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Seismic detection of a thin laterally varying boundary layer at the base of the mantle beneath the central-Pacific

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Abstract. We explore lowermost mantle structure beneath the Pacific with long-period recordings of the seismic core phases SKS, SP_dKS, and SKKS from 25 deep earthquakes. SP_dKS and SKKS are anomalously delayed relative to SKS for lower mantle paths beneath the southwest Pacific. Late SP_dKS arrivals are explained by a laterally varying mantle-side boundary layer at the CMB, having P-velocity reductions of up to 10% and thickness up to 40 km. This layer is detected beneath a tomographically resolved large-scale low velocity feature in the lower mantle beneath the central-Pacific. SKS, SP_dKS, and SKKS data for the generally faster-than-average circum-Pacific lower mantle are well-fit by models lacking any such low-velocity boundary layer. The slow boundary layer beneath the central Pacific may be a localized zone of partial melt, or perhaps a chemically distinct layer, with its location linked to overlying upwelling motions.

Introduction

Pursuing the relationship of fine structure at the Earth's core-mantle boundary (CMB) to larger scale patterns in the overlying mantle is crucial for understanding the region's thermal, chemical and dynamical behavior. Many P- and S-wave structures (V_P and V_S, respectively) for the region just above the CMB have been presented, and several physical explanations put forth (for a review, see Loper and Lay, 1995). However, nearly all seismic methods that study the base of the mantle have inherent uncertainties due to long wavepaths that vertically and laterally average the structure of interest.

Here we analyze travel times and waveforms of SKS, SP_dKS, and SKKS. SP_dKS is an SKS-type wave (Kind and Müller, 1975; Choy, 1977) with the additional complication that it has short segments of mantle-side CMB P-diffraction (P_{diff}) at the source- and receiver-sides of the wavepath (cover, top). Since SKS and SP_dKS have mantle S-wave paths that are nearly identical, SP_dKS-SKS differential times and waveforms provide very localized sampling of lowermost mantle V_P structure, where the segments of P_{diff} in SP_dKS occur.

Previous work demonstrates how 1-D structures with 5% V_P reductions over the lowermost 50-100 km of the mantle can explain anomalous SP_dKS-SKS separations (Garnero et al., 1993), and also that a correlation exists between anomalously large SP_dKS-SKS and SKKS-SKS times (Garnero and Helmberger, 1995a). The latter finding provides evidence for the existence of anomalously low basal V_P (from SP_dKS-SKS), underlying long-wavelength slower than average structure (from large SKKS-SKS times). This paper is an extension of this earlier work, and focuses on modeling variations in anomalously large SP_dKS-SKS times with a slow basal layer possessing lateral variations in thickness. 2-D modeling is presented for an expanded data set, and is motivated by the broad interdisciplinary implications of a such a low-velocity CMB layer.

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SKS, SPdKS, and SKKS Data Set

We examine long-period (LP) WWSSN data from 25 deep focus earthquakes. These data (rather than broadband) were utilized due to the abundance of recordings over a two decade interval, permitting dense spatial sampling in the key distance window of 105°–120°. We retained data only from events having simple sources; most path geometries sample the central or circum-Pacific, a region which we focus on in this paper.

An inherent ambiguity exists concerning contributions to an SP_dKS-SKS anomaly from either source- or receiver-side SP_dKS P_{diff} segments. Such uncertainties can be reduced by analysis of data with criss-crossing SP_dKS paths. We also consider patterns from tomographically-derived aspherical structures in discussing trends in our data set. Figure 1 displays one such model, SKS12WM13 of Liu and Dziewonski (1994), along with wavepath geometries of two of the events studied. We use SKS12WM13 to discuss large scale lower mantle V_S and V_P heterogeneity. Wavepaths in Figure 1 illustrate the sampling of varying structures by SP_dKS: the SW Pacific event has SP_dKS near-source P_{diff} segments in and around the slowest portion of SKS12WM13, while the southern Atlantic event has source- and receiver-side P_{diff} segments in average or faster-than-average structure.

Synthetic seismograms for the 1-D PREM model (Dziewonski and Anderson, 1981) and observations from the two events of Figure 1 are presented in Figure 2. PREM synthetics show the systematic moveout of SP_dKS relative to SKS (Figure 2a, dashed lines). The circum-Pacific data of the Sandwich Is. event to North America (Figure 2b) are well-modeled by PREM, particularly in the distance range near 110°. SP_dKS-SKS interference first initiates near this distance, and the presence or absence of systematic waveform complications (e.g., a double peak SKS pulse) is a diagnostic for modeling basal V_P structure. The Fiji Is. event data (Figure 2c) traverse the slowest lower mantle feature in SKS12WM13 and display anomalously delayed SP_dKS relative to SKS. This is most notable near 110° in distance, where the first upswing of SKS has a double peak. The second of the two peaks is the delayed SP_dKS arrival, and is present for all events with this path geometry.

Anomalously large SKKS-SKS times are present on the same records displaying SP_dKS delays (Figure 3a). SP_dKS and SKKS are both delayed relative to SKS by several seconds more than PREM predictions. SP_dKS-SKS and SKKS-SKS residuals are summarized in Figure 3b. The most anomalous data of Figure 3b (circles) travel through the slowest part of the SKS12WM13 Pacific anomaly. Most circum-Pacific paths have times that scatter about the PREM predictions (crosses).

1-D and 2-D Synthetic Modeling

As mentioned, 1-D structures with 5% reductions in P-wave velocity over the lowermost 50-100 km of the mantle can reproduce the anomalous SP_dKS-SKS observations. However, a 1-D structure is probably inappropriate due to differing source- and receiver-side CMB regions. This is apparent in the contrasting data samples of Figure 2. The Sandwich Is. event is well-modeled by PREM, indicating the receiver-side lowermost mantle V_P (beneath North America) sampled by SP_dKS is PREM-like. More northerly South American events recorded in Canada behave similarly. The anomalous SP_dKS data from the Fiji Is. region sample the same lower mantle beneath North America; thus a 1-D structure with 5% slow basal V_P to explain the Fiji Is. data would contradict the Sandwich Is. observations. Therefore we utilize a generalized ray code that allows differing lowermost mantle structures on the source- and receiver-sides of SP_dKS+SKS wave paths. This permits us to explore scenarios in which a low-velocity basal boundary layer exists beneath slow long-wavelength central Pacific lower mantle structure, with the circum-Pacific region lacking such a layer.

In modeling experiments, SP_dKS-SKS times and waveforms are most effectively perturbed by varying the mantle-side P-velocity at the CMB, which is the only portion of the mantle wave path where SP_dKS and SKS significantly differ (Garnero et al., 1993). This is in accord with dynamical (Stevenson, 1987) and seismological (Garnero and Helmberger, 1995a) arguments that lateral variations in outer core V_P are absent or small enough to not contribute to the differential times.

The sensitivity of P_{diff} segments in SP_dKS to structure far above the CMB is wavelength dependent. For our LP data, structural perturbations more than 100 km above the CMB, such as D″ discontinuity structures 200-300 km above the CMB, have little effect on SP_dKS-SKS predictions. A modeling trade-off exists, however, between thin ($\leq$40 km) intense discontinuous velocity reductions at the base of the mantle and milder linear gradient reductions over larger depth intervals (50-100km) (Garnero and Helmberger, 1995b). However, models with low-velocity structures that extend more that 50 km above the CMB have significant affects on the times and waveforms of other seismic phases, such as core reflected, grazing, and diffracted phases. Mori and Helmberger (1995) analyze waveform stacks of short-period (SP) P, PcP, and a precursor to PcP (with opposite polarity of P) to infer a 5-10% low velocity V_P basal layer, only 10 km thick, for the SW Pacific to North America geometry. The SP P-wave data would show diagnostic travel time and waveform effects if the low-velocities extended further up into the D″ region. Their results are further discussed below.

To explain anomalous SP_dKS-SKS data, we explored discontinuous velocity reductions from PREM on only one side of the SP_dKS wavepaths (to correspond to data having paths through the SW Pacific). The largest SP_dKS-SKS anomalies can be modeled with a source-side 40 km thick boundary layer having 10% V_P reductions. Figure 4 shows an example from the Fiji Is. event of Figure 2; the anomalously delayed SP_dKS are well-modeled by a 40 km layer, with the exception of the first 111.2° record, which displays a smaller SP_dKS-SKS separation than the prediction. Reducing (increasing) the thickness of the low-velocity layer decreases (increases) the separation between SKS and SP_dKS. Modeling the variable SP_dKS-SKS times in Figure 3b (and Figure 4) can thus be accomplished by varying the thickness of the low-velocity boundary layer.

Fixing the V_P velocity reduction at 10%, we searched for thickness of the low-velocity layer that best-modeled each anomalous SP_dKS record from the SW Pacific. Such an approach provides insight on the intensity of lateral variations in the layer necessary to explain the observations. The cover (bottom) displays a map of the anomalous source-side SP_dKS P_{diff} segments, and best fitting low-velocity layer thickness. Lateral variations are apparent on both small and larger scales. Thin basal layer thicknesses (e.g., 5km) produce observable delays in LP SP_dKS due to trapping significant energy in the low-velocity channel. A 40 km thick layer (red segments) best fits much of the data sampling the CMB region to the NE of the Fiji-Tonga sources; intermingled on this trend are indications of thinner regions (blue segments). Larger distance SP_dKS arrivals have CMB P_{diff} segments ≥1000 km in length, thus averaging smaller scale (e.g., 100 km) structures along the P_{diff} path. Such smaller scale heterogeneity can account for the apparent scatter in thicknesses of the low-velocity layer for a given region. P_{diff} segments of SP_dKS (cover) are super-imposed on velocity contours of SKS12WM13. Our path coverage is too sparse to confidently assess geographical correlation of details in this model with our best-fitting layer thicknesses. Nonetheless, a general correlation is apparent: the most anomalous lower mantle feature in SKS12WM13, namely that in the SW Pacific, occurs in the region possessing very slow basal V_P velocities. The CMB region sampled by Mori and Helmberger (1995) is to the northeast of our SW Pacific study area. They model this region with a 5-10% low-velocity layer having thickness 10 km.

A scenario compatible with observations has a 10% low-velocity basal layer underplating the large-scale slow region in the SW Pacific, with intense lateral variations in layer thickness super-imposed on a general trend of diminishing thickness in regions further away from the SW Pacific. In circum-Pacific regions, SP_dKS is not delayed, thus such a layer is either nonexistent, or too thin (< 1-2 km) to be detected with LP data.

Discussion

Other lower mantle studies have presented evidence for reduced V_P in our study area, e.g., up to 3.5% V_P reductions (Silver and Bina, 1993). For other regions, V_P variations in D″ of small and large scale lengths have been proposed (e.g., see Wysession et al., 1992; Souriau and Poupinet, 1994; and Krüger et al, 1995). A thin boundary layer with 10% V_P reductions may have, however, easily gone undetected in past studies due to its localized nature, as well as being masked by (and mapped into) overlying heterogeneity. While this effort focuses on a low-velocity V_P layer, it is interesting to note that large distance diffracted SV waves traveling through the SW Pacific anomaly have anomalously large amplitudes (Vinnik et al., 1989, 1995; and Garnero and Helmberger, 1995b). Also, low and variable V_S reductions exist slightly to the west of our study area (e.g., Wysession et al., 1994). An intense low S-velocity boundary layer similar to what we propose for P-waves

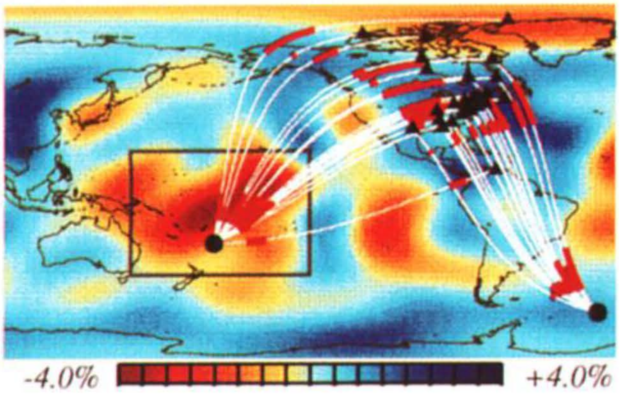

Figure 1. Great circle ray paths (white) and SP_dKS P_{diff} segments (red lines) for the 8/12/67 Fiji Is. and 6/17/67 Sandwich Is. events (black circles), recorded at North American stations (black triangles). δV_S perturbations are shown for the base of the mantle; red (blue) colors signify slower (faster) than average structure (model SKS12WM13, Liu and Dziewonski, 1994). The boxed region corresponds to study area of cover figure.

can reproduce the observed amplitudes. However, the possibility of D″ anisotropy (Vinnik et al., 1989; Lay and Young, 1991; Maupin, 1994; and Vinnik et al., 1995) complicates this issue and requires further investigation.

SKKS-SKS and SP_dKS-SKS data with paths through the tomographically-derived slow region in the SW Pacific are very anomalous. SKKS-SKS anomalies can be explained by reduced V_S in the lower 1/3 of the mantle (Schweitzer, 1990; and Garnero and Helmberger, 1995b) as in SKS12WM13; SP_dKS-SKS anomalies are explained by a variable thickness (5-40 km) boundary layer with V_P reductions of up to 10%. Circum- and northern-Pacific data show little or no SP_dKS-SKS or SKKS-SKS anomalies, suggesting 'normal' or PREM-like lower mantle V_S and basal V_P. This agrees with high resolution analyses of the north Pacific CMB region (Vidale and Benz, 1992), and a CMB region slightly to the west of the Carribean (Mori and Helmberger, 1995). Neither the SKKS-SKS nor SP_dKS-SKS

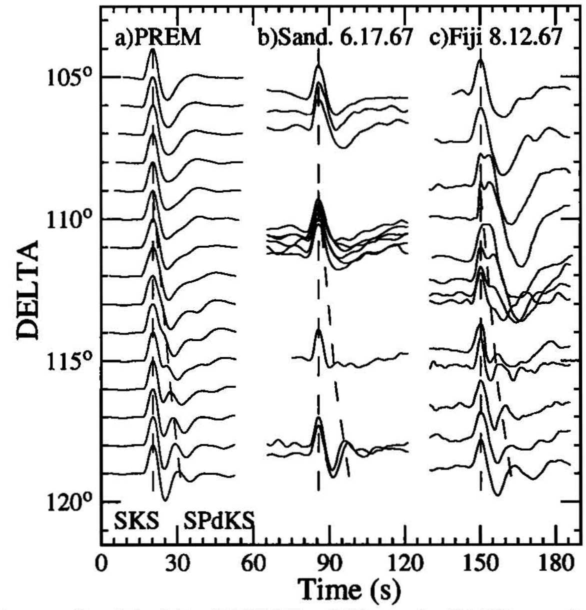

Figure 2. (a) LP WWSSN SKS and SP_dKS synthetic waveforms generated by the generalized ray method (see Helmberger, 1983) for PREM. (b) Sandwich Is. data (6/17/67) and PREM predictions (dashed lines). (c) Fiji Is. data (8/12/67) and PREM predictions (dashed lines). All records and data have been lined up in time and amplitude to the SKS peak.

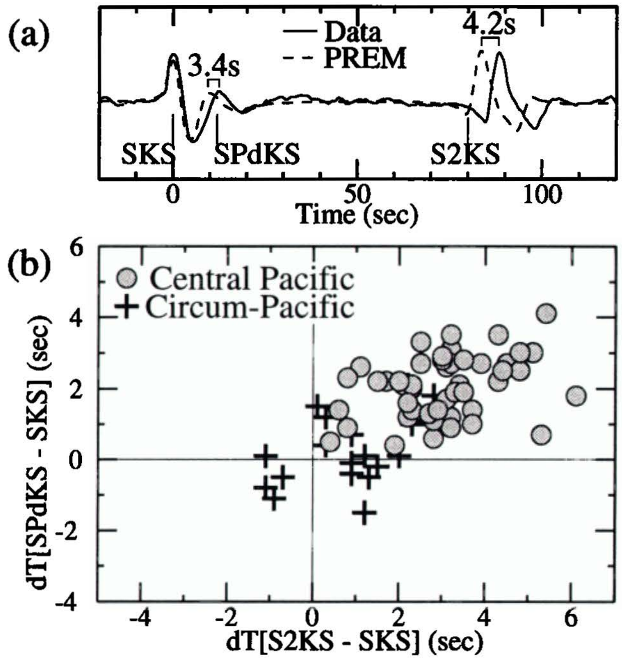

Figure 3. (a) Fiji 1/24/67 LP WWSSN recording at 118.3° (solid) and the corresponding PREM prediction (dashed). Both SP_dKS and SKKS are delayed with respect to SKS. (b) Summary plot of all central- and circum-Pacific data where SP_dKS-SKS and SKKS-SKS residual times could be calculated on single records, as in (a). All residuals are relative to PREM, with a maximum picking error of < ± 0.4 s. The cross-correlation method was used to calculate the difference times. A $\pi/2$ phase shift correction of SKKS relative to SKS was made prior to correlations (Choy and Richards, 1975).

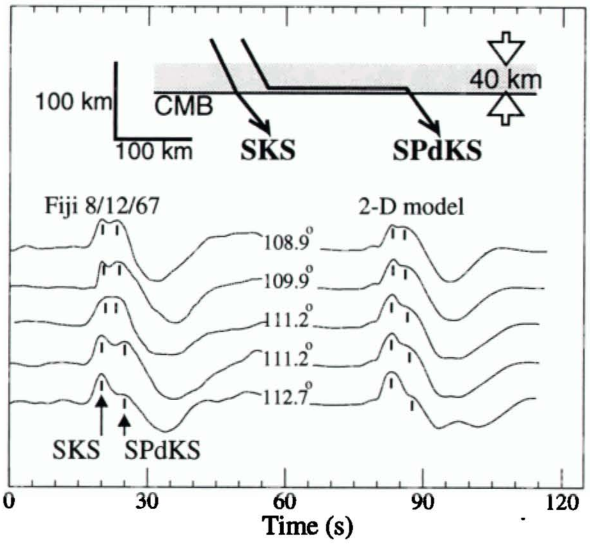

Figure 4. (top) Ray paths of SKS and SPdKS at 110°. (left panel) Fiji 8/12/67 LP SKS and SP_dKS observations. (right panel) Synthetics for a model having a source-side 40 km thick 10% slow CMB boundary layer, with receiver-side CMB in absence of the basal layer. Distances given in middle column.

data have sensitivity to discontinuity structure at the top of D″ (e.g., Lay and Helmberger, 1983), so we cannot relate our results to circum- and central Pacific D″ discontinuity structures (see Nataf and Houard, 1993, for summary map).

LP data do not constrain thickness over which the drop in velocity occurs at the top of the slow basal layer. We have chosen to model it as a step decrease. This is supported by the SP P-wave data of Mori and Helmberger (1995), which require the drop to occur over < few km, and also by SP SP$_d$KS data (Helmberger et al., 1995), which are well-modeled with a discontinuous drop in V_P (10% reduction over 40 km).

An alternative modeling scheme for the anomalous SP$_d$KS data would be to fix the low-velocity layer thickness, and vary the percent reduction of V_P. We do not rule out such a scenario, which would basically change the color scale in the cover figure from thickness to V_P reduction. For a constant layer thickness less than 40 km, V_P reductions greater than 10% would be necessary to model the most anomalous data. Data of Mori and Helmberger (1995), however, provide a constraint on thickness from the time differences between the top-side reflection off the low-velocity layer and PcP. It is left for future work to assess if stronger than 10% reductions in thinner layers better explain all of the data.

A thin slow CMB boundary layer could be thermal or chemical in origin. One possibility is a localized concentration of partial melt, whose presence strongly depends on viscosity, thermal structure, and melt connectivity. Temperature dependence of candidate partial melt materials, e.g., magnesiowüstite, needs further investigation for such hypotheses. Or, lower mantle currents feeding regions of broad upwelling may concentrate CMB chemical reaction products (Knittle and Jeanloz, 1989) into a coherent layer (Kellogg and King, 1993).

Conclusions

Lower mantle structure beneath the Pacific produces anomalously delayed SP$_d$KS and SKKS arrivals relative to SKS. Delayed SP$_d$KS are explained by a laterally varying mantle-side CMB boundary layer, having V_P reductions of up to 10% and thickness up to 40 km. This layer underplates large-scale low velocities (2-4%) and is absent, or too thin to be detected, beneath faster-than-average circum-Pacific lower mantle. Possible physical origins for this slow boundary layer include a localized zone of partial melt, or a chemically distinct layer, with its location linked to overlying upwelling motions.

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References

Choy, G.L., Theoretical seismograms of core phases calculated by frequency-dependent full wave theory, and their interpretation, *Geophys. J. Int.*, *51*, 275-312, 1977.

Choy, G.L., and P.G. Richards, Pulse distortion and Hilbert transformation in multiply reflected and refracted body waves, *Bul. Seism. Soc. Am.*, *65*, 55-70, 1975.

Dziewonski, A.M., and D.L. Anderson, Preliminary reference Earth model (PREM), *Phys. Earth Planet. Int.*, *25*, 297-356, 1981.

Garnero, E.J., S.P. Grand and D.V. Helmberger, Low P-velocity at the base of the mantle, *Geophys. Res. Lett.*, *20*, 1843-1846, 1993.

Garnero, E.J., and D.V. Helmberger, On seismic resolution of lateral heterogeneity in the Earth's outermost core, *Phys. Earth Planet. Int.*, *88*, *117-130*, 1995a.

Garnero, E.J., and D.V. Helmberger, A very slow basal layer underlying large-scale low-velocity anomalies in the lower mantle beneath the Pacific: evidence from core phases, *Phys. Earth Planet. Int.*, *91*, 161-176, 1995b.

Helmberger, D.V., E. Garnero, and X.M. Ding, Modeling 2-D structure at the core-mantle boundary, *J. Geophys. Res.*, (submitted), 1995.

Kellogg, L.H., and S.D. King, Effect of mantle plumes on the growth of D" by reaction between the core and mantle, *Geophys. Res. Lett.*, *20*, 379-382, 1993.

Kind, R., and G. Müller, Computations of SV waves in realistic Earth models, *J. Geophys.*, *41*, 149-172, 1975.

Knittle, E. and R. Jeanloz, Simulating the core-mantle boundary: an experimental study of high-pressure reactions between silicates and liquid iron, *Geophys. Res. Lett.*, *16*, 609-612, 1989.

Krüger, F., M. Weber, F. Scherbaum, and J. Schlittenhardt, Evidence for normal and inhomogeneous lowermost mantle and core-mantle boundary structure under the arctic and northern Canada, *Geophys. J. Int.*, (in press), 1995.

Lay, T., and D.V. Helmberger, A lower mantle S-wave triplication and shear velocity structure of D'', *Geophys. J. Int.*, *75*, 799-838, 1983.

Lay, T., and C.J. Young, Analysis of SV waves in the core's penumbra, *Geophys. Res. Lett.*, *18*, 1373-1376, 1991.

Loper, D. and T. Lay, The core-mantle boundary region, *J. Geophys. Res.*, *100*, 6397-6420, 1995.

Liu, X.-F., and A.M. Dziewonski, Lowermost mantle shear wave velocity structure (abstract), Eos Trans. AGU., *75*, 663, 1994.

Maupin, V, On the possibility of anisotropy in the D″ layer as inferred from polarisation of diffracted S-waves, *Phys. Earth Planet. Int.*, *87*, 1-32, 1994.

Mori, J., and D.V. Helmberger, Localized boundary layer below the mid-Pacific velocity anomaly identified from a PcP precursor, *J. Geophys. Res.*, *100* 20,359-20,365, 1995.

Nataf, H.-C., and S. Houard, Seismic discontinuity at the top of D": a world-wide feature?, *Geophys. Res. Lett.*, *20*, 2371-2374, 1993.

Schweitzer, J., Untersuchung zur Geschwindigkeitsstruktur im unteren Erdmantel und im Bereich der Kern-Mantel-Grenze unterhalb des Pazifiks mit Scherwellen, Phd. thesis, Frankurt Univ., 134 pp., 1990.

Silver, P., and C.R. Bina, An anomaly in the amplitude ratio of SKKS/SKS in the range 100-108° from portable teleseismic data, *Geophys. Res. Lett.*, *20*, 1135-1138, 1993.

Souriau, A., and G. Poupinet, Lateral variations in P velocity and attenuation in the D″ layer, from diffracted P waves, *Phys. Earth Planet. Int.*, *84*, 227-234, 1994.

Stevenson, D.J., Limits on lateral density and velocity variations in the Earth's outer core, *Geophys. J. Int.*, *88*, 311-319, 1987.

Su, W.-J., R.L. Woodward, and A.M. Dziewonski, Degree 12 model of shear velocity heterogeneity in the mantle, *J. Geophys. Res.*, *99*, 6945-6980, 1994.

Vidale, J., and H.M. Benz. A sharp and flat section of the core-mantle boundary, *Nature*, *359*, 627-629, 1992.

Vinnik, L.V., V. Farra, and B. Romanowicz, Observational evidence for diffracted SV in the shadow of the Earth's core, *Geophys. Res. Lett.*, *16*, 519-522, 1989.

Vinnik, L.V., B. Romanowicz, Y. Le Stunff, and L. Makeyeva, Seismic anisotropy of the D″ layer, *Geophys. Res. Lett.*,*22*,1657-1660, 1995.

Wysession, M. E., E. A. Okal, and C. R. Bina, The structure of the core-mantle boundary from diffracted waves, *J. Geophys. Res.*, *97*, 8749-8764, 1992.

Wysession, M. E., L. Bartko, and J. Wilson, Mapping the lowermost mantle using core-reflected shear waves, *J. Geophys. Res.*, *99*, 13,667-13,684, 1994.

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