Mechanisms for seismic anisotropy in the lowermost mantle

M. Kendall — Department of Earth Sciences, University of Leeds, Leeds, LS2 9JT, UK

P. Silver — Department of Terrestrial Magnetism, Carnegie Institution Washington, Washington, D.C., 20015, USA

The boundary layer known as D″ occupies the lowermost few hundred kms of the mantle and can be viewed as the lower-mantle analog of the lithosphere. Convection simulations show that a thermal boundary-layer should exist in this region and strong arguments for a chemical boundary-layer come from evidence of heterogeneity on a wide range of length scales (Loper and Lay, 1995). In many areas the top of the D″ layer is bounded by a seismic discontinuity which delineates dramatic variations in the thickness of the layer (260 km $\pm$ 150 km). There is also mounting evidence for an ultra-low-velocity layer in the lowermost 5–40 km of D″. Explanations for this heterogeneity include iron infiltration from the core, subducted material pooling at the core-mantle boundary (CMB) and primordial material from mantle differentiation. It has also been suggested that this region may be the site of another mantle phase transition. Recent evidence of seismic anisotropy in the lowermost mantle offers additional tantalizing insights into the nature of the D″ region (Kendall and Silver, 1996). While these observations are very interesting from a seismological point of view, they are equally if not more valuable as constraints on the style of mantle dynamics, the mineral physics of the lowermost mantle and core-mantle coupling which may affect the Earth's magnetic field.

Observations of anisotropy in the Earth's mantle.

There are numerous regions of the Earth where seismic anisotropy is present. In the upper-mantle, anisotropy is attributed to the flow- or strain-induced lattice preferred orientation (LPO) of constituent minerals, especially olivine. Another common form of anisotropy is that due to a shape preferred orientation (SPO). In this case, oriented inclusions with one seismic velocity embedded in a matrix characterized by a second velocity generate an effectively anisotropic medium, if the inclusions are small compared to a seismic wavelength. This is known to occur, for example, in the continental crust where it is generally attributed to the preferred alignment of fluid-filled cracks. Regardless of which mechanism is operating, the presence of anisotropy suggests an ordered medium, with a particular fabric or texture. This ordering in turn points to an underlying physical process, such as mantle flow. We may thus use observations of seismic anisotropy to understand this underlying process.

Although studies of lower-mantle anisotropy are still long way from achieving global coverage, it is clear that there are strong lateral variations in the degree of anisotropy. When interpreting the seismic data, care must be taken to isolate the contribution from upper-mantle anisotropy from potential lower-mantle anisotropy. To date, regions below the Caribbean and Alaska show clear evidence for lowermost-mantle anisotropy, while observations in regions beneath the central Pacific are less straightforward. The primary seismic constraints in the Caribbean and Alaskan regions are: (1) the anisotropy has hexagonal symmetry with a vertical symmetry axis (transverse isotropy) (2) high aggregate seismic velocities (3) the existence of a seismic discontinuity ~250 km above the CMB. Beneath the central Pacific, the style of anisotropy seems to be more complex and its existence is intermittent with large regions appearing to be isotropic.

Anisotropy due to mineral alignment

In order to comprehensively evaluate mineral alignment as a viable mechanism for anisotropy, we would need to know the minerals present, their single-crystal elastic constants at CMB conditions, and the degree of LPO development induced by finite strain at these depths. This information for lower mantle minerals is presently incomplete, so we take two approaches. First, we make the assumption that LPO is perfect, and then use the available single-crystal elastic constants to evaluate the anisotropy. This is equivalent to assuming that there is one dominant glide plane, and one dominant slip direction within this plane. The most commonly expected lower mantle minerals are: perovskite (either in an orthorhombic or cubic form), magnesiowüstite (cubic), and to a lesser extent stishovite (tetragonal) or its high *P/T* columbite structure (orthorhombic). These minerals are strongly anisotropic, ranging from 6% to nearly 20% in shear-wave anisotropy, but it is difficult to create the observed form of transverse isotropy through alignment.

The second approach is to assume that LPO exists on one glide plane, but with arbitrary slip direction, and that the glide plane is parallel to the CMB. This would be appropriate for lateral flow along this boundary, and would generate a transversely-isotropic medium. This approach was used by Stixrude (1998), where the glide plane is taken to be that found for low-pressure analogs. In this case, it is found that only columbite supports the seismic data. The transverse isotropy could be explained by LPO of the columbite phase, but this would require it to constitute a quarter of the material in D″ which is excessively high. It would also make the seismic velocities too high. We conclude that LPO in lower-mantle minerals is an unlikely cause for the anisotropy, at least in the Caribbean and Alaskan regions, although we must always allow for the possibility that there is an as-yet unknown mineralogy that dominates D″.

Anisotropy due to oriented inclusions

Effective-medium modelling can be used to investigate the more likely SPO-anisotropy, which is attributed to oriented inclusions within a matrix of contrasting seismic properties. We investigate a range of inclusion shapes, orientations, volume fractions and velocities. The seismic constraints force us to conclude that the inclusions must be horizontally-aligned tabular bodies (disks or layers). The volume fraction required to satisfy the observations decreases as the velocity contrast between the matrix and inclusion material increases. Melt filled inclusions are particularly effective with less than 0.01% volume fraction required to explain the magnitude of the anisotropy.

A slab graveyard in the lowermost mantle?

It seems unlikely that the physical process responsible for this anisotropy is associated with infiltration of core material, primarily due to the fact that iron will lower the seismic velocities and the observations require a mechanism which increases the seismic velocities. Instead, there are a number of arguments which suggest that the anisotropy is associated with the hypothesis that, in places, the lowermost mantle represents a graveyard for subducted material. Regions of anisotropy beneath the Caribbean and north Pacific correlate with predicted CMB locations of palaeo-slabs (Lithgow-Bertelloni and Richards, 1998). They are also regions of high seismic velocities in large-scale tomographic models (Grand *et al.*, 1997). Recent models beneath the Americas, a region where there is clear evidence for lowermost-mantle anisotropy, show a well defined high-velocity anomaly extending from the uppermost mantle to the CMB. The high aggregate shear-velocities can be explained by the retained thermal anomaly of the slab and the anisotropy can be explained by contrasts in the material properties between what was formerly oceanic-crust and oceanic-lithosphere. The alignment of very low concentrations of tabular melt-inclusions explains the anisotropy and partial confirmation of this has come from recent melting experiments on basalt (Hirose *et al.*, 1998). If slabs indeed strongly influence the thermal, compositional and seismological properties of the CMB, they would then appear to play a major role in the mantle's two major thermal boundary layers.

References

Grand, S.P., van der Hilst, R.D. and Widiyantoro, S. (1997) *Geol. Soc. Amer. Today*, **7**, 1–7.

Hirose, K., Ma, Y., Fei, Y. and Mao, H. (1998) Submitted to *Nature*.

Kendall, J.-M. and Silver, P.G. (1996) *Nature*, **381**, 409–12.

Lithgow-Bertelloni, C. and Richards, M. (1998) *Rev. of Geophys.*, **36**, 27–78.

Loper, D.E. and Lay, T. (1995) *J. Geophys. Res.*, **100**, 6397–420.

Stixrude, L. (1998) *Core-mantle Boundary*, AGU-monograph, Gurnis *et al.*, (eds.). In press.