The effect of SKS scattering on models of the shear velocity-structure of the D″ region

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Abstract. Several recent seismological models for the P- and S-wave velocity structure of the lowermost 300 km of the mantle (D″ region) have proposed the existence of first-order discontinuities several hundred kilometers above the core-mantle boundary. Long-period transverse-component S-waves in the distance range 72°–95° provide the clearest evidence for a lower-mantle discontinuity. Arrivals between SH and ScSH in the range 72°–82°, and a double S arrival in the range 90°–95°, have been interpreted as effects of a lower-mantle tripllication produced by a 2.75% velocity increase 280 km above the core. However, it is well established that the D″ layer has significant lateral heterogeneity and caution must be exercised when interpreting lower-mantle signals with radially symmetric structures. This paper explores the possibility that the tangential component complexity, which has previously been interpreted by a discontinuity model, is actually produced by SKS contamination. It is shown that SKS has the wrong timing and ray parameter to possibly account for the SH observations in all but a small portion (77°–80°) of the tripllication range (72°–95°). Even when strong SKS arrivals are apparent on the radial SV components, SKS contamination of the transverse components is usually very minor in the previously modeled long-period data. The fact that SKS is typically nodal in that data set further supports the lower-mantle discontinuity model interpretation. These results do not preclude the existence of lateral variations in the discontinuity or within the D″ layer beneath it, and do not eliminate the need for caution to avoid possible SKS contamination in future data analysis.

Key words: Lower-mantle velocity structure – S-wave tripllication – SKS signals – D″ region – Velocity heterogeneity

Introduction

It is well established that the P- and S-wave velocity gradients at the base of the mantle are anomalous, being lower than gradients in the mid-mantle, and also that the lowermost 300 km of the mantle (D″ region) has significant lateral heterogeneity. However, despite numerous studies of P- and S-wave signals, there is no agreement on the detailed characteristics of the velocity structure in D″ (Cormier, 1985). Several recent studies, typically utilizing synthetic waveform modeling and careful analysis of large, high-quality data sets, are providing significant advances in our understanding of D″ velocity structure. This is an exciting field of research, because accurate seismic models are critical for resolving the questions of compositional stratification of D″ and the existence of any thermal boundary layer above the core-mantle boundary. These are important issues for models of the dynamic, petrological, and thermal evolution of the Earth.

Most seismological studies of the D″ region have attempted to determine radially symmetric velocity models that satisfy either global travel time or diffracted P- and S-wave data sets (e.g. Doornbos and Mondt, 1979; Mula and Müller, 1980; Dziewonski and Anderson, 1981). These usually have resulted in velocity models with smooth negative or slightly positive velocity gradients throughout D″. Generally, such studies incorporate significant horizontal averaging, reducing their sensitivity to fine details of the velocity structure. Also, given the abundant evidence for lateral heterogeneity of D″, it is not clear whether the resulting models are even adequate “average” structures on which to base interpretations of the thermal structure of the region. Body-wave modeling studies that selectively sample separate regions of the D″ layer promise to provide more detailed local velocity structures and hence better control on lateral variations. In most cases, it appears that the scale lengths of predominant lateral variations in D″ are comparable to those in the upper mantle (Ruff and Lettvin, 1984; Lay and Helmberger, 1983a). By this we mean that when analyzing long-period bodywaves, regions with 1,000-km dimensions in D″ have sufficiently stable behavior to allow determination of reliable local structures, as has also proved true in the more variable upper mantle (e.g. Grand and Helmberger, 1984; Walck, 1985).

Several recent detailed studies of P waveforms that sample isolated areas in the D″ layer have indicated substantial fine velocity structure within D″, as well as lateral variations in that fine structure (e.g. Ruff and Helmberger, 1982; Ruff and Lettvin, 1984; Wright and Lyons, 1981). In a recent P slowness study using a temporary network in Australia that recorded P-waves bottoming beneath southeast Asia, Wright et al. (1985) argue for the presence of a sharp increase in P velocity of 2.5%–3.0% about 160 km above the core-mantle boundary. It must be emphasized that all studies of short-period P-waves traversing the D″ region are complicated by the scattering of the signals that occurs along their paths, as well as by the intrinsically high P velocities in the lower mantle which inhibit isolation of discrete tripllication branches, even in short-period data.

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Lay and Helmberger (1983a) utilized the fact that the $S$-wave velocities in $D''$ are significantly lower than the $P$ velocities in detecting a precursor to $ScSH$ that reflects from a lower-mantle velocity discontinuity. Figure 1 shows an example of this arrival, which can be directly observed in rotated $SH$ data profiles. This profile is for a 583-km-deep Sea of Okhotsk event recorded at North American stations spanning a narrow azimuth range from the source. The $S$ and $ScS$ arrivals are clear, as is the systematic arrival labelled $Scd$, which precedes $ScS$ by about 10 s. This arrival produces a distinctive distance-varying interference pattern in the range $74^\circ$–$80^\circ$. Observations of this arrival for numerous events with different source depths and distances led to the interpretation that the arrival results from a triplication produced by an abrupt 2.5%–3% shear-velocity increase above the core-mantle boundary. The model obtained for this particular path, SLHO, is shown in Fig. 2, along with a reference JB model, and synthetics for model SLHO are compared with the data in Fig. 1. The timing, amplitude, and interference effects of $Sed$ are accurately predicted over the entire range.

Figure 3 shows an $SH$ travel-time curve for the SLHO model indicating the timing of the $Sed$ branch. As one would expect, the observed long-period $SH$ signals in the distance range $82^\circ$–$88^\circ$ are generally quite simple, since all the triplication and $ScS$ phases arrive within the instrument upswing. However, beyond $89^\circ$ the triplication opens up again and two arrivals should be apparent. Lay and Helmberger (1983a) showed that this is in fact observed in the data, with the waveforms being modeled well by SLHO.
However, as demonstrated by Schlittenhardt et al. (1985),
synthetics for model SLHO do not closely match all observ-
ations in the range 93°–110°.

By analyzing numerous seismograms from a single region
recorded by the same receiver array it is possible to empir-
cally establish receiver structure effects, to determine the
stability of the Scd arrival, and to develop an appropriate
local D" structure for that particular path. Lay and Helm-
berger (1983a) did this for three D" samples (beneath
Alaska, northern Eurasia, and the Caribbean) and in all
cases, data throughout the range 70°–90° show waveform
complexity that is well predicted by a discontinuity model.
Variations of 50 km in the depth of the discontinuity were
detected between the three regions sampled. However,
the size of the velocity increase did not vary. The general
consistency of the models for such different patches of D"
suggests the possibility that the discontinuity is a global
feature, embedded within the laterally varying D" struc-
ture, but much further data analysis is needed to test this
hypothesis.

The proposal that there is a deep mantle velocity discon-
tinuity has stimulated several additional studies of D". Cor-
mier (1985) suggested that in some cases the Scd arrivals
in Fig. 1 are the result of SKS contamination of the trans-
verse components. This presumably would be the result of
off-circle rotation of the S-polarization angle pro-
duced by near-receiver heterogeneity or by some complex
distribution of heterogeneity in D". Schlittenhardt et al.
(1985) argue that diffracted S and P profiles do not clearly
show the expected post-critical refraction along the discon-
tinuity and feel that the ScsS precursor is due to some other
phenomenon. Schlittenhardt (1983) calculated short-period
P-wave synthetics for a D" model, with a 2.7% P-wave
velocity discontinuity, and concluded that such a structure
is not consistent with some P-wave observations. In this
paper we explore the question of whether SKS contamination
affects the data set initially utilized to detect the Scd
arrival.

Analysis of SKS contamination

Figure 3 shows SH travel-time curves for the SLHO and
JB models along with an SV travel-time curve for the JB
model. SKS arrives between SV and ScsSV in the distance
range 80°–85°, which makes it difficult to use SV signals
to model the D" region (Lay and Helmberger, 1983a, b).
There is clearly a several degree range in which SKS arrives
at the same time as the Scd branch. Figure 4 shows the
longperiod waveform effects produced by SKS in the pre-
crossover triplication range, for the two events analyzed
by Lay and Helmberger (1983a, b) that have the strongest
SV arrivals. In the range 78°–80° the SKS arrival peaks
close in time to the arrival between S and ScsS on the trans-
verse components. It is plausible that given the relatively
strong SKS arrivals, some contamination of the transverse
components could occur, as suggested by Cormier (1985).

Note, however, that this contamination must be systematic
to produce the apparent moveout of the Scd arrival, and
it must change in nature from station to station.

This possibility was explored further by computing SV
and SH synthetic wavetrains for the smooth PREM model
(Dziewonski and Anderson, 1981), which were then rotated
onto incorrect back azimuths, allowing SKS to ‘leak over’
onto the SH in a procedure similar to that in Cormier
(1985). Figure 5 shows a few results of this simulation, with

Appendix A

Figure 3. Comparison of tangential (T) and radial (R) components of two deep-focus Sea of Okhotsk events recorded in North America. The SH and SV peak amplitudes arrive at the same time at all distances. The peak of the SKS arrivals on the radial componenets (arrows) are shown.

Figure 4. Comparison of observed SH and SV waveforms for the Sea of Okhotsk event of 9/05/70 with synthetics for PREM and SLHO. Each SH and SV pair has true relative amplitude. The PREM synthetics are shown with incorrect back azimuth rotations in 10° increments to simulate SKS contamination of the SH component as advocated by Cormier (1985). Such contamination fails to reproduce the observed arrival between S and ScsS at FLO and BLA, and mimics the SCP observation only with at least a 25°
off-azimuth contamination that ruins the agreement with the SV waveform and the SV/SH amplitude ratio.

Observed waveforms from a Sea of Okhotsk event in the triplication range being compared with SLHO and PREM synthetics. For station FLO (74.6°), the small arrival between S and ScsS apparent in the data and in the SLHO synthetics is never reproduced by the PREM models, regardless of the amount of SKS contamination. This is because SKS arrives only a few seconds ahead of ScsS, well after the small arrival of the SH component, at this distance (see Fig. 3). For SCP (77.9°), it does prove possible to pro-
Fig. 6. A similar comparison to that in Fig. 5, but the data are shown with back azimuth rotations that deviate from the great circle by 10° increments. Note the stability of the arrival between S and ScS on the SH observations, even for back azimuth errors of 30°. This illustrates the predominantly SH character of this arrival, consistent with the model SLHO calculations.

Fig. 7. Examples of SH and SV (radial) recordings with true relative amplitudes for Sea of Okhotsk events analyzed by Lay and Helmerberge (1983a). The dashed curves show SH synthetics for model SLHO, which was constructed to produce the triplication arrival between S and ScS indicated by the arrows. Note that the very low amplitude radial components do not have strong SKS arrivals at these times.

Fig. 8. Examples of stations recording SH and SV signals at distances where SKS is well ahead of the S arrival (see the travel-time curves in Fig. 3) along with closer observations at the same stations. Note that the typical SKS contamination apparent on the SH components is a very small fraction of the actual SKS amplitudes (the SH and SV components are on true relative scales). The dashed curves show SH synthetics for model SLHO. Note the agreement between the SLHO calculations and the observed data at these stations at all distances, including distances within the triplication range. This illustrates that receiver complexity is not responsible for the arrival between S and ScS, as well as showing that SKS cannot produce the waveform complexity beyond crossover distance (near 90°).

cannot be attributed to SKS, which arrives much too late. Thus, in this distance range the ScS observations clearly require a different explanation than SKS contamination. The possibility of receiver reverberations was ruled out in their study by individual station analysis.

Figure 6 is similar to Fig. 5 except that the data are shown rotated with back azimuths departing from the great circle. The arrival between ScS and S on the SH component does not vary significantly, even for large off-great-circle rotations. This stability testifies to the predominantly SH character of the arrival. The tests in Figs. 5 and 6 were conducted for the event with the strongest SV and SKS arrivals of all the events used by Lay and Helmerberge (1983a). Figure 7 presents much more typical examples of SH and SV waveforms in the triplication range for several of their events. Each SH and SV pair is plotted with true relative amplitude. There are no strong SKS arrivals on the radial components at the time of the ScS arrivals (arrows), and the SH waveforms are modeled well by the SLHO synthetics. The observed SV/SH amplitude ratios are very consistent with the known P-wave first motion mechanisms of these events (Lay and Helmerberge, 1983a). There is no reason to believe that the S-waves are so strongly contaminated by near-receiver structure that all of the SV signal ends up on the transverse components when the great-circle back azimuth is assumed in the rotation.

By examining observations beyond 84°, where SKS is an isolated first arrival (see Fig. 3), one can obtain a better estimate of how much SKS contamination actually does occur. Figure 8 shows examples of recordings at this distance as well as recordings at closer distances for the same
stations. For these stations, rotation assuming the great-circle back azimuth leads to less than 10% contamination of the SKS signal on the SH component. These same stations show strong Scd arrivals within the triplication range, but these are not accompanied by SKS signals at least ten times as strong on the radial component. Indeed, the SKS arrivals are observed to be nodal, as predicted by the known focal mechanisms. It is also clear in Fig. 8 that the SKS signals cannot possibly account for the double S arrivals observed near 90° (see Figs. 16, 34, and 37 of Lay and Helmberger, 1983a), because SKS is well ahead of the S arrival at this distance. These arguments refute the possibility that the discontinuity models are invalid because of SKS.

It is important to note that this conclusion is based on the long-period waveforms. Short-period waveforms (and occasionally long-period records from notorious stations like OXF) in our data set often show appreciable SKS contamination on the transverse component, partially due to the greater difficulties in accurately digitizing and rotating the short-period records. Thus, analysis of short-period or broadband S-waves must be performed very carefully, and optimally for events with nodal SV arrivals. Zhang and Lay (1984) analyzed data from an array of broadband stations for such events and still found tremendous receiver complexity effects that must also be accounted for.

Discussion

In this paper we have concentrated on establishing whether SKS contamination has led to a misinterpretation of lower-mantle shear-velocity structure by Lay and Helmberger (1983a). There appears to be very little evidence to support this possibility, as it would require a tremendous number of special circumstances to account for the consistency of the SH data and to explain away the lack of SKS signals on the radial components. Clearly the D" layer has lateral heterogeneity, and any radial model (even for a localized portion of the D" region) may be in error to some degree because it attributes scattered effects to a deterministic radial structure. However, the consistency of the observations for nearby stations and from event to event strongly indicate that such errors in the discontinuity models are minor. It has proved possible to determine reliable upper-mantle velocity structures for different tectonic regions despite 10% velocity heterogeneity, which probably greatly exceeds variations in D". There is no question that modeling the D" region is difficult, and data-intensive studies are the best way to reliably account for upper-mantle, source, and receiver effects. While all earth models are undoubtedly simplifications of the actual structure, if they are able to predict the detailed behavior of many observations it seems reasonable to believe they are valid, at least to first order.

Much additional analysis of lower-mantle P- and S-waves is certainly needed, particularly with regard to possible anisotropy and variations in fine scale features. This modeling must be performed with an open mind toward both possible stratification, general heterogeneity, and apparent or intrinsic anisotropy, as advocated by Cormier (1985), given the proximity of D" to the largest compositional and density discontinuity within the Earth.

Conclusions

A detailed analysis of SV and SH waveforms in the distance range 72°–95° has been performed with the intent of appraising the possibility that SKS contaminates the transverse components leading to incorrect D" velocity models. For the data which has previously been interpreted as evidence of a lower-mantle shear-velocity discontinuity, it is very unlikely that SKS has caused any systematic problem. The strongest argument for this is that in the majority of the data the SKS arrival is much smaller than the arrivals on the transverse component, consistent with the known radiation patterns. Furthermore, the timing of SKS is not the same as that of the triplication arrivals on the SH components except over a narrow in distance. Well-controlled experiments show that typically less than 10% of the SKS waveform contaminates long-period SH signals rotated assuming the great-circle back azimuth.

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References

Cormier, V.F.: Some problems with S, SKS, and ScS observations and implications for the structure of the base of the mantle and the outercore. J. Geophys. 57, 14–22, 1985


Mula, A.H., Müller, G.: Ray parameters of diffracted long period P- and S-waves and the velocities at the base of the mantle. Pageoph. 18, 1272–1292, 1980


Ruff, L., Lettvin, E.: Short period P-wave amplitudes and variability of the core shadow zone boundary. EOS 65, 999, 1984

Schlittenhardt, J.: Investigation of the velocity structure of the lowermost mantle with short period Pe/P’/amplitude ratios (abstract). IASPEI Program and abstracts, XVIII General Assembly, IUGG, 259, 1983


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