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THE CARIBBEAN ANOMALY: SHORT-WAVELENGTH LATERAL HETEROGENEITY IN THE LOWER MANTLE

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Abstract. Data from the Archean-Proterozoic Transect Experiment 1989 (APT89) are used to constrain smaller-scale velocity heterogeneity in the lower mantle beneath the Caribbean. We observe large variations in travel time residuals for paths from South America to portable broadband and short-period stations distributed along a 1500km-long transect in central North America. After accounting for near-source and near-reciever contributions, we find variations as large as 3s for P and 8s for S for rays that bottom around 1200km depth. This rapid spatial variation in travel times suggests that we are seeing the western edge of the Caribbean anomaly, a feature previously observed by several investigators. The gradient appears to be about 300km wide. Assuming a path length of 1500km through the anomaly (suggested from previous studies), we find that $\delta v_P/v_P = 2.1\%$ and $\delta v_S/v_S = 3.6\%$ which for S waves is about three times the estimate from long period body waves. The relative velocity ratio for this anomaly is $\delta ln v_S/\delta ln v_P \approx 1.7$, a value slightly larger than typical laboratory values but lower than previous recent seismological studies of lower mantle heterogeneity. With increasing turning depth the observed anomaly appears to decrease in size, although it continues to be visible for shear waves with bottoming depths as great as 2200km. The presence of multiple direct S phases for several records of one of the events studied suggests multipathing induced by the large observed lateral velocity gradients required by the travel time data.

Introduction

The study of lateral velocity variations in the lower mantle is of fundamental importance for understanding the dynamic behaviour of the Earth's interior (e.g. Silver et al., 1988). One such lower mantle feature, the so-called 'Caribbean anomaly', has been the subject of several studies, based on long-period travel times (Julian and Sengupta, 1973; Jordan and Lynn, 1974; Lay, 1983; Dziewonski, 1984; Grand, 1987) and waveform complexity from broad-band records (Vidale and Garcia-Gonzalez, 1988). It appears to be a nearly vertical slab-like feature that has been associated with past subduction of the Farallon Plate (Grand, 1987).

A teleseismic portable experiment, the Archean-Proterozoic Transect Experiment 1989 (APT89), has enabled us to examine this anomaly in unprecedented detail. The 25 broad-band (5s period) and short-period (1s period) stations located along a 1500 km linear traverse from Wyoming to Ontario (Silver et al., 1989; see Silver et al, 1993, this issue) connects the RSTN stations RSON and RSSD (Figure 1). For South American events, the array provides an azimuth range of 14° with instrument spacing of 50–100km. As we will show, the Caribbean anomaly constitutes the dominant contribution to P and S travel time variations across the array for South American events. In addition, the anomaly has a clear effect on broadband and short-period S waveforms, which we have identified as multipathing associated with the strong horizontal velocity gradient.

Data and Waveform Matching

The data set consists of all South American events recorded by the APT89 experiment for which a discrete P-phase was visible (Table 1). Data for one of these events (170 in region Ib) are shown in figure 2, where the phases S and ScS can be seen on most records while sS can be seen on a few. For such data corresponding synthetic seismograms are computed using the CORE method (Clarke and Silver, 1991). Source wavelets are estimated from the reference P phase and are assumed to be common to all phases. Synthetics are obtained using the isotropic PREM model (Dziewonski and Anderson, 1981) at 1 Hz augmented to have a 40 km thick continental crust. In order to fit the waveform shapes, it was necessary to increase the PREM Q model by an empirically determined factor of 1.7. This value is consistent with previous evidence that Q increases significantly with frequency (Sipkin and Jordan, 1979). CMT moment tensor solutions were used in generating synthetics except for events 168 and 259 (Table 1) for which no CMT solution was available. In these cases we chose moment tensors giving consistent polarities and amplitudes for the phases of interest.

The synthetics are utilized to extract the travel times T of detectable phases by making use of a waveform fitting procedure (Bokelmann and Silver, 1991a; manuscript in preparation). In the context of the extraction of the wavelet function, an absolute T is found for the reference phase. Because waveform information is incorporated into the synthetics, we then obtain a relative T for every other observable phase on the record, with respect to the reference phase. This may be regarded as an absolute T, although subject to errors associated with the reference phase T. T's are estimated by a nonlinear search that minimizes the misfit between normalized data and synthetic wavelets. The inversion is stabilized by a constraint that the travel time residuals, δT, are smoothly varying across the transect (figure 1). In this way, ambiguities between multiple minima can be resolved. A confidence interval is obtained for each T on the basis of the dependence of squared misfit on the chosen value of T, a procedure which follows the approach of Silver and Chan (1991) for estimating the confidence intervals for the delay time and fast polarization of split shear waves. Depending on the data quality, the uncertainty is typically near ± 0.1 sec for P and ± 0.3 sec for S at the 95% confidence level.

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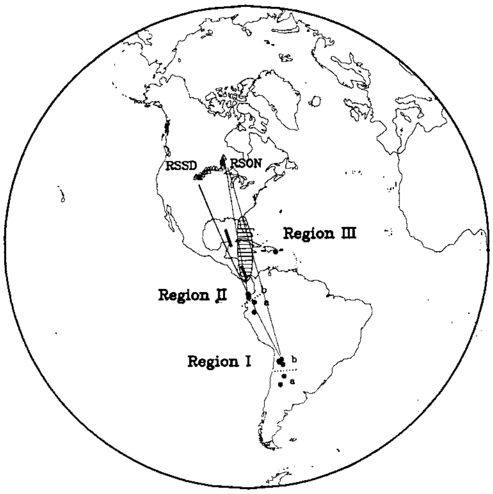

Fig. 1. Shallow and intermediate depth events in South America used to study the lower mantle Caribbean region. The ray coverage to the portable stations between the RSTN sites RSON and RSSD is illustrated for two events. Relative travel times are insensitive to source location errors for such a fan shot. This study suggests a sharp western boundary of the fast anomaly as indicated by the thick lines. Also shown is the location of the anomaly at a depth of 1200 km given as the 50%-contour of Grand (1987).

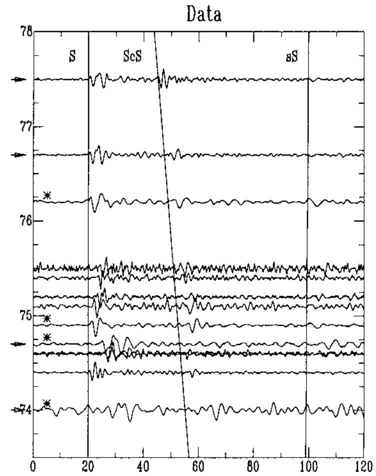

Fig. 2. Transverse components for event 170 showing phases S, ScS and sS (time is in seconds). This event was recorded by two types of instruments (sensors with 5 second (asterisks) and 1 second eigenperiod) giving different waveforms. The scatter in S-arrival time suggests lateral heterogeneity. Note the strong arrivals after S (stations with arrows) which are consistent with multipathing due to the lower mantle heterogeneity.

The strong influence of lateral heterogeneity can be easily seen directly on the record section for a given event. Note for example in figure 2 the large variation in arrival time of the S phase with respect to PREM. Note also the presence of a second phase following direct S for several of the records (especially the top 2 traces). This is not due to source complexity, as this is not seen in the synthetics, which include source complexity through the source wavelet function nor the ScS phase in the data. Below we will argue that these additional phases are rather due to multipathing from a strong lateral velocity gradient in the lower mantle.

Table 1. Events used in this study*

Date (yr/day)	Time	Lat. (deg)	Long. (deg)	Depth (km)	m_b	Δ (deg)	$D_T^{\dagger}$ (P,S) (km)
Ia							
89168	14:57:48.4	−31.41	−67.55	27.0	5.3	83.	2472,2312
89175	12:58:39.1	−28.33	−66.31	21.0	5.4	81.	2362,2210
Ib							
89276	21:33:34.8	−24.10	−66.89	154.0	5.4	77.	2210,2075
89218	08:19:56.1	−23.15	−68.32	114.0	5.3	76.	2151,2017
89170	16:00:47.9	−22.11	−67.55	188.0	5.5	75.	2133,2003
89220	23:44:04.4	−22.72	−68.47	102.0	5.3	75.	2130,1998
IIa							
89282	10:03:19.5	−4.29	−77.56	35.0	5.4	55.	1398,1322
89259	01:49:15.9	−0.59	−77.46	10.0	5.4	52.	1284,1220
IIb							
89176	20:37:32.5	1.13	−79.61	15.0	5.9	49.	1216,1162
89252	01:40:35.8	2.43	−79.76	6.0	6.0	48.	1178,1126
III							
89169	14:06:28.8	17.76	−68.81	62.0	5.9	38.	928, 916

* Source parameters are those of the ISC Bulletin. For all events but 168 and 259 moment tensor estimates from the Harvard moment tensor catalogue are available. The turning depths are computed for the center of the transect using PREM., 1988.

† Turning Depth for P and S.

To correct for near-receiver heterogeneity we use azimuthally dependent P and S station delays obtained in an inversion of globally distributed events (Bokelmann and Silver, manuscript in preparation) excluding contributions from the Caribbean anomaly. These station delays vary by about 1.5 sec for P and 3.5 sec for S, where the Eastern part is faster than the West. Conservative errors of this near-receiver correction are on the order of 0.3 sec for P and 0.6 sec for S. On the other hand P, PcP, S and ScS curves across the transect for the event off the anomalous zone (region 3) are consistent with the station corrections. This suggests that along this path there is no substantial lower mantle heterogeneity and that the azimuthal station corrections are valid for azimuths from South America. It is also unlikely that there is a significant near-source contribution for the events we have examined. We have used only shallow and intermediate focus events, and have avoided deep-focus ones that could be associated with a steeply dipping extension of the slab into the lower mantle. In fact ScS observations are consistent with pure near-receiver heterogeneity confirming that no significant near-source heterogeneity is experienced along the paths.

Results

Figure 3 shows the P and S station-corrected residuals for the events in regions I and II. Within a given region, we have removed an arbitrary constant from all travel times for a given event so as to minimize the variation between events. This constant accounts for errors in source parameters, as well as any differences in near-source elastic properties. For events in these two regions there are clearly large anomalies even after accounting for near-receiver structure. The residual anomaly shows a clear dependence on source region, with the largest variations occuring in region IIb, corresponding to rays with turning depths near 1200 km. This region shows a total variation

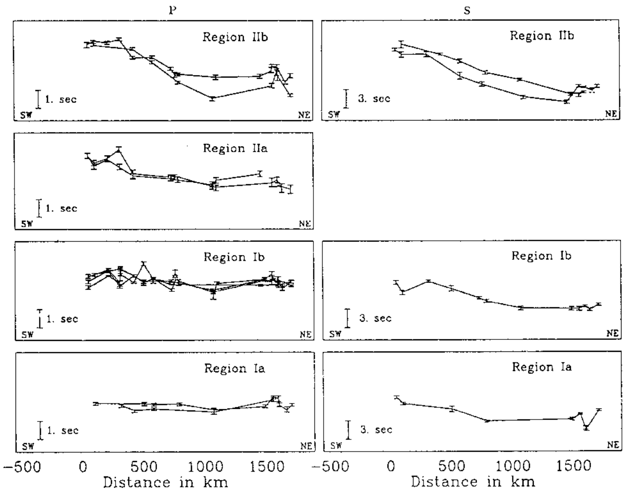

Fig. 3. Reduced travel time residuals (corrected for bulk crustal and upper mantle anomaly) for P (left) and S (right). The events with S waves are (Table 1): 175 in Region Ia, 170 in Region Ib, 176 and 252 (dotted) in Region IIb. The error bars give the 95% confidence region of the travel time estimates. Note the strong change in travel time residual with region (epicentral distance) and position along the transect.

of order 8 seconds in S and 3 seconds in P. Figure 4 shows the corrected travel time residuals of figure 3 at the location of the turning point for P (left) and S (right) assuming that the average residual is the same for each event. The most prominent feature for both P and S is the strong and rapid transition in the northern cluster of points from positive to negative travel time residuals. Examination of differential travel times suggests that the positive residuals in the west are representative of ambient mantle while the negative residuals to the northeast are early and associated with the Caribbean anomaly. This suggests that we have located the western edge of this anomaly and that the transition has a width of about 300km.

In order to assess the depth extent of the anomaly, we have examined the travel times as a function of bottoming

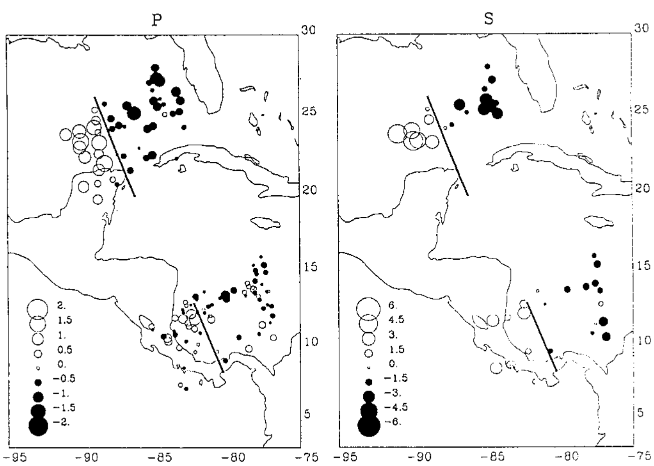

Fig. 4. Travel time residuals due to the lower mantle anomaly shown at the surface projections of the P (left) and S (right) turning points assuming that all events have the same average residual. Note the sharp transitions in the West indicating the Western edge of the Caribbean anomaly.

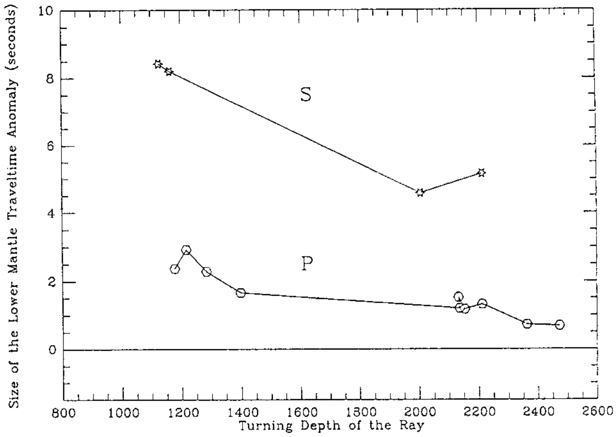

Fig. 5. Maximum variation of the travel time residuals associated with the lateral velocity variation in the lower mantle. With increasing turning depth the anomaly becomes smaller. For P near 2500 km the anomaly is not significantly different from zero indicating heterogeneity only in upper mantle and crust.

depth. For each event-transect set of travel times, we have estimated maximum travel time variation T_{max} across the transect (figure 5). T_{max} is largest for rays turning at about 1200 km (3 seconds for P and 8 second for S) and appears to gradually weaken with depth. For P waves, it approaches the reference level to within twice the assigned error from the upper mantle correction. For S, however, T_{max} does appear to be significantly different from zero in this range, suggesting that the anomaly extends to 2200km depth and perhaps deeper.

Due to the low resolution along the ray paths a tradeoff exists between length of anomalous zone and velocity anomaly. Rays turning at 1200km depth provide the strongest constraint, in that they must account for the largest anomaly with the shortest path through the lower mantle. Assuming a path length of 3000km (spreading the anomaly uniformly along the lower mantle part of the path), yields a velocity anomaly of 1.1% in P and 1.8% in S. A more realistic value is obtained by using the spatial extent determined from previous studies. The tomographic map of Grand(1987) shows that at 1200 km depth the Caribbean anomaly has a length of about 1500km along our paths if we use half the maximum value at that depth to define the boundary. According to Van der Hilst (1990) it is even less. Using this value, we obtain the maximum anomaly 2.1% for P and 3.6% for S as averages over the two events in region IIb, using v_P = 11.7 km/s and v_S = 6.5 km/s.

If this can be regarded as the more probable value, then the size of the anomaly is much larger than estimated from previous studies. For example, the Grand (1987) model shows a fast velocity anomaly of about 1% in S, a factor of nearly 4 smaller than our estimate.

For the two events bottoming near 1200 km we obtain a parameter $\delta ln v_S/\delta ln v_P$ of 1.7±0.2 from P and S velocity anomalies. This is somewhat larger than laboratory values (Isaak et al., 1989) but lower than previous values reported in the seismological literature for lower mantle heterogeneity (e.g. Dziewonski and Woodhouse, 1987). For events with turning points below 2000 km the values become large (2.2 for 89170 and larger). Such a trend has also been reported by Masters and Bolton (1991). While such an increase in $\delta ln v_S/\delta ln v_P$ is predicted by model calculations (Isaak et al., 1992), values above 2.5 are incompatible with known mechanical properties and may be caused by the presence of more than a single dominant source of heterogeneity along these deeper paths.

For purely thermal heterogeneity, for the scale length in the North-South direction to be 1500 km. and assuming $(\delta v/\delta T)_P = 0.5m/s/K$ (Creager and Jordan, 1986), the resulting velocity anomaly requires temperature differences on the order of 500°K to satisfy the observations for the shallower paths.

Velocity gradients of the magnitude implied by the travel time data would be expected to give rise to multipathing and/or slab diffraction (Silver and Chan, 1986; Cormier, 1989). The presence of multiple S phases in figure 2 suggests such a phenomenon. Since the second phase is clearly seen on the short period sensors and appears to have the same frequency content as the first arrival, this suggests multipathing rather than slab diffraction. To test this possibility we first estimated the differential travel times between the two observed arrivals for the records where this was possible. In fact there is a clear trend of decreasing separation time from west to east across the transect. This same trend, with approximately the same travel time difference is seen in simple kinematic three dimensional ray tracing calculations with a tabular 'Caribbean anomaly' of the magnitude suggested by the travel times, imbedded in an otherwise laterally homogeneous earth model (Bokelmann and Silver, 1991b). This suggests that a simple model for the anomaly explains our observations qualitatively. Further exploitation of this phenomenon will be the subject of a subsequent paper.

We have illustrated the importance of broad-band and short-period portable experiments in characterizing lower mantle heterogeneity. The enhanced spatial resolution and high frequency content has demonstrated that the Caribbean anomaly is characterized by strong small-scale velocity gradients which may not be observable using long period data. An important conclusion is that small-scale mantle heterogeneity can now be studied given a station spacing of broadband instruments of 100 km or less.

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