Global Seismic Tomography: A Snapshot of Convection in the Earth

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ABSTRACT

Two new global high-resolution models of the P-wave and S-wave seismic structure of the mantle were derived independently using different inversion techniques and different data sets, but they show excellent correlation for many large-scale as well as smaller scale structures throughout the lower mantle. The two models show that high-velocity anomalies in the lower mantle are dominated by long linear features that can be associated with the sites of ancient subduction. The images suggest that most subduction-related mantle flow continues well into the lower mantle and that slabs may ultimately reach the core-mantle boundary. The models are available from anonymous ftp at maestro.geo.utexas.edu in directory pub/grand and at brolga.mit.edu in directory pub/GSAtoday.

INTRODUCTION

Since forming about 4.5 Ga, planet Earth has been cooling by means of relatively vigorous convection in its interior and by conductive heat loss across the cold thermal boundary layer at the top of the mantle (mainly the oceanic lithosphere). The primary force driving convection is the downward pull of gravity on the cold, dense lithosphere resulting in downwellings of slabs of subducted lithosphere. Understanding the nature of the

Figure 1. Cross sections of mantle P-wave (A) and S-wave (B) velocity variations along a section through the southern United States. The endpoints of the section are 30.1°N, 117.1°W and 30.2°N, 56.4°W. The images show variations in seismic velocity relative to the global mean at depths from the surface to the core-mantle boundary. Blues indicate faster than average and reds slower than average seismic velocity. The large tabular blue anomaly that crosses the entire lower mantle is probably the descending Farallon plate that subducted over the past ~100 m.y. Differences in structure between the two models in the transition zone (400 to 660 km depth) and at the base of the mantle are probably due to different data sampling in the two studies.
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In Memoriam

Robert J. Cordell
Richardson, Texas
February 7, 1997

John Van N. Dorr II
Bethesda, Maryland
December 23, 1996

Paul L. Drummond
Tyler, Texas
January 1996

G. E. P. Eastwood
Victoria, British Columbia, Canada
December 16, 1996

Edwin N. Goddard
Portage, Michigan
February 1, 1997

Marcus G. Langseth
Palisades, New York
January 4, 1997

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San Jose, California
October 31, 1996

Robert C. Stephenson
Newville, Pennsylvania
December 17, 1996

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convective flow is important for deciphering Earth’s thermal history, its internal composition, and the differentiation processes that produced the Earth we know today. It is the fundamental process that moves plates and makes mountains. Conversely, the geometry of plates exerts control on the geometry of subduction and therefore Earth convection. A long-standing goal of geophysics has been to determine the convection pattern within Earth’s mantle. Despite years of study, several first-order aspects of the mantle flow regime remain controversial (see Silver et al., 1988; Davies and Richards, 1992, and Lay, 1994) for extensive reviews). In part, this is due to published global maps of seismic aspherical structure of Earth’s mantle not having sufficient resolution to track flow trajectories from the surface to the deep mantle.

In the upper mantle (~40 to 660 km depth), downwellings can partially be inferred directly from the shape of the subduction-related seismic zones, but such unambiguous tracers cannot be used at greater depth. Many studies have focused on the behavior of subducted slabs near the upper to lower mantle boundary

where deep earthquake activity ceases and a well-defined seismic discontinuity occurs at a global average depth of about 660 km. Near 660 km depth, mantle flow is complex, as a possible viscosity increase accompanies isochemical phase changes in mantle minerals. The 660 km discontinuity may also mark a chemical change that largely prohibits mass flux between the upper and lower mantle. Detailed seismic studies of deep subduction zones suggest that slabs in some arcs descend well into the lower mantle. In other regions, particularly beneath the northwestern Pacific island arcs, evidence exists that some slabs deflect laterally and spread out within the transition zone (Creager and Jordan, 1986; Fischer et al., 1988; Zhou and Clayton, 1990; van der Hilst et al., 1993; Fujioka et al., 1993; Ding and Grand, 1994; van der Hilst, 1995) (Fig. 1). Numerical simulations of flow near the 660 km depth boundary that incorporate phase changes (Machetel and Weber, 1999; Tackley et al., 1993; Tackley, 1995; Honda et al., 1993), viscosity stratification (Hager, 1984; Gurnis and Hager, 1988), and possible compositional changes (Christensen, 1988) predict a wide range of flow behav-

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Global seismic images of the mantle have not been well resolved is limited by block size or the heterogeneity that can potentially be represented in a block representation. The wavelength of the heterogeneity that can potentially be resolved is limited by block size or the highest order harmonic. The results of these and other studies have several well-accepted long-wavelength features, including high-velocity “roots” beneath old continents to several hundred kilometers depth and faster than average structure at the base of the mantle associated with the circum-Pacific ring of fire. However, results are still quite variable for the shorter wavelength structure of mantle heterogeneity, particularly at mid-mantle depths. For example, Richards and Engebretson (1992) found that higher than average seismic velocities within the lower mantle occur in regions with long subduction histories, and they concluded that most slabs sink to the bottom of the mantle. In contrast, Wen and Anderson (1995) claimed a high degree of correlation between seismic structure at the top of the lower mantle and subduction history, and concluded that slabs generally remain in the upper mantle. Clearly, such models do not put sufficient constraints on flow fields, because fundamentally different conclusions were reached from similar, very long wavelength images of the mantle. The nature of lower mantle upwellings is even less well understood. Many believe hotspots are plumes ascending from the core-mantle boundary to the surface (Richards et al., 1989), but no seismic model has imaged such a continuous structure.

**TWO NEW HIGH-RESOLUTION MANTLE STRUCTURE MODELS**

Higher resolution tomographic images of the mantle have not been well accepted, as independent studies show inconsistent results. Here, we present a direct comparison of two new high-resolution models derived by independent groups that for the first time show remarkable agreement, even for short-wavelength structures. A spectacular result of both studies is the detection of long, relatively narrow linear features in the mid-mantle beneath the Americas (Fig. 1) and southern Asia that can be related to subduction history. Both models were derived using body-wave data, but the type, selection, and subsequent processing of the data differ fundamentally. The first model used the traveltimes reported to ISC to map the three-dimensional variation in P-wave speed, depending on poorly constrained state parameters.

Another basic issue is the nature of the large-scale flow field in the lower mantle. Local high-resolution seismic studies show that some slab material descends into the lower mantle, but they do not address the ultimate fate of slabs and their effect on the overall convection pattern of the lower mantle.

Global seismic images of the mantle can provide information about the nature of flow in the mantle as they, in principle, provide a snapshot of the entire convection system. A variety of approaches have been employed to map variations in both compressional (P) and shear (S) wave propagation speeds in the mantle. Maps of P-wave velocity have generally been produced using the travel times of P-waves reported by the International Seismological Centre (ISC; see Dziewonski, 1984; Inoue et al., 1990; and Pulliam et al., 1993). By using a wide range of observations, including the periods of the free oscillations of Earth, the phase velocity of surface waves and the travel times of mantle shear wave body waves, maps of S-wave speed have been found. Recently, Masters et al. (1996), Su et al. (1994), and Li and Romanowicz (1996) have inverted a combination of data types to determine global variations in mantle shear velocity. The model parameterization varies from study to study, because some models use spherical harmonic representations of lateral variations in velocity, whereas others use a block representation. The wavelength of the heterogeneity that can potentially be resolved is limited by block size or the highest order harmonic.

The results of these and other studies have several well-accepted long-wavelength features, including high-velocity “roots” beneath old continents to several hundred kilometers depth and faster than average structure at the base of the mantle associated with the circum-Pacific ring of fire. However, results are still quite variable for the shorter wavelength structure of mantle heterogeneity, particularly at mid-mantle depths. For example, Richards and Engebretson (1992) found that higher than average seismic velocities within the lower mantle occur in regions with long subduction histories, and they concluded that most slabs sink to the bottom of the mantle. In contrast, Wen and Anderson (1995) claimed a high degree of correlation between seismic structure at the top of the lower mantle and subduction history, and concluded that slabs generally remain in the upper mantle. Clearly, such models do not put sufficient constraints on flow fields, because fundamentally different conclusions were reached from similar, very long wavelength images of the mantle. The nature of lower mantle upwellings is even less well understood. Many believe hotspots are plumes ascending from the core-mantle boundary to the surface (Richards et al., 1989), but no seismic model has imaged such a continuous structure.

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velocity; it is discussed in detail by van der Hilst et al. (1997). The second model used a limited set of multiple-bounce shear waves to map shear-velocity variations in the mantle, following the technique presented by Grand (1994). Both models use blocks with dimensions of a few hundred kilometers to parameterize the models.

The differences in data sampling between the P and S studies are large. An advantage of the S study is the use of multiple bounce seismic phases to study the shallow mantle beneath regions devoid of earthquakes or seismic stations where structures cannot be constrained by direct P- or S-wave data. A disadvantage is that S-wave data are fewer, leading to generally worse resolution than for the P-wave study. The P-wave study has excellent data coverage in subduction zones, owing to the large number of earthquakes in these regions. The very different data coverage in the two studies is an advantage for comparing the models, because common structural features are unlikely to be due to systematic errors common to both studies. In regions where both models have adequate coverage, there is amazing agreement for many short-wavelength (<500 km) structures. Resolution tests of the type presented in other papers (e.g., Grand, 1994; van der Hilst et al., 1997) are not included here, but the correlation between independently derived models is a more rigorous test of the reliability of the images in any case.

The seismic models are displayed side by side at common depths in Figure 2. The discussion below focuses on common features in the deeper mantle where coverage is the most complete.

**FIRST-ORDER ASPHERICAL P- AND S-WAVE STRUCTURE OF THE MANTLE**

Both models show striking high-wave-speed structures in the mid-mantle beneath the Americas and southern Eurasia. The anomalies continue intermittently over distances in excess of 10,000 km with apparent widths of only several hundred kilometers. The two models agree in detail for the anomaly beneath the Americas. At shallow depths (Fig. 2A) the fast anomaly stretches from 30°S to about 50°N beneath the central part of North America. At mid-mantle depths (Fig. 2, B and C), the anomaly extends northward beneath the west coast of Hudson Bay to northern Alaska. In the south, both models show the high-velocity zone ending near 1300 km depth. Finally, in the deeper mantle (Fig. 2, D and E), the single linear structure becomes more diffuse or, perhaps, breaks into two structures. Beneath the western Atlantic, high velocities are continuous with shallower structure. Beneath the western part of North America and off the west coast of South America, a second zone of high velocity can be detected. The high-velocity zone beneath southern Eurasia also shows complexities in both models. At shallow depths in the lower mantle (Fig. 2A), high velocities are mapped beneath Indonesia and Europe in accord with high-resolution studies (Spakman et al., 1993; Widiyantoro and van der Hilst, 1996). Below 800 km, the band of high velocities becomes progressively more continuous with depth (Fig. 2B). Between 1200 and 1800 km (Fig. 2, C and D) the high-velocity structure is nearly continuous from Indonesia to Europe, although the signature beneath...
Underscores indicate part of the text that is not fully visible or legible in the image.
**Tomography continued from p. 5**

Note that the high-velocity mid-mantle structures all lie above broad high-velocity zones near the base of the mantle (especially in the S model). Moreover, some vertical mantle cross sections make a case for a connection between mid-mantle slab structure and heterogeneity just above the core-mantle boundary (Fig. 1). Even though the nature of flow between the mid-mantle and its bottom is not yet completely resolved, it is likely that the very long wavelength fast regions in D* (core-mantle boundary) are the ultimate resting place for subducted lithosphere.

We have shown how two ancient subduction systems, the south Asian and western Americas regions, can be associated with large linear mid-mantle seismic anomalies. The P model also shows high seismic velocity in the deep mantle associated with subduction along the Tonga-Kermadec trench. The S model shows little anomaly, which can be explained by very poor resolution. The long history of convergence along the western Pacific has not resulted in a clear continuous mid-mantle anomaly. Along the east coast of Asia, high velocities exist in the upper part of the lower mantle (<900 km) and in the deepest mantle (>1800 km). In the mid-mantle there is little slab signature. Instead, the data are consistent with a discontinuous patchwork of high-velocity anomalies, only some of which are vertically continuous over a large depth range. Interpretation is difficult owing to the complex tectonic development of the region. Northwestward subduction along the ancient Japan and Kurile trenches pre-dates westward subduction along the Izu, Bonin and Mariana trenches which started at about 45 Ma. Subduction in the latter trenches could have been strongly influenced by rapid oceanward trench migration (van der Hilst and Seno, 1993).

Despite the absence of linear features, several studies provide evidence for deep slab penetration into the lower mantle beneath some western Pacific island arc segments (Jordan, 1977; Creager and Jordan, 1986; van der Hilst et al., 1991, 1997). If the seismic models are accurate, the nature of cold downwelling beneath northwestern Pacific arcs is different from that elsewhere. The models are consistent with local intermittent flow into the lower mantle, as seen in numerical simulations by, for instance, Machel and Weber (1991) and Tackley et al. (1993) and discussed by van der Hilst and Seno (1993).

Our seismic models show high-velocity sheets beneath most subduction zones that correlate with at least the past 100 m.y. of subduction. We interpret this as evidence that most subducted lithosphere descends into the deepest lower mantle and possibly reaches the bottom of the mantle. Alternative explanations, such as that subduction zones are preferentially located over existing lower mantle downwellings or that slabs subducting in the shallower mantle trigger lower mantle downwellings without actual flow into the lower mantle, seem unlikely. If lower mantle downwellings exist irrespective of surface tectonics, regions of relatively recent convergence, such as the Marianas and South America, should have lower mantle anomalies that extend as deep as those in regions of more continuous subduction. This is not the case. Slabs in the upper mantle in these regions are equally unlikely to have had enough time to cool the lower mantle sufficiently to cause the large, deep seismic anomalies observed. Furthermore, if slabs remain stagnant in the top of the lower mantle or the transition zone for a long time, far broader seismic anomalies would be expected in the transition zone than observed (Jordan et al., 1993; Puster and Jordan, 1997). Slab deflection has been observed locally (Zhou and Clayton, 1990; van der Hilst et al., 1991; Fukao et al., 1992) but is unlikely to be a widespread phenomenon in the present Earth. Slab deflection could be important on time scales shorter than the characteristic time for mantle-wide overturn (Christensen, 1996; van der Hilst et al., 1997).

**UPWELLINGS**

Our new high-resolution global seismic models show a pattern of high-wave-speed anomalies consistent with most lower mantle downwelling being associated with subducting slabs. The nature of mantle upwelling is far less obvious, but a few prominent slow seismic anomalies are apparent in our models in the deep mantle. The major deep-mantle slow anomaly is a structure beneath southern Africa from the base of the mantle to near 1000 km depth. This feature is also seen in the models of Masters et al. (1996), Su et al., (1994), and Li and Romanowicz (1996). Other generally slow anomalies also seen in most global models are beneath the southwestern Pacific, parts of the East Pacific Rise, the eastern Atlantic near Cape Verde, and the Atlantic near Iceland. Unlike the fast anomalies, these structures are more pronounced at great depth and tend to fade above 1000 km depth.

Upward return flow from the lower to upper mantle is thus not obvious in our seismic images. If this is the case, deep slow anomalous mantle may not rise to shallow depths, and return flow may be diffuse and close to adiabatic. However, imaging of upwellings is more difficult than imaging of lower slabs forming the downwellings. First, upwellings likely occur in seismic regions and are not as well sampled by seismic data, in particular in the shallow mantle. Second, use of first arrivals of seismic waves causes a natural bias toward fast anomalies, because annealing of wavefronts creates a tendency to underestimate slow anomaly amplitudes. Finally, upwellings can be overlooked if they are cylindrical, as suggested by Bercovici et al. (1989), and become more focused as they ascend.

**DISCUSSION**

The two seismic models presented are the most ambitious to date with respect to resolution on a global scale. There are still large gaps in data coverage, but the ability to produce independent models that agree in such detail for large volumes of the mantle marks a milestone in imaging the effects of dynamic processes in the earth. High-velocity anomalies in the mid-mantle are dominated by long, thin structures associated with subduction. The most likely interpretation is that these structures are slabs penetrating to at least 1600 km depth. In some regions there is evidence for downwelling to even greater depth. The generally excellent correlation between P- and S-wave anomalies indicates that they are probably caused by temperature variations. Some significant differences between the P- and S-wave models require further study, although in many cases differences can be attributed to poor resolution in one or both models. The proportionality between P- and S-wave velocity expected from a thermal origin may break down in some parts of the mantle, and, in particular, the disagreement in the D* layer could signal chemical heterogeneity. Better models are within reach, given the large amount of high-quality seismic data becoming available. Such models can reduce uncertainty in plate reconstructions and can help resolve questions such as: What is the nature of upwellings within the deep mantle? Are there truly gaps in subducted slab within the lower mantle, as appears to be the case beneath East Asia? Do slabs continue to the core-mantle boundary, if so, how? What is the cause for the apparent difference in P and S velocity structure in the deepest mantle?

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