

# Coexisting shear- and compressional-wave seismic velocity discontinuities beneath the central Pacific

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**Abstract.** Stacking of broadband shear waves ( $S$ ) and short-period compressional waves ( $P$ ) provides compelling evidence for the existence of a localized discontinuous increase in both  $S$  and  $P$  wave velocity 230 km above the core-mantle boundary (CMB) beneath the central Pacific. Modelling indicates a 1.7% increase in  $S$  velocity ( $V_S$ ) and a 0.75% increase in  $P$  velocity ( $V_P$ ). Similar features have been detected intermittently on a global basis, but seldom with  $S$  and  $P$  structure being resolved in the same location. Previous evidence for anisotropy near the CMB beneath the central Pacific suggests that the discontinuity may be related to anisotropic fabrics induced by flow in the thermal boundary layer above the core.

## Introduction

Encompassing the lowermost  $\sim 300$  km of the mantle, the  $D''$  layer is a chemical and thermal boundary layer overlying the liquid outer core. This important boundary layer influences both mantle convection and the core's geodynamo [Loper and Lay, 1995; Lay et al., 1998]. One of the most important observations about the  $D''$  layer is the existence of a laterally varying, discontinuous seismic velocity increase several hundred kilometers above the CMB [Lay and Helmberger, 1983; Wysession et al., 1998]. The primary evidence for this discontinuity is provided by seismic wave triplications beneath the circum-Pacific margins and northern Eurasia regions, which are generally characterized by relatively high seismic velocities and presumed downwellings in the lowermost mantle [Wysession et al., 1998]. Previous efforts to detect a  $D''$   $V_S$  discontinuity in the low seismic velocity deep mantle under the central Pacific have proved ambiguous [Garnero et al., 1988, 1993; Kendall and Shearer, 1994], but there is recent evidence for a  $V_P$  discontinuity [Reasoner and Revenaugh, 1999]. In order to determine the cause of the discontinuity and its relationship to the  $D''$  boundary layer, it is imperative to establish the existence and nature of any  $D''$  discontinuity in seismically slow, upwelling regions such as the central Pacific.

## Data and Method

Using a large dataset of  $S$  waves from Tonga-Fiji earthquakes recorded in western North America, and re-analysis of  $P$  waves for similar events recorded at short-period stations in California, we apply a stacking algorithm to seek evidence for any  $V_S$  or  $V_P$  discontinuities beneath the central Pacific. Simultaneous observation of  $V_P$  and  $V_S$  discontinu-

ities in the same region is rare, as it is uncommon for  $P$  and  $S$  studies to have similar source-receiver geometries or to use the same analysis method [Weber and Davis, 1990; Weber, 1993; Thomas and Weber, 1997; Ding and Helmberger, 1997]. However, joint  $P$  and  $S$  wave studies are vital to understanding the  $D''$  discontinuity as they provide insight into the variability, transition thickness and topography of the discontinuity, and place physical constraints upon possible mechanisms.

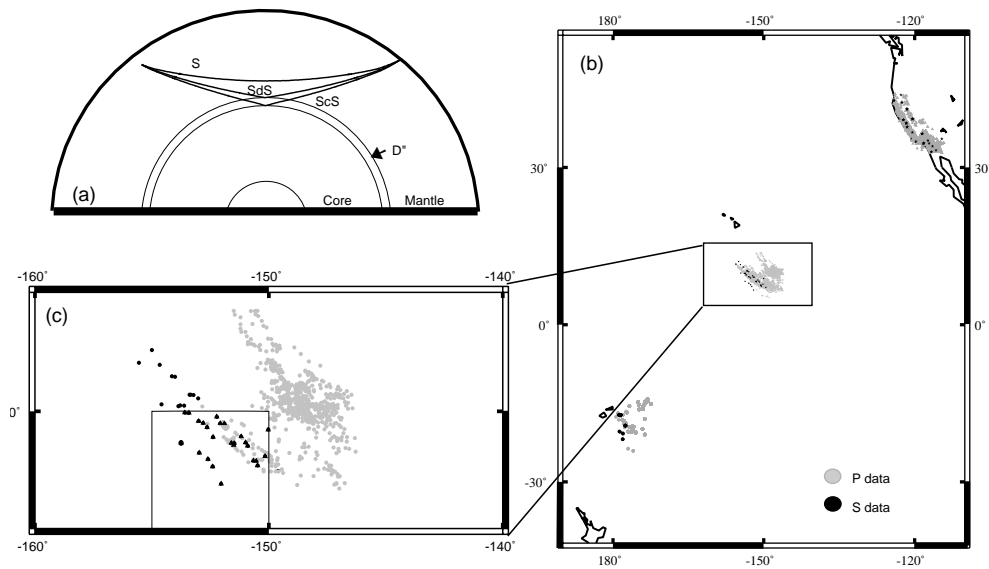
To detect the presence of any  $D''$  shear wave discontinuity, we search between the direct  $S$  and core-reflected  $ScS$  phases for a phase,  $SdS$ , corresponding to reflection from a discontinuity in the lowermost mantle (Figure 1A). In many studies it is possible to identify  $SdS$  phases in individual records and to model their amplitude and timing to estimate the strength and depth of the discontinuity [Wysession et al., 1998]. Our records, however, have high coda levels between  $S$  and  $ScS$ , and we are unable to distinguish a coherent discontinuity arrival in the data (Figure 2). This may suggest that any discontinuity present is weak or varies in depth or lateral extent over the region sampled by our data. Thus, we employ a stacking approach to increase the signal-to-noise ratio of any  $SdS$  arrivals that may be present.

We stack tangential component shearwave records from 21 large earthquakes in the Tonga-Fiji subduction zone recorded by the TERRAScope, BDSN and IRIS networks. Figures 1B, C show the locations of the earthquakes and stations as well as the lower mantle region southeast of Hawaii sampled by any  $SdS$  or  $PdP$  reflections. The seismograms were culled from a larger dataset based on their clean, impulsive arrivals in the distance range 73-85 degrees, the optimal range for resolving  $SdS$ . Processing of the data included removal of the instrument response, deconvolution with a generalized source time function, and filtering between 5-100 seconds. The generalized source time functions were obtained by aligning the traces for each event on the direct  $S$  phase, normalizing the amplitudes, and summing.

We use a double-array algorithm [Yamada and Nakanishi, 1996; Revenaugh and Meyer, 1997] that stacks traces for multiple events ( $i$ ) and multiple stations ( $j$ ) according to the expected moveout of any  $SdS$  arrivals for an assumed reflector at depth  $d$ . The stack is created by summation for values of target depth  $d$ :

$$R(d) = \sum_i \sum_j S_{ij} (\tau_o + \tau_{ij}^{SdS}(d) - \tau_{ij}^{ScS}) \quad (1)$$

where  $S_{ij}$  is the  $j$ th recording of event  $i$ ,  $\tau_o$  is the arrival time of  $ScS$  on the aligned traces,  $\tau_{ij}^{SdS}$  is the predicted arrival time of  $SdS$  and  $\tau_{ij}^{ScS}$  is the calculated arrival time of  $ScS$ . The double array stacking algorithm calculates the travel-times of arrivals from reflectors placed between 2500 to 3030 km depth at 5 km intervals. Traveltimes for depths below

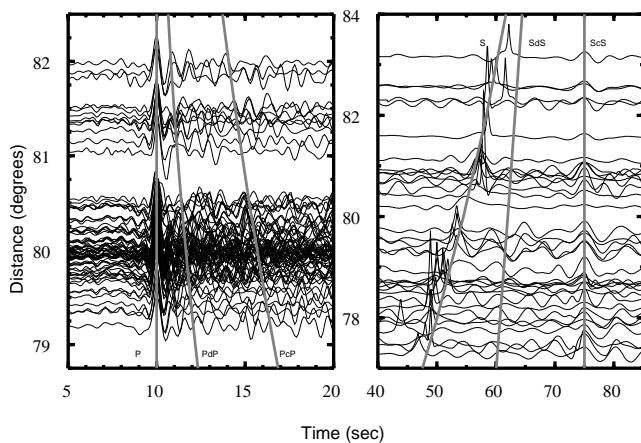


**Figure 1.** (a) Raypath diagram showing direct  $S$ , reflected  $ScS$  and  $SdS$  phases. Similar paths exist for analogous  $P$  phases ( $P$ ,  $PcP$ ,  $PdP$ ). (b) Mercator map projection showing geometry between earthquakes in the Tonga-Fiji subduction zone and receivers in western North America. The circles represent the reflection points of the  $PdP$  (grey) and  $SdS$  (black) raypaths at a depth of 2661 km. (c) Magnified region showing the location of  $SdS$  bouncepoints relative to  $PdP$ . The inset box represents the area for which a subset of  $P$  data are stacked to compare with the  $S$  stack.

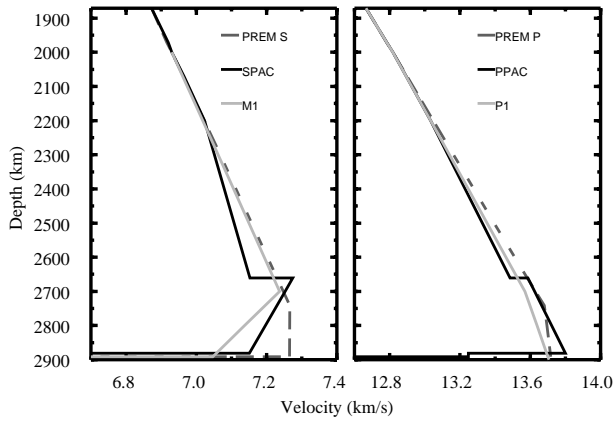
the CMB are obtained by continuing lower mantle velocity gradients below the CMB. The traces in each event are stacked along a move-out curve relative to the  $ScS$  phase. The stack excludes seismograms whose  $SdS$  arrival time is within 8 seconds of the  $S$  peak to avoid contamination by direct  $S$ . 95% confidence intervals are derived from bootstrap resampling of the traces. We align the traces on  $ScS$  as  $ScS$  probably encounters similar deep heterogeneity as the  $SdS$  phase with the exception of boundary layer structure below any discontinuity. To provide reference traveltimes appropriate for the boundary layer in this region, we use model M1, a shear model derived for the region to the northeast of that sampled by our dataset [Ritsema *et al.*, 1997] (Figure 3A). Model M1 has a strong negative velocity gradient in

$D''$  as well as low average shear velocities in the lowermost 200 km of the mantle. The resulting data stacks for the lowermost 350 km of the mantle show a significant peak at approximately 230 km above the CMB (Figure 4A), with no other peak emerging within  $D''$ . The  $SdS$  peak can be modelled by an  $S$  wave discontinuity as shown below.

Our data coverage allows us to compare this new  $S$  wave finding to recent results for  $D''$   $V_P$  structure in this region [Reasoner and Revenaugh, 1999]. A small ( $\leq 0.5\%$ )  $V_P$  discontinuity at 2701 km depth has been proposed in approximately the same region sampled by the shear data based on a similar stacking methodology. Figures 1B,C shows the relative positions of possible  $PdP$  (analogous to  $SdS$ ) reflection points for Tonga-Fiji events recorded in California assuming a reflector 230 km above the CMB. We reexamined the  $P$  wave data, restacking them with traveltimes computed for a reference  $V_P$  model P1, scaled from model M1 using a Poisson's ratio of 0.301 at a depth of 2700 km (Figure 3B). The velocity gradient in P1 below 2700 km was tuned to produce a  $PcP$  stack peak at the CMB. To more directly compare the two datasets, we confined the  $P$  wave stack to include the records that overlap the shear data (Figure 1C). Due to the large quantity of available  $P$  data, this region was further subdivided into  $2.5^\circ$  by  $2.5^\circ$  bins to suppress small scale heterogeneity that can affect the short-period signals. To account for lateral heterogeneity in the depth of the discontinuity, stacks for individual bouncepoint bins were aligned upon the peak amplitude, weighted by the number of traces in each bin, and summed [Revenaugh and Meyer, 1997]. The alignment of the binned regions peaks the amplitude of the discontinuity peak but does not affect the mean depth. The stack amplitudes are normalized to  $P$  because  $PcP$  is too small to use as a reliable reference phase. A  $PdP$  arrival is identified at 230 km above the CMB (Figure 4C). The asymmetry of the  $PcP$  phase (Figure 4B) is evidence for an ultra-low velocity layer (ULVZ) located at the CMB [Garnero *et al.*, 1998].



**Figure 2.** Data profiles of deconvolved and filtered  $P$  (left) and  $S$  (right) seismograms. The traces are aligned on direct  $P$  and  $ScS$  respectively (vertical lines). Other curves indicate the  $S$  phase and predicted  $PdP$ ,  $PcP$ , and  $SdS$  arrival times for the final discontinuity models, PPAC and SPAC (Figure 3).



**Figure 3.** (a) Shear velocity models PREM (dashed grey) *Dziewonski and Anderson, 1981*, M1 (solid light grey) and the preferred model, SPAC (black), with a 1.7% shear discontinuity at 2661 km depth and a 10 km thick ULVZ zone with a 12% velocity reduction. (b) Compressional velocity models PREM (dashed grey), P1 (light grey), and PPAC (black), with 0.75% increase at 2661 km depth and a 10 km thick ULVZ layer with a 4% velocity reduction.

### Results and Discussion

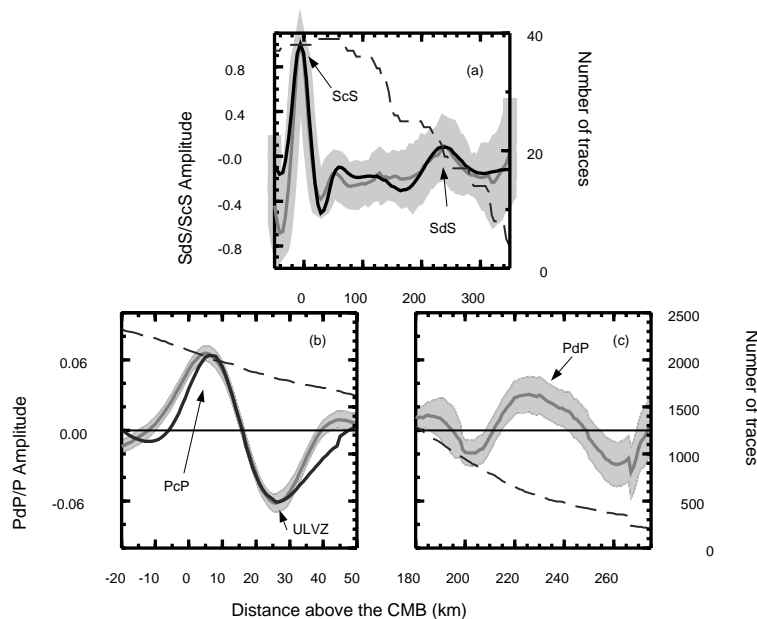
We do not observe clear discontinuity arrivals in the individual seismograms, so to constrain the velocity increase, we model the shear data stack with reflectivity synthetics. Our best fit velocity model is a variation of model M1 with a  $V_S$  increase of 1.7% at 2661 km depth (Figure 3A). Using a modelling approach similar to that of the shearwave study, we find that a 0.75% increase in  $V_P$  at 2661 km depth

best models the *PdP* discontinuity arrival (Figure 4C). The asymmetry of *PcP* due to the ULVZ is best fit with a 10 km thick layer with a 4% drop in  $V_P$  and 12% reduction in  $V_S$  (Figure 4B).

Although there is degeneracy between the magnitude of the discontinuity and the velocity gradients above and below the discontinuity, we place constraints upon the best fit velocity model by comparing model predicted residual traveltimes to previous observations of *ScS-S* and *S<sub>diff</sub>-SKS* differential travel-time residuals [*Ritsema et al., 1997; Russell et al., 1998, 1999*]. From these constraints, we estimate an uncertainty of  $\pm 30$  km in depth and  $\pm 0.4\%$  in the velocity increase of the shear discontinuity.

This evidence for the presence of both *S* and *P* velocity increases beneath the central Pacific provides clues to the origin of the discontinuity. Previous explanations of this feature have included thermal, chemical, or mineral phase change origins. Recent high resolution tomography results suggest that slab penetration into the lower mantle is possible [*Grand et al., 1997*] and under certain conditions, a subducted slab might create a thermal anomaly corresponding to a sharp increase in seismic velocity. However this scenario is not plausible for our observed  $V_P$  and  $V_S$  discontinuity as reconstructions of ancient subduction zones do not predict the existence of a subducted slab in the central Pacific [*Lithgow-Bertelloni and Richards, 1998*].

Another hypothesis is a global phase change in a lower mantle mineral [*Nataf and Houard, 1993; Sidorin et al., 1999*], similar to mineral phase changes associated with the upper mantle discontinuities. Recent theoretical calculations by Sidorin et al. [*1999b*] of a global shear discontinuity produced by a conjectured phase change predict a small dis-



**Figure 4.** (a) *SdS* stack, for traces aligned upon the *ScS* phase. The left vertical axis shows stack amplitude relative to *ScS* (heavy grey line) versus height above the CMB and the right vertical axis gives the number of traces contributing to the stack at each depth (dashed line). *SdS* is modelled by SPAC (thin black line) with a 1.7%  $V_S$  increase 230 km above the CMB. The shaded region denotes the 95% confidence level. (b) A similar figure showing the *PcP* stack with amplitude relative to direct *P* (heavy grey line). Asymmetry of *PcP* is due to an ultra-low velocity zone modelled by PPAC to be 10 km thick, with a 4% drop in *P* velocity and a 12% drop in *S* velocity (thin black line). (c) *PdP* stack with amplitude relative to direct *P* (heavy grey line). *PdP* can be modelled by PPAC with a 0.75% increase in *P* velocity at 2661 km depth (thin black line). *PcP* and *PdP* are shown in separate depth intervals because the binning process searches over a limited depth range for stack peaks to align. The peaks shown are the only significant arrivals in the data stack.

continuity beneath the central Pacific with an approximate elevation of 100 km above the CMB. While the strength of the discontinuity arrival in the data is well matched, our stacking results preclude the presence of the discontinuity so close to the CMB. Setting aside the disagreement in depth, the major difficulty with this hypothesis is the lack of experimental evidence for a phase change in any of the major mineral constituents of the lower mantle, such as perovskite or magnesiowüstite [Stixrude and Bukowski, 1992].

The simultaneous observation of a lower mantle discontinuity and anisotropic fabric detected through shear-wave splitting measurements beneath the central Pacific supports another scenario in which the two features are related [Russell et al., 1998, 1999]. After correction for upper-mantle anisotropy, splitting measurements yielded estimates of 2-3% shear-wave anisotropy near the CMB. Previous studies investigating lower mantle structure with core-grazing *S* waves beneath Alaska and the Indian Ocean also show evidence for a discontinuity coexistent with the onset of anisotropy above the CMB [Matzel et al., 1996; Ritsema, 2000]. In this hypothesis, a global or intermittent anisotropic layer created by flow-aligned heterogeneities or lattice-preferred orientation (LPO) of lower mantle minerals could produce the discontinuity arrivals. The lack of discontinuity arrivals seen in some regions [Wyssession et al., 1998] might be caused by either disruption of the anisotropic fabric or unfavorable azimuthal ray sampling. When a simple anisotropic model simulating transverse isotropy is included in the modelling of the data stacks, we find that we can fit the *PdP* arrival with a 1.7% decrease in  $V_{SV}$  and a 0.5% increase in  $V_P$ . These results highlight the need for future work in both mapping the global characteristics of the discontinuity and in correlating *P* and *S* observations. This work, in conjunction with results from mineral physics and mantle dynamics, should seek to clarify the true nature of the discontinuity thereby increasing our understanding of the base of the Earth's mantle.

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## References

- Ding, X. and D.V. Helmberger, Modelling *D''* structure beneath Central America with broadband seismic data, *Phys. Earth Planet. Inter.*, 101, 245-270, 1997.
- Dziewonski, A., and D.L. Anderson, Preliminary reference Earth model, *Phys. Earth Planet. Inter.*, 25, 297-356, 1981.
- Garnero, E.J., D.V. Helmberger, and G. Engen, Lateral variations near the core-mantle boundary, *Geophys. Res. Lett.*, 15, 609-612, 1988.
- Garnero, E.J., D.V. Helmberger, and S. Grand, Preliminary evidence for a lower mantle shear wave velocity discontinuity beneath the Central Pacific, *Phys. Earth Planet. Inter.*, 79, 335-347, 1993.
- Garnero, E.J., J. Revenaugh, Q. Williams, T. Lay, and L. Kellogg, Ultralow velocity zone at the core-mantle boundary, in *The Core Mantle Boundary*, edited by M. Gurnis, B. Buffett, E. Knittle, and M. Wyssession, pp. 319-334, American Geophysical Union, Washington D.C., 1998.
- Grand, S.P., R.D. van der Hilst, and S. Widiyantoro, Global seismic tomography; a snapshot of convection in the Earth, *GSA Today*, 7, 1-7, 1997.
- Kendall, J.M., and P.M. Shearer, Lateral variations in *D''* thickness from long-period shear-wave data, *J. Geophys. Res.*, 99, 11575-11590, 1994.
- Lay, T., and D.V. Helmberger, A lower mantle S-wave triplication and the shear velocity structure of *D''*, *Geophys. J. R. Astron. Soc.*, 75, 799-837, 1983.
- Lay, T., Q. Williams, and E.J. Garnero, The core-mantle boundary layer and deep Earth dynamics, *Nature*, 392, 461-468, 1998.
- Lithgow-Bertelloni, C., and M.A. Richards, The dynamics of Cenozoic and Mesozoic plate motions, *Rev. Geophys.*, 36, 27-78, 1998.
- Loper, D.E., and T. Lay, The core-mantle boundary region, *J. Geophys. Res.*, 100, 6397-6420, 1995.
- Matzel, E., M.K. Sen, and S.P. Grand, Evidence for anisotropy in the deep mantle beneath Alaska, *Geophys. Res. Lett.*, 23, 2417-2420, 1996.
- Nataf, H.-C., and S. Houard, Seismic discontinuity at the top of *D''*; a world-wide feature?, *Geophys. Res. Lett.*, 20, 2371-2374, 1993.
- Reasoner, C., and J. Revenaugh, Short-period P wave constraints on *D''* reflectivity, *J. Geophys. Res.*, 104, 955-961, 1999.
- Revenaugh, J., and R. Meyer, Seismic evidence partial melt within a possibly ubiquitous low-velocity layer at the base of the mantle, *Science*, 277, 670-673, 1997.
- Ritsema, J., E.J. Garnero, and T. Lay, A strongly negative shear velocity gradient and lateral variability in the lowermost mantle beneath the Pacific, *J. Geophys. Res.*, 102, 20395-20411, 1997.
- Ritsema, J., Evidence for shear velocity anisotropy in the lowermost mantle beneath the Indian Ocean, *Geophys. Res. Lett.*, 27, 1041-1044, 2000.
- Russell, S.A., T. Lay, and E.J. Garnero, Seismic evidence for small-scale dynamics in the lowermost mantle at the root of the Hawaiian hotspot, *Nature*, 396, 255-258, 1998.
- Russell, S.A., T. Lay, and E.J. Garnero, Small-scale lateral shear velocity and anisotropy heterogeneity near the core-mantle boundary beneath the Central Pacific imaged using broadband ScS waves, *J. Geophys. Res.*, 104, 13183-13200, 1999.
- Sidorin, I., M. Gurnis, and D.V. Helmberger, Dynamics of a phase change at the base of the mantle consistent with seismological observations, *J. Geophys. Res.*, 104, 15005-15023, 1999a.
- Sidorin, I., M. Gurnis, and D.V. Helmberger, Evidence for a ubiquitous seismic discontinuity at the base of the mantle, *Science*, 286, 1326-1331, 1999b.
- Stixrude, L., and M. Bukowski, Stability of (Mg, Fe)SiO (sub 3) perovskite and the structure of the lowermost mantle, *Geophys. Res. Lett.*, 19, 1057-1060, 1992.
- Thomas, C., and M. Weber, P velocity heterogeneities in the lower mantle determined with the German Regional Seismic Network; improvement of previous models and results of 2D modelling, *Phys. Earth Planet. Inter.*, 101, 105-117, 1997.
- Weber, M., and J.P. Davis, Evidence of a laterally variable lower mantle structure from P- and S-waves, *Geo. J. Int.*, 102, 231-255, 1990.
- Weber, M., P- and S-wave reflections from anomalies in the lowermost mantle, *Geo. J. Int.*, 115, 183-210, 1993.
- Wyssession, M.E., T. Lay, J. Revenaugh, Q. Williams, E.J. Garnero, R. Jeanloz, and L.H. Kellogg, The *D''* discontinuity and its implications, in *The Core Mantle Boundary*, edited by M. Gurnis, B. Buffett, E. Knittle, and M. Wyssession, pp. 273-297, American Geophysical Union, Washington D.C., 1998.
- Yamada, A., and I. Nakanishi, Detection of P-wave reflector in *D'* beneath the south-western Pacific using double-array stacking, *Geophys. Res. Lett.*, 23, 1553-1556, 1996.

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