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The Pacific plume as seen by S, ScS, and SKS

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Abstract. The forward modeling of S-SKS and ScS-S differential travel time residuals sensitive to structure beneath a localized region of the central Pacific suggests the presence of two anomalous domains: first a broad zone which becomes thinner as it extends into the mid-mantle, where the S-velocity is reduced by -2 to -4%, and which is deflected to the South-East as it "rises" towards the surface; adjacent to it, a smaller domain, where the S-velocity is about 4% higher. These strong velocity anomalies are likely the results of chemical heterogeneity that may involve subducted material, and partial melting. Strong heterogeneity appears to extend, at least locally, well above D", but the morphology of the anomalous domains is more reminiscent of localized rising or sinking currents rather than of a relatively uniform and thick geochemical reservoir.

Introduction

It is critical to resolve the strength, shape and extent of seismic velocity heterogeneity in the lower mantle in order to understand how it relates to the physical and chemical processes that take place in this region (see *Lay et al.,* [1998] for a review). The deep mantle beneath the Central Pacific is thought to experience some vigorous convection, and may be responsible for the largest hotspot observed at the surface of the earth *Russell et al.,* 1998. Tomographic models of this region consistently show a large slow anomaly that extends several hundred kilometers above the core-mantle boundary (CMB) *Liu et al.,* 1994, *Masters et al.,* 1996, *Li and Romanowicz,* 1996, *Grand et al.,* 1997. However, while these models give a reasonable description of the position of anomalous domains, they do not fully explain travel times sensitive to structure in that region *Vinnik et al.,* 1998, *Bréger et al.,* 1998. *Bréger and Romanowicz* [1998] showed that it was possible to use tomographic studies as a starting point for forward modeling of travel times, and proposed a revised model of the lowermost mantle beneath the Central Pacific characterized by a large slow S-velocity anomaly ($\sim -4\%$) extending above D", and adjacent, on its eastern side, to a smaller domain of very fast S velocities (faster by up to 4 to 5%). They used S-SKS and SKKS-SKS differential residuals, which have little sensitivity to heterogeneity in the mid-mantle, and thus poor vertical resolution. In the present study, we apply the forward modeling approach of *Bréger and Romanowicz* [1998] to an extended dataset which includes both S-SKS and ScS-S differential residuals (Figure 1) in an attempt to verify our model and constrain it better at mid-mantle depths.

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Data

We use the $S_{diff} - SKS$ differential travel time residuals of *Garnero and Helmberger* [1993], as well as the measurements of *Vinnik et al.* [1998], and the ScS-S differential travel time dataset of *Russell et al.* [1998]. Residuals are computed with respect to PREM reference model [*Dziewonski and Anderson*, 1981]. ScS and S arrivals are measured on the transverse component and SKS ones on the radial component. The uncertainty on measurements is on the order of 1 to 2s. Dispersive effects are expected to affect measurements of Sdiff travel times so that this uncertainty should be higher at larger epicentral distances. The compiled dataset that we use here provides a particularly good coverage of the lowermost mantle beneath the Central Pacific (Figure 2). We adopt the approach of *Vinnik et al.* [1998], *Bréger et al.* [1998], and *Bréger and Romanowicz* [1998], and analyze the variations of the residuals as a function of epicentral distance when the station or the event is fixed, along narrow linear "corridors".

In Figure 3 are plotted the ScS-S trends which were observed respectively for stations CMB and PAS and the Fiji Islands events of January 19, 1994, and October 19, 1996. Profiles for a fixed station show the same characteristic variations, namely, a decrease of the residuals with increasing epicentral distance, whereas residuals tend to be somewhat more constant when the event is fixed. Similarly, S-SKS differential travel time residuals for a fixed station show some systematic variations, and tend to increase at smaller epicentral distances, while being relatively constant at larger epicentral distances. Although using differential travel times dramatically reduces the effect of upper mantle structure, a small contribution of the Fiji-Tonga-Kermadec subduction zone cannot be excluded for some specific geometries and could contribute to the scatter of the residuals.

Modeling

The approach used here is essentially the same as in *Bréger and Romanowicz* [1998]. In an attempt to foward model the observed residual variations, we first computed the residual values predicted by several recent tomographic S-velocity models. Synthetic residuals were computed using the one-dimensional raypaths

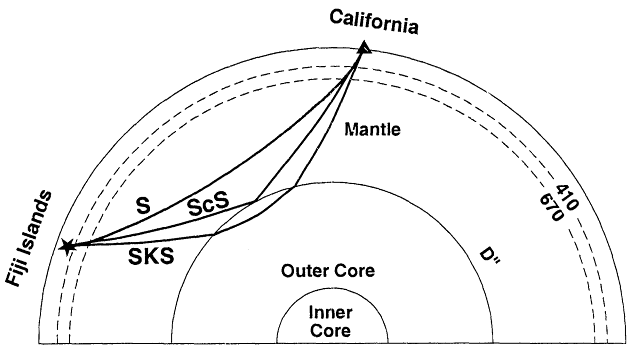

Figure 1. Raypaths discussed in this study.

predicted by PREM. The model that gave the closest match to both S-SKS and ScS-S observations (SKS12, [*Liu and Dziewonski*, 1994]) was chosen as a starting model. Figure 3 and Figure 4 show the predictions of SKS12 (inverted triangles). Interestingly, predicted values generally show the same type of trends, but with somewhat smaller amplitudes. This led us to assume that the original model predicts the position of anomalous domains reasonably well, and by trial and error, this initial model was progressively perturbed in two ways: (1) by keeping the shape of the heterogeneity and increasing its strength, and (2) by applying small vertical and horizontal shifts of no more than 200km. ScS-S (respectively S-SKS) residuals predicted by a perturbed model are shown by filled triangles in Figure 3 (respectively Figure 4). Residuals predicted by the modified models are generally in much better agreement with the observations, and fall within the measurement errors.

The perturbations which were applied to the model are obviously non-unique. There are some trade-offs, particularly between the shape, position, vertical extent, and S-heterogeneity in this domain. In fact, our approach leads to a whole family of models rather than one single 'best' model. The features which are common to all the models can be considered as robust, and are discussed in what follows.

Slow region

We found that the data require a large slow domain extending from the CMB to several hundred kilometers above the CMB, where the S-velocity anomaly is strong and reaches -2 to -4%, which is significantly larger than predicted by SKS12. The shape of this domain is obviously constrained to be quite close to the starting model SKS12, but it is important to note that it is still consistent with what we obtained earlier, starting from tomographic model SAW12D [*Bréger and Romanowicz*, 1998].

The two models presented in Figure 2 both correspond to a slow domain which was modified from the original model SKS12 up to 1500 km above the CMB. In an attempt to roughly assess the sensitivity of our modeling to the vertical extent of the slow region, we com-

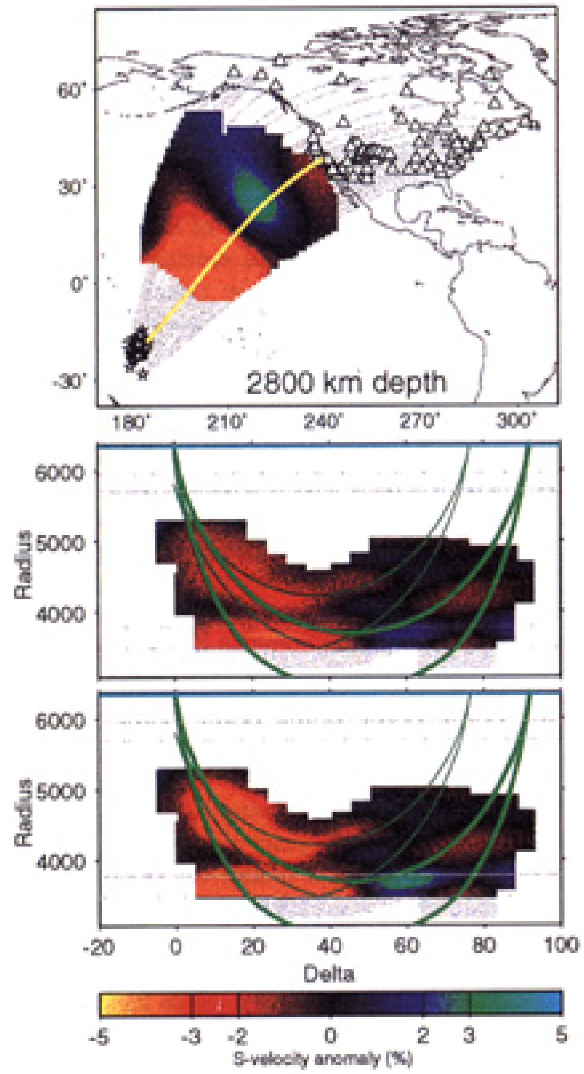

Figure 2. (a) Surface projections of wavepaths analyzed here (grey lines). Sources and stations bounce points are indicated by light blue stars and triangles, respectively. The S-velocity heterogeneity at a depth of 2800km predicted by a model that explains S-SKS and ScS-S travel time residuals reasonably well has been plotted as background. (b) Cross-section through the original model SKS12 [*Liu et al.*, 1994]. and examples of S, ScS, and SKS rays, for the Kermadec Islands event of June 25, 1992 (lat.=-28.17°, long.=-176.22°, depth=21 km) and the Fiji Islands event of January 19, 1994 (lat.=-17.37°, long.=-178.28°, depth=561 km), and stations ARC (thin lines) (Berkeley Digital Seismic Network), and INK (thick lines) (Canadian National Seismic Network). Subhorizontal light blue lines outlines the 410km-discontinuity, the 670km-discontinuity, the top of D", and the CMB. The model is only represented where it is sampled by rays. (c) Same as (b), but for an example of modified model that explains the observed residuals significantly better than the original SKS12. Models that explain the data systematically include, on the one hand, a large slow domain, with S-velocity reductions reaching -2 to -4%, and a smaller domain, where the S-velocity could be as fast as +4%. The details of the heterogeneity distribution can vary from one successful model to another, and are not robust features of the modeling.

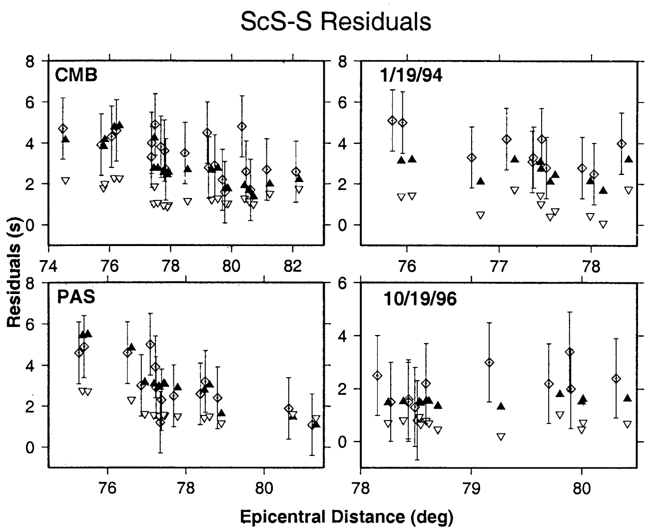

Figure 3. Observed ScS-S differential travel time residuals with respect to PREM [*Dziewonski and Anderson*, 1981], plotted as a function of epicentral distance (gray diamonds), residuals predicted by original model SKS12 [*Liu and Dziewonski*, 1994] (white arrowheads), and residuals predicted by the modified SKS12 model (black triangles). For reference, error bars indicate the 1.5 s typical error on the measurements of the observed differential travel time residuals. Left, residuals for fixed station CMB and PAS. Right, residuals for fixed the Fiji Islands earthquakes of January 19, 1994, and October 19, 1996. The modified model reproduces the observed trends reasonably well.

puted predicted residuals for tomographic models modified up to several successive heights above the CMB. In Figure 5, we compare observed residuals with synthetic ones computed for models that were only modified from the CMB to a height of 500 km (top), and 1200 km (bottom).

Predicted residuals clearly fit the observations better when the model is modified up to 1200 km above the CMB, that is, when the slow anomalous domain extends well above the top of D". This simple test does not preclude the possibility of explaining the observations by a more complex structure localized in the last 300 to 500 km of the mantle. However, such a scenario seems unlikely because it would imply a structure that is less compatible with existing tomographic models. On the other hand, we note that differential residuals appear to rapidly lose their sensitivity as heterogeneity gets shallower, so that we cannot preclude that the anomalous domain extends even higher above the CMB.

Fast region

A few S-SKS profiles for a fixed earthquake show a sudden increase at small epicentral distance (86 to 90°), followed by a decrease of the residuals, when the epicentral distance varies from about 90 to 96° [*Bréger and Romanowicz*, 1998]. Increasing residuals can be easily explained by the fact that S waves spend more time in the slow region with increasing distance, and therefore accumulate an increasingly large delay. However, it is impossible to explain decreasing residuals with the slow structure alone, and introducing a fast region becomes necessary. This region needs to be localized in the last 400 km of the mantle in order to start affecting the S-wave at epicentral distances larger than about 90°. The exact strength, position, and velocity anomaly of this region are difficult to determine precisely considering that it is sampled by only a few profiles, but we estimate that it is a fairly localized domain, with lateral dimensions on the order of 500 km by 500 km, and extending vertically to about 400 km above the CMB respectively, and corresponds to a S-velocity anomaly on the order of 3 to 4%.

Discussion

The family of models proposed here is consistent with an earlier model for the same region, derived exclusively from S-SKS data. Tomographic models seem to give a reasonable estimate of the position of the heterogeneous domain, but significantly higher amplitudes of heterogeneity are required to explain S-SKS and S-ScS differential travel time data. We confirm that the central Pacific anomaly extends at least as high as shown in *Bréger and Romanowicz* [1998], up to at least 1200 km above the CMB. It is not necessarily connected to the Hawaiian hotspot, considering that it deflects to the South-West, away from Hawaii.

It appears as a broad but well-defined area which narrows as it rises rises from the CMB, and is thus morphologically different from the type of uniform layer of chemically distinct deep mantle material, as proposed by *Kellogg et al.,* [1999].

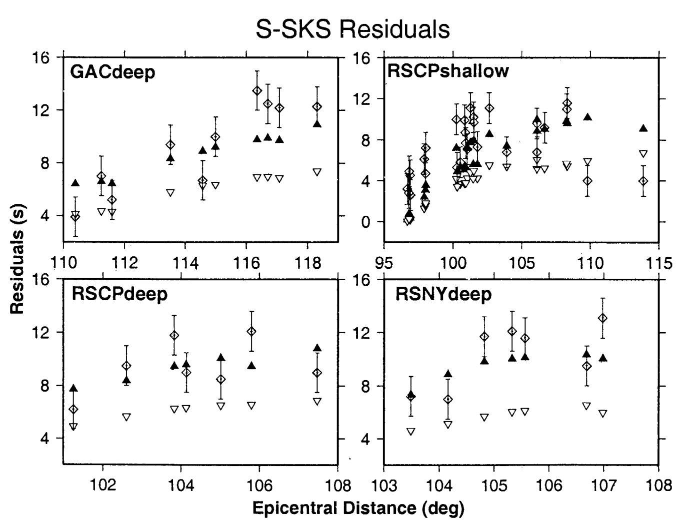

Figure 4. Same as Figure 3 for S-SKS differential travel time residuals observed at station RSCP for shallow and deep events, and stations GAC and RSNY for deep events. Residuals show a systematic increase with epicentral distance, due to the increasingly large time spent by the S wave in the slow domain.

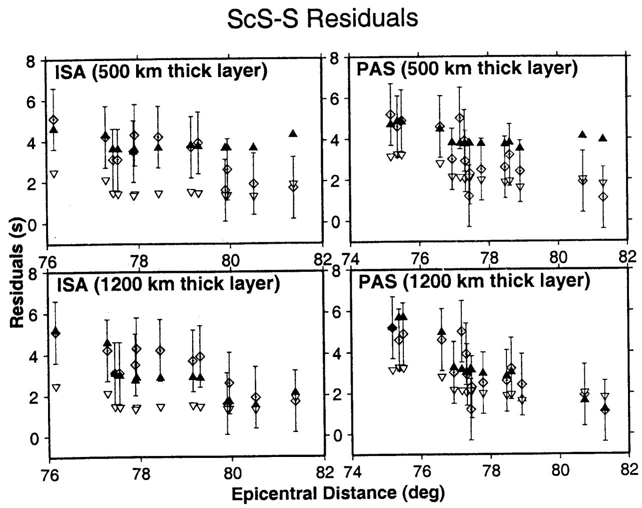

Figure 5. Same as Figure 3 for S-ScS differential travel time residuals observed at station ISA (left) and PAS (right), comparing models modified from the CMB to a height of 500 km (top), and 1200 km (bottom) above the CMB.

The heterogeneous domains identified here are likely associated with physical or chemical anomalies rather than purely thermal anomalies, as suggested by the presence of some very large anomalies and lateral gradients. In particular, some degree of partial melting could explain an S-velocity reduction by as much as as -3 to -4%.

The laterally varying splitting of S-waves propagating in that region of the deep mantle has been traditionally explained by the shearing and mixing of heterogeneous material [*Vinnik et al.*, 1998], and by small-scale convective structure in the thermal boundary layer [*Russell et al.*, 1998]. However, we note that the paths for which Sdiff was strongly split in *Vinnik et al.* [1998] also correspond to a pronounced interaction with the fast domain identified here. Some frozen anisotropy in the fast region could be an alternate explanation consistent with the splitting observed in other fast velocity regions such as beneath Alaska and Central America. This possibility will be explored further.

Finally, the strong gradients associated with the border of this upwelling need to be taken into account when correcting core phases, before any inference can be made on structure in the core, and in particular the inner core [*Bréger et al.*, 2000].

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