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On the inversion of Sd particle motion for seismic anisotropy in D"

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Abstract.
In order to make accurate estimates of anisotropy in D", as measured from observations of *Sdiff* (*Sd*) it is necessary to correct the observed waveforms for anisotropy outside of the deepest mantle as well as side refraction along the path, and to pick arrivals of SVd and SHd as accurately as possible. We show that corrections based on estimates of upper mantle anisotropy inferred from *SKS*/*SKKS* splitting measurements are sometimes insufficient and propose a master event method to directly obtain more accurate corrections on specific source-station paths. Our study illustrates the complexity of structure that needs to be taken into account when addressing issues of D" properties using seismic body wave methods. We also describe a method to accurately measure the arrival time of the corrected *SVd* wave.

Introduction

In the past few years, evidence for the existence of anisotropy in the D" region of the mantle has been accumulating, based on observations of travel time discrepancies between *SV* and *SH* components of waves sampling the deepest part of the mantle, such as *S* diffracted (*Sd*) [*Vinnik et al.*, 1989a; 1995; 1997; *Lay and Young*, 1991; *Garnero and Lay*, 1997] or *ScS* [*Kendall and Silver*, 1996; *Matzel et al.*, 1996]. As such studies become more quantitative, it is critical to accurately correct the records of *Sd* (or *ScS*) for unwanted perturbing effects, and to pick the *SV* and *SH* arrivals as accurately as possible. Indeed, in the presence of strong *SHd*, *SVd* can be easily distorted by coupling between *SV* and *SH*, due to propagation of *Sd* in the azimuthally anisotropic mantle outside D" or by side refraction of *SHd*. We here describe improved *Sd* processing techniques, and demonstrate that the results thus obtained may depart significantly from those based on the standard approach. This is illustrated with examples for the paths between the Fiji-Tonga region and stations in North America (Fig. 1).

Master event technique

In the presence of azimuthal anisotropy outside D" (receiver anisotropy), the spectra of the observed S components of motion at the earth's surface, $SV(\omega)$ and $SH(\omega)$ respectively are related to the unperturbed spectra, $SV_0(\omega)$ and $SH_0(\omega)$ through [*Farra et al.*, 1991]:

$$\begin{Bmatrix} SV_0(\omega) \\ SH_0(\omega) \end{Bmatrix} = F^{-1}(\omega) \begin{Bmatrix} SV(\omega) \\ SH(\omega) \end{Bmatrix} \quad (1)$$

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where ω is angular frequency, and $F(\omega)$ is the matrix of the frequency response of the anisotropic layer. The related waveforms: $SV_0(t)$, $SH_0(t)$, $SV(t)$ and $SH(t)$ can be found from their spectra by inverse Fourier transformation. For a small incidence angle and on the assumption of hexagonal receiver anisotropy with a horizontal axis of symmetry, the elements of $F(\omega)$: $SV_{sv}(\omega)$, $SV_{sh}(\omega)$, $SH_{sv}(\omega)$, and $SH_{sh}(\omega)$ can be expressed as functions of β and δt, the angle in the horizontal plane between the fast direction of anisotropy and the radial (R) direction, and the delay of the slow split wave relative to the fast one, respectively [*Vinnik et al.*, 1992]. Assuming $SH_0(\omega) = 0$, $SH_{th}(t)$, the theoretical $SH(t)$ for arbitrary β and δt, can be obtained from the observed $SV(t)$ through

$$SH_{th}(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \frac{SH_{sv}(\omega)}{SV_{sv}(\omega)} SV(\omega) \exp(i\omega t) d\omega \quad (2)$$

Similarly, assuming $SV_0(\omega) = 0$, the expression for $SV_{th}(t)$ to be derived from the observed $SH(t)$ is

$$SV_{th}(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \frac{SV_{sh}(\omega)}{SH_{sh}(\omega)} SH(\omega) \exp(i\omega t) d\omega \quad (3)$$

The assumption of $SH_0(\omega) = 0$ in (2) corresponds to observations of SKS or $SKKS$. The actual values of β and δt minimize the rms difference between $SH_{th}(t)$ and $SH(t)$ [*Vinnik et al.*, 1989b]. The values of the parameters of anisotropy thus found can be used to correct the recordings of *Sd*, using (1). *Vinnik et al.* [1989a, 1995] did not correct recordings of *Sd* of Fiji-Tonga events at IRIS station HRV and a neighbouring Geoscope station WFM, because the analysis of SKS and $SKKS$ for this path (Fig. 1) has shown that $\beta = 0°$. In such a situation, $SV_{sh} = SH_{sv} = 0$. At some other stations, *Kendall and Silver* [1996] applied corrections, using the parameters of anisotropy derived from the analysis of splitting of SKS.

We here demonstrate that the corrections, if derived from observations of SKS and $SKKS$, can be misleading. Instead, we propose a more efficient technique, where the corrections are derived directly from the observations of *Sd*. The idea is to derive the corrections from the 'master' recordings of *Sd*, with extremely weak *SV* radiation in the source, as compared with *SH*. On the assumption of transverse anisotropy in D" (hexagonal anisotropy with the vertical axis of symmetry), there should be no coupling between *SHd* and *SVd*. This means that the signal, which can be present in the *SV* component of the master event is not *SVd*, but an effect of receiver anisotropy or side refraction of *Sd*. The critical assumption of transverse isotropy in D" is based mainly on the observation, that the amplitude of *SVd* is correlated with that of *SKKS* rather than *SHd* [*Vinnik et al.*, 1995]. Additional arguments in favour of this as-

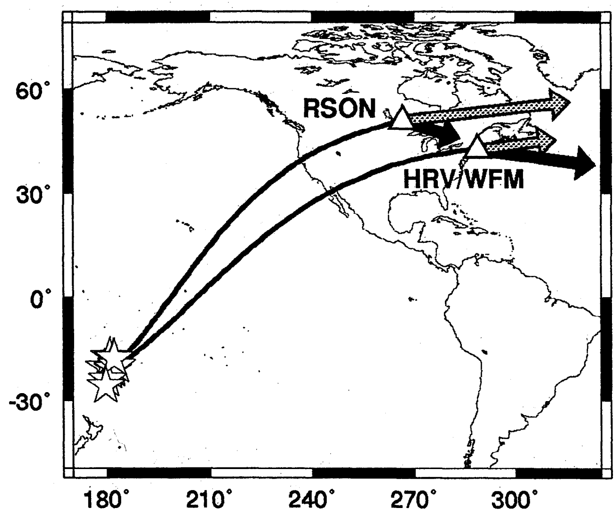

Figure 1. Surface projection of paths between Fiji-Tonga earthquakes and seismograph stations considered. The grey and black arrows indicate the fast direction of anisotropy, at each station, as obtained using standard SKS splitting measurements and the master event method described in the text, respectively.

sumption are provided by the results of data processing, which are obtained through this study and discussed in the last section.

Receiver anisotropy is manifested by quarter-period phase shift between the R or SV and SH components of Sd. The parameters of this anisotropy can be evaluated by minimizing the rms difference between $SV(t)$ and $SV_{th}(t)$, as derived through (3). The correction eliminating this signal can then be applied to other records of Sd with a similar wavepath. Contrary to azimuthal anisotropy, side refraction is manifested by either 0 or π phase shift between the two components of Sd. The deviation from the theoretical back azimuth of the event can be evaluated by the analysis of the corresponding covariance matrix, and the effect can be eliminated by appropriate rotation of the R, SH coordinate frame.

In what follows, we illustrate applications of the master event technique to the records of deep events at station HRV/WFM. The list of events is modified from *Vinnik et al.* [1995] by including two additional Fiji-Tonga events (88070 and 86146a; the numbers here indicate year and Julian day of the event). The records were integrated to obtain displacement and low-pass filtered with a corner at around 9 s. The records of radial (R) and vertical components were rotated by 25° to obtain SV component of Sd. SV amplitudes of SKS, $SKKS$ and Sd are only slightly different from those in the R component, but the rotation sometimes improves signal/noise ratio, if the noise is formed by multiply reflected P-waves. Figure 2 shows two recordings (88070 and 93190), with very weak or missing SKS and $SKKS$, and for comparison, a record with strong $SKKS$ (93219). Take-off angles of $SKKS$ and Sd are very close, and the weakness of $SKKS$ at these epicentral distances implies that the focal mechanism is unfavourable for generating SVd. This is further confirmed by calculations of synthetic seismograms with the reflectivity technique [*Kind and Mueller*, 1975]. The SV component of Sd in the records of events 88070 and 93190 is clearly coupled with SH: the SV component of every record looks like the derivative of the SH component, which is characteristic of azimuthal anisotropy.

For the records in Figure 2a,b, and one additional similar record, we deconvolved the two components of Sd by the respective SHd. Deconvolution eliminates differences between the records depending on the differences between source functions and magnitudes of the individual events. To minimize noise, the deconvolved components are stacked (Fig. 3A). There is a quarter-period phase shift between the components of Sd, which is characteristic of azimuthal anisotropy. The parameters of anisotropy are determined for the stacked components via (3). The resulting estimates of α, az-

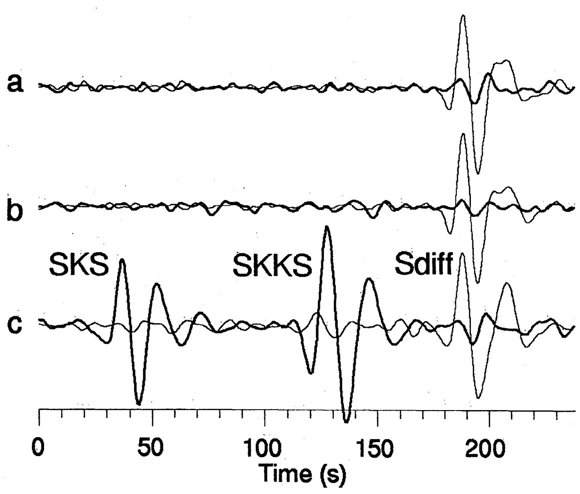

Figure 2. (a) and (b) Examples of records at HRV (88070 and 93190, respectively) for which no $SKS/SKKS$ energy is present. Polarity is inverted for the record of the event 88070. (c) For comparison, a record (93219) with strong $SKS/SKKS$ presence.

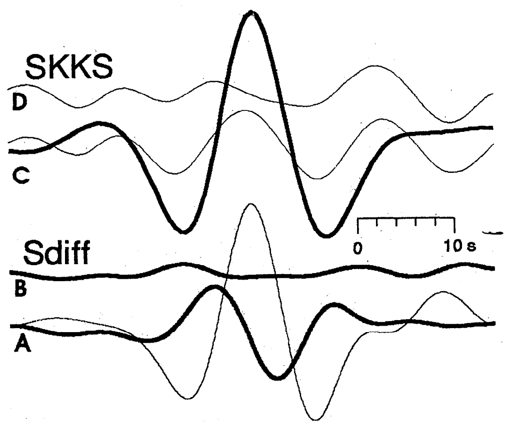

Figure 3. (A): SV (bold line) and SH components of Sd of the master events, deconvolved by SH and stacked. SV is amplified 3 times relative to SH. (B): The same SV component, as in (A), but corrected for receiver anisotropy inferred from (A). (C): SV and SH components of $SKKS$, deconvolved by SV and stacked. SH is amplified 3 times relative to SV. (D): The same SH component as in (C), but corrected for the side refraction of $SKKS$.

imuth of fast velocity counted clockwise from North, and δt are 100° and 1.2s, respectively and differ from 80° and 0.8s, as found by *Vinnik et al.* [1989b] from the analysis of SKS. When the stacked SVd is corrected by using (1) with $\alpha = 100°$ and $\delta t = 1.2s$, the signal is reduced to the level of noise (Fig. 3B).

To verify that the particle motions of SKS or $SKKS$, in our records, are compatible with the direction of anisotropy determined by *Vinnik et al.* [1989b], we considered seven recordings of events with strong SKS or $SKKS$. The azimuth of fast axis of this receiver anisotropy (80°) is close to back azimuths of the Fiji-Tonga events at HRV/WFM (around 263° or 83°), which would imply that no correction for upper mantle anisotropy should be needed.

We deconvolved both horizontal components of $SKKS$ by the SV component of $SKKS$, and stacked the deconvolved components (Fig. 3C). The stacked SH component of $SKKS$ is correlated with the SV component, indicating that it is due to side refraction. The signal in the SH component is reduced to the level of ambient noise by determining the principal motion direction in $SKKS$ and rotating the coordinate frame correspondingly (Fig. 3D). The direction thus determined differs by 5° from the true back azimuth. A similar result is obtained in experiments with SKS. A signal with a quarter-period phase shift relative to SV is clearly missing in SH in Figure 3C, which suggests that the azimuth of fast axis of receiver anisotropy is indeed in agreement with that determined by *Vinnik et al.* [1989b]. This confirms that the value of α found above for Sd is distinctly different from that suitable for SKS and $SKKS$. Another example of a similar discrepancy is provided by the data of station RSON (RSTN network), where the parameters of receiver anisotropy appropriate for Sd, as determined via (3), are 115° and 0.6s, different from 80° and 1.7 s obtained from SKS splitting [*Vinnik et al.*, 1992]. Effect of this anisotropy in the records of Sd can be eliminated with the correction obtained from the master event analysis, but not using the parameters appropriate for SKS. In what follows, we illustrate the consequence of these corrections for differential travel time measurements.

Measurement of $SVd - SHd$ differential travel times

The corrected records at HRV/WFM with detected SVd are displayed in Figure 4a. The arrivals of SHd in Figure 4a are identified by comparing them with the theoretical first motion directions for the respective focal plane solutions. In two cases (events 93080 and 86146a), when the first arrivals of SHd are too weak to be seen, their arrival times are determined by interpolating $SHd - SKKS$ differential times for the neighbouring events (94068, 89320 and 86146b). The procedure for detecting first motion in SVd and determining $SVd-SHd$ differential time, which is illustrated by Figure 4a, consists of several steps. First motion of $SKKS$ is identified by Hilbert transforming $SKKS$ and matching the first cycle of the transformed waveform of $SKKS$ to the raw SKS [*Choy and Richards*, 1975]. We verify with the help of synthetic seismograms, that this technique works well even in the distance range where the SKS waveform is distorted by $SPdKS$. To iden-

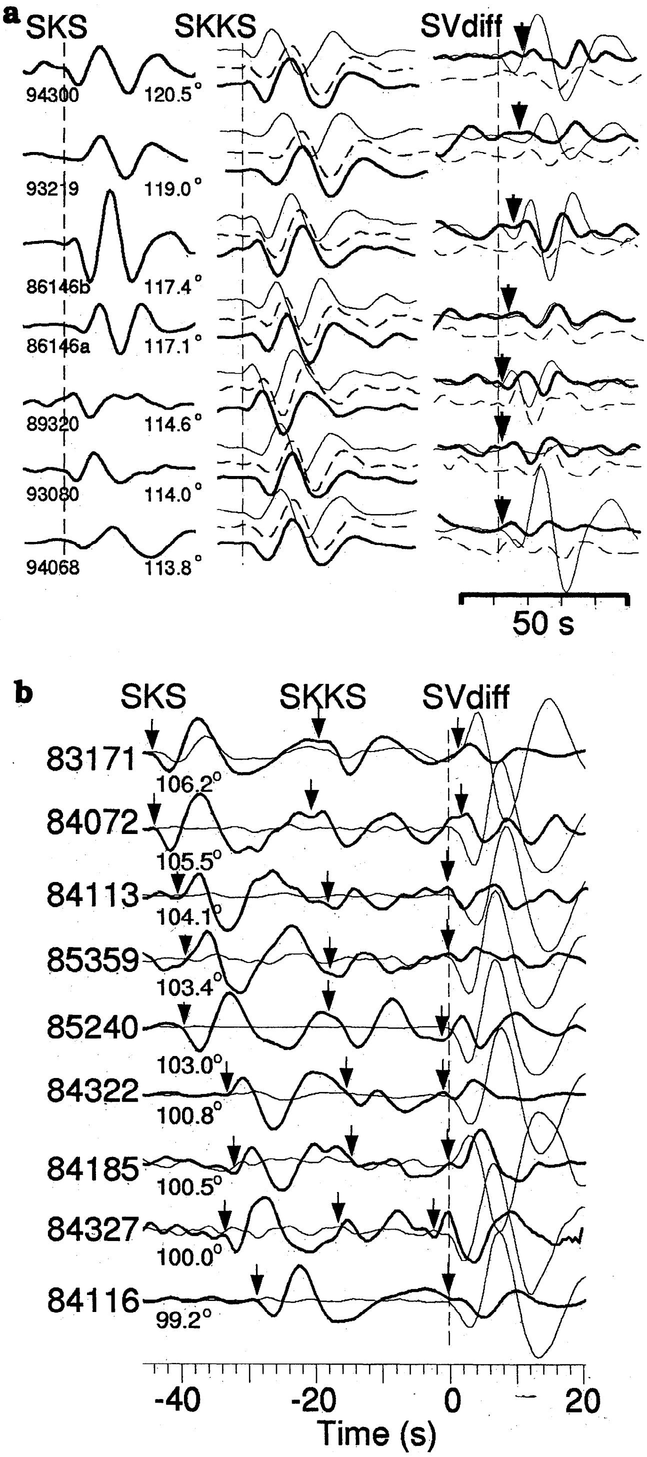

Figure 4. (a) SV and SH components of the records at HRV/WFM. Left column - SKS. Central column - $SKKS$ (bold line), synthetic $SKKS$ (dashed line) and Hilbert-transformed $SKKS$ (thin line). Right column - SV component of Sd (bold line), synthetic SV component of Sd (dashed line) and SH component of Sd (thin line). SV components of Sd are amplified twice relative to SH. Arrivals of SKS, $SKKS$ and SHd correspond to the vertical dashed lines. The records are corrected for receiver anisotropy. (b) R (bold line) and SH components of the records at RSON, corrected for side refraction and receiver anisotropy. Arrivals of SHd correspond to the vertical dashed line.

tify SVd arrivals, synthetic seismograms are calculated with the isotropic reflectivity technique for the reference model PREM [*Dziewonski and Anderson*, 1981] with an S velocity in D" reduced by 4%. The synthetics are calculated for the source functions providing good fit between the theoretical and observed waveforms of $SKKS$ and for the focal plane solutions of the corresponding events. Differential time between $SKKS$ and SVd can be found accurately in synthetics calculated for an arbitrary source function with a sharp onset, and, using this time, the arrival of SVd is identified in the synthetic corresponding to the actual source function. The SVd arrival in the real record can be identified by comparing the real record with the theoretical waveform.

The synthetic SVd waveforms in Figure 4a are generally not much different from the real ones, in support of the transverse isotropy assumption. Some differences should not be surprising, considering extreme complexity of the lower mantle in the study region. A rule of thumb derived from our experiments is that the sign of SVd first motion should always be the same as that of $SKKS$, and at large distances there should be correlation between the waveforms of $SKKS$ and SVd. Remarkable features of the SVd signals are their distance-dependent delays relative to SHd, as indicated by the arrows in Figure 4a. A similar trend is present in the records of RSON, where a generally similar processing procedure was applied to the raw data (Fig. 4b). These measurements, as well as similar ones at other stations, have been used to infer the presence of strong anisotropy in D", locally reaching 10% or more [*Vinnik et al.*, 1997], which is an order of magnitude stronger than previously reported.

Discussion and conclusions

The distance-dependent delays of SVd relative to SHd would hardly be detected without our technique. This is well illustrated by comparing the raw record of event 93219 (Fig. 2c) and its processed version in Figure 4a. Whereas the first visible arrival in the SV component of Sd in Figure 2c is delayed relative to SHd by about 15 s, the true SVd arrival, as shown by Figure 4a, is delayed by only 6 s. In a number of other cases considered at HRV/WFM, the signals previously interpreted as the SVd arrivals are either fully suppressed or significantly modified by the corrections. This eliminates some internal inconsistencies noted in previously published data [*Maupin*, 1995].

The assumption of transverse isotropy in D" is critical to the correction method proposed. It is supported by four arguments: (1) the earlier observation that the amplitude of SVd is correlated with that of $SKKS$ rathen than SHd [*Vinnik et al.*, 1995]; (2) the isotropic reflectivity synthetics computed with different models for SH and SV yield SVd waveforms in good agreement with observed ones; (3) the delays of SVd are similar in pairs of records at similar epicentral distances, one of which contains very strong SHd, and requires large correction for SV, whereas in the other, SHd is weak, and the correction is insignificant: compare 94068 with 93080 and 86146a with 86146b in Figure 4a; (4) strong discrepancies between the estimates of receiver anisotropy based on the $SKS/SKKS$ and Sd data are found at some stations, but they are missing at other stations, along practically the same wavepaths in D".

The discrepancies can be an effect of unmodelled complexity of the crust and upper mantle beneath the receiver, but another explanation cannot be excluded. The wavepaths of Sd and $SKKS$ are very similar in the upper mantle beneath the receiver, but they are strongly different in the lowermost mantle. Hence, it is conceivable that anisotropy in the lowermost mantle is azimuthal but laterally variable, and it contributes differently to $SKKS$ and Sd. Transverse isotropy in D" can be a result of averaging azimuthal anisotropies along the wavepath of Sd or ScS.

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