Vol. 7, No. 4 April 1997

GSA TODAY

A Publication of the Geological Society of America

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

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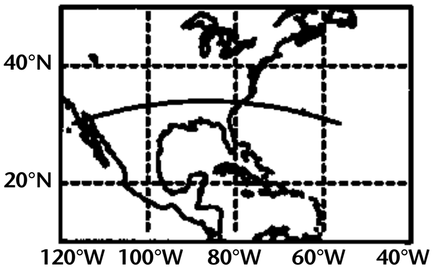

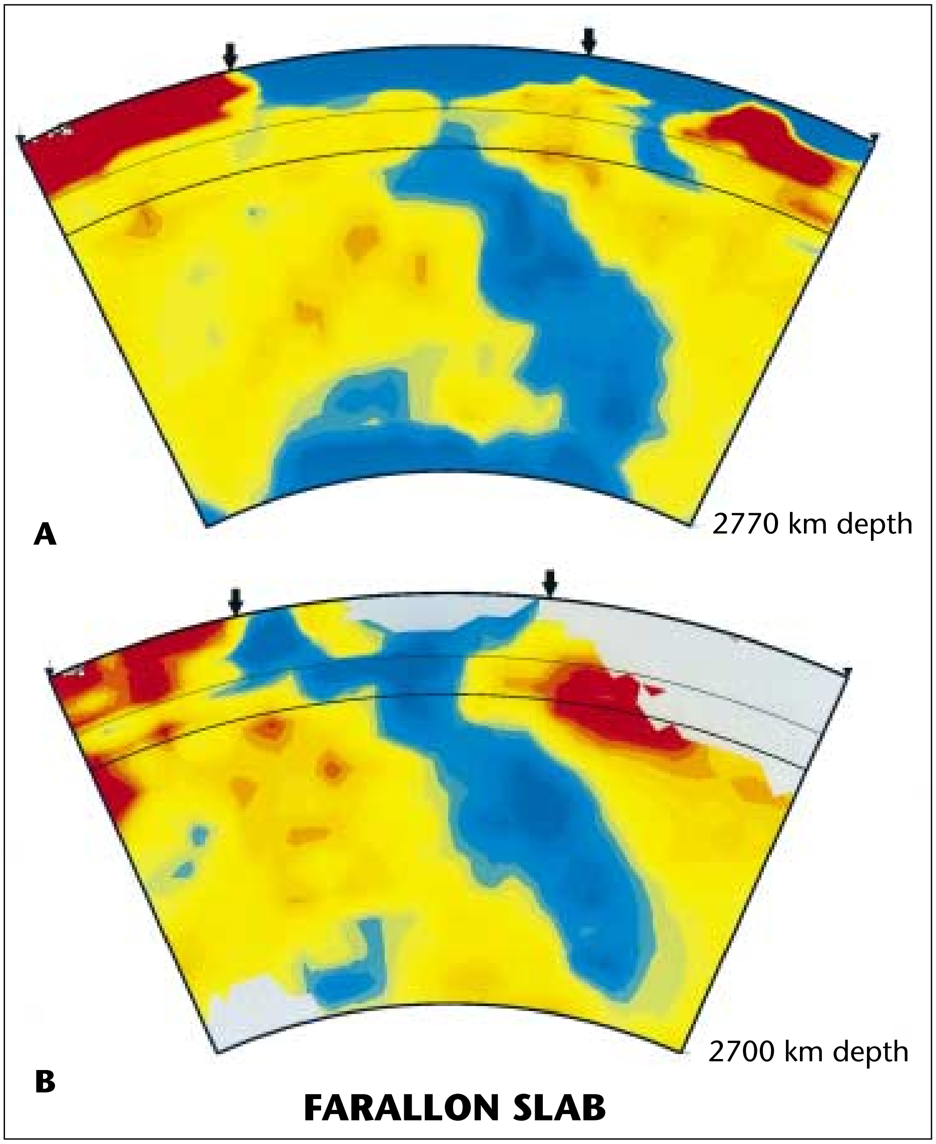

Figure 1. Cross sections of mantle P-wave (A) and S-wave (B) velocity variations along a section through the southern United States. The endpoints of the section are 30.1°N, 117.1°W and 30.2°N, 56.4°W. The images show variations in seismic velocity relative to the global mean at depths from the surface 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.

GSA TODAY April 1997
Vol. 7, No. 4

GSA TODAY (ISSN 1052-5173) is published monthly by The Geological Society of America, Inc., with offices at 3300 Penrose Place, Boulder, Colorado. Mailing address: P.O. Box 9140, Boulder, CO 80301-9140, U.S.A. Periodicals postage paid at Boulder, Colorado, and at additional mailing offices. **Postmaster:** Send address changes to GSA Today, Membership Services, P.O. Box 9140, Boulder, CO 80301-9140.

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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., 1991; Fukao et al., 1992; 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, 1991; 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-

Tomography *continued on p. 3*

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ior 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 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.

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, but 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

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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.

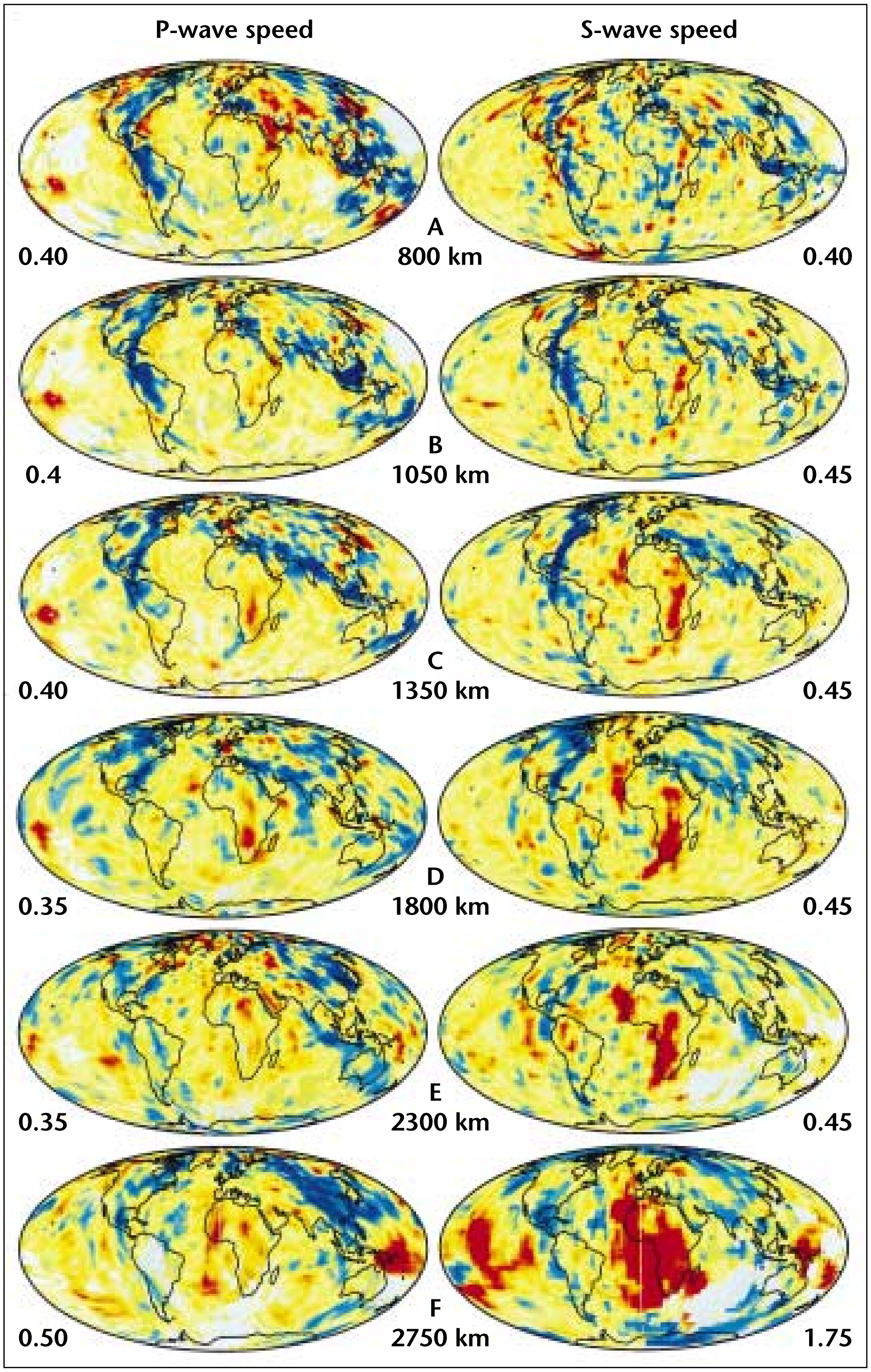

Figure 2. Comparison of P- and S-wave models, showing variations in seismic velocity at given depths through the lower mantle. Numbers at the sides of the images are the maximum anomaly in terms of percentage difference from mean velocity. Blue indicates faster than average, and red indicates slower than average. The white regions have no significant data sampling.

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

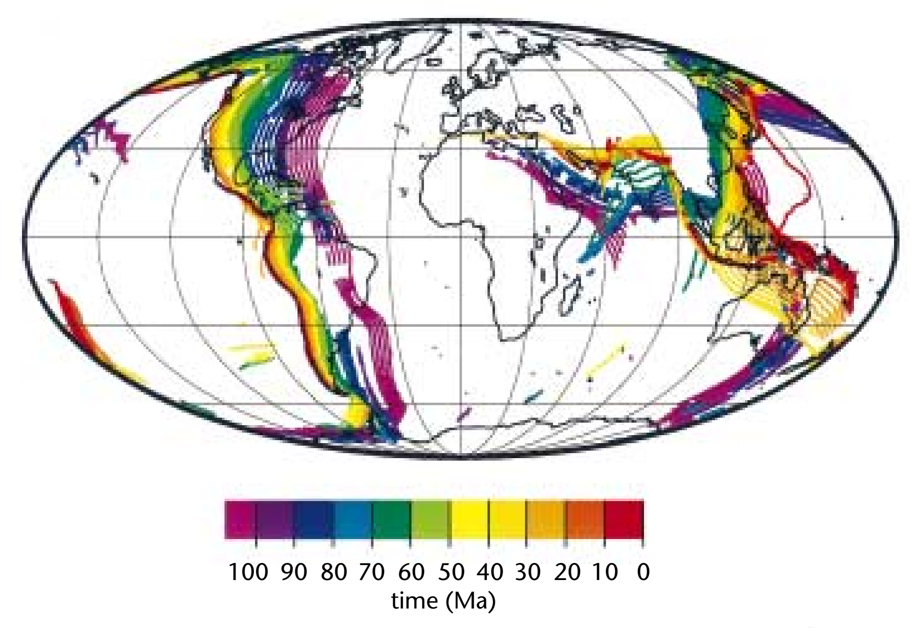

Figure 3. Map showing the location of subduction zones in a hotspot reference frame during the past 110 m.y. The subduction history model was taken from Lithgow-Bertelloni and Richards (1997). Reds show the present locations of convergence; blues show the approximate location of convergence in the past with respect to the present-day location of continents. Note the hiatus in convergence beneath South America from 50 to 100 Ma and the relative youth of many of the subduction zones in the western Pacific.

Indonesia tends to vanish below 1500 km. In the deep mantle, both studies show higher velocities to the south of the shallower structure. The S model shows the anomalous structure continuing farther west than the P model.

Other structures common to the two models include a high-velocity zone in Asia along the 90° meridian in the deep mantle, a patchwork of high-velocity anomalies in eastern Asia, and low-velocity anomalies beneath southern and eastern Africa and parts of the southern Pacific.

The worst disagreement between the two models occurs in regions of poor resolution for one model or the other. These regions are primarily in the Southern Hemisphere and beneath the Pacific Ocean. The S model has limited resolution beneath the western Pacific and southeastern Asia, so that some pronounced anomalies in the P-wave study do not show the same amplitude in the S-wave study. The deepest mantle is less well sampled in the P-wave study, because no core reflected or transmitted waves are used. The comparison at the bottom of the mantle is the most perplexing. Both models (Fig. 2F) have broader structures than in the mid-mantle and agree on a broad high-velocity zone beneath eastern Asia, a sharp contrast between high velocity beneath the Atlantic west of 30°E and low velocity to the east, and generally low velocities beneath Africa, New Guinea, and parts of the southern Pacific. However, the S model shows high velocity at the base of the mantle beneath Alaska and the Arctic Ocean and beneath Europe and Saudi Arabia, whereas the P model shows low velocities.

The model comparisons are important for two reasons. First, agreement of P- and S-wave velocity anomalies in the mid-mantle is consistent with the structures being thermal in origin. The only caveat is at the bottom of the mantle where some notable disagreements could indicate a chemical origin for some seismic signals in the D" (core-mantle boundary) region (see Wysession et al. [1992] and Loper and Lay [1995] for discussion of chemical variation in D"). Second, the comparison builds confidence in tomographic models. Although the important differences need study and model refinement, the mid-mantle agreement between the current versions of our two independently derived models is better than for previous models (see Masters et al. [1996] for comparison of other models). The observation that this is true even on scales of hundreds of kilometers in certain regions is particularly exciting.

THE FATE OF SLABS

The linear high-velocity features in the mid-mantle can be associated with past subduction sites. At shallow depths (Fig. 2A), there is a clear correlation of high wave speed with present subduction sites, especially for the P model. Many high-velocity zones near 700 km depth can be connected to seismically imaged upper mantle slabs (van der Hilst et al., 1991; Fukao et al., 1992; Spakman et al., 1993; Ding and Grand, 1994; van der Hilst, 1995; Widiyantoro and van der Hilst, 1996). At greater depths, the correlation of high wave speed and present subduction zones is less obvious. However, slabs that have penetrated deep into the lower mantle must have subducted when subduction zones were not all in their present locations. Figure 3 shows past convergence regions as a function of time in a hotspot reference frame. Note that in the past, the Farallon plate was subducting farther east, and convergence of the ancient Tethyan sea was occurring south of Asia. The two large, linear high-velocity anomalies correlate well with this history, as the deeper parts of the anomalies are located near more ancient subduction sites. Agreement is especially good at mid-mantle depths.

The continuity of long, narrow high-velocity zones from the upper mantle to depths in excess of 1500 km in regions of ancient subduction is convincing evidence for large-scale flow of subducted slabs into the deep mantle. Assuming that the mid-mantle fast anomalies are slabs implies that upon reaching about 700 km depth, slabs sink nearly vertically through the lower mantle. Using these results and plate reconstructions, one can estimate slab sinking rates. The significant linear anomaly that extends to about 1300 km depth beneath western South America in both models can be used in this way. Because subduction beneath South America appears to show a hiatus from about 50 to 100 Ma, Grand (1994) argued that the bottom of the anomaly represents the leading edge of the slab subducted 50 Ma. Using an upper mantle subduction rate of 10 cm/yr implies an average lower mantle slab descent rate of 1–1.5 cm/yr. This slow rate implies significant slab deformation in the deeper mantle in accord with the 300–600-km-wide linear features that we interpret as slab. The decrease in slab descent rate implies increased resistance to subduction with depth consistent with an increase in viscosity with depth (see Gurnis and Hager, 1988) or an endothermic phase change near 660 km depth (see Tackley, 1995).

Seismic structure in the deepest mantle (Figs. 2E and F) is unlike that in the mid-mantle. In particular, long linear features are absent, and correlations between high-velocity structures and old subduction sites are less clear. However, there is also less certainty in the location of subduction further in the past. Furthermore, there is a growing consensus that viscosity increases in the deepest mantle (Forte and Mitrovica, 1996; King and Hager, 1994; Peltier and Jiang, 1996; Bunge and Richards, 1996), and this may cause lateral smearing of descending slab.

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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 predates 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, Machetel 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 the long slabs forming the downwellings. First, upwellings likely occur in aseismic 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?

ACKNOWLEDGMENTS

We thank Suzanne Kay, Michael Wysession, Gene Humphreys, Eric Sandvol, and John McBride for thoughtful and constructive reviews, and Bernhard Steinberger for the plot of subduction history. Grand thanks Lamont-Doherty Observatory for use of their seismic film chip library and Mrinal Sen for use of his reflectivity code. Van der Hilst and Widiyantoro thank Bob Engdahl for help with processing the ISC traveltime data used in the P study. Funding for this research was provided by National Science Foundation grants EAR-9404875 (Grand) and EAR-9628087 (van der Hilst).

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Manuscript received January 13, 1997; revision received February 11, 1997; accepted February 11, 1997. ■

GSA Today Science Co-Editor Appointed

Molly F. Miller, Vanderbilt University, is a new science co-editor of *GSA Today*. She will work with the continuing science co-editor, Suzanne M. Kay (Cornell University). Both have been appointed for a three-year term, 1997–1999.

Molly F. Miller

Miller's broad-based research uses the modern and ancient relations between soft-bodied, bottom-dwelling animals and the enclosing sediment to identify long-term changes in benthic communities and to reconstruct (integrating sedimentologic data) ancient depositional environments and paleogeography. Currently she is using biogenic structures in otherwise sparsely fossiliferous rocks in the Transantarctic Mountains to document the response of freshwater animals to climate change following late Paleozoic glaciation.

As a Sigma Xi national lecturer, Miller gives talks on Antarctic earth science and its importance. She has edited a book of earth-science activities for K–12 teachers and has also served as GSA Southeastern Section chair. She holds degrees from the College of Wooster (B.A.), George Washington University (M.S.), and UCLA (Ph.D.). At Vanderbilt she is a professor of geology and holds a Chair of Teaching Excellence.

GSA Today science editors are charged to obtain high-quality, focused articles that collectively reflect and summarize current topics and discoveries in the earth sciences. All submissions, whether solicited or volunteered, are reviewed; most require revision before acceptance.

"*GSA Today* is an ideal vehicle for presenting the newest ideas on emerging developments to a broad earth science audience," Miller said. "I look forward to being part of the process."