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LATERAL VARIATIONS NEAR THE CORE-MANTLE BOUNDARY

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Abstract. Differential travel times between S and SKS (T_{S-SKS}), and SKKS and SKS ($T_{SKKS-SKS}$), along with amplitude behavior have been used to study lateral variations at the core-mantle boundary. The data were recorded by the World Wide Seismographic Station Network (WWSSN) and the Canadian Seismograph Network (CSN) from source regions in South America and the Fiji-Tonga area. A core-mantle boundary region traversed by SKS and S beneath the mid-Pacific from the Fiji-Tonga area to North American stations shows the most anomalous behavior in T_{S-SKS}. SKS and S are anomalously separated by up to 8 seconds. In addition to T_{S-SKS} anomalies, SKS and SKKS are anomalously separated by 2 to 3 seconds. A model fitting T_{S-SKS} for this anomalous region requires one or more of the following: (1) up to 5% increase in the top 300 km of outer core velocity; (2) a large scale high Vs region (2% increase) in the lower mantle NE of Tonga; (3) lateral variations in D" shear wave velocities of up to 3%. However, (1) above predicts a decrease in $T_{SKKS-SKS}$, contradicting the observations. This suggests that (2) and (3) are more likely explanations in modeling this data set.

Introduction and Data

Understanding the core-mantle boundary (CMB) is of fundamental importance to the earth sciences. This study attempts to tie together information from S, S_{diff}, SKS, and SKKS, to forward model a CMB region in the mid-Pacific exhibiting anomalous amplitude and differential travel time behavior for these phases.

Long and short period seismograms recorded worldwide at WWSSN and CSN stations from deep focus earthquakes in the Fiji-Tonga area and in South America have been used (Table 1.) Differential travel times between SKS and S (T_{S-SKS}) were measured from seismograms by differencing the onset times of S and SKS. Distance ranges used for SKS and S were from 80 to 100 degrees. Anomalously large differential travel time residuals (δT_{S-SKS}) with respect to predictions of the Jeffrey-Bullens model (JB) of up to 8 seconds were found for a mid-Pacific CMB region. This region was sampled by Fiji-Tonga events recorded at North American stations, and is the focus of this report (Figure 1.)

Also in Figure 1 are D" regions studied by Lay and associates and Vs profiles resulting from detailed waveform and travel time analysis of S phases and associated triplications [Lay and Helmberger, 1983; Young and Lay, 1987.] The hatched region in Figure 1

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TABLE 1. Event information as reported by ISC.

Date	Lat.	Long.	Depth	m_b	Region
08/25/63	17.50S	178.80E	565	6.1	Fiji-Tonga
10/09/67	21.10S	179.18W	633	6.2	Fiji-Tonga
02/10/69	22.70S	178.61E	673	6.9	Fiji-Tonga
04/28/81	23.72S	179.98E	540	6.0	Fiji
08/23/68	21.95S	63.64W	513	5.6	S. Bolivia
10/25/73	21.96S	63.65W	517	6.1	S. Bolivia
04/01/81	27.31S	63.32W	554	5.9	Argentina

(from this study) does not show evidence for a lower mantle Vs triplication as seen in the other regions. Evidence for a triplication in the long period data would be seen as SH pulse distortions from around 90 to 94 degrees due to an interference effect of the direct S and the S traversing the high Vs discontinuity lid [Young and Lay, 1987]. Figure 2 has SH synthetics for the model SYL1 (shown by Young and Lay [1987] to model the India region of Fig. 1), along with SH data from a representative Fiji event. SH pulse complications predicted by SYL1 are not evident in the Fiji data. Schlittenhardt, et al. [1985] also report no evidence for a D" discontinuity for such events.

Figure 3 shows a representative profile of long period radial component seismograms from a Fiji event. SKS onsets have been aligned to show the stability of T_{S-SKS}. When the traces are plotted absolutely in time, there is scatter in arrival times of up to 10 seconds, preventing a confident estimate of apparent velocity at the bottom of the mantle from $dT/d\Delta$. δT_{S-SKS} is interpreted here as being dependent on Vs in D" and V_P in the outer core, since S and SKS travel similar paths for our distance range.

Events in South America recorded in North America do not show the large δT_{S-SKS} anomalies seen from the Fiji-Tonga region. The Young and Lay [1987] model

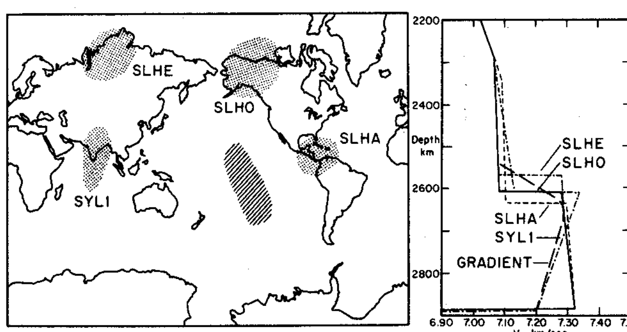

Fig. 1. Map of D" regions studied by Lay and associates (dotted) and anomalous lower mantle region of this study (hatched.) The box on the right contains models corresponding to regions of Lay and associates. Figure is modified from Young and Lay [1987].

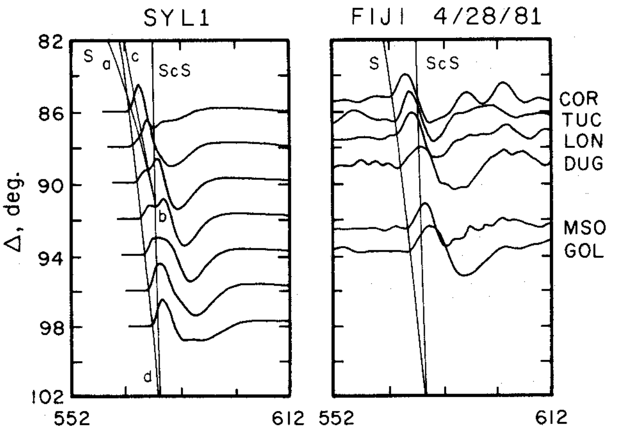

Fig. 2. Comparison of SH synthetics for SYL1 of Young and Lay [1987] and a Fiji event (4/28/81). The amplitudes have been normalized and the data have been shifted to line up with the travel time curve.

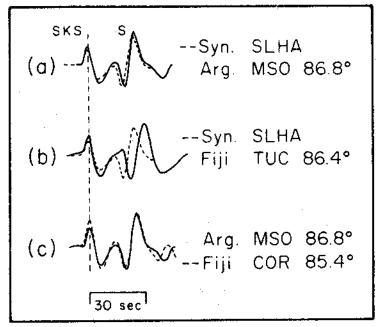

Fig. 4. LP radial component seismogram comparisons: (a) an Argentine event WWSSN record and SLHA synthetic; (b) a Fiji event record and SLHA synthetic; (c) Fiji event record and Argentine event record.

SLHA nicely predicts SKS - S behavior for the Argentina source region. Figure 4a shows a sample Argentine event seismogram and a corresponding SLHA synthetic generated by the Cagniard de Hoop technique [Helmberger, 1983] as filtered by a long period instrument. Figure 4b illustrates that SLHA does poorly in modeling the Fiji record; Ts-sks at station TUC is 6 seconds larger than the synthetic. This anomaly is further illustrated by comparing South American data directly to Fiji-Tonga data (Figure 4c.) To match SKS - S separations of the two data sets, one must pick seismograms from South American events with Δ up to 2 degrees larger than that of Fiji-Tonga events. Note that

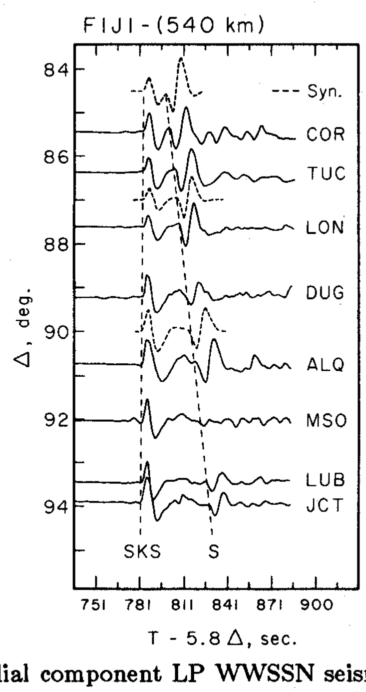

Fig. 3. Radial component LP WWSSN seismograms for the 4-28-81 Fiji event. SKS is lined up and amplitudes are normalized. Synthetics for a 5% increase in V_P in outermost 300 km of the core are dotted.

a 50 km difference in source depth for a given Δ will only produce about a half second difference in $\delta T_{S\text{-}SKS}$.

Modeling the Data

Anomalous $T_{S\text{-}SKS}$ times imply SKS is anomalously fast, S is anomalously slow, or a combination of both. Thus, to model $T_{S\text{-}SKS}$ one can explore different structural possibilities that speed up SKS and/or slow down S. The first set of models tested were variations of the JB model. The outer core P velocity structure of Hales and Roberts [1971] has been used as the reference outer core model. Spherically symmetric mantle modeling attempts included: (i) up to 5% decrease in Vs from the 670 km discontinuity down to the CMB; (ii) exploring gradients different from JB in the bottom 300 to 600 km of the lower mantle; and (iii) different D" models allowing for a Vs discontinuity up to 3%. These attempts were unsuccesful because both SKS and S are similarly affected by spherically symmetric model changes.

Since SKS travels through the core, a modeling attempt to speed up SKS was made by increasing V_P in the top 300 km of the outer core, thus increasing $\delta T_{S\text{-}SKS}$. A 5% V_P increase in the outermost core predicts $T_{S\text{-}SKS}$ times that match anomalous Fiji-Tonga data (Figure 3.) Since lateral variations in $\delta T_{S\text{-}SKS}$ exist for the Fiji-Tonga data from around 1 to 8 seconds, an outer core model (as above) fitting these would have to vary laterally. However, fluid dynamic arguments imply that lateral variations in velocity and density in the outer core are negligible [Stevenson, 1987], suggesting such a model is unlikely.

By increasing V_P at the top of the outer core, and thus decreasing the outer core velocity gradient, predicted $T_{SKKS\text{-}SKS}$ times are decreased (by speeding up SKKS relative to SKS.) However, $T_{SKKS\text{-}SKS}$ times are observed to be anomalously large by 2 to 3 seconds, agreeing with Schweitzer and Muller [1986]. This suggests increasing outer core velocity (and decreasing the outer core V_P gradient) is not a plausible explanation for the anomalous $T_{S\text{-}SKS}$ times.

Studies of multiple ScS travel times have suggested velocity heterogeneities around 1000 km in scale length in the mantle beneath the western Pacific [Sipkin and

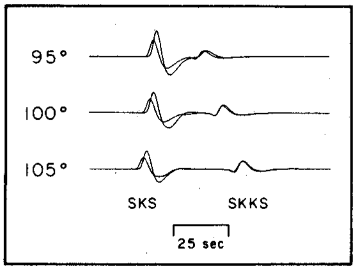

Fig. 5. WKBJ synthetics for SKS and SKKS going through a large scale high Vs region (earlier arrivals with smaller amplitudes) and the same phases in absence of such a feature (larger later arrivals).

Jordan; 1980]. It is possible to have such lower mantle velocity anomalies that SKS encounters while S and SKKS miss it almost entirely. Using the WKBJ technique, [see Chapman, 1978 and Helmberger et al., 1985], many tests of this type were conducted. Consider a region about 1500 km wide by 2000 km high, with a maximum velocity increase of about 1.8% in its center. If this high Vs region is placed in the lower mantle such that it affects SKS and hardly affects SKKS and S, then this will increase Ts-SKS and TSKKS-SKS. This Vs perturbation speeds up SKS by about 2 seconds and diminishes its amplitude (Figure 5), both in agreement with data from Fiji-Tonga to North America [Schweitzer and Muller, 1986]. Nevertheless, 2 seconds is not nearly enough to explain the large δTs-SKS anomalies (Figure 6.) There is a trend in the residuals plotted such that δTs-SKS increases to the Southeast beneath the Hawiian volcanic chain.

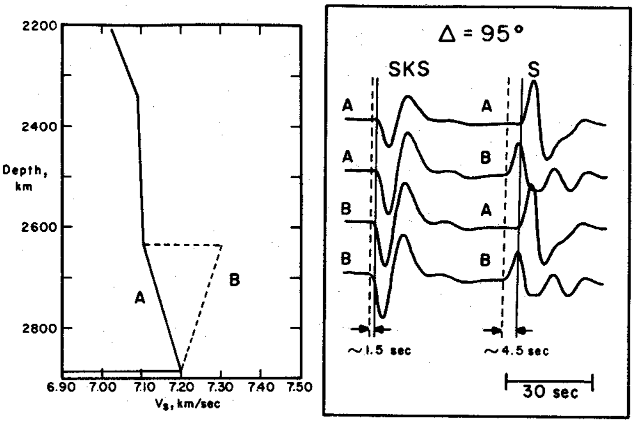

Fig. 7. Two model extremes used in a 2-D varying D" model (left) and results of different runs in which SKS and S traversed through either model A or B (right.) The largest δTs-SKS occurs for SKS passing through model B and S traveling through model A.

Since no evidence for a D" discontinuity has been found for the mid-Pacific, tests were conducted for a laterally varying D" where the discontinuity "fades" in and out. More specifically, a 2-D model was used where SKS encounters a D" discontinuity before entering and after exiting from the core, while S traverses the bottom of the mantle where the discontinuity is nonexistent. That is, the D" discontinuity fades out in the mid-Pacific thus slowing down S relative to SKS while not distorting the waveform of SH, and increasing δTs-SKS (Figure 7.) The model A in Figure 7 is the ex-

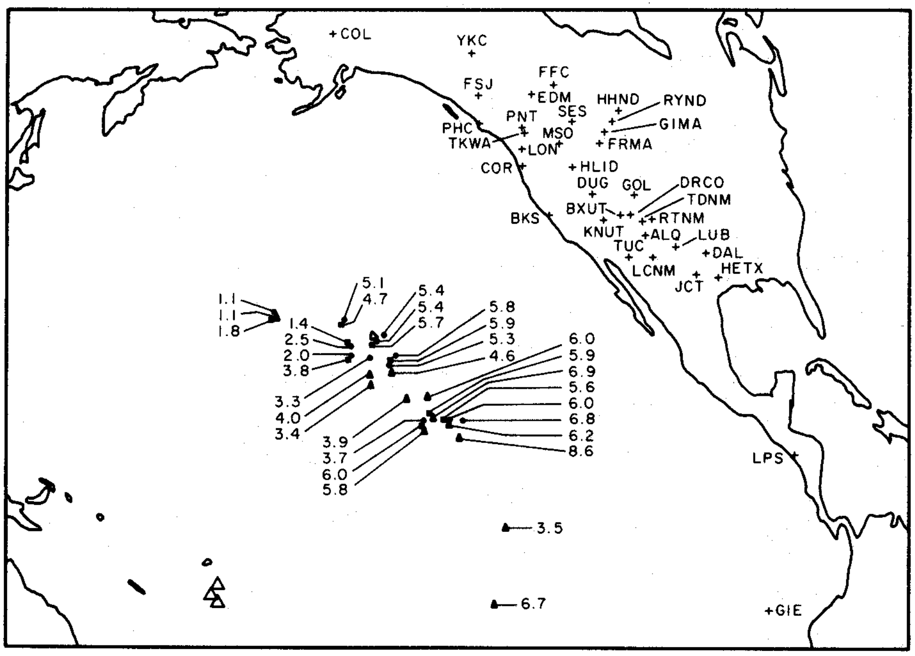

Fig. 6. δTs-SKS residuals with respect to JB. Triangles at lower left are Fiji -Tonga events. Residuals are plotted at the turning points of S and SKS projected to the surface. Each point represents a residual from one source receiver pair. Solid triangles, squares and circles correspond to different events.

treme that S encounters in the mid-Pacific, and model B is bordering the mid-Pacific such that only SKS passes through it. Different combinations of synthetics are given for SKS and S going through model A or B. It is found that δT_{S-SKS} can be increased by 6 seconds when SKS passes through model B and S passes through model A. By varying the degree to which a D" discontinuity fades out, and varying the 2-D model azimuthally makes it geometrically feasible to model the data in Figure 6. This 2-D model also increases $\delta T_{SKKS-SKS}$ by up to 1.5 seconds. Our data, however, cannot resolve sharpness in the D" discontinuity velocity jump in the regions bordering the mid-Pacific. We assume these bordering regions are similar to the Lay and associates D" regions (Figure 1), so we choose a B type model relative to model A, though the discontinuity may be smeared out as in model GRADIENT (Figure 1.) A 2-D laterally varying D", along with the possibility of a high Vs region in the lower mantle described above, are currently our favored explanations for these large mid-Pacific anomalies.

Discussion and Conclusion

Other factors may contribute to large δT_{S-SKS} anomalies. Synthetic tests show that a 10 km increase in CMB radius will increase δT_{S-SKS} by 1 second. No S wave splitting was noticeable, suggesting anisotropy isn't affecting our measurements.

Many studies have investigated velocity gradients in the lowermost mantle (for example, Phinney and Alexander, 1969; Doornbos and Mondt, 1979; Mula and Muller, 1980; and Bolt and Niazi, 1984). In past studies, both negative and positive D" velocity gradients have been proposed. This issue is not addressed in this paper, and it is noted that changes in the Vs gradient at the bottom of the mantle only slightly affect δT_{S-SKS} for our distance range.

We propose a laterally varying D" where the discontinuity fades away in the mid-Pacific along with the possibility of a large scale Vs increase (2%) NE of Fiji-Tonga in the lower mantle. Evidence supporting this is: (1) we find no evidence for a D" triplication in the mid-Pacific, (2) there are variations in travel time and amplitude of S, suggesting lateral variations, and (3) the proposed structural changes can well model the δT_{S-SKS} and $\delta T_{SKKS-SKS}$ observations.

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References

Bolt, B. A., and N. Niazi, S velocities in D" from diffracted SH-waves at the core boundary, *Geophys. J. R. astr. Soc., 79,* 825-834, 1984.

Chapman, C. H., A new method for computing synthetic seismograms, *Geophys. J. R. astr. Soc., 54,* 481-518, 1978.

Doornbos, D. J., and J. C. Mondt, P and S waves diffracted around the core and the velocity structure at the base of the mantle, *Geophys. J. R. astr. Soc., 57,* 381-395, 1979.

Hales, A. L., and J. L. Roberts, Velocities in the outer core, *Bull. Seismol. Soc. Am., 61,* 1051-1059, 1971.

Helmberger, D. V., Theory and application of synthetic seismograms, in *Earthquakes: Observation, Theory and Interpretation,* Soc. Italiana di Fisica, pp. 173-222, 1983.

Helmberger, D. V., G. Engen, and S. Grand, Notes on wave propagation in laterally varying structure, *J. Geophys., 58,* 82-91, 1985.

Lay, T., and D. V. Helmberger, A lower mantle S-wave triplication and the shear velocity structure of D", *Geophys. J. R. astr. Soc., 75,* 799-838, 1983.

Mula, A. H., and G. Muller, Ray parameters of diffracted long period P and S waves and the velocities at the base of the mantle, *Pageoph., 118,* 1272-1292, 1980.

Phinney, R. A., and S. S. Alexander, The effect of a velocity gradient at the base of the mantle on diffracted P waves in the shadow, *J. Geophys. Res., 74,* 4967-4971, 1969.

Schlittenhardt, J., J. Schweitzer, and G. Muller, Evidence against a discontinuity at the top of D", *Geophys. J. R. astr. Soc., 81,* 295-306, 1985.

Schweitzer, J., and G. Muller, Anomalous difference traveltimes and amplitude ratios of SKS and SKKS from Tonga-Fiji events, *Geophys. Res. Lett., 13,* 1529-1532, 1986.

Sipkin, S. A., and T. H. Jordan, Multiple ScS travel times in the western Pacific: Implications for mantle heterogeneity, *J. Geophys. Res., 85,* 853-861, 1980.

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

Young, C. J., and T. Lay, Evidence for a shear velocity discontinuity in the lower mantle beneath India and the Indian Ocean, *Phys. Earth Planet. Int., 49,* 37-53, 1987.

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