperature that are much larger than believed realistic for the bottom half of the mantle. The proportion of pv and mw has a relatively small effect on dlnσ, but a 1-3 mole % iron enrichment is compatible with our data and renders reasonable temperature variations. Interestingly, the data suggest iron enrichment not only near the very base of the mantle but also in the shallower mantle. Indeed, while the V_P and V_S correlation is high (~0.8) between the surface and ~1500 km depth, it then gradually decreases to a meager 0.5 near the CMB. Beneath 1500 km depth dlnσ is less then half of that in the top 1000 km.

Mid-mantle interfaces?

While tentative and in need for further study, the inferred large-scale aspherical variation in bulk composition in the deep mantle is largely consistent with the KHH99 model. We have also begun a search for evidence for the interface and thermal boundary layer that marks the top of the deep layer in the KHH99 model. For this purpose we examined short period data from deep earthquakes recorded at dense receiver arrays in the western US and at the FREESIA network in Japan. Specifically, we searched for evidence of scattering or phase conversion at interfaces in the mid mantle using time-slowness and azimuth-slowness stacks [*Castle & Van der Hilst*, 2002a].

Using data from earthquakes beneath the Mariana arc we detected scattered energy from near 1600 km depth beneath the western Pacific, in accord with earlier findings [*Kaneshima & Helffrich*, 1999]. In contrast, the examination of data from earthquakes beneath Tonga-Kermadec and South America did not yield robust evidence for scattering in the mid mantle, despite significant amplification of the part of the record where the *S*-to-*P* conversions are expected (i.e., between the arrival of direct *P* and the depth phase *pP*). Experiments with synthetic data indicated that we should be able to detect changes in elastic parameters if they exceed ~2%, occur over a depth interval less then ~50 km, and if the interface dip is less than ~30°. Although we may have overlooked more subtle gradients, our studies to date suggest that scatterers may exist at mid-mantle depths but do not delineate a global interface anywhere between ~1000 and ~2000 km depth in the mantle [*Castle & Van der Hilst*, 2002a]. In the context of the KHH99 model, the intermittent scattering near 1600 km depth [*Kaneshima & Helffrich*, 1999; *Castle & Van der Hilst*, 2002a] can perhaps be caused by slab fragments that have accumulated above the intrinsically more dense deep mantle domains.

Caveat: the need for dense receiver arrays and deep earthquakes restricts this search to a few relatively small regions in the deep mantle. Moreover, these regions are all beneath convergent margins, where according to the KHH99 model downwellings can suppress the deep interface to beyond 2000 km depth or even to the CMB. To search for scatterers at larger depths than 2000 km we examined the short period array data for precursors to *ScP*, but also this search yielded largely negative results [*Castle & Van der Hilst*, 2002b].

Discussion

Studies of relative wavespeed variations in the lower mantle reveal aspherical variations in composition that are consistent with the cartoon presentation of the KHH99 model, but to date our analyses of body wave scattering does not provide convincing evidence for a global interface that would mark the top of a deep "layer". This renders unlikely the existence of a laterally continuous and compositionally homogeneous hot abyssal layer (HAL) that is separated from the overlying mantle by a thermal boundary layer, but it leaves the possibility that for depths larger than, say, 1700 km, the average properties of the lower mantle away from major downwellings differs from regions beneath major convergent margins.

The basic features of the KHH99 model may thus hold, but the nature, origin, and geological evolution of the deep anomalous domains must be reconsidered. In particular, we must explore other processes for producing and preserving compositional heterogeneity in the deep mantle. Depending on factors such as the composition and thermal structure of the lithospherics slabs (or slab fragments) and the history of plate motion (e.g., duration and rate of plate convergence, variation in age of the plate at the trench, rate of plate boundary migration, and the occurrence and duration of trench roll back associated with slab deflection and stagnation in the transition zone), slabs may not all make it to the CMB but can be recycled at different depths in the mantle. Much of the recycling may take place in the (conventional) low viscosity upper mantle, some of it may involve the middle mantle, and only some downwellings may interrupt the abyssal realm, thus preserving compositional heterogeneity in the deep mantle over long periods of geological time.

If the slabs that carry more fertile plates (e.g., plateau and OIB basalts, plume heads) sink preferentially to larger depth than the slabs that are on average more 'barren', this system of thermo-chemical convection could produce and maintain poorly mixed and compositionally distinct domains in the deep mantle with the required geochemical signatures without requiring deep "layers" and mid-mantle interfaces [*Albarède & Van der Hilst*, manuscript in preparation].

Conclusions

From tomographic imaging with carefully selected *P* and *S* data we conclude that there are large scale spatial variations in $R=\mathrm{dln}V_S/\mathrm{dln}V_P$ and V_S and bulk sound speed correlation that can be related to the pattern of mantle convection, with the strongest indication for compositional heterogeneity in the deep mantle away from major downwellings. However, compositional changes - for instance a 2-3% iron enrichment - may also be required to explain the inferred variations in Poisson's ratio, V_P, V_S, and bulk sound speed in the deep mantle beneath subduction zones where tomographic imaging does not reveal deep slab penetration, for example beneath Alaska and the Bering Sea region. There are several caveats, however. First, our results for bulk sound- and shear wavespeed do not yield consistent temperature anomalies with the derivates and equations of states used, which could indicate a problem with the derivatives or anelasticity of the bulk modulus (ignored so far). Second, the equations of states used to extrapolate data over large pressure and temperature ranges assume constant mineralogy and phase chemistry of the lower mantle. If changes in elastic parameters occur due to transitions in, for instance, the perovskite structure, as suggested by *Shim et al.* [2001], these extrapolations may not be justified.

Our studies support the main aspects of the KHH99 model but render it unlikely that between 1000 km depth and the top of the D'' region a laterally continuous and internally homogeneous layer exists that is separated from the overlying mantle by a thermal boundary layer or sharp compositional interface. Alternative processes for producing an preserving chemically different regions must thus be explored. Compositional heterogeneity may survive in the deep mantle if the recycling of lithospheric slabs of different composition and thermal structure occurs as different depths, but further research is required to assess the geodynamic feasibility of this thermo-chemical convection model and its ability to produce sufficient heat.

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