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Seismic anisotropy in the D" layer

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Abstract. We present observations of diffracted SV (SVd) for a path between the Fiji-Tonga islands and the eastern coast of North America at distances greater than 110°. Observed features of S diffracted suggest that coupling between SVd and SHd can be ruled out as a first order effect for this path. Arrivals of SHd are late relative to IASP91 travel-times by about 10 s, and those of SVd are late relative to SHd by 3 s, for most records. The slope of the log(SVd/SHd) spectral ratio is around $3Hz^{-1}$ in the range 0.06-0.15 Hz. A transversely isotropic low-velocity layer in the lowermost mantle with a thickness of 200-300 km may account for most of the observed properties of SVd.

Introduction

The D" layer at the base of the mantle is a region where processes of prime importance for understanding Earth dynamics are likely to take place. These vigorous processes are responsible for a complicated and heterogeneous structure of D". Among the most important sources of data on the structure of D" are records of P and S waves diffracted at the core mantle boundary (CMB). It has been known for a long time that Sd is polarized as SH at distances exceeding $105-110°$. This view has been based on observations of Sd in the period range around 20 s and theoretical arguments (Teng and Richards 1968). Recently, a few observations of SVd at distances between 107° and 120° were reported by Vinnik et al. (1989). The amplitude ratio SVd/SHd was frequency-dependent, and there was a phase shift between similar frequencies in SVd and SHd. Two explanations for the phenomenon of long-range propagation of SVd were discussed. One is a zone of negative S velocity gradient at the base of the mantle. The second is azimuthal anisotropy at the base of the mantle. In the latter case, the radial (R) and transverse (T) components of Sd would be coupled due to shear-wave splitting. Lay and Young (1991) reported travel time differences between arrivals of SVd and SHd at distances around 100° for a wavepath under the northern Pacific, which they attributed to anisotropy in D".

We here present observations of SVd for paths between the Fiji-Tonga islands and the eastern coast of the US. Two records for this path were already discussed by Vinnik et al. (1989). The number of available records is now much larger, which allows us to investigate the nature of the phenomenon in more detail.

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Observations of SVd

The records discussed here are obtained at stations HRV (42.51N, -71.56W, IRIS) and WFM (42.61N, -71.49W, GEOSCOPE), for deep events in the Fiji-Tonga region (Table 1). Fig. 1 shows the surface projections of typical wavepaths between source and receiver regions, and the source mechanism distribution. Fig. 2 presents observations, low-pass filtered with 0.1 Hz cut-off to suppress microseismic noise. Intermediate events are not considered, because their depth phases, sSKS, pSKS, sSKKS and pSKKS could be mistaken for SVd. Arrivals of SKS and SKKS are consistent with IASP91 traveltimes (Kennett and Engdahl 1991) to within 1 - 2 s, whereas those of SHd are systematically late by around 10 s (Table 1). Arrivals of SVd are seen in many records. Effects of upper mantle anisotropy, as shown by the T component records of SKS and SKKS, are either weak or nonexistent. The deep events can be divided into two groups: a northern one, with back azimuths around 267° (86146,89320,93080 and 94068) and a southern one, with back azimuths around 264°.

The two hypotheses proposed by Vinnik et al. (1989) can be tested by using the records of events with different radiation patterns. Take-off angles of SVd and SKKS differ by only a few degrees and, in an isotropic medium, changes of the amplitude of SVd should be strongly correlated with those of SKKS and practically independent of those of SHd, as a function of source radiation pattern. The second hypothesis implies that due to azimuthal anisotropy, SHd and SVd are coupled. Then the amplitudes of SVd and SHd should be strongly correlated. We note that the amplitudes of SKS and SKKS in Fig. 2 are strongly correlated, which implies that their variations are affected not so much by path effects as by the source radiation patterns. Large variations in the amplitude ratio SKKS/SHd in Fig. 2 are strongly correlated with those predicted for the respective focal mechanisms. The amplitudes of SVd normalized by amplitudes of SHd are strongly correlated with those of SKKS (Fig. 3a), while no significant correlation is found between the amplitudes of SVd and SHd (Fig. 3b).

Table 1. List of records. δt is traveltime residual of SHd relative to IASP91. The residual is not given when SHd is not seen (93080). The residuals of SKS and SKKS are close to 0 s.

Δ	date	Lat. (°N)	Lon. (°W)	depth (km)	station	δt (sec)
114.28	94 068	-18.04	-178.41	563	HRV	12.5
114.37	93 080	-18.04	-178.53	589	HRV	..
114.53	89 320	-17.36	-179.43	555	HRV	11.4
114.68	93 190	-19.78	-177.49	398	HRV	11.1
116.17	91 273	-20.67	-178.52	590	HRV	10.4
117.18	86 167	-22.04	-178.93	547	WFM	12.7
117.51	90 177	-22.02	-179.47	587	HRV	10.5
117.58	94 090	-22.06	-179.53	580	HRV	9.5
117.68	86 146	-20.19	178.86	538	WFM	9.5
118.79	90 203	-23.15	-179.83	559	HRV	10.3
119.13	93 219	-23.87	-179.85	523	HRV	12.5
120.56	94 300	-25.78	179.42	535	HRV	9.5

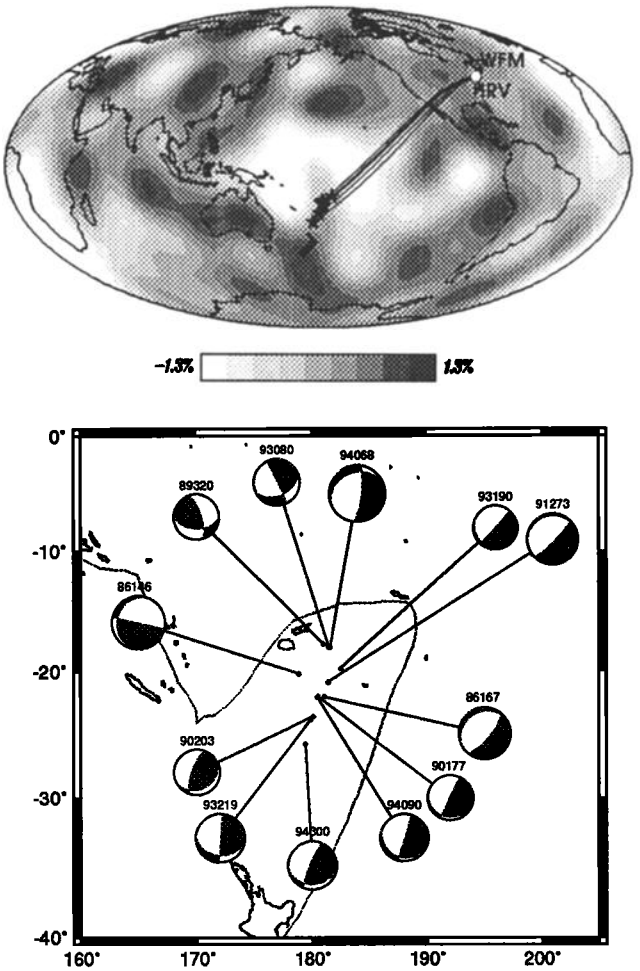

Figure 1. Top: Surface projections of typical raypaths considered in this study shown on a background displaying the lateral variations of S velocity in D" from Su et al. (1994). Note the low velocities in the central Pacific where the raypaths sample the D" region. Bottom: spatial distribution and source mechanisms for the events considered.

The relations between SVd and SHd for the records of northern and southern groups are different. In the records of the northern group, SVd and SHd arrive simulatenously (Fig. 2). To demonstrate the relation between SVd and SHd in the southern group, we have stacked both components of Sd for the records with the best signal/noise ratio. We verify that all the first motions in SHd and SKKS for these records are similar, and so are the waveforms of Sd. Travel time corrections for stacking are found by correlating SHd, and the same corrections are applied to SVd. The amplitudes of both SVd and SHd are normalized by those of SKKS. The results of stacking (Fig. 4) show that SVd is delayed relative to SHd by 3 s, and the dominant period in SVd is about 2 s shorter than in SHd.

Numerical modelling

The data suggest that SVd and SHd propagate independently, but, in the southern group, with different velocities. Such properties are characteristic of a transversely isotropic (anisotropic with vertical symmetry axis) medium (Cormier 1986, Doornbos et al. 1986). Wavefields in this medium are close to those in the isotropic medium, provided isotropic velocities are equal to the horizontal velocities of the anisotropic medium (Doornbos et al., 1986). We simulate propagation of Sd by using standard reflectivity techniques (Kind and Mueller 1977) and assuming different models for SV and SH. The synthetics are calculated for a representative source mechanism and depth. The rise time of the displacement in the source was chosen equal to 10 s.

The models tested are modifications of IASP91 that fall into two groups. In group A, both S velocities near the base of the mantle decrease linearly with depth. In group B, S velocities drop sharply and remain constant in the layer bottoming at the core-mantle boundary. Each model is specified by the group and thickness of the layer in km. The gradients are approximated by stacks of layers several kilometers thick. P velocity remains unperturbed, and density and attenuation are taken from PREM (Dziewonski and Anderson 1981). The same records have been stacked as in Fig. 4, but with the cut-off frequency of the low-pass filter shifted to 0.15 Hz. The resulting spectral ratios SVd/SHd are compared in Fig. 5 with the theoretical ratios at a distance of 117°. Every model considered provides approximately 10 s delay of SHd relative to IASP91 in 115°-120° distance interval and 3 s delay of SVd relative to SHd. Among these models, only A220, A320, A420 and B220 provide a slope of log(SVd/SHd) around $3Hz^{-1}$, similar to the observed slope, whereas the slopes for B150 and B320 are very different. Model A420 does not fit the observed spectral ratio level. Successful A320 and B220 models are shown in Fig. 6, and theoretical seismograms for A320 are presented in Fig. 7.

Discussion and conclusions

The observed Sd phases propagate in a region with known anomalously low S velocities in the lowermost

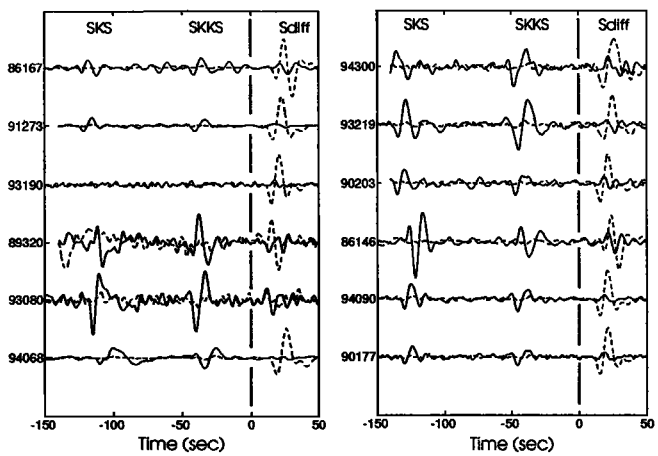

Figure 2. Radial (solid lines) and transverse (dashed lines) components of records listed in Table 1 starting at the theoretical arrival time of Sdiff for model IASP91 (Kennett and Engdahl 1991). SVd is seen in most records. Records of events 86146 and 86167 were previously shown by Vinnik et al., 1989.

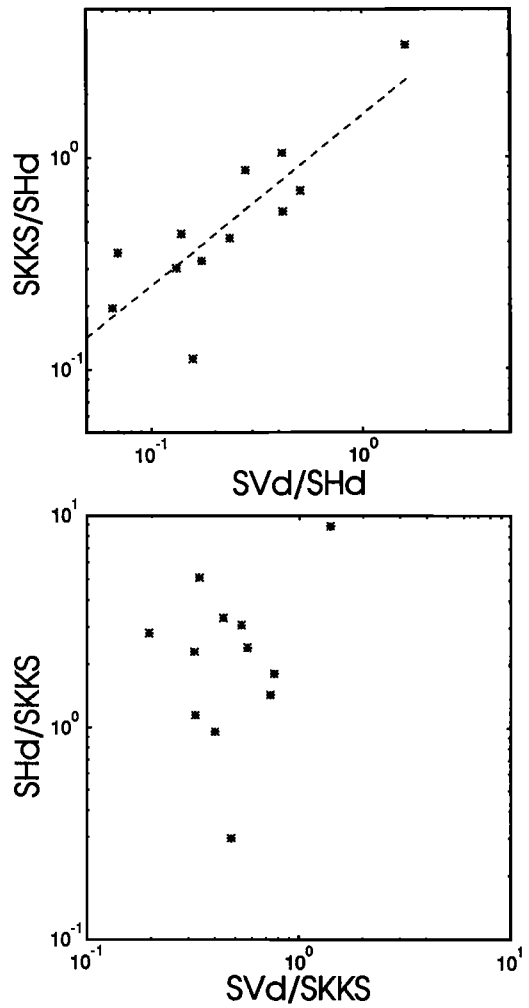

Figure 3. a) Amplitudes of SKKS normalized by SHd versus those of SVd for the records in Fig. 2. When one of the phases is not seen, the amplitude of the noise in the respective time window has been used.b)SHd versus SVd amplitudes, normalized by SKKS.

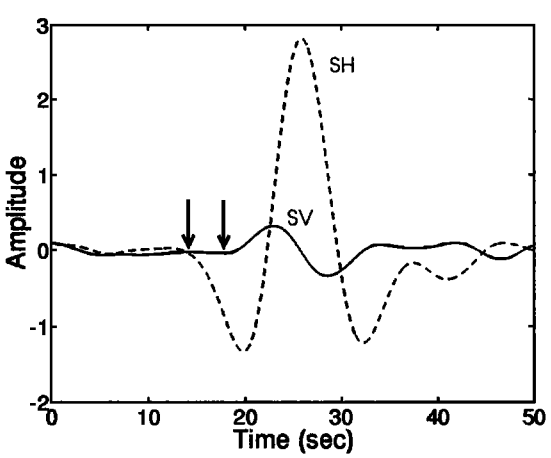

Figure 4. Stack of SHd and SVd waveforms of events 86167, 90177, 94090, 90203, 91273 and 93219. Note that the first motion in SVd is 3 s late relative to that in SHd, and the dominant period in SVd is shorter than in SHd. 94300 has not been included in the stack because of its more complicated waveforms,a nd 93190 because of shallower depth.

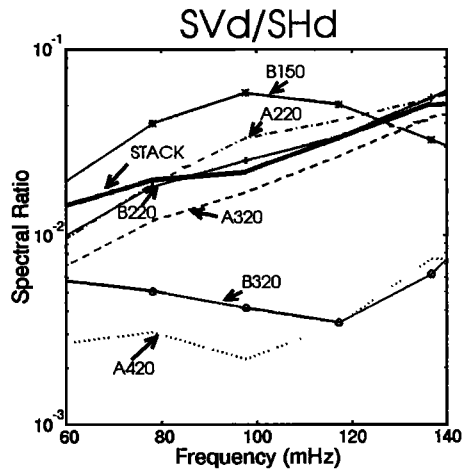

Figure 5. SVd/SHd spectral ratios in the observations (stack) and the theoretical seismograms for 117° epicentral distance.

mantle (Fig. 1). Late arrivals of SHd in our data are caused by this anomaly, and are broadly consistent with the travel time data reported for this region by Garnero and Helmberger (1993). Maupin (1994) analysed records 86167 and 86146 and concluded that the horizontal components of Sdiff are coupled due to azimuthal anisotropy. We believe that a transversely isotropic low-velocity layer in the lowermost mantle is able to explain most of the observed properties of SVd in the southern group, whereas the relatively small northern group is anomalous. Azimuthal anisotropy in D" can be present as a second order effect, weaker than in the model considered by Maupin (1994). Peculiarities of the Sd particle motions of events 86146 and 86167 which were regarded by Maupin (1994) as indication of coupling between the components, are better explained by the assumption that these events belong to different groups. We note that the difference between the waveforms of SVd and SHd in Fig. 4 is larger than in our synthetics (Fig. 7). This discrepancy suggests that the structure of the real mantle is more complicated than the model. The difference between the data for the two closely spaced groups of events suggests that

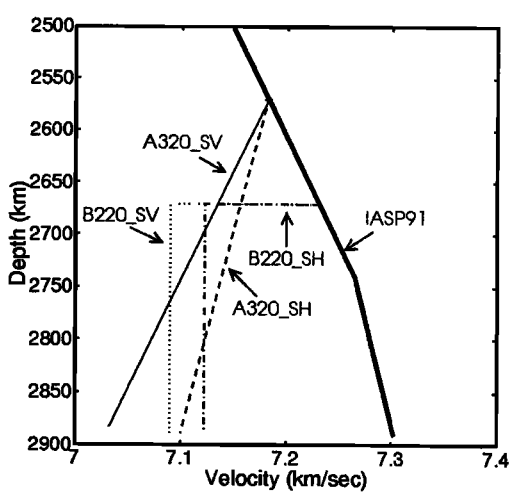

Figure 6. Examples of successful models.

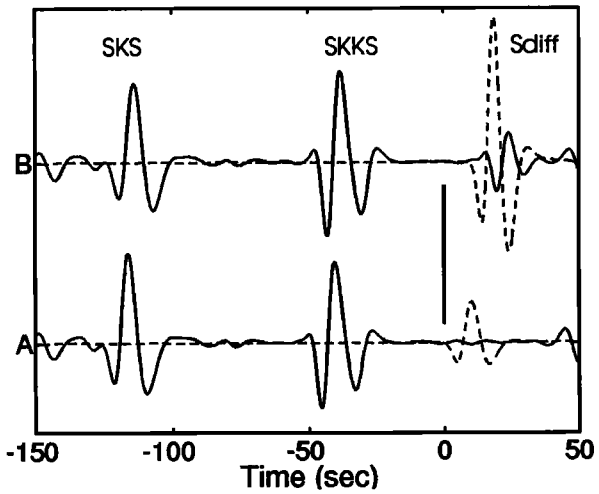

Figure 7. Theoretical radial (solid lines) and transverse (dashed lines) components for IASP91 (A) and A320 (B). Epicentral distances are 115°. Note that in (A) SVd is practically not seen. Arrivals of SHd in B are later than in A and SVd arrives later than SHd.

a strong contribution to the observed effects may come from the mid-mantle of the source region. This contribution is critical for our interpretations, and it deserves careful attention in future studies. The vertically polarized wave (SV) in our model is slower than the horizontally polarized SH. Magnitude of anisotropy is model dependent, and is in the range between approximately 1% and a fraction of 1%. The phenomenon described by this model is reminiscent of the well known Rayleigh/Love wave incompatibility, which is explained by transverse isotropy of the upper mantle. This is, most likely, the effect of averaging variously oriented azimuthal anisotropies (Babuska and Cara 1991), and we hypothesize that the same effect could be responsible for transverse isotropy of the lowermost mantle. Like in the upper mantle, azimuthal anisotropy in D" could be caused by lattice preferred orientation which may arise within the convective boundary layer.

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