Seismological constraints on the fate of slabs and the scale of mantle convection

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Seismic tomography is a technique to interpret seismic data in terms of spatial variations in wave speed and attenuation (as proxies for temperature and - perhaps - bulk chemistry) on many different length scales, from small hydrocarbon reservoirs to planetary interiors. To obtain constraints on the scale of convection in Earth's mantle seismologists attempt to image the trajectories of convective flow, i.e. the collapsed thermal boundary layers (TBL). The thermal anomalies associated with slabs of subducted lithosphere sinking from the top TBL and plumes that rise from a bottom or internal TBL produce a detectable change in the amplitude and propagation speed of transmitted seismic waves. Notice, however, that in general the cold downwellings are easier to detect than the upwellings: they are often associated with seismicity (giving a wealth of natural sources for imaging and delineating unequivocally the seismogenic parts of the slabs) and there are also some ray theoretical problems with the imaging of low wavespeed anomalies associated, for instance, with plumes. Seismic imaging can also provide unique insight in spatial variations in composition by combining the structural information contained in different seismic waves (e.g. P- and S-waves).

In this presentation I review the seismological evidence pertinent to the fate of slabs and discuss new results regarding (structural and compositional) heterogeneity at large depths in Earth's mantle.

Evidence for deep subduction

There is now increasing evidence for slabs of subducted lithosphere penetrating into the lower mantle. Of particular interest is the inference of long, linear structures of higher than average seismic wave speed that have now been detected by several research groups. These structures are pronounced in high resolution inversions based on cellular representations of the model (e.g. Van der Hilst *et al.*, 1997; Grand *et al.*, 1997), but they are consistent with previous models that used a spherical harmonic representation (e.g. Su *et al.*, 1994). These deep mantle structures are located beneath regions with a long history of plate convergence and subduction, and in many cases the deep anomalies are continuous to seismogenic parts of slabs in the shallower mantle. If interpreted as remnant slab material, two sheet-like downwellings can be identified (Farallon and Tethys slabs) that continue to at least some 1800 km depth (Van der Hilst *et al.*, 1997; Grand *et al.*, 1997). Some segments of these structure appear to connect to seismologically observed heterogeneity at the base of the mantle; being unable to penetrate into the core the narrow downwellings simply spread out to form long wavelength structure above the CMB.

The fates of slabs and end-member models of mantle convection

The evidence for material transport between upper and lower mantle implies that the increase in intrinsic density across the upper mantle transition zone, if any, must be small. While this transition zone is not an efficient barrier for radial flow, trajectories of flow across it are almost certainly more complex than expected from simple whole mantle convection.

High resolution regional tomography, and also the recent global models, reveal a range of complex subduction behaviour between, approximately, 400 and 900 km depth. Slabs seem to penetrate into the lower mantle beneath some regions with (e.g. Tonga, Java, parts of South America) or without (e.g. Mariana, N. Kurils, Aegean, Central America) detectable kinks or buckles, and are deflected and trapped in the transition zone beneath others (Izu Bonin, Banda). Part of this complexity can be explained by considering downwelling beneath rapidly migrating plate boundaries (retrograde trench migration; slab roll back) and some form of resistance to downward flow (due to, for instance, an endothermic phase change, an increase in viscosity, a slight increase in intrinsic density, or any combination of these). This can result in local layering of convective flow, which is likely to be short-lived (i.e. important only on time scales characteristic of rapid plate reconfigurations - up to tens of millions of years). Slabs of young lithosphere or slabs with rapidly changing geometries are thus less likely to sink into the lower mantle and are more likely to be recycled in the upper mantle.

Furthermore, slabs that do manage to sink across the upper mantle transition zone do not seem to have a smooth, unobstructed ride to the core mantle boundary. The tomographic models suggest that near approximately 2000 km (this depth is not yet well constrained) the sheet-like downwellings disintegrate and break up in smaller fragments, some of which may be continuous all the way to the CMB (e.g. parts of the Japan and Central America slabs). We have recently added new data sets that provide better sampling in the lowermost mantle than the P-wave ray paths used in our previous studies, and inversions with this superior data coverage confirms that a transition in the pattern of heterogeneity occurs between approximately 1800 and 2200 km depth. This lower mantle transition roughly coincides with a change in spectral properties of the wavespeed anomalies, and - interestingly - with a change in the relation between P- and S- wavespeed (as revealed by several research groups). This suggests that in the lowermost 800 or so km of the mantle there are large regions where the propagation speed of P- and S-waves is no longer dictated by temperature alone and where lateral variations in bulk chemistry may have to be invoked in order to explain the data.

The latter inference is still rather tentative, in part because the magnitude of wavespeed variations are somewhat uncertain but also because the partial derivatives of elastic parameters that are required for a quantitative interpretation of wavespeed perturbations are not yet available from experimental or theoretical mineral physics. If real, it would imply a compositional stratification in the mantle at much larger depth than the isochemical phase change between upper and lower mantle. Undulations of the associated compositional boundary can be substantial; and downwellings may depress the boundary by hundreds of kilometres, perhaps all the way to the core mantle boundary. At such large depths, this form of 'penetrative convection' would be very difficult to distinguish from more conventional convection on the basis of seismology alone.

A hybrid convection model

The model that begins to emerge from seismic imaging and fluid dynamical modelling is characterized by essentially whole mantle flow with added complexity in the upper mantle transition zone (regional, transient) and, perhaps, near 2000 km depth. The amount of flux between upper and lower mantle has not yet been quantified from the current tomographic images, but integrated over time they would predict substantial mass exchange across the 660 km discontinuity, which is inconsistent with end-member layered convection models suggested on the basis of noble gas data. A (severely distorted) compositional boundary in the bottom half of Earth's mantle could perhaps go a long way towards reconciling inferences from geophysical modelling and the existence of the distinct reservoirs deduced from the isotope record. In addition, over the life time of Earth, mantle convection is not likely to be a steady state process. While geochemistry can constrain evolution over long periods of geologic time, seismic imaging merely gives a 'snap shot' of a time dependent geologic process. However, in combination with numerical modelling of mantle flow and the use of plate reconstructions as time dependent boundary condition we are now beginning to investigate transient phenomena in this complex convective system. Continued integration of seismic imaging, mineral physics, and numerical flow modelling would enable us to improve the characterization of wavespeed perturbations, to map out regions of suspected chemical heterogeneity, and study how they can survive convective stirring in order to explain the isotope record. After all, there is only one Earth.

References

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