

A STUDY OF LATERAL INHOMOGENEITIES IN THE UPPER MANTLE BY MULTIPLE ScS TRAVEL-TIME RESIDUALS

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Abstract. An analysis of records of multiply reflected ScS phases from ten deep-focus earthquakes yields near-vertical one-way travel-time residuals varying from +5.0 to -3.5 s. Continental and oceanic residuals overlap and both indicate large lateral variations. Similar values are found for the older oceanic basins and for continental shields. Most, if not all, of the variations can be attributed to differences in the lithosphere and asthenosphere. The mantle under Hawaii, Iceland and Trindade (South Atlantic) Islands is anomalously slow, all being postulated hotspots. In the case of Trindade, petrological data is consistent with a pronounced low-velocity zone and large S delays. Some recent studies assumed that stations on oceanic islands were representative of the ocean as a whole and it has been suggested that continent-ocean differences extend deeper than 400 km. The present results indicate that oceanic islands are anomalous, and that differences between oceans and continents need not extend below 200 km. This does not rule out the existence of deep lateral inhomogeneities, but only the proposal that continents, in general, are faster than oceans to depths greater than 400 km.

One of the basic premises of plate tectonic theory is that relatively thin plates (50-75 km under oceans and 150-250 km under continents) are moving about over a partially molten asthenosphere [Anderson, 1962; Anderson & Sammis, 1970]. Because of the distribution of seismic stations and earthquakes, most studies of the structure of the Earth have a strong continental bias. Free oscillation results [Jordan & Anderson, 1974; Gilbert & Dziewonski, 1975; Anderson et al., 1975] indicate that the average Earth has slower seismic velocities than determined from most body-wave solutions. Studies of great-circle surface wave dispersion curves [Anderson & Toksöz, 1963] indicate the same. Most of the information regarding oceanic upper mantle structure, to depths greater than 100 km, has come from surface wave studies. They indicate that the oceanic lithosphere is faster than the continental one, but the oceanic asthenosphere is slower, being probably both slower and thicker. Because of the limited depth resolution of surface waves, and lateral variations in the oceans, it is important to test the basic plate tectonic premise by independent means.

Sipkin & Jordan [1975] studied lateral inhomogeneities of the upper mantle by use of the phase ScS for a number of deep events. They found a difference of 5 sec between oceans (slow) and

continents (fast), and argued that continental and oceanic mantle must differ to at least 400 km and possibly as deep as 600 km. However, their oceanic data rests entirely on the use of only 4 stations, which they presume to represent normal ocean: KIP, Hawaii; RAR, Cook Islands; AFI, Samoa, and BEC, Bermuda. All of these are on volcanic islands whose activity is in no case older than 30 m.y. It is questionable, indeed, whether any island station can be taken as standing on typical oceanic lithosphere. In order to investigate travel-time anomalies in areas where no stations are available, we studied travel-time residuals for multiply-reflected ScS waves. The surface-reflection points of many of these phases are at places which cannot be studied by use of direct phases, such as S or ScS.

The residual δ (observed minus Jeffreys-Bullen (JB) times), say for ScS₂, may be written:

$$\delta_{ScS_2} = A_{epic} + A_{refl} + A_{rec}.$$

A_{epic} , the anomaly at the epicenter, is due to possible mislocation, uncertainty in the origin time, and structure around the epicenter; A_{refl} is the contribution at the surface reflection point and A_{rec} the contribution at the receiver, due to local structure under the station. Clearly because of the quasi-vertical incidence of any ScS path, the anomalies A_{epic} and A_{rec} are approximately the same for ScS or any ScS_n. Therefore, the difference in time residuals $\delta_{ScS_2} - \delta_{ScS}$ clearly represents A_{refl} , which, in turn, because of the steep incidence of any ScS_n, is approximately equal to twice the one-way anomaly to a vertical S, due to upper mantle structure under the reflection point. In the case of a higher order ScS_n, such anomalies at the various reflections would clearly add up to:

$$[1/2] \cdot \{ (o-c)_{ScS_n} - (o-c)_{ScS} \}.$$

We used long-period records from ten deep-focus events (see Table 1) at 49 WSSN stations. A total of 77 ScS₂, 15 ScS₃ and 2 ScS₄ were used. Records were digitized and cross-correlated to obtain $o_{ScS_2} - o_{ScS}$. At distances larger than 70°, the phase S was used rather than ScS, and the time anomaly obtained, therefore, was $(o-c)_{ScS_2} - (o-c)_S$. Computed values were corrected for ellipticity and for topographical elevation at the surface-reflecting point. We estimate that the resulting values are accurate to ±0.5 sec. Additionally, we calculated a number of cross-correlations between records of the same event at different stations, in order to compare residuals at KIP, POO, AKU and WIN (see Fig. 1) with delays on the North American conti-

Table 1 : Seismic Events used in this Study

No.	Region	Date	Origin Time	Latitude	Longitude
1.	Fiji-Tonga	9 Oct 67	17:21:46.2	21.10 S	179.3 W
2.	North Argentina	8 Dec 62	21:27:21.0	25.78 S	63.13 W
3.	Fiji-Tonga	10 Feb 69	22:58:03.3	22.75 S	178.76 E
4.	North Argentina	9 Sep 67	10:06:44.5	27.62 S	63.15 W
5.	Sea of Okhotsk	29 Jan 71	21:58:03.2	51.69 N	150.97 E
6.	Sea of Okhotsk	30 Aug 70	17:46:08.9	52.36 N	151.64 E
7.	Banda Sea	18 Oct 64	12:32:24.9	7.17 S	123.86 E
8.	Peru-Brazil	15 Feb 67	16:11:11.8	9.05 S	71.34 W
9.	Banda Sea	11 Feb 69	22:16:11.5	6.76 S	126.74 E
10.	Peru-Brazil	3 Nov 65	01:39:03.2	9.04 S	71.32 W

ment, as determined by Hales & Roberts [1970].

Results are shown on Fig.1. The Pacific Ocean exhibits strong lateral variations: values averaging +0.9 sec are found along the line Fiji-Southwest U.S., whereas the Northern Pacific averages -1.2 sec. Strong positive anomalies are found in the Arctic's Eurasia Basin (+2.3 sec), in the Philippine Sea (~3 sec), in the Tasman Sea (+3.9 sec) and at the Mid-Pacific Mountains (~5 sec). Values at the trenches (-1.1 ±0.6 sec at the Alaska trench, 0.4±2 sec off Guatemala) are largely scattered, the reflection being undoubtedly affected by the descending slab. South America also shows lateral variations, and can be separated into two regions: the Andes, where no substantial anomaly is found (relative to JB), and the Brazilian shield, averaging -2.15±1 sec. An intermediate zone, located along the slopes of the Andes, makes a smooth transition and averages -1.2 sec.

It is not possible to account for these data with Sipkin & Jordan's [1975] hypothesis of a simple continent vs. ocean difference. Their model of a 5 sec. delay of oceanic travel-time would lead to a total delay of 20 sec for ScS₃, and 30 sec for ScS₄. No such values are obtained in the present study and such a discrepancy between ocean and continent is not revealed by our data. Furthermore, the small anomaly of +1 sec, only 250 km away from Bermuda, is inconsistent with their assumption that station BEC (-3.5 sec late) is representative of the mean ocean floor.

On the other hand a good correlation exists between the values of the anomalies and the age of the plate: negative anomalies ~-1.5 sec are found in the Northcentral Pacific, where the ocean floor is about 100 m.y. old. On the opposite, the region of the Pacific between 125 and 150°W shows positive anomalies of ~1 sec. Simil-

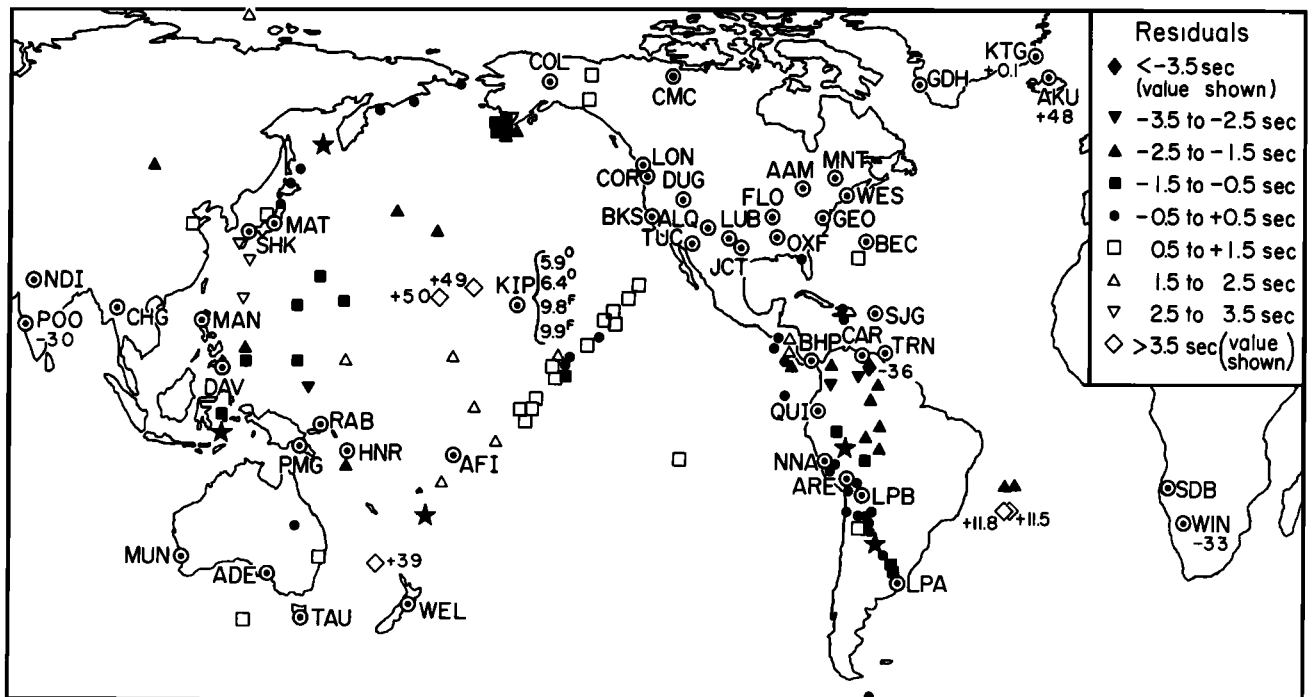


Fig.1: Map of the world showing one-way S anomalies as described in legend. Values of anomalies larger than 3.5 sec in absolute value are shown on map. Stars each identify 2 events. Circled dots are stations with 3-letter code. Numbers adjoining stations are one-way anomalies from direct S or ScS correlations. At KIP, superscripts O and F identify values from respectively Okhotsk Sea and Fiji. Antarctic stations SBA (Scott Base) and SPA (South Pole) used in study, are not shown on map.

arly, the Brazilian shield exhibits anomalies of -2 to -3 sec; ScS delays at P00, India (-3 sec) and WIN, South Africa (-3.3 sec), both stations on shield, are also similar. Delays in the Brazil Basin (-2.05±0.5 sec) do not differentiate substantially this old oceanic floor from the adjoining Brazilian shield. The similarity in travel-time between the older parts of the ocean and old continental shield argues against deep structural differences and suggests that both regions have poorly-developed low-velocity zones. It is worthwhile checking this important result with other data. For this purpose, we compute one-way travel-times above 180 km, for a variety of structures. Leeds et al. [1974] and Kausel et al. [1974] determined oceanic crustal and upper mantle structure as a function of age from Rayleigh waves crossing the Pacific. They found phase velocity increasing with age and attributed it to thickening of the lithosphere at the expense of the asthenosphere. Although their models are not unique, they should yield roughly the right average shear velocity for the upper mantle. They fixed the base of their model at 180 km and it is therefore convenient to compare average velocities above this level. This is done in Table 2. Residuals in the Pacific vary from -2.6 sec, for 150 m.y. old crust to +1.3 sec, for young, ~5 m.y. old crust. A value of +1.9 sec is extrapolated for the ridge, although this is a minimum value, since the mantle under the ridge is likely to be slower than assumed. An estimate for the mid-Atlantic ridge is +3.6 sec, obtained by modifying a structure proposed by Francis [1969], for the region South of Iceland. Alternate estimates of +2.5 to 5.2 sec are obtained from measured P-delays at Iceland. These values are roughly consistent with those found in this study for AKU by direct measure of S and ScS delays. A value of +4.4 sec was recently reported along the mid-Atlantic ridge by Girardin & Poupinet [1974]. The value obtained from Leeds et al.'s structure for 100 m.y. old lithosphere (-1.6 sec) agrees almost exactly with the value (-1.5 sec) found here for the oceanic region of this age in the Northcentral Pacific.

The variation of shear velocity with depth in the published models [Jordan & Anderson, 1974; Anderson et al., 1975] considered by Sipkin & Jordan [1975] also gives support to the idea that variations in the ScS residuals are due primarily to variations in the upper mantle. For example, the spread of one-way vertical S travel-time for a variety of models, is 2.0 sec to 50 km, increasing to 3.0 sec to 200 km. Differences between models remain between 1.6 to 3.2 sec down to 700 km, indicating that most of the variation is above 200 km. The present conclusions may be compared with those of Tryggvason [1961] who used a particularly favorable geometry of events to study both oceanic and continental structure. He concluded that at a depth less than 400 km, possibly at 140 km, the difference between oceanic and continental structure had disappeared. Our results also compare favorably with those of Hart & Press [1973] who used S_n velocities across the Atlantic to investigate the cooling of the lithosphere away from the ridges. They found a large similarity between continents and old oceanic floor.

Finally, strong positive anomalies are found for rays propagating in the top section of proposed mantle hotspots: ScS at KIP, Hawaii, is delayed 6 sec from the Sea of Okhotsk, and 9.8 sec from the Fiji-Tonga area. ScS₂ recorded at WIN from two deep Peruvian earthquakes of almost identical epicenter both show an anomaly of +11.5 sec at their reflecting point, located at the island of Trindade. The observed data at KIP suggests that the top part of the upwelling column has to be made of slow material, even if the total vertical travel-time agrees with JB [Best et al., 1974]. This would require a vertical inhomogeneity in the column, with a higher velocity at the bottom, as proposed by Anderson [1975]. In Anderson's model, the top part of a plume is slower than normal mantle, due to increased partial melting, the deeper part being faster, due to chemical differences. Finally, the anisotropy observed at Hawaii could result from the horizontal distance (300 km) between KIP and the presumed hotspot column.

Table 2 : JB Residuals for the Upper 180 km Vertical S travel-Time in a variety of models.

Model	Reference	Computed Residual	Observed value (this study)
LKK	Leeds et al. [1974], 150 m.y.	-2.6 sec	
LKK	" " 100 "	-1.2	-1.6
LKK	" " 70 "	0.0	} +0.9 at 50 m.y.
LKK	" " 10 "	+1.3	
CANS D	Brune and Dorman [1963] (Canadian shield)	-1.3	-2. (Brazilian shield)
C2	Anderson et al. [1975] (Average Earth)	-0.7	
CIT11A	Anderson and Toksoz [1963]	-0.6	
SHR14	HelMBERGER and Engen [1974] (North America)	-0.2	

In the case of Trindade, Oversby [1971] and Baker [1973] have shown that the island is unique among Atlantic islands in its degree of under-saturation, suggesting origin from a hydrous mantle. This is consistent with a greater degree of partial melting and large S delays. The large contrast between S anomalies at Trindade (+11.5 sec) and in the nearby Brazil Basin (-2 sec) constrains this partially molten region to a restricted area and strongly advocates for the existence of a hotspot, as proposed by Minster et al. [1974].

Conclusion. Lateral variations of S travel-time residuals as reported in this letter occur over distances too short to let them be associated with structures 400 km or deeper. Rather, they seem to correlate fairly well with the general pattern of plate tectonics. Delays, in general, decrease with the age of the plate and are largest for oceanic islands and recently active continental areas. The older oceanic lithosphere has residuals similar to continental shields. The residuals are generally consistent with variations in the upper 200 km found by independent means. The responsible structures should primarily be sought in the lithosphere and asthenosphere. A study of relative attenuation of the seismic phases used in this study, presently under way, will yield additional data and will be the subject of a separate paper.

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References

- Anderson, D.L., The Plastic Layer of the Earth's Mantle, Scientific American, July 1962.
- Anderson, D.L., Chemical Plumes in the Mantle, Bull. Geol. Soc. Amer., in press, 1975.
- Anderson, D.L., R.S. Hart and T.H. Jordan, An Earth Model Based on Free Oscillations and Body Waves, J. Geophys. Res., in press, 1975.
- Anderson, D.L. and C. Sammis, Partial Melting in the Upper Mantle, Phys. Earth Plan. Int., **3**, 41-50, 1970.
- Anderson, D.L. and M.N. Toksöz, Surface Waves on a Spherical Earth; 1. Upper Mantle Structure from Love Waves, J. Geophys. Res., **68**, 3483-3500, 1963.
- Baker, P.E., Islands in the South Atlantic, in: The Oceans Basins and Margins, Vol.1, pp.493-553, Plenum, New-York, 1973.
- Best, W.J., L.R. Johnson and T.V. McEvelly, ScS and the Mantle Beneath Hawaii, EOS Trans. AGU, **55**, 1147, 1974.
- Brune, J.N. and J. Dorman, Seismic Waves and Earth Structure in the Canadian Shield, Bull. Seism. Soc. Amer., **53**, 167-210, 1963.
- Francis, T.J.G., Upper Mantle Structure along the Axis of the Mid-Atlantic Ridge near Iceland, Geophys. J. Roy. Astr. Soc., **17**, 507-520, 1969.
- Gilbert, F. and A.M. Dziewonski, An Application of Normal Mode Theory to the retrieval of Structural Parameters and source mechanisms from Seismic Data, Phil. Trans. Roy. Soc. London, **278A**, 187-269, 1975.
- Girardin, N. and G. Poupinet, Teleseismic S travel-time delays for Mid-Atlantic Ridge Earthquakes, Phys. Earth Plan. Int., **9**, 306-313, 1974.
- Hales, A.L. and J.L. Roberts, The Travel-Times of S and SKS, Bull. Seism. Soc. Amer., **60**, 461-489, 1970.
- Hart, R.S. and F. Press, S_n velocities and the composition of the lithosphere in the Regionalized Atlantic, J. Geophys. Res., **78**, 407-411, 1973.
- HelMBERGER, D.V. and G.R. Engen, Upper Mantle Shear Structure, J. Geophys. Res., **79**, 4017-4028, 1974.
- Jordan, T.H. and D.L. Anderson, Earth Structure from Free Oscillation and Travel-Times, Geophys. J. Roy. Astr. Soc., **36**, 411-459, 1974.
- Kausel, E.G., A.R. Leeds and L. Knopoff, Variations of Rayleigh Wave Phase Velocity across the Pacific Ocean, Science, **186**, 139-141, 1974.
- Leeds, A.R., E.G. Kausel and L. Knopoff, Variations of Upper Mantle Structure under the Pacific Ocean, Science, **186**, 141-143, 1974.
- Minster, J.B., T.H. Jordan, P. Molnar and E. Haines, Numerical Modelling of Instantaneous Plate Tectonics, Geophys. J. Roy. Astr. Soc., **36**, 541-576, 1974.
- Oversby, V.M., Lead in Ocean Islands: Faial, Azores and Trindade, Earth Plan. Sci. Lett., **11**, 401-406, 1971.
- Sipkin, S.A. and T.H. Jordan, Lateral Heterogeneity of the Upper Mantle determined from the travel-times of ScS, J. Geophys. Res., **80**, 1474-1484, 1975.
- Tryggvason, E., Wave Velocity in the Upper Mantle below the Arctic-Atlantic Ocean and Northwest Europe, Annali di Geofisica, **14**, 379-392, 1961.

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