# Deep Subduction and Aspherical Variations in $P$-Wavespeed at the Base of Earth's Mantle

Rob D. van der Hilst

*Massachusetts Institute of Technology,Department of Earth, Atmospheric, and Planetary Sciences, Cambridge, Massachusetts*

Sri Widiyantoro[1]

*Research School of Earth Sciences, Australian National University, Canberra, Australia*

Kenneth C. Creager, and Thomas J. McSweeney[2]

*Geophysics Program, University of Washington, Seattle, Washington*

We review some recent results of tomographic imaging that are relevant for deep subduction and the structure of the lowermost mantle. Tomography reveals long, narrow structures of higher than average seismic wavespeed in the lower mantle that are continuous to seismogenic slabs in the upper mantle and whose geographical distribution correlates very well with locations at the surface of plate convergent zones in the past 120 Ma. Near 2000 km depth these long linear features disintegrate into smaller segments. However, in several regions narrow downwellings seem to continue to the base of the mantle where they spread out to form long wavelength structure, thus supporting speculations of a relationship between deep subduction and structural complexity in the lowermost mantle. Upwellings seem to be less ubiquitous than downwellings but are not yet well imaged by the $P$-wave data used. These observations confirm many previous results based on residual sphere analysis and are consistent with whole mantle convection with significant internal heating owing to radioactive decay. Despite whole mantle overturn, it appears that convective flow is significantly distorted in the upper mantle transition zone and also in a transitional interval between approximately 1800 and 2300 km depth. The deep change in planform of

## INTRODUCTION

Numerous analyses of seismic body waves, both compressional and shear waves, have indicated a significantly enhanced level of structural heterogeneity in the lowermost several hundreds of kilometers of the Earth's lower mantle. Indeed, it has been argued that the amplitude and the scale of the lateral variations in seismic wavespeeds in the core mantle boundary region are comparable to those observed in the lithospheric part of the

---

[1] Now at: Department of Geophysics and Meteorology, Bandung Institute of Technology, Bandung, Indonesia.

[2] Now at: IRIS, Data Management Center, Seattle, WA 98105.

The Core-Mantle Boundary Region
Geodynamics 28

convection is not necessarily due to changes in state, but joint inversion of *P*- and *S*-wave data begin to indicate that it coincides with a change in the ratio between bulk sound and shear wavespeed. This behavior of the elastic moduli, which is reported elsewhere, suggests widespread chemical heterogeneity near base of Earth's mantle. The lowermost 800 km or so of the mantle thus contains important clues for understanding the composition and evolution of Earth. Unfortunately, it is poorly sampled by direct *P*-waves, but data coverage can be improved by using core phases. Our preliminary study shows that the current *P* model explains much of the *PKP* differential travel time residuals that have been used to study heterogeneity just above the core mantle boundary, but that it underestimates their amplitude. Joint inversion of the differential times along with our direct *P* data is expected to reduce this apparent bias in heterogeneity level in our current wavespeed model and it fully exploits the advantages of differential residuals without having to make assumptions about the location of the anomalies.

Earth's upper mantle. This need not be surprising since these regions represent the thermal (and perhaps chemical) boundary layers of convection in Earth's mantle. For excellent reviews of this subject we refer to *Jordan et al.* [1989], *Lay* [1989], *Lay et al.* [1990], *Wysession* [1996b], and *Loper and Lay* [1995].

Our understanding of the nature, origin, and evolution of the heterogeneity in the CMB region hinges critically on the issue as to the scale of mantle flow, and, in particular on the existence of significant thermal boundary layers elsewhere in Earth's mantle, for instance at 660 km depth. Although still controversial [*Lay*, 1994; *Loper and Lay*, 1995], several investigators [e.g., *Davies and Gurnis*, 1986; *Wysession, 1996a,b*; *Kendall and Silver*, 1996] have speculated that at least part of the aspherical structure above the CMB can be attributed to the deep subduction of slabs of former oceanic lithosphere. This interpretation implies significant mass exchange between upper and lower mantle associated with downwellings and is inconsistent with convection models that invoke layered convection with some flux between the layers by means of plumes to explain the isotope data [e.g., *Kellogg and Wasserburg*, 1990; *O'Nions and Tolstikhin*, 1994; *Allègre et al.*, 1995].

The postulated relationship between deep subduction and aspherical structure in the lowermost mantle is supported by the strong correlation between the locations of subduction in the geologic past (in particular in the Mesozoic) and the distribution of high wavespeed anomalies in the lower mantle according to tomographic images of long wavelength structure [*Richards and Engebretson*, 1992]. The tomographic model used for that study [*Su and Dziewonski*, 1992] represents the effects of dynamic processes averaged over long periods of time and does not reveal the trajectories of mantle flow in sufficient detail to demonstrate that slabs are indeed connected to the CMB region. However, the main conclusions drawn from long wavelength imaging are substantiated by evidence from recent tomographic imaging, which strongly supports con-vection models in which lowermost mantle structure is causally related to the deep subduction of former oceanic lithosphere.

The tomographic model from which examples are drawn here [*Van der Hilst et al.*, 1997; *Widiyantoro*, 1997] is based on data associated with first arriving body waves. The major disadvantage of such tomography with respect to studies of the lowermost mantle is the uneven data coverage; there are large regions where sampling is inadequate, especially in the southern hemisphere. In future studies we aim to improve this situation by incorporating phases other than *P*; for example the core phase *PKP* and the core diffracted ($P_{\mathrm{diff}}$) and reflected phases (*PcP*). Despite the extensive processing by *Engdahl et al.* [1998] we expect that bulletin data are too noisy for this purpose. Instead, we aim to use high-quality data determined by waveform cross correlation techniques, which can be supplemented by our routinely processed phase data after additional quality control and under application of a proper weighting scheme.

The construction of differential travel time residuals, for instance *PcP*-*P* or $PKP_{\mathrm{DF}}$-$PKP_{\mathrm{AB}}$, helps to extract struc-tural signal pertinent to aspherical wavespeed variations in the lowermost mantle. Indeed, it is often assumed that differential *PKP* residuals are only sensitive to structure just above the CMB. We show that heterogeneity maps based on differential data determined from waveform analysis of the different *PKP* arrivals are consistent with our current *P*-wave model. A joint inversion of the different classes of phase data does not rely on an explicit isolation of structural signal and is expected to produce better constraints on lower mantle heterogeneity than either data set alone. In turn, the improved model will enable the calculation of more accurate mantle corrections which may help extract the subtle signal pertinent to CMB topography, heterogeneity, if any, of the outer core, and isotropic and anisotropic structure of the inner core.

## EVIDENCE FOR DEEP SUBDUCTION

*Van der Hilst et al.* [1997] and *Grand et al.* [1997] reported recent advances in the imaging of the aspherical structure of the Earth's (lower) mantle. They showed, for the first time, that tomographic inversions of travel time data now begin to show agreement on structural features on length scales of 500-1000 km, even less in the best sampled regions. The *P*-wave model [*Van der Hilst et al.*, 1997; *Widiyantoro*, 1997], hereinafter referred to as P97, is based on a large data set of reported *pP*- and *P*-wave arrival times and earthquake locations originally published by the International Seismological Centre (ISC) and the U. S. Geological Survey's National Earthquake Information Center (NEIC) but extensively reprocessed by Engdahl and co-workers [*Engdahl et al.*, 1998]. The technique used is very similar to that described by *Widiyantoro and Van der Hilst* [1996] in their regional study of Indonesia. The *S*-wave study [*Grand*, 1994] - the current model, presented in *Grand et al.* [1997], is hereinafter referred to as S97 - is based on carefully processed travel times extracted from a range of shear wave arrivals. For the interpretation of the data, both studies use local basis functions (constant wavespeed blocks, or cells, with dimensions of the order of 2° × 2° × 150 km) for the parametrization of the model space, which enables the detection of spatial variations in wavespeeds on a scale length that is significantly smaller than when global basis functions, such as spherical harmonics, are used for the representation of structure. The potential resolution of variations in wavespeed over relatively short distances allows the mapping of mantle structure in well sampled regions of the mantle in a detail that was not previously possible.

P97 and S97 reveal long, narrow linear features of faster-than-average seismic wavespeeds in the mid mantle beneath the Americas and beneath southern Asia (Figure 1). These linear structures are detected to at least 1800 km depth. Once identified, these structural features can also be recognized clearly in long wavelength models of shear wavespeed such as those published by *Su et al.* [1994], *Li and Romanowicz* [1996], *Masters et al.* [1996], in the *P*-wavespeed model by *Bolton and Masters* [1996], and in earlier block-model inversions using the original set of ISC travel time residuals [*Inoue et al.*, 1990; *Vasco et al.*, 1994]. This robustness of the observations along with results of resolution tests with synthetic data calculated from known aspherical test models (e.g., Figure 2A,B in *Van der Hilst et al.* [1997]) supports the existence of the long, linear structures in the lower mantle.

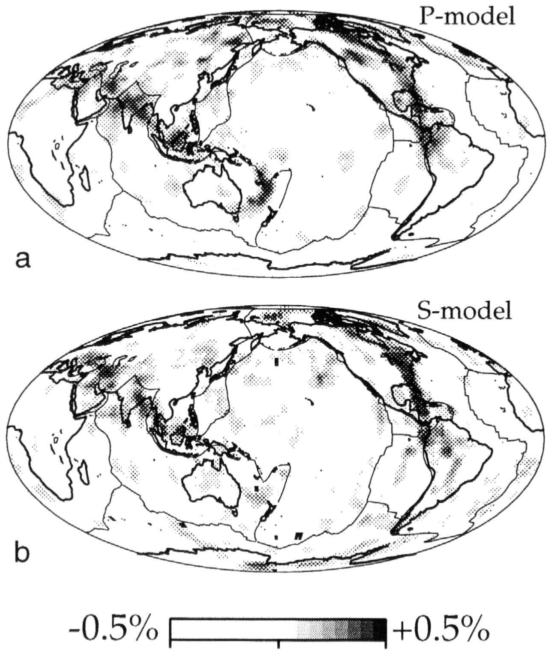

**Figure 1.** Lateral variation in compressional (top) and shear (bottom) wavespeeds in the lower mantle at about 1350 km depth (After *Van der Hilst et al.* [1997] and *Grand et al.* [1997]). For display purposes the diagrams only depict the mantle region where the wavespeed is higher-than-average.

Displays of wavespeed variations at several depths demonstrate that the long, narrow structure in the lower mantle beneath the Americas can be traced over a large depth interval (Plate 1). In the uppermost part of the lower mantle (700 km, bottom panel in Plate 1) the fast anomalies form a narrow structure that extends with only few interruptions from the Hudson Bay region in northern Canada across central America to as far south as northern Chile in South America. Comparison with *S* wave maps at the same depth [*Grand et al.*, 1997] indicates that variations in amplitude and sign

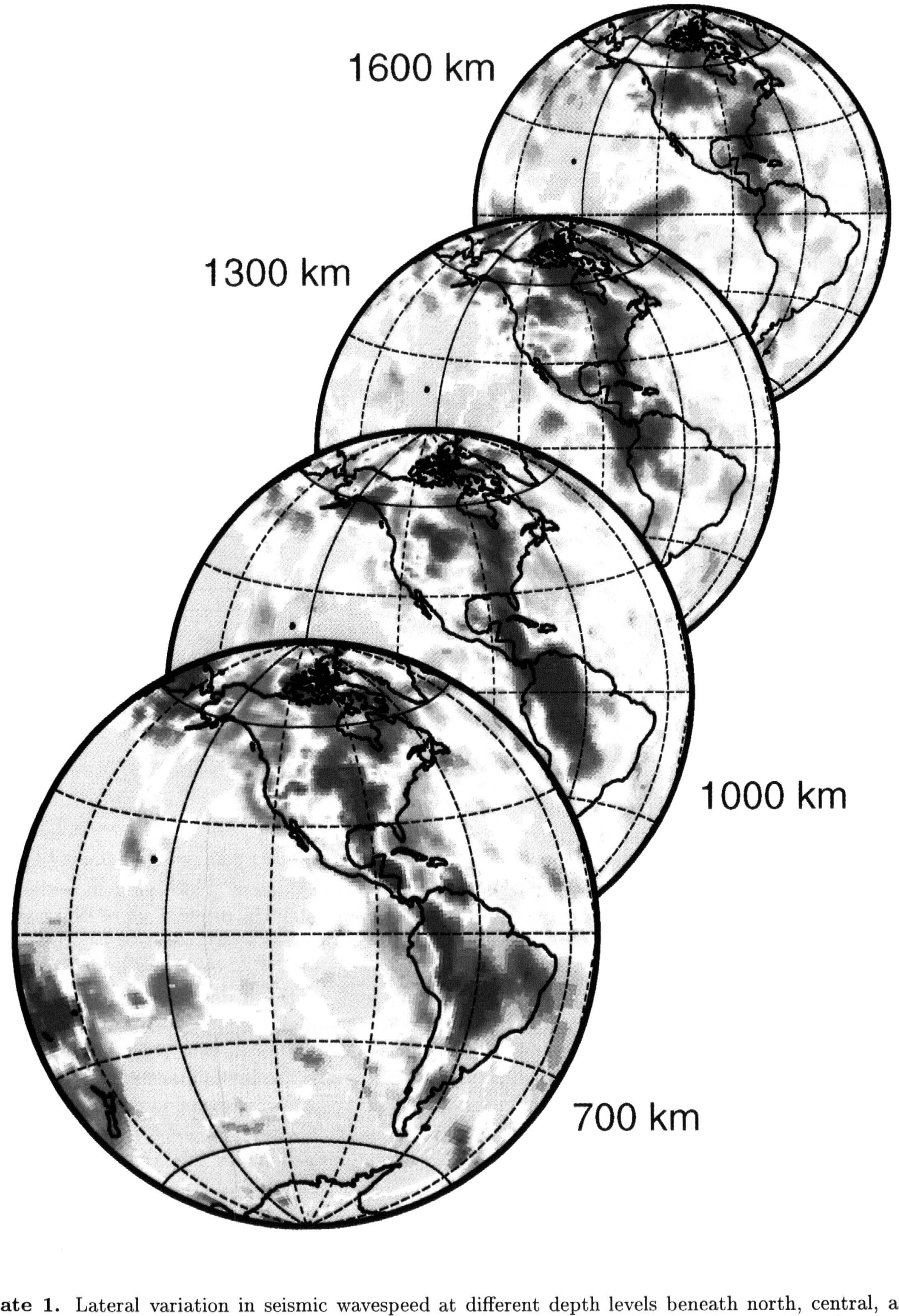

**Plate 1.** Lateral variation in seismic wavespeed at different depth levels beneath north, central, and south America after the model published by *Van der Hilst et al.* [1997] and *Widiyantoro* [1997]. Mantle regions with insufficient data coverage are depicted in gray.

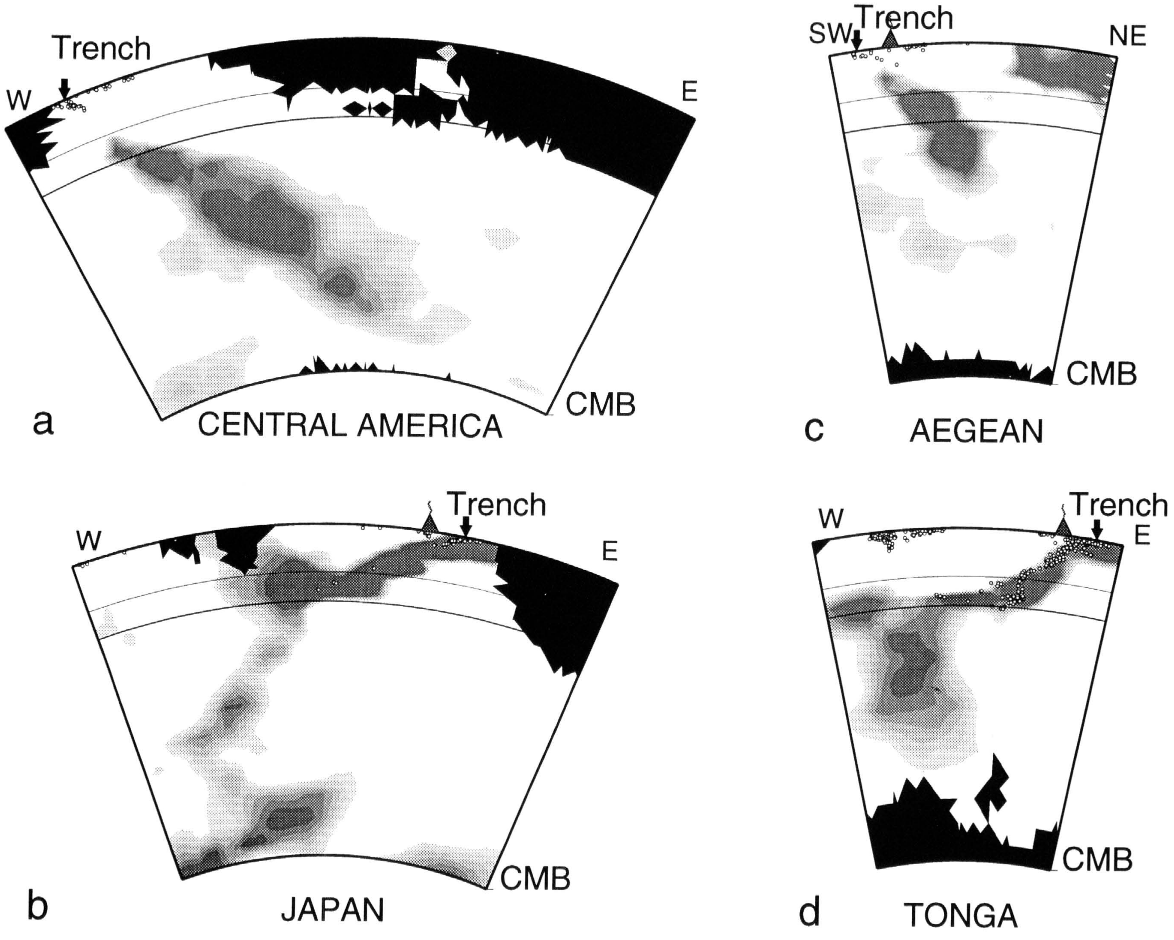

**Figure 2.** Vertical mantle sections from the Earth's surface to the core mantle boundary across (a) Middle America, depicting the lower mantle structure known as the 'Caribbean' anomaly, (b) central Japan and east Asia, (c) southeastern Europe, across the convergent margin between the African and Eurasian plates, and (d) northern Tonga. For display purposes the diagrams only depict the mantle region where the wavespeed is higher-than-average. Mantle regions with insufficient data coverage are depicted in black.

of the wavespeed perturbations along the strike of the linear feature are probably real. This may justify the interpretation of even smaller scale structure than has so far been discussed in literature. At larger depth, the anomalies become slightly broader (note that in Plate 1 the dimensions of the maps are adjusted to account for the decreasing radius within Earth) and the geometry changes, in particular in the far north where alternations of high and low wavespeed are visible [also in S97]. Beneath southernmost South America the high wavespeed anomaly is not visible beneath about 1300 km depth due to a deflection of the structure at a shallower depth in the mantle [*Grand*, 1994; *Engdahl et al.*, 1995; *Grand et al.*, 1997]. Vertical mantle sections further illustrate the continuity of high wavespeed trajectories from the upper mantle to very large depths in the lower mantle (Figure 2).

The continuity of the deep high wavespeed anomalies to subduction zones delineated by seismicity in the upper mantle and the strong spatial correlation with locations of known convergent margins in the Mesozoic [*Richards and Engebretson*, 1992; *Grand*, 1994; *Van der*

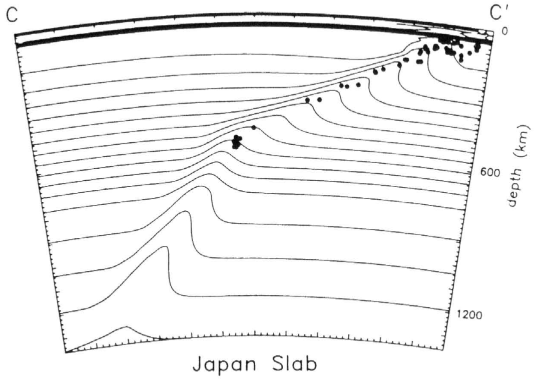

**Figure 3.** Cross section CC' from *Creager and Jordan* [1986]. The contours connect points of constant $P$ wavespeed. The location of the cross section is almost the same as that used for Figure 2b. The increase in dip angle in the top of the lower mantle is in excellent agreement with inferences from tomographic imaging (Figure 2b).

*Hilst et al.*, 1997; *Grand et al.*, 1997] provide strong support for the ability of slabs to sink across the upper mantle transition zone and the 660 km discontinuity into the lower mantle. Indeed, the recent tomographic models confirm inferences pertinent to the fate of slabs from studies based on residual sphere analysis for selected arc segments [*Jordan*, 1977; *Creager and Jordan*, 1984, 1986; *Fischer et al.*, 1988]. Compare, for instance, the result of tomographic imaging (Figure 2b) with inferences from residual sphere analysis for central Japan (Figure 3). For other regions, for instance Java and Izu Bonin, the residual spheres were less diagnostic of unhindered slab penetration into the lower mantle and the tomography indicates severe deformation and even deflection of the slab [e.g., *Van der Hilst et al.*, 1991; *Fukao et al.*, 1992; *Widiyantoro and Van der Hilst*, 1996]. Flow in the lower mantle induced by conductive cooling across an interface without mass exchange does not provide a plausible explanation for the observations described above. For a review of arguments against the significance of thermal coupling across a boundary layer at around 660 km depth we refer to *Jordan et al.* [1989]. Here we only make some simple inferences from the cross sections displayed in Figure 2.

The time scale for dynamic processes in the upper mantle is significantly shorter than in the higher viscosity lower mantle. Yet, there is an excellent geographical match between the fast anomalies in the upper- and lower mantle. Many lower mantle anomalies seem to be continuous to rapidly developing, subduction related structures in the upper mantle. Consider, for instance, the structure beneath Tonga (Figure 2d) and the Marianas [*Creager and Jordan*, 1986; *Van der Hilst et al.*, 1991]. Barring coincidence, the excellent match of lower mantle structures with transient features in the upper mantle is hard to explain by separate flow regimes coupled by heat exchange alone [*Jordan et al.*, 1989]. Moreover, thermal coupling of flow regimes on either side of an interface effectively decouples lower mantle flow from the motion of plates and is not likely to produce the observed geometry (e.g., constant dip angle) of the high wavespeed anomalies, for instance for Central America and southeastern Europe (Figures 2a,c). Also, for several subduction systems the time constraints provided by the known tectonic history and the inferred depth to the leading edge of the high wavespeed slab rule out a controlling role of a very slow physical process such as thermal conduction, unless the tectonic reconstructions are in error or flow in the lower mantle is much faster than expected from its high viscosity.

The seismological observations described above can best be explained by some form of whole mantle flow with substantial flux across the upper mantle transition zone into the lower mantle. We have not yet used our images to quantify the amount of mass exchange but they suggest that it should be at least the volume involved in the slabs of subducted lithosphere. While this 'slab flux' is likely to be a lower bound of the actual mass exchange [*Puster and Jordan*, 1997], it is up to two orders of magnitude higher than expected from mantle flow models used to explain noble gas data [e.g., *Hofmann*, 1997].

## COMPLEX FLOW ACROSS THE UPPER MANTLE TRANSITION ZONE

The conclusion that the seismic data can best be explained by large scale convective flow does not mean that the upper mantle transition zone has no effect on the flow pattern. On the contrary: flow across the upper mantle transition zone can be complex, with local deflection and kinking of the slab between 500 and 1000 km in depth, in particular in some segments of the western Pacific arc system [e.g., *Zhou and Clayton*, 1990; *Van der Hilst* et al., 1991; *Fukao et al.*, 1992; *Van der Hilst*, 1995; *Thoraval et al.*, 1995; *Widiyantoro and Van der Hilst*, 1996; *Castle and Creager*, 1997].

It has been argued from seismic observations and numerical and analog modeling of mantle flow that rapid lateral motions of the convergent margin can be causally related to changes in the morphology of the slab when the down-wellings interact with changes in physical properties at or near the 660 km discontinuity (e.g., a 30-fold jump in viscosity; an endothermic, iso-chemical phase change in mantle silicates; possible changes in rheology; perhaps a slight increase in intrinsic density). Several feed back relationships have been investigated [*Zhong and Gurnis*, 1995] but the complex geodynamical system is not yet fully understood. A more complete discussion of this issue is beyond the scope of this paper and for an overview of the arguments and modeling results we refer to *Gurnis and Hager* [1988], *Van der Hilst and Seno* [1993], *Zhong and Gurnis* [1995], *Griffiths et al.* [1995], *Christensen* [1996], and *Olbertz et al.* [1997].

While the effect of the 660 km discontinuity on downwellings is still debated, its role in stratifying mantle flow far away from convergent margins is perhaps even more uncertain. Owing to limited data coverage our technique does not constrain upper mantle structure beneath such regions, but *Katzman et al.* [1997] provide compelling evidence for upper mantle heterogeneity beneath the western Pacific, which they interpret in terms of convective rolls above the 660 km discontinuity.

## TRANSITION TO THE LOWERMOST 800 KM OF THE MANTLE

What is the ultimate fate of the slabs that sink, somehow, across the upper mantle transition zone? The new class of high resolution models suggests that linear features that are related to subduction of former oceanic lithosphere persist to at least 1800 km depth and that some of them continue all the way to the base of the mantle. For instance, the high wavespeed anomaly beneath central America (Figure 2a), which was first associated with subduction more than two decades ago [*Jordan and Lynn*, 1974], provides support for the postulation by *Kendall and Silver* [1996] that piling up of slab material atop the CMB in that region results in an effective anisotropic medium that causes the shear wave splitting that they observed. The deep anomaly as inferred from P97 is very similar to the structure deduced from S97, although the correlation between variations in $P$ and $S$ wavespeed seems to break down just above the CMB. Another region beneath which narrow high wavespeed anomalies form a continuous trajectory from the Earth's surface to the CMB is central Japan [Figures 2b, 3]. The anomaly is relatively narrow in the mid mantle but spreads out at the base of the mantle to form a large scale high wavespeed anomaly above the CMB.

These examples suggest that some downwellings can reach the CMB, but this may not be the fate of all slabs. Indeed, in P97 the heterogeneity pattern of the mid mantle does not seem to connect in a simple way to the large scale anomalies above the CMB. This is illustrated in Plate 2, which depicts the lateral variation in $P$-wavespeed according to P97 at 1300, 2100, and 2700 km depth, respectively. The long, linear structures that characterize the mid-mantle seem to disintegrate across a depth interval of roughly 1800-2300 km, in which the pattern of heterogeneity seems to be dominated by a distribution of - in map view - more equidimensional structures. This change in the planform of mantle structure roughly coincides with a change in heterogeneity spectrum [*Su and Dziewonski*, 1992; *Liu and Dziewonski*, 1994, this issue] but the inferred depth interval over which the changes occur is somewhat model dependent which renders the inference of this transition zone in the lower mantle tentative.

Even though a change in physical parameters or composition may not be required to explain the observed change in heterogeneity pattern [*Bercovici et al.*, 1989; *Glatzmaier et al.*, 1990] it is interesting to note that the transition zone as speculated upon by *Van der Hilst et al.* [1997] coincides with the depth range where the proportionality between variations in $P$- and $S$-wavespeed begins to break down [*Bolton and Masters*, 1996; *Robertson and Woodhouse*, 1996; *Su and Dziewonski*, 1997]. A joint inversion of $P$- and $S$- data for global variations in bulk sound and shear wavespeed by *Kennett et al.* [1998] confirms most previous conclusions and shows that the contribution of changes in bulk modulus to the variations in seismic wavespeed decreases gradually with increasing depth in the lowermantle and reaches a minimum at about 2000 km depth. The amplitudes of variations in bulk modulus increase again towards the base of the mantle but at those depths there appear to be large regions where the ratio of bulk sound and shear wavespeed anomalies can no longer be explained by thermal perturbations alone. The inferred behavior of the elastic moduli is suggestive of large scale chemical heterogeneity in the lowermost mantle [*Robertson and Woodhouse*, 1996; *Su and Dziewonski*, 1997; *Kennett et al.* 1998].

The presence of widespread chemical heterogeneity near the base of the mantle may also explain the high frequency (1 Hz) precursors to the core phase $PKP_{\mathrm{DF}}$, which are thought to be caused by small (10s of km) randomly distributed scatters [*Haddon and Cleary*, 1974].

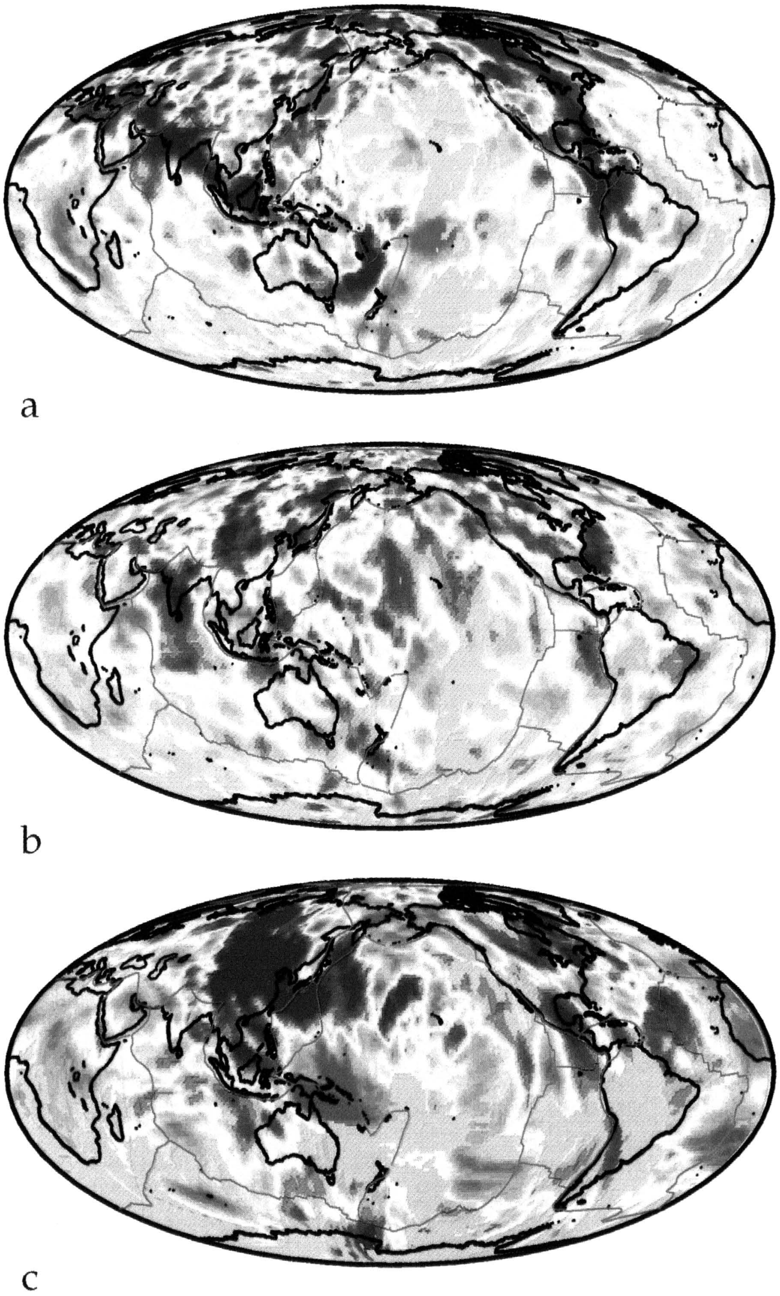

**Plate 2.** Lateral variation in *P*-wavespeed at 1350 (a), 2100 (b), and 2750 km depth (c). The gray patches indicate regions where sampling by the *P*-paths used in our study is unsufficient to constrain variations in wavespeed.

*Hedlin et al.* [1997] and *Shearer et al.* [this issue] provide compelling evidence that such scatterers can exist up to at least several hundreds of km above the CMB, perhaps throughout the lower 1000 km of the mantle.

## HOW ABOUT UPWELLINGS?

Low wavespeed anomalies are not as well imaged by our tomographic technique as the fast anomalies associated with downwellings. Large scale upwellings in the deep mantle are difficult to detect in the mid-mantle if they become more focused and cylindrically shaped as they ascend [e.g., *Bercovici et al.*, 1989]. There may also be a natural bias towards the imaging of high wavespeed anomalies since slow areas can be overlooked by first arriving waves owing to diffraction [*Wielandt*, 1987; *Nolet and Moser*, 1993]. For practical purposes, however, another important complication for plume imaging is that upwellings are usually not located in regions where many earthquakes occur. As a result, the effective data coverage by first arriving $P$ waves is typically significantly worse than that of the mantle regions associated with downwellings. Mantle structure beneath intraplate regions is better mapped by tomographic studies that exploit structural information from direct and multiply reflected body waves and from surface waves [e.g., *Su et al.*, 1994; *Grand*, 1994; *Masters et al.*, 1996]. Even though we are not as confident in the low wavespeed anomalies as in the fast structures, we can make some first order observations from the current whole mantle $P$-wave model.

Some large scale features stand out owing to slower-than-average $P$-wave propagation. In agreement with inferences from shear wave data [*Su et al.*, 1994; *Grand et al.*, 1997], the $P$-wave images suggest that beneath southern Africa a slow anomaly extends upwards from the core mantle boundary to a depth of about 800 km. A possible continuation to even shallower depths can not be resolved with the data used. Beneath the Society Islands in the southwest Pacific our results suggest the presence of a continuous conduit of slower-than-average wavespeeds from Earth's surface to a depth of about 2500 km. This structure is not well resolved, but the observations could not all be attributed to smearing in radial direction since in our imaging we do not use $P$-waves with such small ray parameters that they would travel sub-vertically from a 2500 km depth to Earth's surface. Interestingly, the low wavespeed feature does not seem to connect to the pronounced slow anomaly above the CMB, which is located vertically below the Ontong Java plateau, i.e. much further to the west. We remark, however, that within the current model uncertainties these structures may well represent different parts of a single, large slow anomaly in the lowermost mantle beneath the southwest Pacific.

## $P$-WAVESPEED ABOVE THE CMP FROM TOMOGRAPHY

At this stage of model development we chose not to discuss the images of the structure above the CMB in detail or compare them with independent wavespeed variations from independent studies. We realize that the current model is severely influenced by uneven sampling, as is evident from the large gray patches in Plate 2c, and that construction of better $P$-wave models is possible. In fact, we are in the process of adding complementary data in order to reduce the sampling problem and thus improve the lower mantle part of our model [*Kárason et al.*, 1997]. A detailed comparison with other results is not so meaningful either; previously published $P$-wave models constrain structure at much longer wave lengths (e.g., the model by *Wysession* [1996a] based on $P_{\text{diff}}$ differential residuals) and the comparison with $S$-wave models is complicated by the effect of chemical heterogeneity and, perhaps, seismic anisotropy. We do note, however, that the amplitude of anomalies in the lowermost mantle is generally lower in P97 than suggested by other studies, which probably indicates that too much damping was used to constrain the solution. Despite these uncertainties, several robust features in the images can be addressed.

A pronounced, well resolved structure of higher-than-average compressional wavespeed is located in the lowermost mantle beneath east Asia. This high wavespeed anomaly has also been reported by previous investigators of heterogeneity in the lowermost mantle. Mounting evidence from seismic imaging for deep subduction [e.g., *Creager and Jordan*, 1986; *Kamiya et al.*, 1989; *Van der Hilst et al.*, 1997] suggests that this structural heterogeneity above the CMB is the result of deep subduction of former oceanic lithosphere beneath island arcs in the west Pacific and southeast Asia. Figure 2b suggests that the downwelling is locally continuous from Earth's surface to the lowermost mantle and spreads out to form long wavelength structure atop the CMB. The patches of high velocity beneath the Americas (Plate 2c) are consistent with inferences from long wave length models [e.g., *Su et al.*, 1994] and possibly represent remnants of previously subducted lithosphere (e.g., Figure 2a). Other robust observations are the pronounced slow anomalies in the lowermost mantle vertically below southern Africa and the Ontong Java plateau in the west Pacific. The former is less well constrained by the data used to construct P97 (note the gray areas in Plate 2c) than in *S* wave studies [*Su et al.*, 1994; *Grand et al.*, 1997]. The latter is in excellent agreement with previous *P*-wave tomography [*Inoue et al.*, 1991; *Vasco et al.*, 1994], *S*-wave tomography [*Su et al.*, 1994; *Masters et al.*, 1996; *Li and Romanowicz*, 1996], and with inferences from imaging with *ScS-S* differential travel times [*Wysession et al.*, 1994], anomalous core diffractions [*Wysession*, 1996a], core refracted shear waves *SKS* [*Garnero and Helmberger*, 1993; *Liu and Dziewonski*, 1994, this issue], and compressional *PKP* waves [*Garnero et al.*, 1993; *Song and Helmberger*, 1997]. As mentioned above, this pronounced low wavespeed anomaly seems confined to the lowermost 300 or so km of the mantle, whereas further to the east, beneath the southwestern Pacific Society Islands, a (poorly constrained) low velocity conduit is continuous from a depth of approximately 2500 km to Earth's surface. A possible connection between two slow anomalies just above the CMB beneath the south Pacific and the conduit to shallower depths is not resolved by the data used.

Variations in *P* wavespeed seem to differ significantly from shear heterogeneity in some regions above the CMB. Perhaps the most significant disparity between *P*- and *S*- anomalies occurs beneath the Alaska and the Bering sea; P97 suggests that *P* wavespeed is lower than average whereas most shear wave studies reveal faster than average wave propagation [e.g. *Lay et al.*, 1997]. A joint inversion of *P*- and *S*-bulletin data reveals anomalous ratios between bulk sound and shear wavespeed in this region, indicating variations in bulk composition [*Kennett et al.*, 1998].

## ADDITIONAL CONSTRAINTS FROM LATER PHASES SUCH AS PKP

The sampling of structure in the lowermost mantle by compressional waves can be improved significantly by the addition of travel time data from phases such as the core reflections (*PcP*) or arrivals at distances in and beyond the *P*-wave shadow zone, such as core diffractions ($P_{\rm diff}$) and refractions (*PKP*). For these phases the bulletin data are rather noisy, despite the careful processing by *Engdahl et al.* [1998]. Therefore, for the extraction of structural signal pertinent to the lowermost mantle from these phases we will initially rely on waveform data. Here we present results of a reconnaissance study that should lead to the incorporation of *PKP* data in our global tomography.

Ray paths of the phase $PKP_{\rm AB}$ bottom in the shallow regions of the outer core and are almost core grazing (Figure 4). As a result, $PKP_{\rm AB}$ paths are significantly longer near the base of the mantle than the steeper paths associated with the phase $PKP_{\rm BC}$, which bottom in the lower regions of the outer core, or with $PKP_{\rm DF}$, which pass through the inner core (Figure 4). If heterogeneity in the outer core can be neglected and if large $PKP_{\rm DF}$ residuals owing to inner core anisotropy (as used by, e.g., *Morelli et al.*, 1986; *Shearer and Toy*, 1991; *Creager*, 1992; *Song and Helmberger*, 1993; *Tromp*, 1993; *Song*, 1996; *Creager*, 1997] are omitted from the data set, differential residual times formed by pairing the *AB* branch with the *BC* or *DF* branch (referred to as *AB-BC* times and *AB-DF* times, respectively) are expected to be most sensitive to structure in the lowermost mantle [e.g. *Sylvander and Souriau*, 1996; and many others].

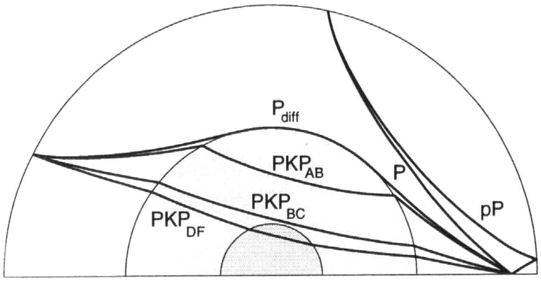

**Figure 4.** Path geometry and nomenclature of the compressional phases that have been or will be used in our whole mantle tomography. The *P* and *pP* phases have been used in the model discussed here (P97). Differential times for the various *PKP* branches and $P_{\rm diff}$ have been used by *Kárason et al.* [1997].

Figure 5a shows about 1150 observed $PKP_{\rm AB}$-$PKP_{\rm DF}$ and $PKP_{\rm AB}$-$PKP_{\rm BC}$ travel time residuals [*McSweeney*, 1995; *McSweeney et al.*, 1997] with respect to the global average according to model *ak135* [*Kennett et al.*, 1995] plotted at the core entrance and exit points of the $PKP_{\rm AB}$ paths. The $PKP_{\rm BC}$ and $PKP_{\rm DF}$ entrance and exit points are located nearly directly beneath sources and receivers and fill in gaps in *P* wave sampling beneath South America, Tonga-New Hebrides, Indonesia, the Philippines, Japan, China, Europe, North America and parts of Africa. The data used in Figure 5a do not include times from rays that traverse the inner core parallel to the spin axis so they do not contain the large (> 5s) signals produced by inner core anisotropy. However, heterogeneity in the inner core can have a significant effect on *AB-DF* residuals [*Creager*, 1997], which will have to be accounted for in tomographic inversions based on these data.

In order to assess the compatibility of the structural signal in the *P* and the *PKP* data we computed travel

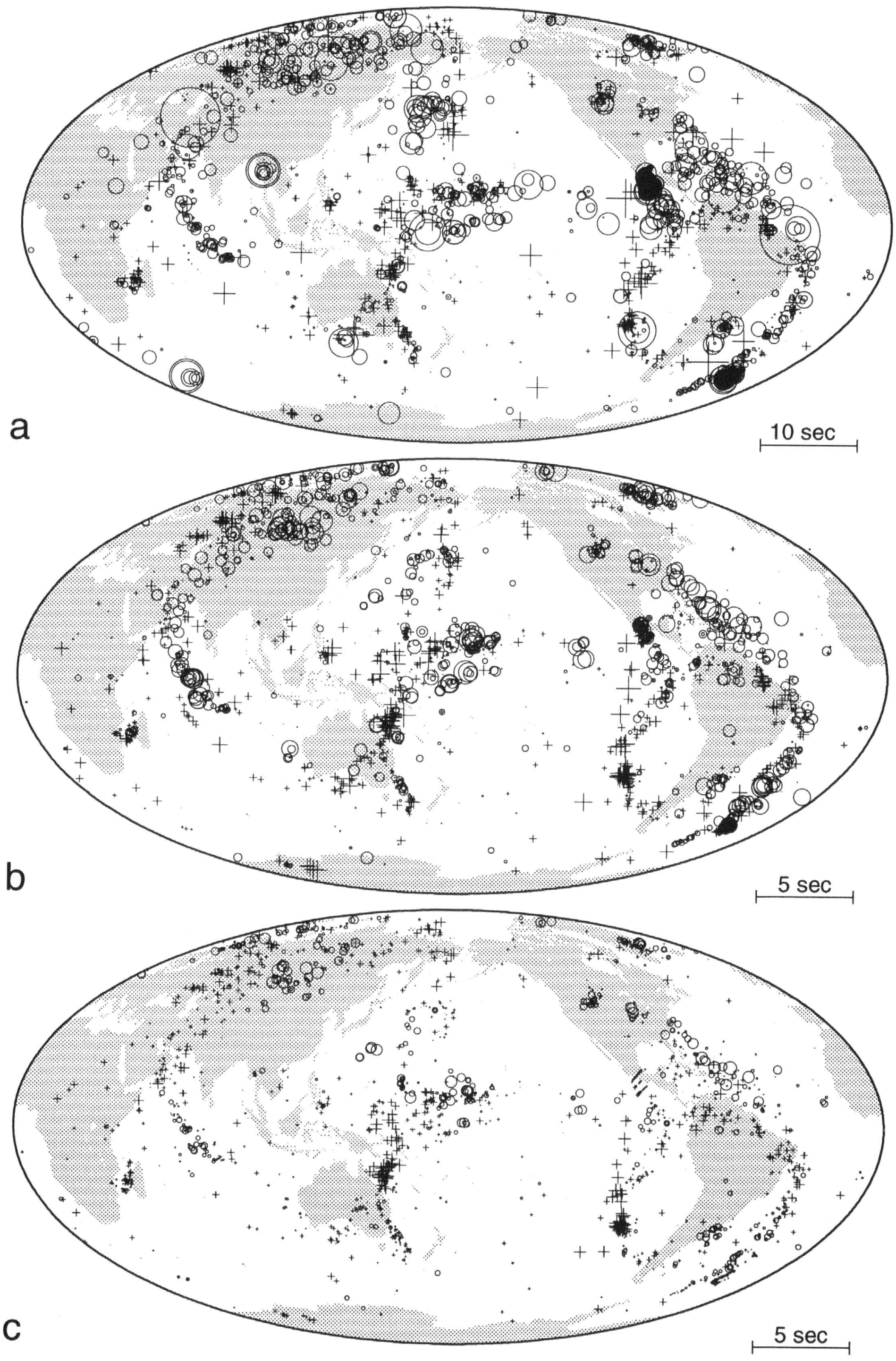

**Figure 5.** (a) *PKP*$_{\mathrm{AB}}$-*PKP*$_{\mathrm{DF}}$ and *PKP*$_{\mathrm{AB}}$-*PKP*$_{\mathrm{BC}}$ differential travel time residuals determined from waveform cross correlation and projected at the entry and exit intersections of the *PKP*$_{\mathrm{AB}}$ path with the core mantle boundary. Pluses are positive residuals, circles are negative. (b) Predictions from the *P* wave model by *Van der Hilst et al.* [1997] using the same paths as in (a). (c) Same as (b) except predictions are calculated from the lowermost 900 km of the mantle. Note the difference in symbol scale. For a detailed description, see *McSweeney* [1995] and *McSweeney et al.* [1997].

times by tracing the *PKP* paths used by *McSweeney et al.* [1997] and *McSweeney* [1995] through model P97. Subsequently, we compared model predictions with observations: qualitatively by visual inspection of the differential residuals in map view and quantitatively by computing the correlation coefficient between the maps. The contribution of structure in different depth ranges was investigated by considering 5 intervals bounded by interfaces at 0, 660, 1400, 2000, 2600, and 2889 km depth. For structure in the individual layers, the correlation coefficients are 0.20, 0.13, 0.16, 0.19, and 0.14, respectively. Differential travel time residuals calculated for the whole earth, i.e., all five layers, are displayed in Figure 5b; the correlation coefficient is 0.32. The predictions for the bottom 900 km, i.e., layers 4 and 5, are plotted in Figure 5c and show a correlation with observations of 0.24. Notice that the symbol scale used for the model predictions (Figures 5b and 5c) is two times as large as that used for the observations (Figure 5a). Our analysis suggests that the current *P* model underestimates the size of the residuals by up to half an order of magnitude, which is in accord with the findings by *Song and Helmberger* [1997]. This is due to (1) damping of the tomographic solution and (2) the complementary nature of *P* and *PKP* sampling in the deep mantle. *PKP* ray paths sample many regions that are not well sampled by *P* and which have therefore acquired only a small anomaly, if any, in the inversion.

There are two main points we want to make on the basis of this comparison. First, there is a remarkable agreement, in map view, between observed *PKP* data and the predictions from P97, which, we stress, was constructed without the core phases. This is evident from the spectacular match of predicted and observed residuals along the equator: eastward from Brazil into the Atlantic, westward from South America into easternmost Pacific, the east-west gradients beneath the central Pacific, and the anomalies beneath the Indian ocean. Also for central Asia and north America the model predictions agree remarkably well with the observations. $PKP_{\mathrm{AB}}$ does not sample much of the pronounced high wavespeed anomaly beneath east Asia, but the sampling improves further to the north and the agreement between model and data is excellent. Just west of the date line in the northern and central Pacific, east-west gradients over relatively small distances are revealed by both the observations and the predictions from P97, which suggests that such relatively small scale structure and the associated steep velocity gradients are real. There are also disagreements. For instance, for the region east of Australia the gradients are reversed, and for the Indian Ocean southeast of Africa the sign of the observed anomalies is opposite of the P97 predictions. However, both regions are poorly sampled by the *P* paths used for the tomography (Plate 2c).

Second, the maps displayed in Figures 5b and 5c and the correlation coefficients computed for different depth intervals suggest that structure in a significant fraction of the lower mantle can contribute to the signal contained in the differential travel time residuals. Apparently, some structure, for instance deep slabs, can be sampled differentially by the *PKP* branches owing to the slight difference in take off angle between the $PKP_{\mathrm{AB}}$ path and either the $PKP_{\mathrm{BC}}$ or the $PKP_{\mathrm{DF}}$ path. Even though we have overestimated its effect by using ray theory, which ignores the effective width of rays, differential sampling may violate the assumptions underlying conventional interpretations of differential residuals. However, it is not a problem in tomographic inversions since the residuals are back projected along all path segments involved [*Van der Hilst and Engdahl*, 1991]. We therefore expect that the inclusion of *PKP* data (and other core data) will improve the constraints on aspherical structure in the entire lower mantle, although most improvements are expected in the lowermost 800 km.

## SUMMARY AND CONCLUSIONS

There is increasing consensus from seismological and geodynamical studies that slabs of subducted lithosphere sink deep into Earth's lower mantle and that present-day mantle convection is predominated by some form of whole mantle flow. The pattern of heterogeneity in the upper mantle is determined by ocean-continent differences and by narrow slabs of subducted lithosphere delineated by seismicity. In the mid-mantle, long linear features are detected to at least 1800 km depth and are continuous to seismogenic slabs in the upper mantle beneath major convergence zones. The linear structures may disintegrate at even larger depth but there is evidence that some slabs sink to the base of the mantle and connect to structural heterogeneity atop the CMB, providing strong support for a relationship between aspherical structure at the base of the mantle and material recycled from Earth's surface.

We may have overlooked slow anomalies as a result of uneven data coverage and a combination of diffraction and wavefront healing, but the current images seem to indicate that the aspherical structure in the Earth's lower mantle is predominated by downwellings. This asymmetry in the planform of mantle flow is consistent with thermal con-vection that is driven primarily by internal heating (decay of radio-isotopes) and conductive cooling through the top thermal boundary layer, with basal heating due to cooling of the core amounting to less than 20% of the total energy required for convection [*Schubert et al.*, 1980, *Loper*, 1985; *Davies*, 1988; *Sleep*, 1990; *Davies and Richards*, 1992].

In this scenario of essentially mantle wide flow we identify two depth intervals (between 500-800 km and 1800-2300 km in depth) where the planform of mantle heterogeneity related to convection changes.

Under certain conditions (which depend on thermal structure of the slab, rate of subduction, age of lithosphere, subduction history, trench migration, membrane strength, etc.) the upper mantle transition zone can distort flow trajectories and cause a transient layering that prevents slabs from sinking into the deeper mantle. Along with the increase in viscosity [*Bunge et al.*, 1996] such transient processes may filter out significant amounts of small scale and rapidly varying structures, which may explain the difference between the heterogeneity spectrum of the upper and lower mantle.

At larger depth the character of heterogeneity changes again: between approximately 1800 and 2300 km depth the planar, sheet like slabs seem to break down into laterally more confined downwellings that, eventually, spread out to form long wavelength structure at the base of the mantle. In the scenario of 'penetrative convection' as proposed by *Silver et al.* [1988] this transition in the planform and spectrum of heterogeneity could indicate the depth where the intrinsic density of the ambient mantle increases owing to changes in bulk chemistry so that downwellings lose their excess negative (thermal) buoyancy. The observations could also be indicative of resistance to flow due to deep phase changes in the mantle silicates, for instance stishovite [*Kingma et al.*, 1995], but such transformations are still enigmatic [*Kesson, personal communication*, 1997]. If the change in the planform of heterogeneity does not mark the maximum penetration depth of slabs there must be significant lateral flow within the sheet-like structures towards and into the more localized and equidimensional downwellings (which may be detectable by other means, such as the analysis of birefringence of $S$ waves that bottom in this depth interval).

Support for changes in bulk chemistry in the bottom 800 km or so of Earth's mantle comes from joint inversions of $P$- and $S$-data, which indicate that the ratio of variations in bulk- and shear wavespeed is anomalous and inconsistent with expected thermal effects [*Bolton and Masters*, 1996; *Robertson and Woodhouse*, 1996; *Su and Dziewonski*, 1997; *Kennett et al.*, 1998]. The conclusive interpretation of these increasingly robust observations awaits better and more mineral physics data pertinent to the physical con-ditions of the lowermost mantle. However, widespread heterogeneity is also invoked to explain the high frequency precursors to the $PKP$ arrivals [*Hedlin et al.*, 1997; *Shearer et al.*, this issue], and it may represent primitive mantle that survived convective mixing in a mantle with depth dependent viscosity [*Gurnis and Davies*, 1986; *Loper*, 1985; *Davies and Richards*, 1992]. This may go towards reconciling whole mantle flow with inferences from noble gas data (see *Hofmann* [1997] for a review), but the volume of the lowermost 800 km of the mantle is too small to encompass all geochemical reservoirs.

The depth interval between approximately 2000 km and the CMB thus contains many clues to a better understanding of the composition, dynamics, and the thermal and chemical evolution of Earth's mantle. Differential travel times have traditionally been used to isolate structural signal from the CMB region but the relation to heterogeneity in the mantle above is perhaps of as much fundamental interest as the boundary layer structure itself. Unfortunately, in the current global models based on $P$-wave data poor sampling prohibits a more detailed description of the variations in $P$ wavespeed in the bottom 800 km of the mantle. Advances can be made by inclusion of core phases. Preliminary results indicate that $PKP$ data are compatible with our $P$-wave model. However, it also shows that structure in a large part of the lower mantle can contribute to differential $PKP$ signal. Models for heterogeneity above the core mantle boundary based on differential residuals alone can thus be contaminated by structural signal from sources elsewhere in the mantle. A joint inversion of the different classes of phase data will produce better constraints on lower mantle structure than either data set alone. In turn, the improved model enables the calculation of more accurate mantle corrections which may help the extraction from waveforms of structural signal pertinent to more detailed structure of the base of the mantle, CMB topography, and subtle heterogeneity, if any, in the outer core, and may create a clear observation window for further investigations of the inner core.

**Note added to proof.** Recently, we have successfully incorporated a range of $PKP$ and $P_{\mathrm{diff}}$ differential travel time residuals in inversions for variations in compressional wavespeed in Earth's mantle [*Kárason et al.*, 1997]. The definition and resolution of structure in the bottom 500 or so km of the mantle has improved dramatically, but the conclusions of this paper do not need to be revised. The new model reduces the variance of the differential times significantly without degrading the fit to the $P$ data (as was to be expected from the complementary nature of sampling). The wavespeed variations above the CMB are consistent with independent models. However, in accord with the observations made above we detect sharp lateral gradients in some parts of the core mantle boundary region. The change in planform of heterogeneity from the mid mantle to the CMB region is even more pronounced than inferred from the model used here, and we now begin to resolve the deep slow anomaly beneath Africa and also the connection between the slow anomalies above the CMB and the low wavespeed conduit that continues to shallow depths beneath the southern Pacific.

**Acknowledgments**: We thank Hrafnkell Kárason for discussions, access to his preliminary whole mantle model based on *P*, *pP*, *PKP*, and $P_{\text{diff}}$ data, and for producing Figure 4. Constructive reviews by Peter Shearer, Xiaodong Song, and Michael Wysession improved the manuscript. We thank Michael Gurnis and the coeditors for organizing this monograph, and Bethany Matsko and Frederik Simons for their assistance with the LaTeX preparation of the final manuscript. This research was supported by NSF grant EAR9628087.

## REFERENCES

Allègre, C. J., M. Moreira, and T. Staudacher, $^4$He/$^3$He dispersion and mantle convection, *Earth Planet. Sci. Lett.*, 136, 629-646, 1995.

Bercovici, D., G. Schubert, and G. Glatzmaier, 3-dimensional spherical models of convection in the Earth's mantle, *Science*, 244, 950-955, 1989.

Bolton, H., and G. Masters, A region of anomalous $d\ln V_s/d\ln V_p$ in the deep mantle, *(abstr.) EOS Trans. Am. Geophys. Un.*, 1996.

Bunge, H.-P., M.A. Richards, and J.R. Baumgardner, The effect of viscosity stratification on mantle convection, *Nature*, 379, 436-438, 1996.

Castle, J.C. and K.C. Creager, Topography of the 660 km seismic discontinuity beneath Izu-Bonin: implications for tectonic history and slab deformation (submitted).

Christensen, U.R., The influence of trench migration on slab penetration into the lower mantle, *Earth Planet. Sci. Lett.*, 140, 27-39, 1996.

Creager, K.C., Anisotropy of the inner core from differential travel times of the phases *PKP* and *PKIKP*, *Nature*, 356, 309-314, 1992.

Creager, K.C., Anisotropic structure and rotation of the inner core, *(abstr.) EOS Trans. Am. Geophys. Un.*, 78, F458, 1997.

Creager, K.C., and T.H. Jordan, Slab penetration into the lower mantle, *J. Geophys. Res.*, 89, 3031-3049, 1984.

Creager, K.C.,and T.H. Jordan, Slab penetration into the lower mantle below the Mariana arc and other island arcs of the northwest Pacific, *J. Geophys. Res.*, 91, 3573-3589, 1986.

Davies, G.F., Ocean bathymetry and mantle convection, 1, Large-scale flow and hot spots, *J. Geophys. Res.*, 93, 10447-10480, 1988.

Davies, G.F., and M. Gurnis, Interaction of mantle dregs with convection: lateral heterogeneity at the core-mantle boundary, *Geophys. Res. Lett.*, 13, 1517-1520, 1986.

Davies, G.F., and M.A. Richards, Mantle convection, *J. Geol.*, 100, 151-206, 1992.

Engdahl, E.R., R.D. van der Hilst, and J. Berrocal, Imaging of subducted lithosphere beneath South America, *Geophys. Res. Lett.*, 22, 2317-2320, 1995.

Engdahl, E.R., R.D. van der Hilst, and R.P. Buland, Global teleseismic earthquake relocation from improved travel times and procedures for depth determination, *Bull. Seism. Soc. Am.* (in press, 1998).

Fischer, K., T.H. Jordan, and K.C. Creager, Seismic constraints on the morphology of deep slabs, *J. Geophys. Res.*, 93, 4773-4783, 1988.

Fukao, Y., M. Obayashi, H. Inoue, and M. Nenbai, M., Subducting slabs stagnant in the mantle transition zone, *J. Geophys. Res.*, 97, 4809-4822, 1992.

Garnero, E.J., and D.V. Helmberger, Travel times of *S* and *SKS*: implications for three-dimensional lower mantle structure beneath the central Pacific, *J. Geophys. Res.*, 98, 8225-8241, 1993.

Garnero, E.J., S.P. Grand, and D.V. Helmberger, Low *P*-wave velocity at the base of the mantle, *Geophys. Res. Lett.*, 20, 1843-1846, 1993.

Glatzmaier, G.A., G. Schubert, and D. Bercovici, Chaotic, subduction-like downflows in a spherical model of convection in the Earth's mantle, *Nature*, 347, 274-277, 1990.

Grand, S.P., Mantle shear structure beneath the Americas and surrounding oceans, *J. Geophys. Res.*, 99, 11591-11621, 1994.

Grand, S.P., R.D. van der Hilst, and S. Widiyantoro, High resolution global tomography: a snapshot of convection in the Earth, *Geol. Soc. Am. Today*, 7, 1-7, 1997.

Griffiths, R.W., Hackney, R., and R.D. van der Hilst, A laboratory investigation of effects of trench migration on the descent of subducted slabs, *Earth Planet. Sci. Lett.*, 133, 1-17, 1995.

Gurnis, M., and G.F. Davies, The effect of depth-dependent viscosity on convective mixing in the mantle and the possible survival of primitive mantle, *Geophys. Res. Lett.*, 13, 541-544, 1986.

Gurnis, M. and B.H. Hager, Controls on the structure of subducted slabs, *Nature*, 335, 317-321, 1988.

Haddon, R.A.W., and J.R. Cleary, Evidence for scattering of seismic *PKP* waves near the mantle-core boundary, *Phys. Earth Planet. Inter.*, 8, 211-234, 1974.

Hedlin, M., P.M. Shearer, and P.S. Earle, Seismic evidence for small-scale heterogeneity throughout the Earth's mantle, *Nature*, 1997.

Hofmann, A., Mantle geochemistry: the message from oceanic volcanism, *Nature*, 385, 219-229, 1997.

Inoue, H., Y. Fukao, K. Tanabe, and Y. Ogata, Whole mantle P-wave travel time tomography, *Phys. Earth Planet. Inter.*, 59, 294-328, 1990.

Jordan, T.H. and W.S. Lynn, A velocity anomaly in the lower mantle, *J. Geophys. Res.*, 79, 2679-2685, 1974.

Jordan, T.H., Lithospheric slab penetration into the lower mantle beneath the sea of Okhotsk, *J. Geophys. Res.*, 43, 473-496, 1977.

Jordan, T.H., A.L. Lerner-Lam, and K.C. Creager, Seismic imaging of boundary layers and deep mantle convection, In *Mantle Convection*, edited by W.R. Peltier, pp. 98-201, Gordon and Breach Scientific Publishers, 1989.

Kamiya, S., T. Miyatake, and K. Hirahara, How deep can we see the high velocity anomalies beneath the Japanese island arcs? *Geophys. Res. Lett.*, 15, 828-831, 1988.

Kárason, H., R.D. van der Hilst, and K.C. Creager, Improving seismic models of global P-wavespeed by the inclusion of core phases, (*abstr.*) *EOS Trans. Am. Geophys. Un.*, 78, F17, 1997.

Katzman, R., L. Zhao, and T.H. Jordan, High resolution, 2D vertical tomography of the central Pacific mantle using *ScS* reverberations and frequency-dependent travel times, *J. Geophys. Res.* (in press, 1998).

Kellogg, L., and G.J. Wasserburg, The role of plumes in Helium fluxes, *Earth Planet. Sci. Lett.*, 99, 276-289, 1990.

Kendall, J.-M., and P.G. Silver, Constraints from seismic anisotropy on the nature of the lowermost mantle, *Nature*, 381, 409-412, 1996.

Kennett, B.L.N., E.R. Engdahl, and R. Buland, Constraints on seismic velocities in the Earth from travel times, *Geophys. J. Int.*, 122, 108-124, 1995.

Kennett, B.L.N., Widiyantoro, S., and R.D. van der Hilst, Joint seismic tomography for bulk-sound and shear wave speed, *J. Geophys. Res.* (in press, 1998).

Kingma, K.J., R.E. Cohen, R.J. Hemley, and H.K. Mao, Transformation of stishovite to a denser phase at lower mantle pressures, *Nature*, 374, 243-245, 1995.

Lay, T, Structure of the core-mantle transition zone: A chemical and thermal boundary layer, *EOS Trans. Am. Geophys. Un.*, 70, 49, 54-55, 58-59, 1989.

Lay, T., T.J. Ahrens, P. Olson, J. Smyth, and D. Loper, Studies of Earth's Deep Interior: goals and trends, *Phys. Today*, 43, 44-52, 1990.

Lay, T. The fate of descending slabs, *Ann. Rev. Earth Planet. Sci.*, 22, 33-61, 1994.

Lay, T., E.J. Garnero, C.J. Young, and J.B. Gaherty, Scale length of shear velocity heterogeneity at the base of the mantle from *S* wave differential travel times, *J. Geophys. Res.*, 102, 9887-9909, 1997.

Li, X-.D. and B. Romanowicz, Global mantle shear-velocity model developed using nonlinear asymptotic coupling theory, *J. Geophys. Res.*, 101, 22245-22272, 1996.

Liu, X.-F., W.-j. Su, and A.M. Dziewonski, Improved resolution of lowermost mantle shear wave velocity structure obtained using *SKS-S* data, (*abstr.*) *EOS Trans. Am. Geophys. Un.*, 75, 232, 1994.

Liu, X.-F., W.-j. Su, and A.M. Dziewonski, Global analysis of shear wave velocity anomalies in the lowermost mantle, (this volume).

Loper, D.E., A simple model of whole mantle convection, *J. Geophys. Res.*, 90, 1809-1836, 1985.

Loper, D., and T. Lay, The core-mantle boundary region, *J. Geophys. Res.*, 100, 6397-6420, 1995

Masters, G., S. Johnson, G. Laske, and H. Bolton, A shear-velocity model of the mantle, *Phil. Trans. R. Soc. Lond.* A, 354, 1385-1411, 1996.

McSweeney, T.J., Seismic constraints on core structure and dynamics, Ph. D. thesis, University of Washington, Seattle, 1995.

McSweeney, T.J., K.C. Creager, and R.T. Merrill, Depth extent of inner-core seismic anisotropy and implications for geomagnetism, *Phys. Earth Planet. Inter.*, 101, 131-156, 1997.

Morelli, A., A.M. Dziewonski, and J.H. Woodhouse, Anisotropy of the inner core inferred from *PKIKP* travel times, *Geophys. Res. Lett.*, 13, 1545-1548, 1986.

Nolet, G. and T.-J. Moser, Teleseismic delay times in a 3-dimensional Earth and a new look as the *S*-discrepancy, *Geophys. J. Int.*, 104, 185-195, 1993.

Olbertz, D., M.J.R. Wortel, and U. Hansen, Trench migration and subduction zone geometry, *Geophys. Res. Lett.*, 24, 221-224, 1997.

O'Nions, K., and I. Tolsthikin, Behavior and residence times of lithophile and rare gas tracers in the upper mantle, *Earth Planet. Sci. Lett.*, 124, 131-138, 1994.

Puster, P., and T.H. Jordan, How stratified is mantle convection, *J. Geophys. Res.*, 102, 7625-7646, 1997.

Richards, M.A., and D.C. Engebretson, Large-scale mantle convection and the history of subduction, *Nature*, 355, 437-440, 1992.

Robertson, G.S., and J.H. Woodhouse, Ratio of relative *S* to *P* velocity heterogeneities in the lower mantle, *J. Geophys. Res.*, 101, 20041-20052, 1996.

Rodgers, A., and J. Wahr, Inference of core-mantle boundary topography from ISC *PcP* and *PKP* traveltimes, *Geophys. J. Int.*, 115, 991-1011, 1993.

Schubert, G., D. Stevenson, and P. Cassen, Whole planet cooling and the radiogenic heat source content of Earth and Moon, *J. Geophys. Res.*, 85, 2531-2538, 1980.

Shearer, P.M, and K.M. Toy, *PKP(BC)* versus *PKP(AB)* differential travel times and aspherical structure in the Earth's inner core, *J. Geophys. Res.*, 96, 2233-2247, 1991.

Shearer, P.M., M.A.H. Hedlin, and P.S. Earle, *PKP* and PKKP precursor observations: implications for the small scale structure of the deep mantle, (this volume).

Silver, P.G., R.W. Carlson, and P. Olson, Deep slabs, geochemical heterogeneity, and the large-scale structure of mantle convection, *Rev. Earth Planet. Sci.*, 16, 477-541, 1988.

Sleep, N.H., Hotspots and mantle plumes, *J. Geophys. Res.*, 95, 6715-6736, 1990.

Song, X., Anisotropy in the central part of the inner core, *J. Geophys. Res.*, 101, 16089-16097, 1996.

Song, X., and D.V. Helmberger, Anisotropy of Earth's inner core, *Geophys. Res. Lett.*, 20, 2591-2594, 1993.

Song, X., and D.V. Helmberger, *PKP* differential travel times: implications for 3-D lower mantle structure, *Geophys. Res. Lett.*, 24, 1863-1866, 1997.

Su, W.-j., and A.M. Dziewonski, Predominance of long-wavelength heterogeneity in the mantle, *Nature*, 352, 121-126, 1992.

Su, W. -j., R.L. Woodward, and A.M. Dziewonski, Degree 12 model of shear velocity heterogeneity in the mantle, *J. Geophys. Res.*, 99, 6945-6981, 1994.

Su, W.-j., and A.M. Dziewonski, Simultaneous inversion for 3D variations in shear and bulk velocity in the mantle, *Phys. Earth Planet. Inter.*, 100, 135-156, 1997.

Sylvander, M., and A. Souriau, P-velocity structure of the core-mantle boundary region inferred from *PKP(AB)-PKP(BC)* differential travel times, *Geophys. Res. Lett.*, 23, 853-856, 1996.

Thoraval, C., P. Machetal, and A. Cazenave, A locally layered convection inferred from dynamic models of the Earth's mantle, *Nature*, 375, 777-780, 1995.

Tromp, J., Support for anisotropy of the Earth's inner core from free oscillations, *Nature*, 366, 678-681, 1993.

Van der Hilst, R.D., and E.R. Engdahl, On ISC *pP* and *PP* data and their use in delay time tomography of the Caribbean region, *Geophys. J. Int.*, 106, 169-188, 1991.

Van der Hilst, R.D., E.R. Engdahl, W. Spakman, and G. Nolet, Tomographic imaging of subducted lithosphere below northwest Pacific island arcs, *Nature*, 353, 37-42, 1991.

Van der Hilst, R.D., and T. Seno, Effects of relative plate motion on the deep structure and penetration depth of slabs below the Izu-Bonin and Mariana island arcs, *Earth Planet. Sci. Lett.*, 120, 375-407, 1993.

Van der Hilst, R.D., Complex morphology of subducted lithosphere in the mantle beneath the Tonga trench, *Nature*, 374, 154-157, 1995.

Van der Hilst, R.D., S. Widiyantoro, and E.R. Engdahl, Evidence for deep mantle circulation from global tomography, *Nature*, 386, 578-584, 1997.

Vasco, D.W., L.R. Johnson, R.J. Pulliam, and P.S. Earle, Robust inversion of IASP91 travel time residuals for mantle $P$ and $S$ velocity structure, *J. Geophys. Res.*, 99, 13727-13755, 1994.

Widiyantoro, S., Ph.D. Thesis, Australian National University, Canberra, 1997.

Widiyantoro, S., and R.D. van der Hilst, Structure and evolution of lithospheric slab beneath the Sunda arc, Indonesia, *Science*, 271, 1566-1570, 1996.

Widiyantoro, S., and R.D. van der Hilst, Mantle structure beneath Indonesia inferred from high-resolution tomographic imaging, *Geophys. J. Int.*, 130, 167-182, 1997.

Wielandt, E., On the validity of the ray approximation for interpreting delay times, In *Seismic Tomography*, edited by G. Nolet, pp. 85-98, D. Reidel Publishing Company, Dordrecht, The Netherlands, 1987.

Wysession, M.E., Continents of the core, *Nature*, 381, 373-374, 1996.

Wysession, M.E., Imaging cold rock at the base of the mantle: the sometimes fate of slabs? In *Subduction: Top to Bottom*, edited by G.E. Bebout, D.W. Scholl, S.H. Kirby, and J.P. Platt, American Geophysical Union, *Geophysical Monograph Series, Am. Geophys. Un.*, 96, 369-384, 1996.

Wysession, M.E., L. Bartkó, and J. Wilson, Mapping the lowermost mantle using core-reflected shear waves, *J. Geophys. Res.*, 99, 13667-13684, 1994.

Zhong, S. and M. Gurnis, Mantle convection with plates and mobile, faulted plate margins, *Science*, 267, 838-843, 1995.

Zhou, H.-W., and R.W. Clayton, $P$ and $S$ wave travel time inversion for subducting slabs under island arcs of the northwest Pacific, *J. Geophys. Res.*, 95, 6829-6851, 1990.

---

R. D. van der Hilst, Massachusetts Institute of Technology, Department of Earth, Atmospheric, and Planetary Sciences, Rm 54-514, Cambridge MA 02319, U.S.A. (email: hilst@mit.edu)

S. Widiyantoro, Research School of Earth Sciences, Australian National University, Canberra ACT 0200, Australia.

K.C. Creager, and T.J. McSweeney, Geophysics Program, University of Washington, Seattle WA 98195, U.S.A.