ANISOTROPIC STRUCTURES AT THE BASE OF THE EARTH'S MANTLE

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revised for Nature: October 5 , 1997

The D" shell at the base of the mantle is a thermal and compositional boundary layer, where vigorous dynamic processes may be taking place [1–4]. An important property of D" is its seismic anisotropy, expressed in different velocities for horizontally and vertically polarized S waves, diffracted ($SHdiff$ and $SVdiff$) or reflected at the core-mantle boundary [5,6]. The nature of this anisotropy has been the subject of debate [7–11]. Our analysis of various seismic phases generated in the Kermadec-Fiji-Tonga zone and recorded at stations in north America (Fig. 1) reveals a region at the base of the mantle beneath the south-west Pacific, where horizontally propagating SV is slower than SH by at least 10 %. The observed anisotropy is by an order of magnitude larger than previously thought to exist in the lower mantle, and corresponds to lateral variations of SH velocity of about the same magnitude. This anisotropy might be generated by mixing and shearing of a strongly heterogeneous material of the boundary layer.

The first part of our analysis is based on the residuals of differential travel times between seismic phases $SHdiff$ and $SKS/SKKS$ relative to those for standard model $PREM$ [12]. Differential travel times are helpful because they are not sensitive to errors in focal parameters of seismic events and structural complexities in the source region. Contrary to earlier studies [13,14], we consider (1) not the absolute values of the residuals, but the slopes of the resulting time-epicentral distance plots, (2) not the average residuals for many stations, but the individual slope for every station, and (3) not only the residuals for deep events, but also for intermediate and shallow events. Shallow events broaden the distance interval available for SKS. For the given source-receiver geometry (Fig. 1) and a fixed station, changes of the wavepath occur practically only at the source side of the wavepath. The slope of the plot is controlled mainly by the slowness of $SHdiff$ and, consequently, by SH velocity at the source side of D". The slope is negative, positive or equal to 0, if SH velocity is higher, lower or similar to that in $PREM$.

The residuals as a function of epicentral distance show a remarkable trend, consistent from station to station, for shallow and deep events and whether SKS or $SKKS$ is used as reference phase. Fig. 2 shows examples for 3 best stations. Each panel can be divided into two parts, with rapidly increasing residuals at shorter distances, and slowly rising or decreasing residuals at larger distances. To make this trend better visible, we divide each set of measurements into two subsets corresponding to epicentral distances smaller or equal and greater or equal than a variable cutoff distance. When the best fitting position of the cutoff and linear fits on both sides of it are obtained by regression, the average variance reduction is twofold with respect to a single regression line. Confidence intervals for the slopes of the regression lines are usually around $\pm 0.1 - 0.3 s/^{\circ}$, but they exceed $\pm 1.0 s/^{\circ}$ for deep events at CCM, left of the kink (Fig. 2a). If the latter data are excluded, the average values of the slopes in Fig. 2a are $1.12 \pm 0.2 s/^{\circ}$ and $-0.21 \pm 0.2 s/^{\circ}$, left and right of the kink, respectively. Note that the epicentral distance of the kink varies (e.g. $116 - 117^{\circ}$ at HRV; $103 - 104^{\circ}$ at RSON), depending on the epicentral distance range of the Kermadec-Fiji-Tonga seismic zone to the given station. Comparable results are obtained for the other stations where a similar analysis was performed: RSCP, LMQ, RSNY and GAC (Fig. 1).

The features in Fig. 2 cannot be explained by mantle complexity immediately beneath the seismic foci, because the change of slope is present in the data for both deep and shallow events. Therefore, our preferred explanation for the kink is a first-order change in the properties of the lowermost mantle at the source side of the wavepath. Moreover, SKS and $SKKS$ raypaths are separated in D" by a distance exceeding 10°, and a similar trend in the residuals in Fig. 2

with respect to SKS and $SKKS$ implies that the effect is mainly in the travel times of $SHdiff$. If the position of the kink for every station is inverted for the position of the corresponding border in the D" layer, assuming that SH enters D" at a height of 300 km above the CMB, the estimates for different stations are mutually consistent and correspond to the white bar in Fig. 1b. In experiments with synthetic seismograms, the anomaly of slowness of $1.1s/^\circ$ corresponds to S velocity in D" reduced approximately by 10 % with respect to $PREM$. The region of anomalously low SH velocity is located to the north-east of the bar (Fig. 1b), whereas SH velocity to the south-west of the bar is either slightly elevated or normal. Qualitatively, this division is confirmed by two recent tomographic models [16,17] (Fig. 1b), but the magnitude of the low-velocity anomaly in both models is about 3 times smaller than in our data. Robustness of our technique is confirmed by other data [15].

The residuals of $SKKS - SKS$ differential travel times relative to $PREM$, derived from our data (Fig. 3) are positive, with an average value around 2 s. Comparable residuals were reported for similar wavepaths in earlier studies [13,18,19]. For other paths beneath the Pacific and America, the residuals are close to 0 [18,19]. As argued by [18], these positive residuals can only be explained by anomalously low S velocity in the lowermost mantle on the source side, due to the longer paths of $SKKS$ relative to SKS. Our data, however, indicate that, on the source side, SKS and $SKKS$ propagate in a region of D" with normal SH velocity (Fig. 1b). Since SKS and $SKKS$ are SV polarized, to explain the discrepancy, we suggest that, while SH velocity is normal, SV velocity in the lowermost mantle on the source side is anomalously low.

To obtain quantitative estimates of this anisotropy, we assume that the lowermost mantle is intrinsically isotropic, finely layered, and horizontally stratified. For long waves, it behaves like a homogeneous transversely isotropic medium with a vertical axis of symmetry [20]. In this medium, $SHdiff$ and $SVdiff$ propagate independently, with $SHdiff$ faster than $SVdiff$, which is consistent with the seismic observations [5]. Incidence angles of SKS and $SKKS$ in D" are around 30° and 60°, respectively. Data of SV velocity as a function of incidence angle in a finely layered medium can be found in many publications, such as [21,22]. The lowest

SV velocities are observed for either vertical or horizontal propagation, whereas the highest values are characteristic of angles around 45°. For angles around 30° and 60°, the SV velocities are intermediate between the minimum and maximum velocities. To explain residuals of around 2 s, SKS and $SKKS$ velocities in a layer 300 km thick should be about 10 % lower than standard velocity. Then the difference between SH and SV velocities for horizontal propagation can be even higher than 10 %. This prediction can be tested by observing propagation of $SHdiff$ and $SVdiff$.

The seismic phase $SVdiff$ is usually weak, and can be easily distorted by effects of azimuthal anisotropy in the mantle outside D" and side refraction of $SHdiff$. To eliminate these effects and to pick arrivals of $SVdiff$ accurately, a special technique [23] is devised, which is illustrated in [23] for the records of HRV/WFM and RSON. For the present study, a search for $SVdiff$ has been conducted in the records of the deep Fiji-Tonga events at seismograph stations shown in Fig. 1b. The best data set has been obtained at the same stations, as in Fig. 2: HRV/WFM, RSON and CCM. Fig. 4 shows the observed differential times $SVdiff - SHdiff$. Remarkable features of the detected $SVdiff$ signals are their distance-dependent delays relative to $SHdiff$. The slope of any of the plots in Fig. 4 is the difference in slowness between $SVdiff$ and $SHdiff$ at the source side of the wavepath. We determined the slopes separately for the epicentral distances on both sides of the kinks in Fig. 2. At shorter distances the slopes are close to 0 $s/°$, whereas at larger distances they are in the range of 1.0 - 1.6 $s/°$, with a standard error of $\pm 0.4 - 0.6$ $s/°$. Magnitude of anisotropy can be determined as the ratio between the slopes of the plots in Fig. 4, and the standard slowness of 8.4 $s/°$. Then anisotropy is weak (not more than a few percent) in the region of very low SH velocity (NE of the white bar in Fig. 1b), and around 15% in the region of normal SH velocity, SW of the bar. Anisotropy of around 15% is stronger by about an order of magnitude than reported elsewhere, but consistent with our estimates based on the $SKKS - SKS$ differential times.

Additional data on the properties of D" beneath the south-west Pacific are provided by the the observations of $SPdKS$ (Fig. 1a). This phase propagates as $Pdiff$ in D" and as SKS elsewhere [24]. $Pdiff$ beneath the southwest Pacific is anomalously slow [18,19], with a remarkable correlation between the anomalous delays of $SPdKS$ relative to SKS and positive $SKKS - SKS$ residuals, similar to those shown in Fig. 3. An explanation for this phenomenon is partial melting [25]. The anomalously slow $Pdiff$, however, propagates on the source side in a medium with normal SH velocity (Fig. 1b), which is hard to reconcile with a strong reduction of S velocity, expected in the case of partial melting. Since, as we have demonstrated, the $SKKS - SKS$ residuals are related to anisotropy, the correlation between them and $SPdKS$ delays suggests that the delays are affected by anisotropy, as well. Moreover, east of the white bar in Fig. 1b, where, according to our data, anisotropy is weak, the low P velocity layer, if present, is very thin [26]. Assuming that the $SPdKS$ delays are related to anisotropy, we note that the low horizontal P velocity in a fine-layered horizontally stratified medium is possible, if the variations of S velocity between the layers are much stronger than those of P velocity [21]. Another possibility to be considered is lattice preferred orientation [27].

For normal distribution of random variations of S velocity in the stack of thin horizontal layers with m mean and σ standard deviation, the SH/SV velocity ratio for horizontal propagation is expressed [21] as $SH/SV \approx \sqrt{1 + 4(\sigma/m)^2}$. For S anisotropy of 15%, σ thus evaluated is 28% of m. It is not possible to explain the variations exceeding a few per cent solely by temperature variations [28]. S velocity can be significantly lowered by partial melting or/and by accumulation of crystalline Fe-alloy products of chemical reactions between iron of the outer core and mantle perovskite [29]. Among these possibilities, relatively weak variations of P velocity favour partial melting. The layered structure in D" could be generated by convective mixing and shearing, in about the same way, as finely layered structures are apparently created in the lower crust. The strongly anisotropic region of D", if projected on the surface of the earth, is close to Polynesia, a region of unusual thermal agitation, where a large-scale thermo-chemical plume may be present at the top of the lower mantle [30]. The anisotropic region in D" could be related to the same plume.

Finally, comparable magnitudes of lateral heterogeneity and anisotropy suggest that lateral variations of anisotropy can be mistaken for lateral velocity variations, when the models are derived under the assumption of isotropy. Whatever its origin, the observations of strong and laterally variable anisotropy add a new dimension to the question of properties and processes in D".

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Figure Captions

Figure 1. (a) Schematic representation of the wavepaths of SKS, $SKKS$, $Sdiff$ and $SPdKS$. The wavepaths of $Sdiff$ for two different positions of the source (stars) differ only at the source side. The lightly hatched area indicates the region where SH is slow, as discussed in the text. The darker hatched area is the region where SH velocity is elevated or normal, but SV is much slower than SH. (b) Surface projections of wavepaths superimposed on a tomographic model of SH velocity in D" [16]. The light gray zone of the wavepath indicates approximately the D" leg of $Sdiff$ for the shortest distances considered. The white bar corrresponds to the kink for $SHdiff - SKS$ residuals, discussed in text. Insert: close-up look at the source side of the wavepaths. Epicenters of deep Fiji-Tonga events and of shallow Kermadec-Fiji-Tonga events are shown by filled and open stars, respectively. The background tomographic model of SH velocity in D" is [17]. The polygon indicates the zone of ultra-low P velocity in D", as found by [19].

Figure 2. Residuals of differential travel times with respect to those for PREM [12]. $SHdiff - SKS$ and $SHdiff - SKKS$ for HRV/WFM, RSON and CCM, and corresponding regression lines. The data labeled shallow are for shallow and intermediate events; all others are for deep events. Numerical values of the slopes of the regression lines with their respective confidence intervals are shown in the upper left and lower right corners of each panel.

Figure 3. $SKKS - SKS$ residuals for all paths in Fig. 1b.

Figure 4. Delays of $SVdiff$ with respect to $SHdiff$ as a function of epicentral distance for stations HRV/WFM, RSON and CCM. Each data set is approximated by two regression lines. The boundaries between the corresponding distance intervals are taken from Fig. 2. Numerical values of the slopes of the regression lines with their respective confidence intervals are shown in the upper left and lower right corners of each panel.