Test of tomographic models of D" using differential travel time data

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Abstract

We compare local measurements of SH-velocity in D" under the Pacific Ocean with four recent S-velocity models derived with different techniques. From the local measurements, we find evidence for both strong fast and slow anomalies with an amplitude sometimes exceeding 10%, as well as strong lateral velocity gradients. The tomographic models underestimate the magnitude of the observed anomalies by roughly a factor of 3. The model that best matches both the sign and the localisation of the anomalous structures is exclusively an SH model. This indicates, in particular, that the presence of anisotropy in D" may not be ignored and that it is important to separate SH and SV contributions in tomographic studies of the lowermost mantle.

Introduction

Over the past few years, global tomographic models of mantle S-velocity have been developed with higher resolution than was previously attainable, in particular in the lowermost mantle [*Liu et al.,* 1994; *Masters et al.*, 1996; *Li and Romanowicz*, 1996; *Grand et al.*, 1997]. While there is qualitative agreement in the large scale features of these models, there are many differences in the details of the 3-D structure recovered. Such details are of interest for geodynamics and mineral physics interpretations, it is therefore important to confirm the validity of specific models and particularly for the deepest mantle, where strong lateral variations and strong anisotropy [e.g. *Vinnik et al.*, 1997] have recently been documented. These recent findings raise issues as to whether standard wave propagation approaches used in tomography, which assume smooth structure, are appropriate, and whether, at least in D", the assumption of isotropy is justified.

The path between earthquake sources in the Fiji-Tonga Islands and North American stations provides an optimal setting for a local comparison experiment with several large earthquakes each year recorded at a large number of stations in North America. We adopt the approach of *Vinnik et al.* [1997] and consider the variation with distance of $SH - SKS$ travel time residuals for a fixed source or a fixed station along narrow azimuthal corridors. This allows us to infer variations in SH-velocity in well specified locations in D". We then compare the mapped anomalies with those of four recent tomographic S-velocity models.

Method and data

The data used are $SH - SKS$ travel time residuals with respect to the reference model PREM [*Dziewonski and Anderson*, 1981], from two data collections: one assembled from a combination of analog and digital data [*Garnero et al.*, 1988] and the other a smaller set of measurements made by us on digital records at IRIS station LON. In both cases, we considered deep, intermediate and shallow events.

Travel times were picked manually with an accuracy around 0.5-1s. No cross-correlation method was used, so the broadening of the S pulse with respect to that of SKS du to differential attenuation should not affect the residuals significantly.

For a fixed source in the Fiji-Tonga region or a fixed receiver in North America, we selected a subset of paths corresponding to a narrow azimuthal range (at most a few degrees) and, as in *Vinnik et al.* [1997], plotted the residuals as a function of epicentral distance. A similar analysis was also performed by *Garnero and Helmberger* [1993] and *Ritsema et al.* [1997], but these authors binned their data into much broader azimuth ranges and did not separate the contribution of each station or event, which resulted in estimates of velocity averaged over broader regions. We considered epicentral distances larger than 84^o where S starts diving into D". By using differential travel times, the effect of upper mantle heterogeneities and errors in focal parameters are minimized. Assuming the outer core is laterally homogeneous [*Buchbinder*, 1972], the observed travel time anomalies must originate in the deepest mantle, where the paths of SKS and S differ the most (Fig. 1).

SKS is unlikely to contribute significantly to the observed trends since the time spent by SKS in D" is no more than 1/5 of that of S. Finally, since deep and shallow events produce consistent trends, as also documented by *Vinnik et al.* [1997], and since there is a good agreement between the trends observed at different stations, upper-mantle anisotropy should not affect our results.

Under these assumptions, we will be discussing structure near the base of the mantle as seen by SH-polarized waves, which, in the presence of anisotropy [e.g. *Vinnik et al.*, 1989; 1995; 1997], could be somewhat different from the structure seen by SV-polarized waves. When the source or the receiver is fixed, and for a fixed azimuth, the S leg nearest to the fixed point remains roughly fixed whereas the other leg samples an increasingly larger portion of D" as epicentral distance increases (Fig. 1). The slope of the corresponding residual versus distance plot can be attributed to heterogeneity in that particular region of D". A positive slope will be characteristic of locally low SH-velocities in D", and a negative slope of high velocities. The magnitude of the slope allows us to give a crude estimate of the magnitude of the local velocity anomaly.

Results

We present measurements for fixed station LON in Fig. 2a. The corresponding sources and wavepaths are given in Fig. 1a. The residuals show a strong increase with distance between 84^o and approximately 89^o. The slope changes abruptly around 89^o and returns to a value close to 0 as S starts sampling a domain where SH-velocity is well predicted by PREM. *Vinnik et al.* [1997] reported several similar observations for $SH - SKS$ residuals at other stations and for different epicentral ranges for which S dives deeply into D" and diffracts along the CMB, and demonstrated that this result was very stable and that the trend was not a near source effect. The interest of station LON is twofold. First, it corresponds to a slightly smaller distance range than considered by *Vinnik et al.* [1997] (approximately $84 - 106^0$ against $96 - 120^o$) where S is diffracted only for the largest distances, while at smaller distances S samples the uppermost part of D". The residuals for station LON indicate that the anomalous region is not localised at the CMB but extends throughout the whole D" layer. Second, the path considered corresponds to more northerly azimuths, which allows us to document the existence of a transition zone between very low and "normal" SH-velocities, northwest of where it has been reported so far.

We next consider a fixed event and, again, an azimuthal window of only a few degrees. This allows us to explore the lowermost mantle beneath the northwestern portion of the Fiji-Tonga to North America paths.

Data for event 06/25/92 are shown in Fig. 2b. Residuals at distances smaller than 96^o decrease regularly with distance with a slope of almost -1s/deg indicating very high SH-velocities and a strongly fast anomaly. A kink around 96^o, beyond which anomalies stop accumulating, indicates that the S-wave starts sampling a region with normal velocities in D". Another event (07/11/92, Fig. 2c) confirms the slopes observed in Fig. 2b. The abrupt kink present in the residual versus distance plots also suggests the existence of a sharp boundary between the two domains.

Residuals for event 08/25/63 (Fig. 2d) exhibit the opposite trend for slightly smaller azimuths, with a plateau followed by a rather strong increase with distance. The region of interest is northeast of the one considered in Fig. 2b and 2c.

Measurements for events 03/17/66 and 08/25/63 (Fig. 2e and 2f) allow us to extend the distance range previously considered. In Fig. 2e, there is a strong increase with distance between two plateaus which, at the shorter distances, confirms what we see on Fig. 2d. Fig. 2f does not exhibit any plateau at small distances but shows a clear flattening of the slope at large distance. Note here the increased scatter in the data, probably due to the larger interval of azimuths considered.

The exact geometries of the anomalous regions are hard to determine: there are trade-offs between depth extent and magnitude, and, in the presence of strong local anomalies, raypaths might be quite different from those predicted by PREM. If we assume that the heterogeneity of the mid mantle does not exceed 3-4%, as indicated by global tomography, the contamination by mid mantle structure is a second order effect. But the deeper S and SKS dive, the more apart they travel. In principle, it becomes therefore possible to explain residuals by adding structure in the lower mantle above D". This is a source of uncertainty in our study, and the reason why our analysis remains only qualitative.

We have identified five distinct regions (R1..) and three transition domains (T1..) in the deep mantle underneath the Pacific and now compare those with four S-velocity tomographic models (M1..) in Fig. 3. The low SH-velocity region (R2) in the Southwest Pacific is present in all 4 tomographic models. M1, M2 and

M3 saturate around -3% whereas M4 predicts a milder value. Region R1 only exists in models M1 and M4; in this region, model M2 only shows a small reduction of the magnitude of the anomaly while M3 is still saturated. M1, M2 and M3 predict high velocities in Region 3, while,for M4, velocities are still low. Proceeding east, only M1 matches the travel time results for region R4, with, however, an anomaly around -1.5% against the -4% that we report here. Finally, our estimate of the anomaly in region R5 is in agreement with models M1 and M4 but not with M2 and M3. As for the transition domains (Fig. 3), the first one (T1), in the Southwest Pacific, has already been described in Vinnik et al., (1997). It is well predicted by models M1 and M4. The second one (T2) is present in M1 where we expect it from the present data. It is further northeast in M2, but is absent in M3 and M4. T3 is only present in model M1.

Model M1 is in best agreement with our results. Transition regions and signs of anomalies are generally fairly well predicted, although the magnitude of the largest anomalies that we report are well in excess of what M1 predicts. Note however that, although the magnitude of the anomalies is underestimated, the relative scaling of the anomalies is in agreement with the local data.

Discussion

Local variations of SH-velocities in D" beneath the Pacific are on the order of 3 times larger than predicted by global mantle tomographic models, as well as tomographic models derived specifically for D" using body-wave data sensitive to that region (Wysession, 1996, Kuo and Wu, 1997).

The trends observed in Fig. 2 and 3 cannot be obtained with anomalies with magnitude less than 3-4%, since 2D ray-tracing calculations for the four tomographic models considered do not produce slopes even close to the ones we observe. We illustrate this in Fig. 2g-i, where we present S, SKS and $S-SKS$ synthetic residuals for event 25/06/92 and model M1. We note the qualitative agreement between synthetics (Fig. 2i) and data (Fig. 2b), with, however, much larger amplitudes in the data. Fig. 2g and 2h confirm that the anomaly originates in SH rather than in SKS.

The success of M1 in matching the spatial variations of SH velocity predicted by the local travel time measurements can be understood as follows. This model, based upon a waveform inversion method, was obtained using tangential components exclusively: this is an "SH" velocity model, and it is therefore the most appropriate to compare with our $SH - SKS$ travel time residual plots. Other distinct features of the derivation of M1 are that (1) it was obtained using waveform data and a theoretical approach based on the Nonlinear Asymptotic Coupling Theory (NACT) [*Li and Romanowicz*, 1995] which is better suited for the modeling of broadband body waveforms compared to the Path Average Approximation (PAVA) [*Woodhouse and Dziewonski*, 1984] generally used. And (2) each body wavepacket in a seismogram is considered separately, which allows us to assign larger weights to weaker phases, such as Sdiff, which are sensitive to lowermost mantle structure.

The other 3 models (M2, M3 and M4) were derived using a combination of SH and SV sensitive data and a variety of inversion techniques (PAVA and travel times for M3 and M4, WKBJ for M2). As shown by *Vinnik et al.* [1997], anisotropy in D" can be locally very strong ($>$ 10%) and far in excess of the 1-3% generally proposed. Under such conditions, anisotropy is not a second order effect, and inverting SV and SH data simultaneously under the assumption of isotropy is likely to result in a biased picture of the average S-velocity. Separating the SH component is a first step towards a refined tomographic approach for the lowermost mantle.

Conclusions

Our analysis of differential $SH - SKS$ travel time residuals demonstrates that the D” region beneath the Pacific exhibits strong velocity contrasts. Both high and low S-velocity domains where anomalies could reach a magnitude of $\pm 10\%$ have been detected, and the transition between these domains can be very abrupt, which implies strong lateral velocity gradients. If we add anisotropy to this already complex picture, it becomes clear that D” presents challenging conditions for global tomography. In the future, particular attention to the complexity of D” structure and anisotropy must be given in global tomographic studies.

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Figure Captions

Figure 1. (a) Left: schematic representation of the wavepaths of SKS and $Sdiff$ for a given azimuth and a fixed station. The wavepaths of S for two different positions of the source (stars) differ mostly on the source side. If we have two adjacent regions where SH-velocity is respectively low (light gray), and normal (dark gray), differential $SH - SKS$ travel time residuals increase with distance until S starts propagating in the normal region, where they remain constant. Right: surface projection of the wavepaths considered for fixed IRIS station LON (Fig. 3a). The light gray zone of each wavepath indicates the D" leg of S. The diamond corresponds to a D" exit point for which S starts sampling the region with normal SH-velocity. (b) Same as Fig. 1a, but for fixed event 08/25/63, and variable station.

Figure 2. (a) Left: schematic representation of the wavepaths of SKS and $Sdiff$ for a given azimuth and a fixed station. The wavepaths of S for two different positions of the source (stars) differ mostly on the source side. If we have two adjacent regions where SH-velocity is respectively low (light gray), and normal (dark gray), differential $SH - SKS$ travel time residuals increase with distance until S starts propagating in the normal region, where they remain constant. Right: surface projection of the wavepaths considered for fixed IRIS station LON (Fig. 3a). The light gray zone of each wavepath indicates the D" leg of S. The diamond corresponds to a D" exit point for which S starts sampling the region with normal SH-velocity. (b) Same as Fig. 1a, but for fixed event 08/25/63, and variable station.

Figure 3. Comparison between the results of the analysis of $SH - SKS$ differential travel time residuals, and four recent tomographic models adopted from: M1, *Li and Romanowicz* [1996], M2, *Liu et al.* [1994], M3, *Masters et al.* [1996]

and M4, *Grand et al.* [1997]. We assigned a qualitative anomaly (black symbols) to five distinct regions (R1-5), based on the slope of the residual versus distance plots: "+","0", and "-" indicate respectively faster, equal to and slower SH velocities compared to PREM. Large (or small) symbols indicate anomalies larger (or smaller) than $\pm 10\%$ in magnitude. We also underline three transition domains (T1-3, broken lines) defined by D" exit points (triangles) associated with a kink in the residuals/distance plots. Each yellow triangle is from this study and has been assigned, on the M4 frame, a letter corresponding to the plot from which it originated in Fig. 2. Green triangles are from *Vinnik et al.* [1997].