High-resolution investigation of shear wave anisotropy in D″ beneath the Cocos Plate

J. M. Rokosky and T. Lay

Institute of Geophysics and Planetary Physics and Earth Sciences Department, University of California, Santa Cruz, California, USA

E. J. Garnero

Department of Geological Sciences, Arizona State University, Tempe, Arizona, USA

S. A. Russell

Weston Geophysical Corporation, Lexington, Massachusetts, USA

Received 22 October 2003; revised 19 February 2004; accepted 9 March 2004; published 3 April 2004.

[1] Broadband shear wave signals from 16 deep South American earthquakes are used in a high-resolution analysis of lowermost mantle structure beneath the Cocos Plate. Shear wave splitting of 162 ScS phases is generally compatible with vertical transverse isotropy (VTI) in the D″ region, with little path length or spatial dependence across the 200 $\times$ 800 km^2 area sampled. Assuming a 250 km thick D″ layer, the VTI has an average value of 0.63%. ScS-S differential travel time anomalies for the same data indicate a lateral gradient in positive D″ transverse component velocity perturbations, increasing northward. S-wave triplication arrivals from a shear velocity discontinuity at the top of D″ show splitting similar to the ScS phases, but with smaller magnitude. Vertical resolution remains limited, but the data are consistent with VTI material being concentrated in just the upper portion or at the top and bottom of D″. *INDEX TERMS:* 7203 Seismology: Body wave propagation; 7207 Seismology: Core and mantle; 8120 Tectonophysics: Dynamics of lithosphere and mantle—general; 8124 Tectonophysics: Earth's interior—composition and state (1212). **Citation:** Rokosky, J. M., T. Lay, E. J. Garnero, and S. A. Russell (2004), High-resolution investigation of shear wave anisotropy in D″ beneath the Cocos Plate, *Geophys. Res. Lett.*, *31*, L07605, doi:10.1029/2003GL018902.

1. Introduction

[2] The several hundred kilometer thick D″ region above the core-mantle boundary (CMB) appears to be a zone of intense thermal and chemical heterogeneity [e.g., *Lay et al.*, 1998]. Seismological studies in the past thirty years have revealed significant complexity of this lowermost mantle region, based on the existence of acute seismic velocity heterogeneity, seismic velocity discontinuities at varying depths, and shear wave anisotropy [e.g., *Garnero*, 2000].

[3] Studies of the deep mantle beneath Central America suggest that it is a region of particularly high shear velocities with a 2–3% velocity discontinuity 200–300 km above the CMB [e.g., *Kendall and Nangini*, 1996; *Ding and Helmberger*, 1997; *Grand*, 2002]. Previous work provides ample evidence for shear wave splitting consistent with vertical transverse isotropy (VTI) [e.g., *Kendall and Silver*, 1998]. *Garnero and Lay* [2003] suggest that D″ anisotropy beneath Central America is relatively uniform over a lateral extent of 1500 km, but they do not preclude the existence of small-scale variations. High-resolution investigations of localized regions are needed to resolve the scale on which anisotropy varies in D″, which is crucial for uncovering the mechanism(s) by which deep mantle anisotropy arises. We explore the nature of ScS splitting in the lower mantle beneath a localized region under the Cocos Plate, assessing the fine scale spatial variations and depth extent of D″ anisotropy and its relationships to volumetric velocity heterogeneity.

2. Data and Methods

[4] Our data include records from 16 intermediate and deep focus South American events recorded by 49 broadband stations in California (see full details in the auxiliary material[1]). Epicentral distances for the recordings range between 60–86° and ScS paths sample the D″ region below the Cocos Plate, just west of Central America (1–18°N; 267–277°E). Broadband seismograms are deconvolved by the instrument responses and resulting band-pass filtered displacement records are corrected for estimates of near receiver lithospheric anisotropy [*Polet and Kanamori*, 2002]. The receiver corrections are made using lithospheric anisotropy models primarily based on SKS, which has very similar incidence angles beneath the stations as the ScS phases in our data. A small (0.24 s) shift is made for the CMB reflection coefficient advance of ScSV; this varies slowly with distance, but precise correction requires knowledge of the velocity gradients at the CMB. For 227 traces in which impulsive ScS arrivals can be identified for both radial and transverse components, splitting is assessed by comparing the arrival time of the ScS peak on each component (Figure 1). The onset of ScS and S phases is often ambiguous in our data, but the wave shapes are generally simple and impulsive. We observe very little coupling between the ScSH and ScSV arrivals, enabling a simple measure of polarization anomaly. There is no sig-

[1] Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2003GL018902.

0094-8276/04/2003GL018902$05.00

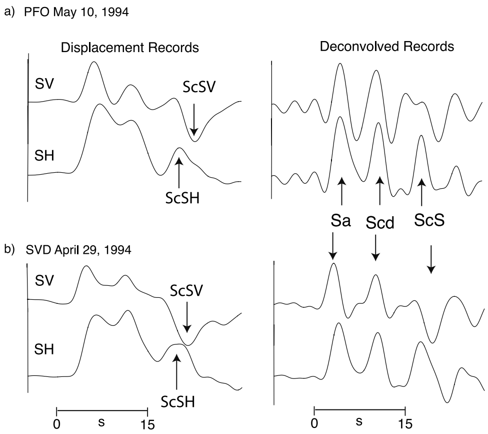

Figure 1. Slightly filtered ground displacement recordings (left) and corresponding source-wavelet-deconvolved traces (right) for two events in the data set. The delays of ScSV are readily apparent in the displacement records, but deconvolution improves the time resolution of arrivals as well as isolation of the Scd phase between S(ab) and ScS.

nificant frequency content shift between S and ScS that would warrant an attenuation dispersion correction.

[5] Average event source wavelets, obtained by stacking aligned transverse component S and ScS arrivals of a given event, are deconvolved from the SH and SV waveforms in order to equalize signals between events and to improve temporal resolution of arrivals. Transverse components are used to estimate the source time functions due to their relatively simple propagation effects. Deconvolution tends to impart high-frequency noise to traces, so a low-pass butterworth filter with a corner at 0.3 Hz is applied to the deconvolved records. New measurements of ScS splitting are made for the deconvolved records using the same procedure employed for raw traces. The 0.3 Hz filter generally provided clean signals, however, to test for sensitivity to the filter, we also filter the deconvolved traces separately with a 0.2 Hz low-pass butterworth filter corner and re-measure splitting for these traces. Records are assigned overall quality ratings based on the compatibility between all three splitting measures. We consider a range of ±0.5 s between the three measures acceptable. In all, we retain 162 splitting measurements for further use. The splitting measurements from 0.3 Hz deconvolutions are shown in Figure 2.

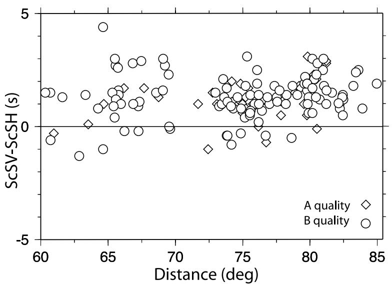

Figure 2. dt(ScSV-ScSH) differential arrival time measurements from 0.3 Hz filtered deconvolved traces, plotted versus epicentral distance. Positive values indicate delayed ScSV arrivals.

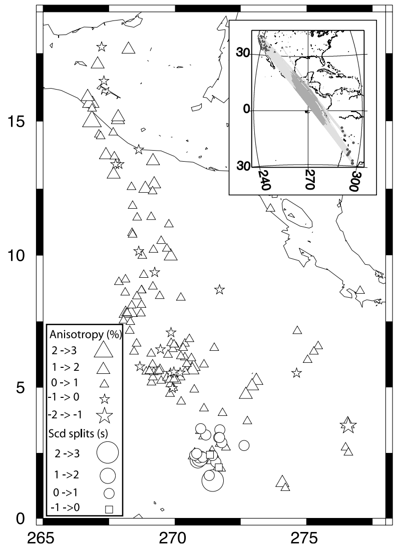

Figure 3. A map showing the strength of shear wave anisotropy (%) estimated from ScS splitting measurements made from 0.3 Hz filtered deconvolved traces, adjusted for relative path lengths within a 250 km thick D'' layer and Scd splitting measurements (in seconds). The data are plotted at CMB reflection points for the ScS arrivals. Inset: Map showing events and stations utilized in this study, with corresponding ray paths through PREM.

[6] To account for path length variations within D'', we use ScS path lengths computed for a 250 km thick D'' layer to estimate average percent anisotropy (Figure 3). This assumes uniform anisotropy throughout the layer, which we ultimately do not favor, but allows us to compare results directly with previous work by *Garnero and Lay* [2003].

[7] To assess any relationship between velocity structure and anisotropy in D'' we calculate differential travel times for our data. For both raw and deconvolved (0.3 Hz filtered) transverse component records, S and ScS peaks are identified and differential travel times (ScS-S) calculated. Cross-correlation is not used because the deconvolved spike-trains provide clear peak-to-peak measurements. Predicted ScS-S differential times for reference model PREM at 1 Hz are subtracted from these values to yield residuals dt(ScS-S). We further correct these residuals for a mantle shear wave tomography model [*Grand*, 2002] down to a depth of 250 km above the CMB. We use these values and ScS path lengths through D'' to calculate estimates of shear wave velocity heterogeneity in D'' (Figure 4). Two other aspherical mantle models were used to make corrections, but the results (presented in auxiliary material) do not change significantly. Since our ScS data are close to grazing the CMB, these corrected differential times characterize the horizontally propagating S velocity in D'', which will correspond to the fast polarization in a VTI medium.

[8] In order to constrain the depth extent of the anisotropic layer, we identify shear wave triplication arrivals in our data set. Deconvolved records are scanned for evidence of an arrival between S and ScS compatible with a reflection (Scd) from a rapid shear velocity increase at the top of D''. Records at distances for which SKS arrivals could interfere

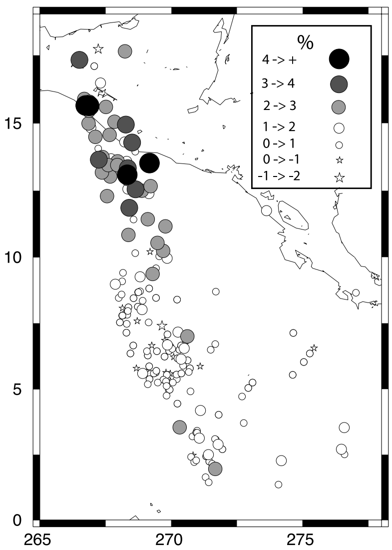

Figure 4. A map showing the shear wave velocity heterogeneity estimates (%) for 0.3 Hz filtered deconvolved traces corrected for aspherical heterogeneity in the model of *Grand* [2002] down to 250 km above CMB. The data are plotted at CMB reflection points for the ScS arrivals. Positive values denote faster SH velocities than in model PREM.

with any discontinuity arrivals are discarded, as are records with complex coda between S and ScS. For the 19 records in which a clear discontinuity arrival is identified on both transverse and radial traces, we calculate relative arrival times of the Scd peaks to assess any connection between this discontinuity and the observed ScS splitting.

3. Results

[9] Splitting measurements for deconvolved traces range between −3.2 s (ScSV arriving prior to ScSH) and +4.4 s (ScSV delayed relative to ScSH) across the region, with an average value of +1.2 s (Figure 2). In most cases ScSV is delayed relative to ScSH. As the path length of ScS in D″ increases by 30–40% in this distance range, we would expect a thick, uniform anisotropic D″ layer to produce splitting that grows in magnitude with increasing distance. While the scatter is high, there is no apparent trend with epicentral distance, which suggests that the anisotropic region that these data sample may be relatively thin or laterally variable.

[10] Estimates of anisotropy within a 250 km thick D″ layer range between −1.7% and +2.8%, with an average value of +0.63%. A positive percent anisotropy denotes SV arriving after SH. The spatial distribution in estimated anisotropy is shown in Figure 3. In general, there is no clear pattern in the distribution of ScS splitting across the field of study, suggesting homogeneity at this scale.

[11] The values of dt(ScS-S) range from +3.0 s to −6.57 s, with an average value of −1.7 s, compatible with a regionally high-velocity D″. These values, converted to percent velocity anomaly over the paths in a 250 km thick D″ layer, are shown in Figure 4. Estimates of shear velocity perturbation range between −1.48% (slower than PREM) and +4.68% (faster than PREM), with an average value of +1.03%. Velocity anomalies increase northward by a percent or two, an observation that is consistent with previous work in the region [*Grand*, 2002; *Garnero and Lay*, 2003]. There is no clear corresponding northward gradient for the ScS splitting observations (Figure 3).

[12] While a strong spatial correlation is not apparent, there is a weak overall correlation between velocity heterogeneity and anisotropy observed in the data (Figure 5). Stronger velocity anomalies tend to have larger splitting, but the scatter obscures any simple spatial pattern and weakens the correlation. The travel time measurements are for the fast polarization (ScSH) grazing a VTI medium, so the sense of correlation is as expected, but the important point is that splitting increases with volumetric SH velocity as well.

[13] We find clear evidence of Scd phases in 19 records (see examples in Figure 1) with most having some splitting. Fourteen show Scd arriving earlier on the transverse record, 3 show no splitting between ScdH and ScdV arrivals and 2 show an earlier arrival of the phase on the SV record, with all of the observations being in the southern portion of our corridor (Figure 3). Scd splitting measurements range between −0.2 and +1.2 s. Scd phases in our distance range sample the uppermost portion of the D″ region below the discontinuity about 250 km above the CMB. Thus, if the anisotropic region giving rise to the ScS splitting extends downward from this discontinuity we would expect to see Scd splits similar to splitting of ScS phases, but with smaller magnitudes. We compare Scd and ScS splits for the 12 records in which clear measures were obtained for both phases. Although there is no systematic trend between the two, the Scd splits are smaller than ScS splits in all but one case, suggesting that this is a possible scenario. Additional observations of Scd splitting will be needed for qualitative modeling of the depth distribution of anisotropy.

4. Discussion and Conclusion

[14] The average value of estimated anisotropy for this work (0.6%) is consistent with previous work on a larger scale in the region. *Garnero and Lay* [2003] find average anisotropy of 0.5–1% over a large region, encompassing our study area. Stronger anisotropy may be present if it is concentrated in a layer less than 250 km thick. We also find scatter in anisotropy measurements comparable to that found by *Garnero and Lay* [2003] on a larger scale. This similarity in scatter even at higher spatial resolution is

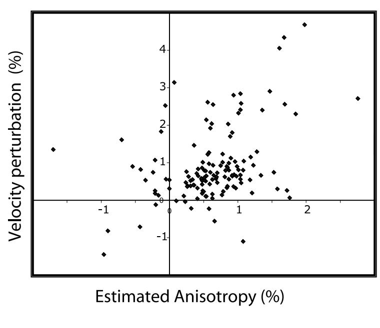

Figure 5. Correlation between estimates of shear wave anisotropy and shear wave velocity heterogeneity from records for which both ScS splitting and differential time measurements were obtained.

intriguing and suggests that variations in anisotropy may exist at scales smaller than can be resolved even with our level of sampling (well below Fresnel zone resolution). Alternatively, there may be noise processes, particularly associated with the correction for upper mantle anisotropy that are not well constrained at present. As in previous work, we note that the lithospheric anisotropy corrections do not always result in a linear polarization of all incoming S phases.

[15] Our measurement procedure assumes decoupling of SV and SH, which is consistent with VTI for grazing paths, and VTI has been proposed for adjacent regions of D″ [e.g., *Kendall and Silver*, 1998]. However, some data under the Caribbean do show coupling between SV and SH, possibly consistent with slight tilting of a hexagonal symmetry axis from the vertical [*Garnero and Lay*, 2003]. Careful inspection of our highest quality observations indicate clean offset of impulsive single arrivals on the SV and SH components. Observations where the ScS pulses involve several peaks or less stable waveforms may in some cases be consistent with more complex splitting with fast and slow arrivals on both great-circle polarizations, but usually even the more complex ScS waveforms appear to have simple relative shifts of SV and SH.

[16] We find a pattern and magnitude of velocity heterogeneity similar to previous work in this region [*Garnero and Lay*, 2003], suggesting significant variations in velocity over lateral scales of 800 km. The weakness of the correlation between velocity heterogeneity and anisotropy suggests that the relationship between the mechanisms causing anisotropy and heterogeneity may be complex. Velocity heterogeneity in D″ is generally attributed to a mix of thermal and chemical heterogeneity; either of which may affect anisotropy. Cooler, higher velocity material may be stiffer, and better able to preserve mineralogical and structural fabrics that can cause anisotropy in an extensively sheared boundary layer. Lower temperatures may also shift deformation into the dislocation glide domain, favorable for development of lattice preferred orientation (LPO). Chemical heterogeneity could provide increased material of strongly contrasting material properties that can shear into an anisotropic structure, or it may provide enhanced amounts of material that has suitable deformation mechanisms to acquire LPO. While thermal and chemical heterogeneity may both contribute to the development of anisotropy, it is still possible that localization of deformation into thermal boundary layers plays a role in limiting the correlation between volumetric parameters and anisotropy. Resolving the vertical distribution of anisotropy is key to addressing this.

[17] The existence of Scd provides some vertical resolution of lower mantle structure that ScS observations alone intrinsically lack. The observation of splitting of Scd requires that some anisotropy must be concentrated at depths several hundred kilometers above the CMB, the deepest penetration depth of Scd. *Garnero and Lay* [2003] observed some regions with no Scd phases but strong Sdiff or ScS splitting, suggesting that the phenomena of velocity discontinuities and anisotropy may be decoupled to some extent. We also find records in our dataset for which any Scd arrival is very weak, while ScS splitting is clearly observed (notably near 7–9°N in Figure 3), corroborating the suggestion that at least some D″ anisotropy occurs in regions that lack a well-developed reflection. If the mechanisms behind the D″ discontinuity and the ScS splitting are at least partially decoupled, there may be at least two distinct anisotropic layers within D″ in some regions, one near the top of D″ which affects ScS and Scd and one at greater depth, possibly just above the CMB, that further affects ScS.

[18] **Acknowledgments.** Data were provided by the BDSN, Trinet and IRIS data centers. Supported by NSF grant EAR0125595. We appreciate reviews by two anonymous reviewers and Michael Wysession. Contribution number 475 of the Center for the Study of Imaging and Dynamics of the Earth, IGPP, UCSC.

References

Ding, X., and D. V. Helmberger (1997), Modeling D″ structure beneath Central America with broadband seismic data, *Phys. Earth Planet. Inter.*, *101*, 245–270.

Garnero, E. J. (2000), Lower mantle heterogeneity, *Annu. Rev. Earth Planet. Sci.*, *28*, 509–537.

Garnero, E. J., and T. Lay (2003), D″ shear velocity heterogeneity, anisotropy, and discontinuity structure beneath the Caribbean and Central America, *Phys. Earth Planet. Inter.*, *140*, 219–242.

Grand, S. P. (2002), Mantle shear-wave tomography and the fate of subducted slabs, *Philos. Trans. R. Soc. London, Ser. A*, *360*, 2475–2491.

Kendall, J.-M., and C. Nangini (1996), Lateral variations in D″ below the Caribbean, *Geophys. Res. Lett.*, *23*, 395–402.

Kendall, J.-M., and P. G. Silver (1998), Investigating causes of D″ Anisotropy, in *The Core-Mantle Boundary Region*, *Geodyn. Ser.*, vol. 28, edited by M. Gurnis et al., 97–118, AGU, Washington, D. C.

Lay, T., Q. Williams, and E. J. Garnero (1998), The core-mantle boundary layer and deep Earth dynamics, *Nature*, *392*, 461–468.

Polet, J., and H. Kanamori (2002), Anisotropy beneath California shear wave splitting measurements using a dense broadband array, *Geophys. J. Int.*, *149*, 313–317.

E. J. Garnero, Department of Geological Sciences, Arizona State University, Box 871404, Tempe, AZ 85287-1404, USA.

T. Lay and J. M. Rokosky, Institute of Geophysics and Planetary Physics and Earth Sciences Department, University of California, Santa Cruz, 1156 High Street, Santa Cruz, CA 95064, USA. (jrokosky@es.ucsc.edu)

S. A. Russell, Weston Geophysical Corporation, 57 Bedford Street, Suite 102, Lexington, MA 02420, USA.