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The effect of D″ on PKP(AB−DF) travel time residuals and possible implications for inner core structure

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Abstract

The hypothesis that the deep inner core is anisotropic is based on PKP travel time observations at large distances and relies on a small number of very anomalous measurements for paths quasi-parallel to the Earth's rotation axis. Here, we analyze a global dataset of PKP(AB−DF) travel times residuals, and discuss their significant dispersion (±2 s), and coherent large scale patterns. We show that the trends observed for quasi-equatorial paths are consistent with predictions from recent tomographic mantle models, when the latter are modified to account for strong heterogeneity at the base of the mantle under the Pacific Ocean and Africa, as documented in several recent studies. Likewise, for polar paths, we show that a large part of the signal could be explained by deep mantle structure. The effects of complex structure in the deep mantle on PKP(AB−DF) travel times should be carefully considered in order to reliably estimate the anisotropic structure of the central part of the inner core.

Keywords: seismology; core; mantle; body wave; propagation

1. Introduction

Fifteen years ago, Poupinet et al. [1] showed that waves turning in the inner core (PKIKP, PKP(DF) or simply DF) and travelling parallel to the Earth's rotation axis were on average 1–2 s faster than those propagating along the equatorial plane. These observations were later interpreted in terms of inner core anisotropy [2], which could simultaneously explain the anomalous splitting of core sensitive free oscillations [3]. This pioneer work was followed by many studies confirming and refining this interpretation [4–13]. Although the existence of cylindrical anisotropy, with an average strength of about 3–3.5%, in the inner core now seems widely accepted, there is no consensus on the details of its distribution. There are indications that it may be weaker near the surface than towards the center of the inner core, and that it may be laterally varying. Notably, some recent results suggest that there might be anisotropy in only one hemisphere of the inner core [14], and even that the top 250 km may be isotropic [15], which is hard to reconcile with normal mode data, which require anisotropy to be present in the top third of the inner core [8,11,16].

In order to study inner core structure using the phase PKP(DF), outer core sensitive phases PKP(BC) and PKP(AB) (Fig. 1A) are generally

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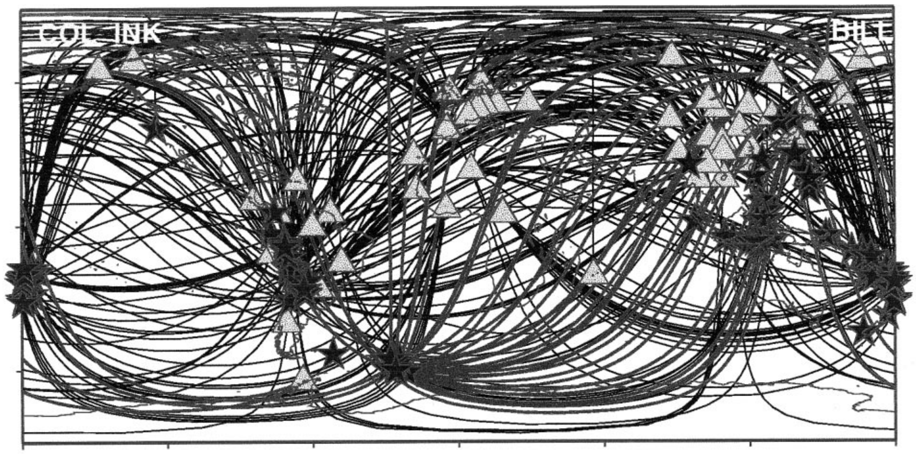
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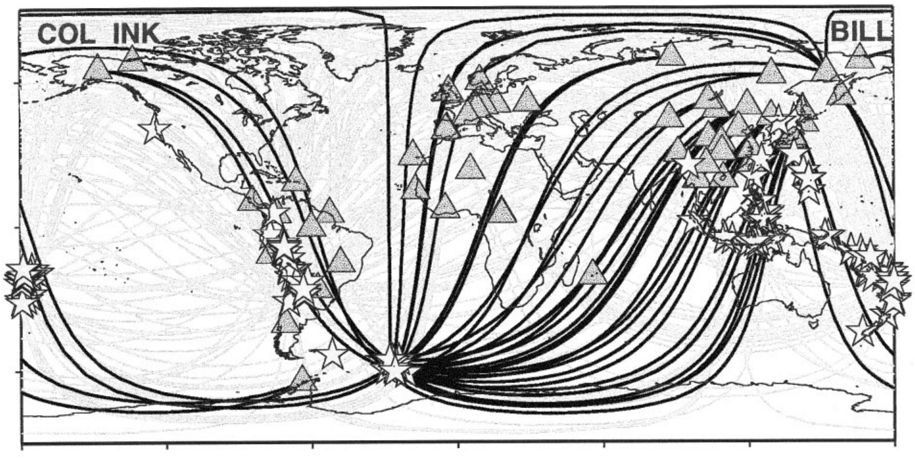
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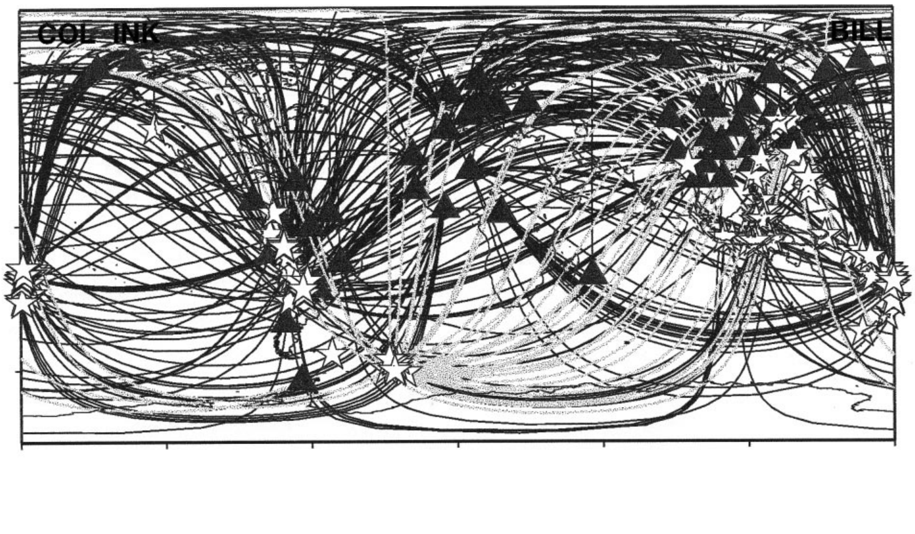

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used as reference phases. Differential travel times PKP(BC−DF) and PKP(AB−DF) have the advantage of reducing earthquake mislocation and origin time errors, near-source and near-receiver structure, and are, in principle, less sensitive than absolute times to large scale deep mantle structure. Bréger et al. [17] showed recently that PKP(BC−DF) differential residuals were incompatible with a simple model of inner core anisotropy, and suggested that their complex behavior could be explained by a complex inner core structure, but also proposed that contamination of PKP(BC−DF) residuals by D″ heterogeneity could have been generally underestimated and suggested deep mantle structure as a complementary, or even alternative explanation. On the other hand, PKP(AB−DF) differential travel times obtained at large distances (150–180°) are particularly valuable, since at those distances PKP(DF) uniquely samples the central part of the inner core. Although it has been often recognized that mantle heterogeneity contributes to the large scatter observed in the PKP(AB−DF) travel time residuals [18–20], so far, it has been assumed that the large scale trend observed, namely an increase of residual as the path approaches the Earth's rotation axis, is best explained in terms of the effect of inner core anisotropy on the PKP(DF) phase [6,9].

We have assembled a dataset of 335 PKP(AB−DF) differential travel times which we measured on the vertical component of Geoscope,

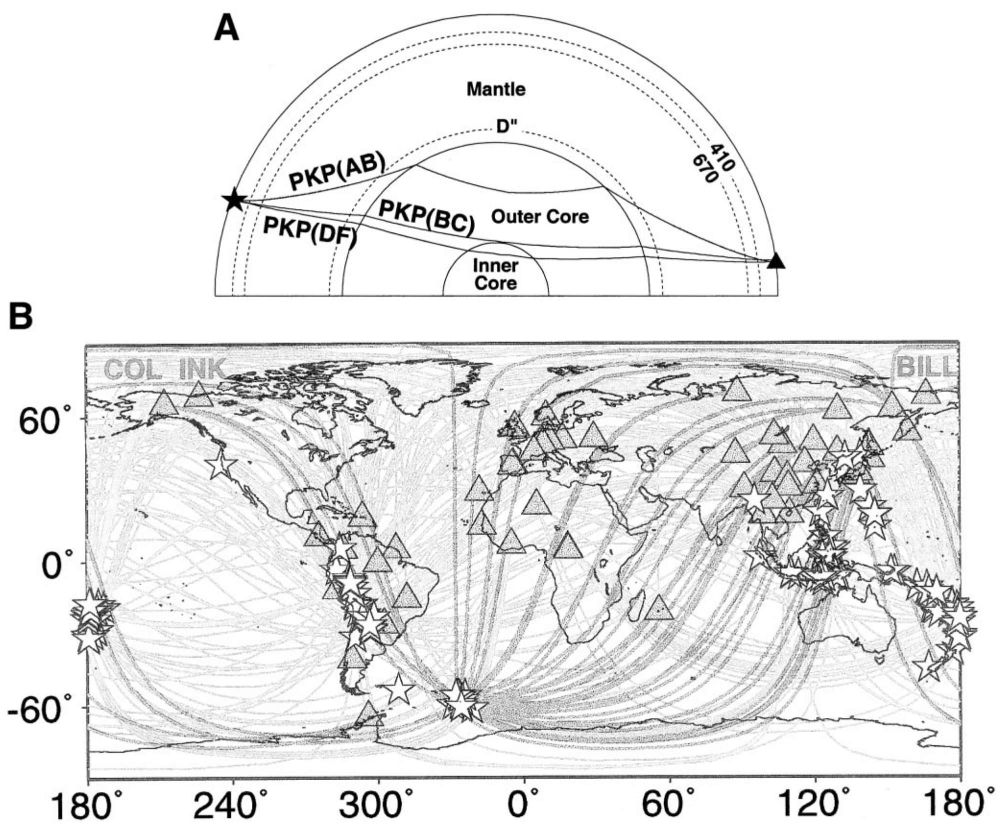


Fig. 1. (A) Schematic representation of the wavepaths of PKP(DF), PKP(AB), and PKP(BC) discussed in this study. (B) Earthquakes (stars), stations (triangles), and projections of the raypaths analyzed. We used 137 events from 1987 to 1998, and 57 stations. Our dataset consists of our own measurements and data from [6]. The geographical distribution is representative of currently available data. Note the large number of quasi-equatorial paths ($\xi > 45°$, green lines), but the reduced number of quasi-polar paths ($\xi < 45°$, red lines).

IRIS, GRSN, and Mednet broadband records and combined them with the previously assembled collection of [6]. PKP(AB−DF) differential times were determined by overlapping the PKP(AB) waveform with the Hilbert transform of PKP(DF). Residuals were computed with respect to the Preliminary Reference Earth Model [21]. Standard ellipticity corrections [22] were applied. The global coverage provided by this dataset is similar to that of other studies, with a large number of quasi-equatorial paths but considerably fewer paths approaching the Earth's rotation axis (Fig. 1B).

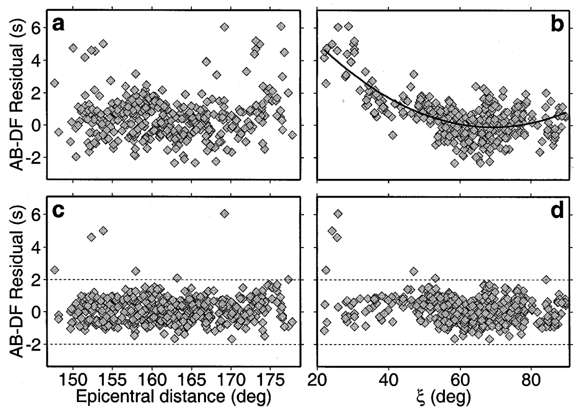


Fig. 2. AB−DF differential travel time residuals as a function of epicentral distance (a) and angle ξ of the path in the inner core with respect to the rotation axis (b). Typical measurement errors are in the order of 0.1–0.2 s, and error bars would have the height of diamonds. The best fitting second degree polynomial in $\cos^2\xi$ (solid line) is shown in (b) to outline the observed trend. Such a trend is expected, at fixed distance, for models of constant cylindrical anisotropy in the inner core. (c and d): Same as (a) and (b) after correction for the MMM model. Mean residuals are 1.05 and 0.67 s, respectively before and after correction using MMM. Note that a few large residuals at low ξ remain unexplained. These correspond to South Sandwich Islands paths to stations COL and BILL. The complexity of these particular paths has been noted previously, for instance, BC−DF residuals differing by more than 2 s for neighboring stations [14,17].

2. AB−DF differential residuals as a function of polar angle

Plots of AB−DF residuals as a function of epicentral distance and angle with respect to the rotation axis (Fig. 2a,b) are consistent with results from previous studies [6,9]. In particular, the trend with angle (hereafter called ξ) is as expected for a simple model of constant cylindrical inner core anisotropy. The dispersion observed around that trend is of the order of ±2.5 s, which is also consistent with earlier work [6,9,18–20] and is much larger than measurement uncertainty. The distribution of AB−DF data as a function of angle ξ is very non-uniform (Fig. 3a). There are only a small number of data points for ξ between 0 and 30°, and most of these correspond to earthquakes in the South Sandwich Islands region. Interestingly, the distribution of mean AB−DF travel time anomalies as a function of ξ (Fig. 3b) indicates that the largest anomalies correspond to the poorest sampling. In order to obtain a rough estimate of the contribution of mantle structure to AB−DF residuals, we computed synthetic anomalies based on a recent tomographic model. We used Grand's [23] recent S-velocity model and converted it to P, assuming $\mathrm{dln}(Vs)/\mathrm{dln}(Vp) = 2$. Although it has been shown that P and S anomalies do not always vary in proportion [24], an S-velocity model was preferred to a P-velocity velocity model for several reasons. First, there is reasonably good agreement between recent S-velocity tomographic models in the lowermost mantle [23,25–27]. The low harmonic degrees are in particular very similar which suggests that S models now give a good description of large scale D″ heterogeneity. S-velocity models were also recently shown to give a rather accurate description of the shape of heterogeneity in the deep mantle beneath the Central Pacific [28], and Africa [29] 'plumes'. These two regions are particularly important because they are, so far, the two most anomalous domains of D″. P-velocity models of the deep mantle, on the other hand, are still rather different [30–33], and suffer from uneven coverage in D″ in oceanic regions, which are of most interest in the present study. We verified that the distribution of P-velocity anomalies predicted by a model recently derived specifically for D″ [32] was compatible with that predicted using our S derived P model, which suggests that this approach is reasonable. We

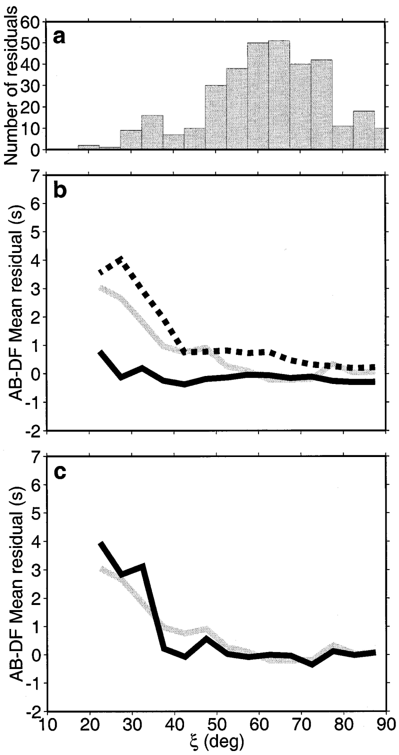


Fig. 3. (a) Number of AB−DF residuals as a function of angle ξ of the path in the inner core with respect to the Earth's rotation axis. (b) Plotted as a function of ξ, mean AB−DF residuals observed (solid gray line), and predicted by Creager's [5] inner core constant (3.5%) anisotropy model (dashed line), and by a combination of the original tomographic model as well as ULVZs (solid black line). The combined effect of ULVZs and heterogeneity predicted by the tomographic model is not sufficient to explain the average AB−DF variations. (c) Same as (b) with observed residuals (gray line) compared to predictions by our MMM model. Mean residuals were obtained by averaging observed anomalies over 5° in ξ. The root mean square differences between average observations and predictions are 0.32 s for the tomographic model, 0.19 s for the inner core model, 0.24 s for a model combining the tomographic and inner core models, and 0.14 s for our modified mantle model, and the scatter of the mean residuals is estimated at 1.8 s.

have computed synthetic travel time residuals using ray theory. The ray tracing was done in the spherically symmetric PREM model [21]. For a few paths, we have verified that the residuals obtained are within 0.5 s of those computed for a typical path from South Sandwich Islands to northern Eurasia, using an acoustic 2D finite difference algorithm [34].

Mean synthetic residuals are presented in Fig. 3b. As pointed out in earlier studies [18–20], it is difficult to produce synthetic residuals larger than about 1 s with any existing tomographic model. For comparison, we also plotted the predictions for a standard 3.5% constant inner core anisotropy model that has been proposed to fit AB−DF data [6]. As expected, this model reproduces the variations with ξ well, slightly overpredicting them (a model with 2.75% constant anisotropy would provide the best fit). We tried the combination of both the mantle and the inner core model (not shown), but the fit is actually slightly degraded.

Because they represent a smoothed image of heterogeneity in the mantle, tomographic models usually underpredict the trends associated with data which sample regions where strong or small scale heterogeneity may be present. This has been demonstrated, in particular, using S-SKS travel time residuals sampling D″ in the central Pacific and Africa [29–31]. These studies showed, however, that it was possible to perturb the existing models locally, in order to obtain good fits to S-SKS, SKKS-SKS or S-ScS travel time observations [29–31]. The required perturbations, although non-unique in their details, could be achieved effectively by keeping the shape of the boundaries between fast and slow anomalies fixed, and increasing the amplitudes of fluctuations, mostly in D″ (the bottom 300 km of the mantle), by a factor of 2–3. While there is some trade-off between the amplitude increase and the depth range affected, the modification of the starting tomographic model has been shown to be necessary only in the deepest mantle, where the paths of the two phases in the differential pair differ the most. In the light of these studies, we have adopted a similar approach to try to better model our AB−DF observations.

The geometry of the pair AB/DF is quite similar to that of S/SKS: SKS and PKP(DF) dive at steep angles into the core, while S and PKP(AB) graze the CMB at large distances, diffract over a few degrees, and can accumulate large residuals in the strongly heterogeneous D″. As found from

global tomographic studies, the lowermost mantle presents two major very slow, large scale anomalous domains: one beneath the Central Pacific, and one beneath Africa (e.g. [24–34]). We have assumed, as in [29–31], that slow velocity anomalies were strongly underpredicted under the Pacific and Africa, and we have increased their amplitude in the very bottom of the mantle, while not changing their shape. All anomalies slower than 0.3% for depths greater than 2500 km only were saturated to 2% P-velocity reduction. Note that the thickness of the layer over which the model is modified trades off with the assigned P-velocity reduction.

In addition, in the computation of synthetic AB and DF residuals, we have included the effect of ultra low velocity zones (ULVZs) in places where they have been reliably documented [35]. ULVZs are particularly important to consider because they represent a very large average P-velocity reduction, and may significantly slow down PKP(AB) at the largest distances. We assigned values of 10% for the P-wave velocity reduction and 10 km for the thickness of the ULVZ. These values are conservative since some regions of D″ have been shown to experience P-velocity reductions of more than 10% over a few tens of kilometers (e.g. [35,36]). There are also trade-offs between thickness of ULVZs and velocity reductions, which will not affect the resulting fits significantly, in terms of our conclusions. In what follows, we will describe the prediction of the modified mantle model, first looking at specific source regions.

3. Predictions of the modified mantle model

3.1. *Residuals for earthquakes in the Fiji Islands source region (equatorial paths)*

For events in the Fiji Islands source region, the observed AB−DF residuals as a function of azimuth (Fig. 4a) and angle ξ (Fig. 4b) show systematic long wavelength variations, as well as large local scatter (in excess of 2 s), which cannot be explained by either the tomographic (Fig. 4a,b) or inner core models considered previously (Fig. 4c,d). While we note that the tomographic model predicts more local scatter, both the inner core and mantle models predict very little long wavelength variation as a function of either azimuth or ξ. The small effect of inner core anisotropy is in agreement with the fact that, for this particular source region, only angles $\xi > 43°$ are sampled, while the effect of anisotropy only starts to be significant at $\xi < 40°$.

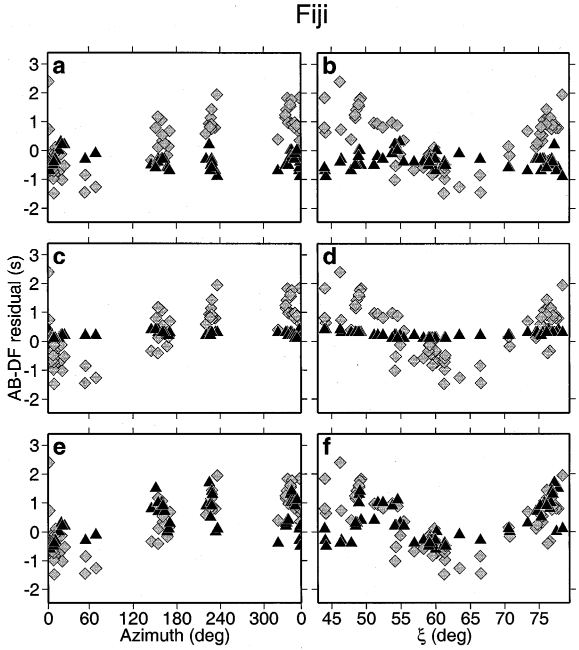
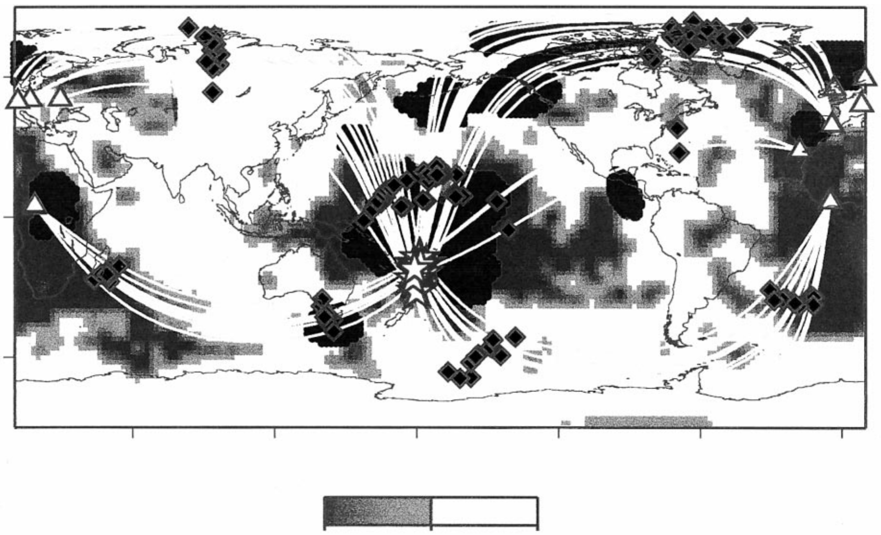
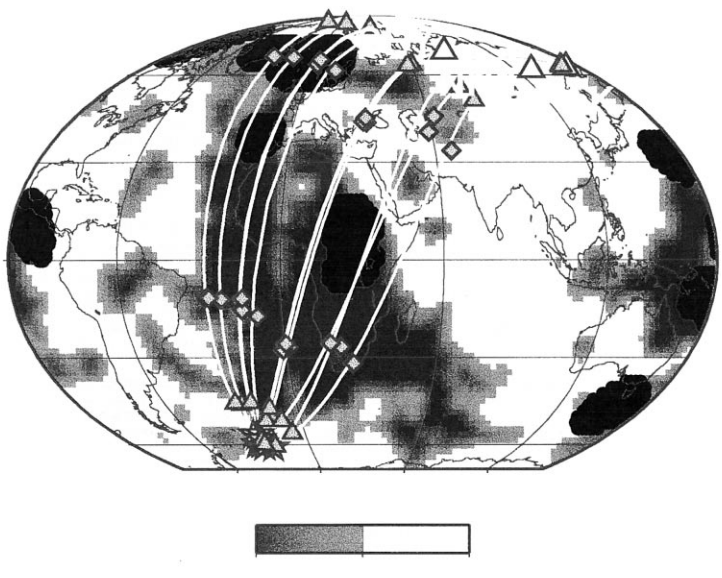
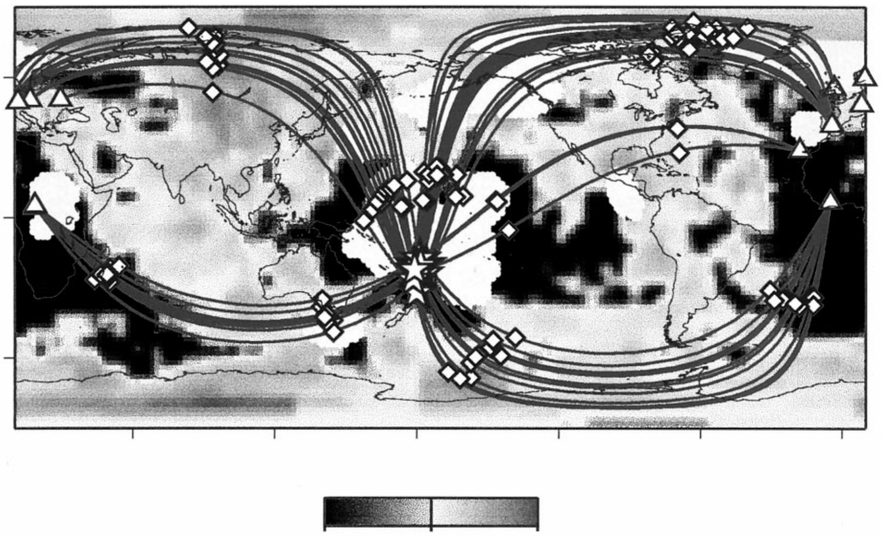


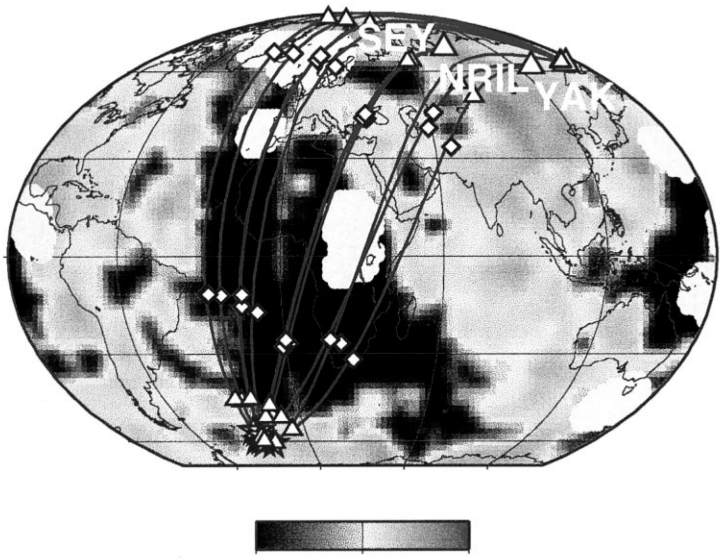
Fig. 4. Observed AB−DF travel time residuals (gray diamonds) for events located in the Fiji Islands region as a function of azimuth from the source (left) and angle ξ with respect to the Earth's rotation axis (right). Predicted anomalies (black triangles) are (a)(b) for the tomographic model described in (c)(d) for Creager's [5] inner core anisotropy model, and (e)(f) for the MMM model

Synthetic residuals computed using this revised model (MMM, Fig. 5) now show a better agreement with the observations (Fig. 4e,f), even though we did not attempt to adjust the model to fit the data on any particular path. The modified tomographic model predicts the large scale trends and local scatter of the observed residuals. On the other hand, we verified that combining the nonmodified mantle model with ULVZs does not significantly improve the fit compared the original tomographic model alone. Note that the fit of the









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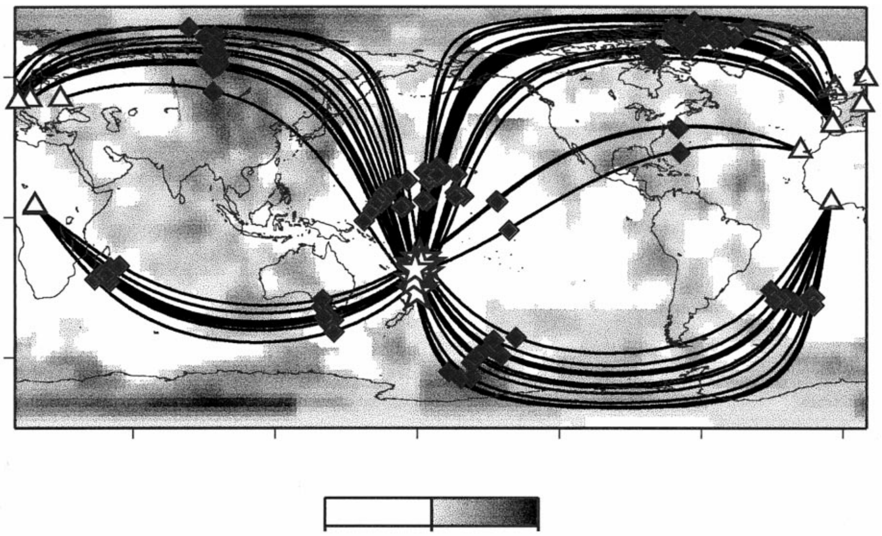

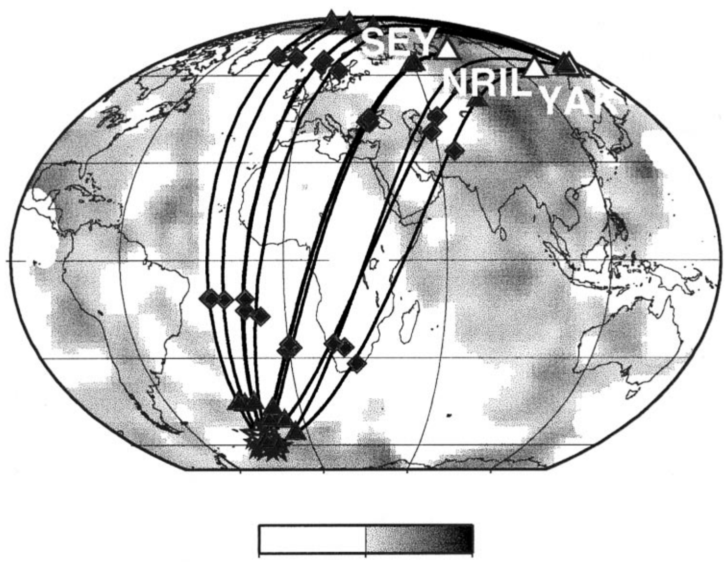
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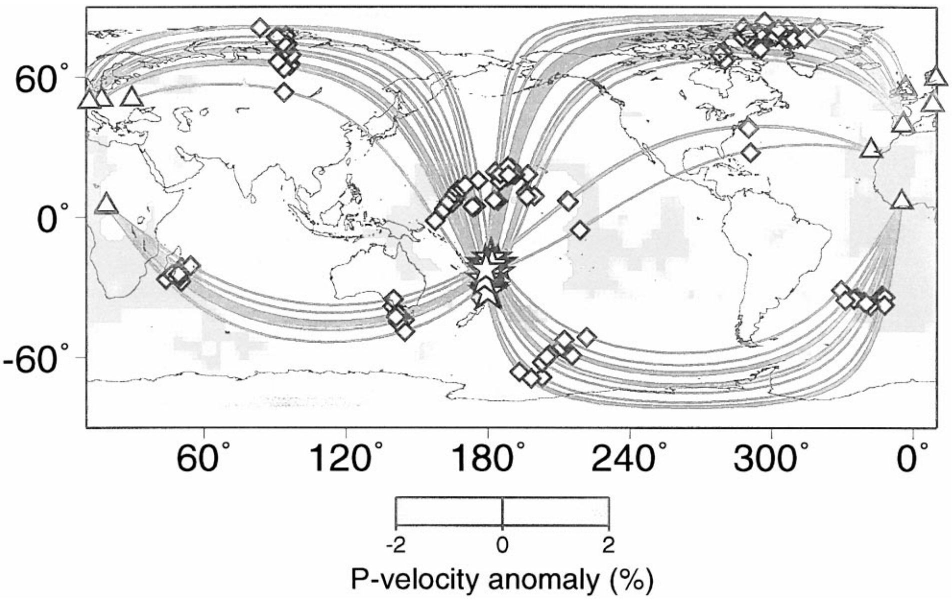


Fig. 5. Projections of the raypaths (blue lines) for the Fiji Islands events (white stars) used in this study, along with the corresponding stations (white triangles). Also indicated are the regions where ULVZs have been documented (bright yellow), and the points were the AB ray enters and exits the outer core (diamonds). The background MMM P-velocity model has been modified from Grand's S-velocity model [24].

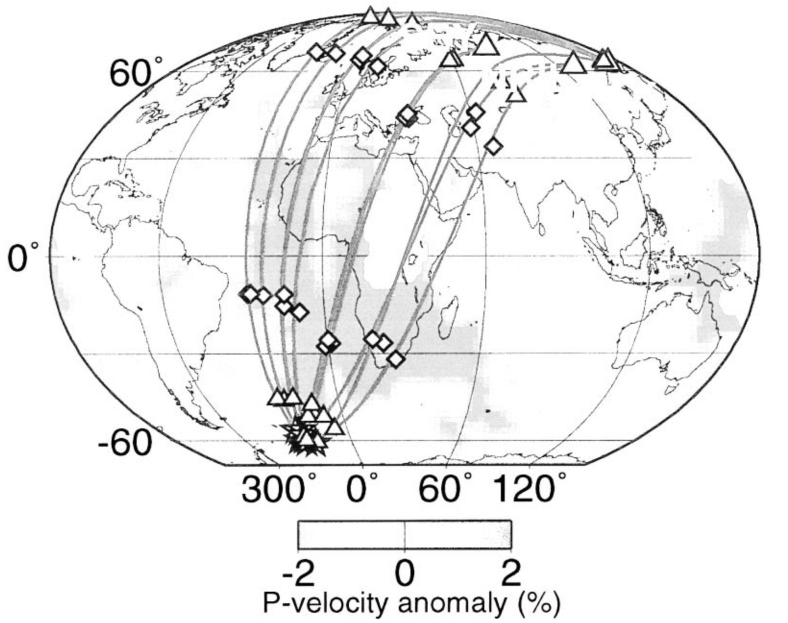


Fig. 6. Projections of the raypaths (blue lines) associated with stations SEY (Seymchan, Russia, 62.93°N 152.37°E), NRIL (Norilsk, Russia, 69.50°N 88.44°E), and YAK (Yakutsk, Russia, 62.017°N 129.72°E) (white triangles), along with the corresponding events (white stars) in the South Sandwich Islands source region. Also indicated are the regions where ULVZs were detected (bright yellow regions), and the points were the AB and DF rays enter and exit the outer core (diamonds and triangles, respectively). The background P-velocity model is the same as in Fig. 5.

MMM model is not perfect, and in particular, additional forward modeling of paths at azimuth of less 60° (and mostly $\xi < 50°$) could improve it significantly. This could be achieved by adjusting the lateral extent of ULVZs near the source or the receiver. It is not the purpose of this study, however, to provide a best-fitting model, which would involve resolving many trade-offs which are beyond the scope of this paper. This simple experiment demonstrates how it is possible to explain both the scatter and large scale variations observed in the differential residuals by an effect of locally strong heterogeneities in the deep mantle, primarily on AB, with a distribution as documented from previous work.

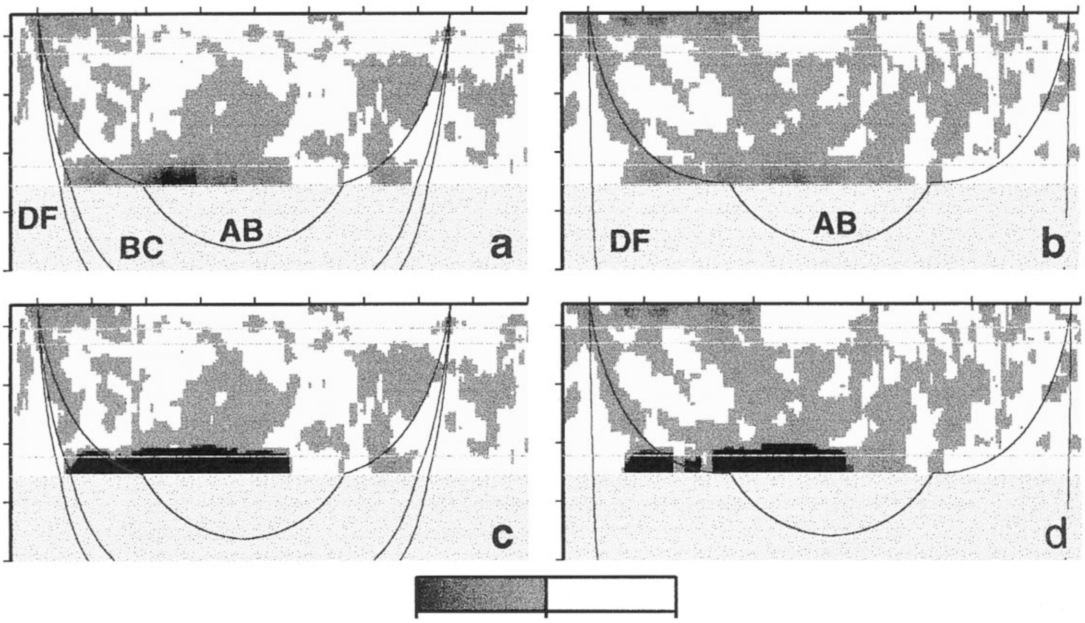
After departing from the Fiji Islands region, AB and DF both travel through several hundred kilometers of slow mantle. Although heterogeneity is large there [29,37,38], the resulting anomaly does not exceed about 1 s, because DF and AB are similarly affected. Similarly, when AB and DF later exit the outer core and propagate into the strong slow African anomaly before being recorded at African stations (Fig. 5), no differential residual larger than 2 s is produced (Fig. 4). Some weakly anomalous differential residuals corresponding to paths sampling the very heterogeneous African region have also been reported [39]. They do not contradict the existence of a very slow region in this part of the deep mantle, as again, DF and AB can sense the same structure, accumulate similar residuals, and yield differential residuals close to zero.

3.2. South Sandwich to Eurasia (polar paths)

In some other regions, however, DF may propagate through a normal to fast heterogeneous region in the lowermost mantle, while AB experiences some large delays due to a consistently very slow anomaly. We believe this is the case for the quasi-polar paths from South Sandwich Islands events to northern Eurasia (Fig. 6). There is actually direct evidence of an average mantle contamination of about 4 s on PKP(AB): for South Sandwich Islands events, station SEY (62.93°N 152.37°E) reports an average AB−DF residual of 5.0 s, but an average DF residual of −1 s [6]. This type of path happens to correspond to a geometry for which AB spends most of its time in the lower mantle within the large African slow anomaly (Fig. 7), while DF misses the zone of strongly reduced velocity. In addition, there are several paths which, on the receiver side, sample the very anomalous ULVZ region recently detected beneath Iceland [36]. Predictions of the inner core anisotropy model (Fig. 8) are unable to match either the short or the long wavelength trends and amplitudes of AB−DF travel time residuals, at the three stations considered, whereas the MMM model explains the large values of the residuals as well as their variations much better, as a function of both the longitude of the CMB entry point of AB, and of angle ξ.

3.3. Effect on the complete dataset

We now compute the predictions of the MMM model for the complete, global dataset. Fig. 3c shows the predictions of the modified mantle model, without adding inner core anisotropy, as a function of angle ξ. The fit to both the trend and variation with angle of the binned data is at least as good as that obtained with the inner core anisotropy model in Fig. 3b. Fig. 2c,d shows the AB−DF residuals corrected for model MMM as a function of distance and ξ. While MMM has not been adjusted to provide a best fit for individual paths, and therefore some dispersion remains, a surprising result is that the trend of increasing residuals with decreasing ξ (Fig. 2b) has practically disappeared (Fig. 2d). However, several unexplained anomalies are still present at angles close to 25°. These correspond to paths from South Sandwich Islands to stations COLA and BILL (Fig. 1b). These paths have previously been identified, on the basis of PKP(BC−DF) travel time measurements, as particularly anomalous, and correspond to very strong small scale lateral variations [40]. Comparing individual measurements at COL and neighboring station INK (Fig. 1b), we find travel time residuals for (AB−DF) of 5 s and 2.6 s respectively, indicating that a highly complex zone is sampled somewhere along these paths, requiring strong heterogeneity. DF and AB station legs for COL and INK are



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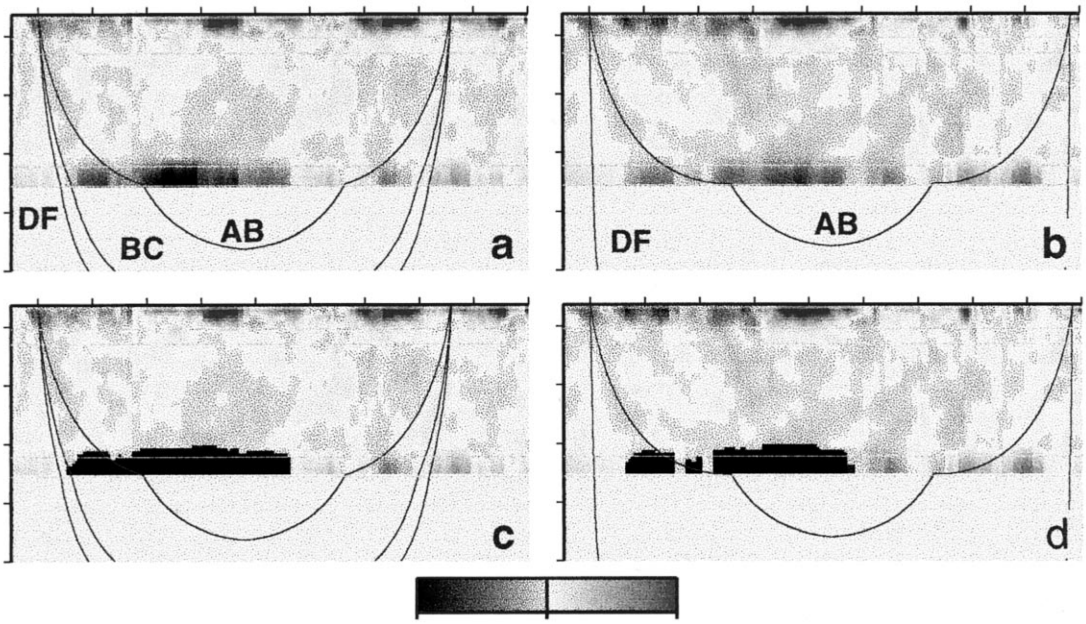

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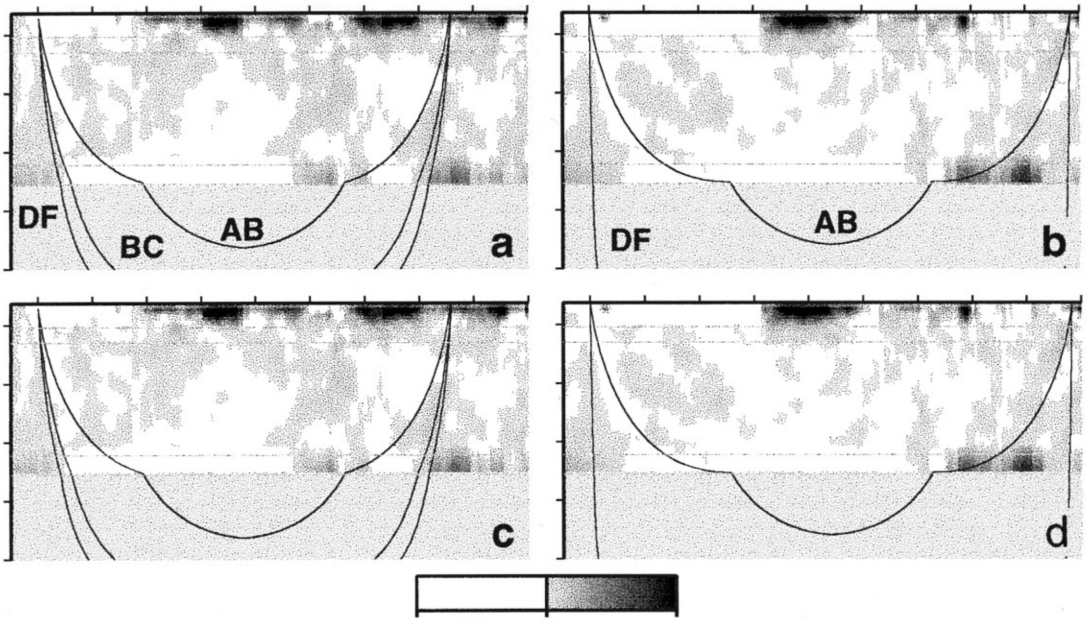

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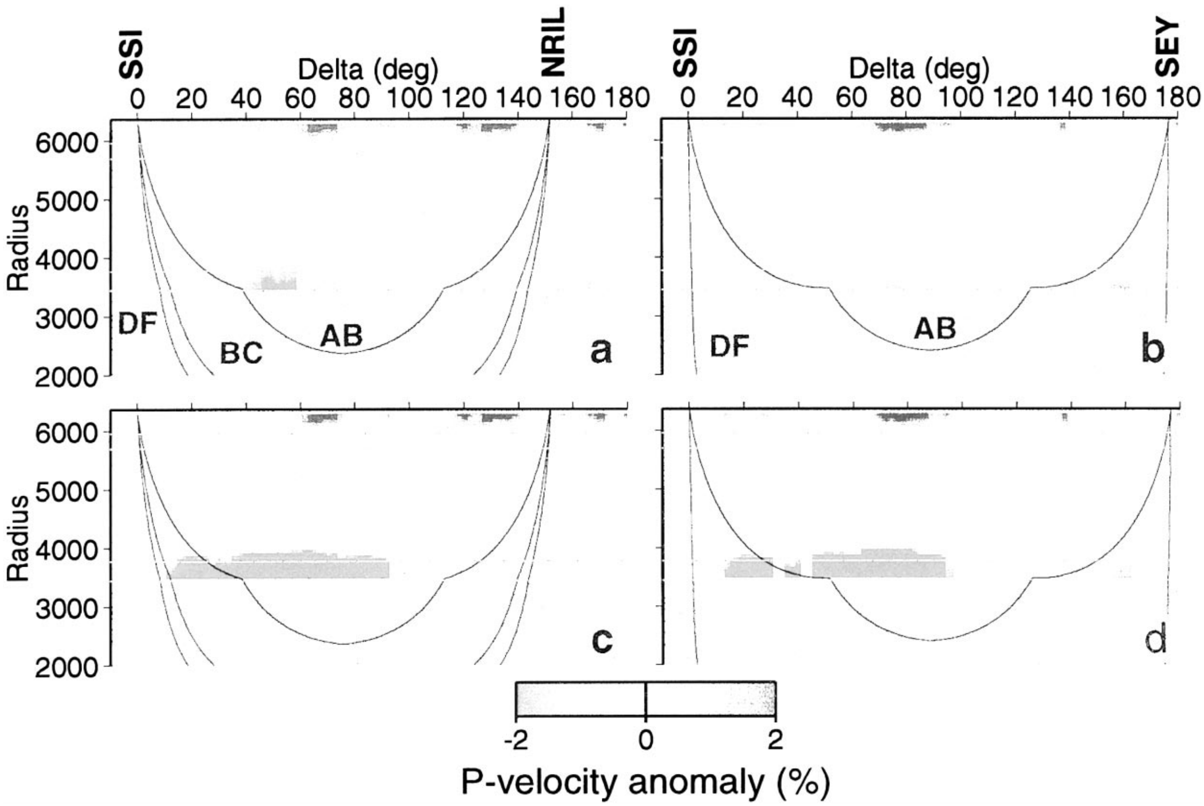

Fig. 7. (a) Cross section through the original tomographic model for a path between South Sandwich Island event 93/01/10 (−59.42°N −25.78°E 33 km) and station NRIL (distance 151.50°). Also plotted are AB, BC, and DF raypaths. (b) Same as (a) for a path to station SEY (distance 176.37°). Also plotted are the AB and DF raypaths (BC does not exist at this distance). (c and d) Same as (a) and (b) for the modified MMM velocity model. Note that the latter model is arbitrary outside regions sampled by our paths.

separated by about 400 km at the CMB. While a very complex anisotropic pattern could be present in the inner core, these strong local variations could also result from heterogeneity in D″ given what we independently know about the deep mantle. For example DF at COL could be sampling a fast region on the border of an ULVZ, as has been documented to exist in the Central Pacific [29], while both DF and AB would be traveling through the ULVZ at INK. The effect of subducted slabs along the raypaths could also contribute to the differential travel times [41].

4. Discussion

Observations of PKP(AB−DF) travel time residuals exceeding 5–6 s are generally interpreted as evidence for the presence of a 3.5% average cylindrical anisotropy in the bulk of the inner core. Because of the uneven distribution of sources and receivers, these residuals happen to be, for a large part, associated with raypaths between the South Sandwich Islands region and northern European, North American and Russian stations, which sample the edge of the African plume, at the base of the mantle. AB−DF differential residuals are extremely sensitive to P-velocity variations at the base of the mantle [18–20], and we have shown that it is possible to explain their trends, and even their sometimes large values, using a simple modification to an existing tomographic model that takes into account the complexity of the D″ region, as recently documented.

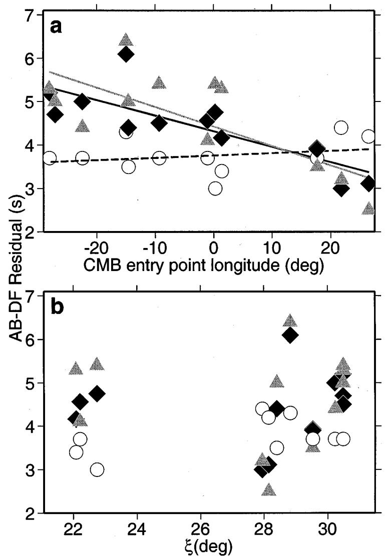

Fig. 8. AB−DF residuals for stations SEY, NRIL, and YAK, and South Sandwich Islands earthquakes, plotted as a function of the longitude of the point where AB enters the outer core (a) and as a function of ξ (b). We compare observations (black diamonds, black line), to predictions for Creager's [5] inner core anisotropy model (white circles, dashed line), and our modified tomographic model (gray triangles, gray line). The rms residual is 0.32 s for Creager's model, and 0.16 s for the MMM model.

Our forward modeling of AB−DF travel times suggests that these large distance residuals are likely to be significantly affected by the strong heterogeneity present in the deep mantle beneath the Pacific and Africa, and that this heterogeneity must be taken into account accurately before making inferences from this type of data regarding the strength and characteristics of inner core anisotropy. The latter may have been much overestimated, and, as Fig. 3b,c shows, there are strong trade-offs between both effects.

The MMM model which we have used to correct PKP(AB−DF) data is not a definitive model, since, with the exception of the ULVZ regions, it has not been designed to fit any specific dataset. It should not be expected to provide particularly good fit to other dataset sensitive to D″ structure; it is a composite model reflecting recent evidence on the strength and distribution of heterogeneity in D″ [29–31,35,36]. While the MMM model, with all its trade-offs, may be valid in the regions sampled by our dataset, we make no claims that it is valid everywhere on the globe. Our goal in defining it globally was only to qualitatively illustrate the point that current tomographic models underestimate amplitudes of lateral variations in D″. In fact, MMM only amplifies low velocity zones, but stronger anomalies in high velocity regions are also needed in some places [29]. Also, MMM should not be expected to predict absolute residuals better than standard tomographic models. Such travel times are very sensitive to mislocation effects, and to the structure of the whole mantle, which is not accounted for in MMM.

Because MMM is not a real model, more accurate inferences on whether or not any anisotropy is still required in the central part of the inner core cannot be made at this point. In particular, DF absolute residuals should also be considered. We note however that, in order to attribute the observed trends in differential travel times to DF, rather than AB, a much more complex model of inner core anisotropy or lateral heterogeneity in the inner core [17] would be required, as has been suggested for the very anomalous paths from the South Sandwich Islands to station COL [40]. While the former deserves further investigation, the latter would imply extremely strong lateral gradients of velocity within the inner core, in order to explain the local scatter in the data as discussed above. This is physically much less plausible than a D″ origin, considering that the inner core is thought to have been formed by freezing of liquid core material largely homogenized through vigorous convection. The strength of a primarily D″ interpretation lies in its ability to explain both long and short wavelength trends in the data.

The large distance data discussed here provide insight only into the structure of the deepest two-thirds of the inner core. In order to make inferences about the shallower parts, PKP(DF) absolute travel times, PKP(BC−DF) travel times [41], and normal mode data [42] must be considered also. Recent evidence based on PKP data in the BC range suggests however that at least one hemisphere may be isotropic [14]. Interestingly, quasi-polar paths sampling this hemisphere also happen to propagate almost exclusively in a region of the

deep mantle which seems to be less heterogeneous than Africa or the central Pacific: there is so far no evidence for ULVZs between longitudes of 60 and 150°E (Fig. 6). Recently, we have discussed complex trends in BC−DF travel time data for polar paths, which require complex structure (anisotropic or isotropic) either at the top of the inner core, or at the bottom of the mantle [17]. While this needs to be investigated further, the possible lack of anisotropy near the top of the inner core [15] requires a reconsideration of anomalous normal mode splitting [42].

There has been a lack of consensus as to the details of anisotropic structure in the inner core. We believe that the contamination of inner core sensitive data by structure at the bottom of the mantle may have been generally underestimated, and that future efforts to derive realistic models of inner core structure will have to accurately account for such effects.

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