3D structure of the lowermost mantle: implications for core sensitive body wave data

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Abstract

We here summarize our recent results in which we have shown that heterogeneity at the base of the mantle is stronger than described by tomographic models. In particular, our studies and those of other groups indicate that the borders of the African and Pacific "plumes" at the base of the mantle must be the sites of strong gradients and complex structure.

This organized heterogeneity at the base of the mantle affects the travel times of PKP phases sensitive to core structure. We show that, indeed, at least 80% of the variance in PKP(AB-DF) differential travel times can be explained byD" structure. While recent models have proposed complex inner core anisotropy structure to explain the observed trends in PKP(AB-DF) and PKP(BC-DF) data, we propose that this complexity originates at the base of the mantle. Between 1and 2 sec of anomaly on some very anomalous paths between South Sandwich Islands and Alaska remains to be explained. This can be done either by invoking a simple model of inner core anisotropy, or increased complexity in mantle structure. The former has the advantage of also providing an explanation for anomalous splitting of inner core sensitive modes. However, mantle structure needs to be better resolved before this issue can be clarified.

1. Tomographic models of the mantle

Global tomographic S velocity models of the mantle consistently show that the structure of the bottom few hundred km of the mantle is distinct from the overlying bulk of the lower mantle: there is a significant increase in the rms of lateral velocity variations, and the spectrum of lateral heterogeneity changes from white to red, with a dominant contribution of degree 2 structure (e.g. Li and Romanowicz, 1996). In particular, the existence of two large low-velocity anomalies at the base of the mantle, one centered in the Pacific Ocean and the other under Africa, are now well documented. Recent models indicate that these anomalies, which are very broad at their base near the core-mantle boundary, extend at least several hundred km into the lower mantle (figure 1). There are indications, however, that the tomographic inversions have a tendency to provide a smoothed version of the structure at the base of the mantle, and do not accurately recover the lateral gradients and strength of heterogeneity.

In a series of recent studies, we have performed forward modeling of differential travel times of lowermost mantle sensitive phases (S,Sdiff,SKS and ScS) which reveal strong lateral heterogeneity in the central Pacific Ocean, significantly higher in amplitude than predicted by existing tomographic models (Bréger et al., 1998; Bréger and Romanowicz, 1998; Bréger et al., 2000c). Our procedure involves starting from an existing tomographic model and perturbing it so as to improve fits to the data. We find that the position and shape of tomographic velocity anomalies are rather stable but that the tomographic models significantly underpredict the amplitudes of the lateral variations and the associated gradients. Two main features are present in the region of D" sampled by our data: a zone of very low S-velocity (-4% with respect to standard models) likely related to the base of a thermal "plume". This zone appears to become more narrow and deflect to the south-west as it extends well into the lower mantle, at least 1000 km above the core-mantle boundary (figure 2).

To the east of this zone, a spatially limited region of very fast S-velocity (+5%) which is confined to D", does not seem to be related to any known past subduction. The large amplitude of this anomaly cannot be explained by thermal effects alone, and thus implies the presence of chemical heterogeneity. Such strong lateral velocity gradients have also been observed in the vicinity of the African plume (e.g. Ritsema et al., 1998), and indicate that the large Pacific and African plumes may have very sharp borders which may be the site of vigorous dynamic processes. Previously found anisotropy in the central Pacific (e.g. Vinnik et al., 1998) could in particular be associated with the fast anomaly on the eastern border of the plume described above, reconciling the observations of SHdiff leading SVdiff observed in regions of fast velocity in D" around the Pacific rim (Alaska, mid-America) with those in the central Pacific (e.g. Lay et al., 1999).

The existence of strong lateral gradients of structure in D" has also been documented in P velocity studies (Ni and Helmberger, 2000; Helmberger et al., 2000). Also, there is evidence for very strong lateral variations associated with ultra-low velocity zones (ULVZ), within which the velocity may be reduced by 10% or more over a thickness of several tens of km, and which are present in differ-

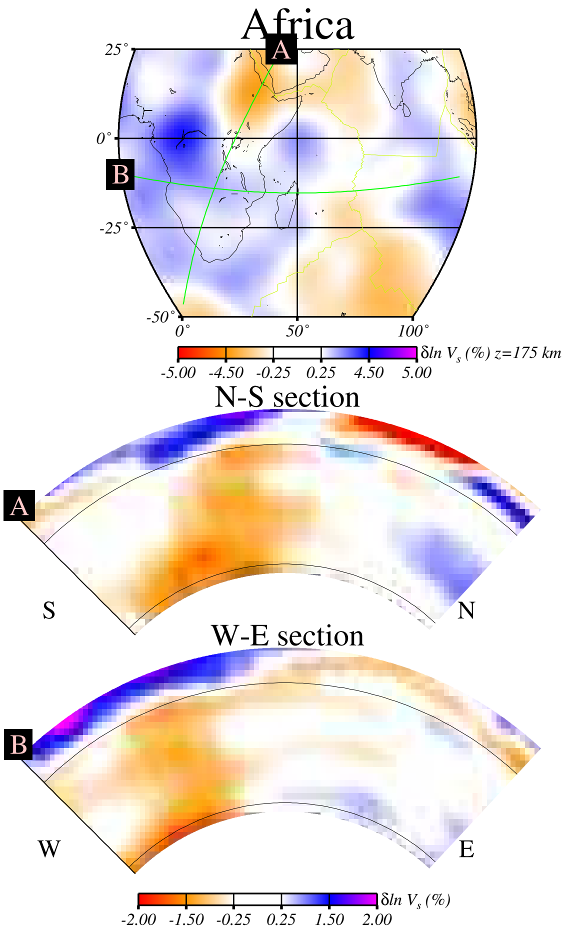

Figure 1: Horizontal (top) and vertical (bottom) cross-sections through model SAW24B16 (Mégnin and Romanowicz, 2000), under Africa, showing broad-based "upwelling" deflected to the east as it rises through the mantle.

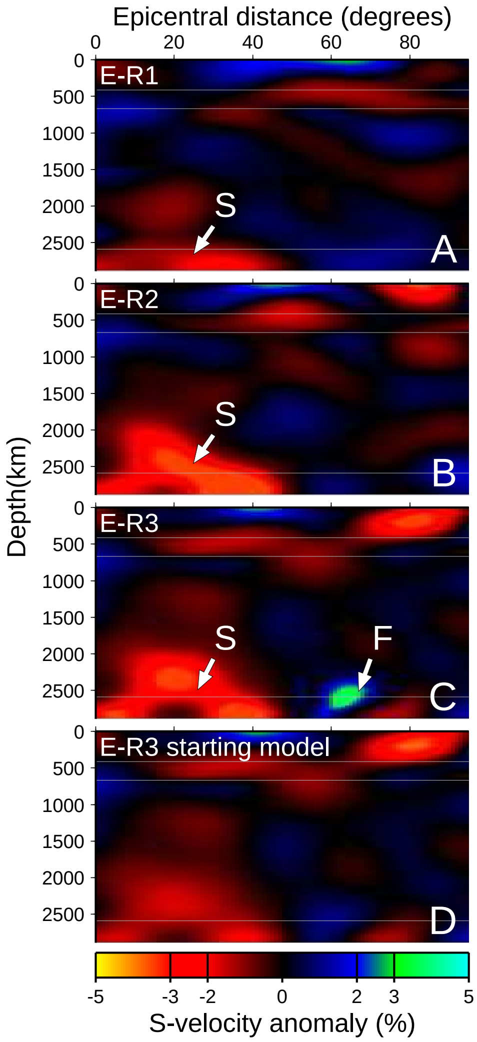

Figure 2: (A),(B),(C): Vertical cross-sections across the Pacific Ocean for the modified model of Bréger and Romanowicz (1998), for increasingly easterly paths from Fiji-Tonga to north America. (D) shows the original tomographic model (SAW12D, Li and Romanowicz, (1996) for the same cross section as C. "S" and "F" indicate locations of slow and fast anomalies for which strength had to be increased to fit the Sdiff-SKS travel time data by forward modeling.

ent locations around the globe, in particular under Africa and the Pacific (Garnero and Helmberger, 1995;1996). Strong lateral variations of structure at the base of the mantle are thus now well documented and likely due to thermal and chemical dynamic processes occurring in the boundary layer at the core-mantle boundary.

It is therefore important to accurately evaluate the effects of this complexity on global datasets of PKP travel times, which are the primary source of information on inner core structure and anisotropy. In order to minimize the effects of mantle heterogeneity on PKP travel times, differential travel times between the inner core traversing phase PKP(DF) and outer core phases PKP(BC) or PKP(AB) are formed. However, in the presence of strong lateral variations occurring on short spatial scales at the base of the mantle, the difference in travel times of PKP(DF) compared to PKP(BC) and even more so PKP(AB) (which has grazing incidence in D") could be significantly affected.

2. Implications for models of the inner core

Originally proposed models of inner core anisotropy were rather simple, and involved constant or depth varying transverse isotropy with fast axis parallel to the earth's rotation axis to explain faster propagation of PKP waves on polar paths compared to equatorial paths (e.g. Morelli et al., 1986) as well as anomalous splitting of the inner core sensitive free oscillations (Woodhouse et al., 1986). As high quality data from broadband recordings have become widely accessible, models of inner core anisotropy based on the global analysis of differential PKP travel time data have recently become rather complex, indicating in particular that only the western "quasi" hemisphere could be anisotropic (Tanaka and Hamaguchi, 1997; Creager, 1999), or that an asymmetric discontinuity exists in the inner core, separating an isotropic outer shell from an anisotropic inner shell (Creager, 1999). So far, no physical mechanism has been proposed to explain such asymmetric models of inner core anisotropy.

On the other hand, we have documented strong small scale variations in the trends of PKP(BC-DF) as a function of angle of the DF path with respect to the earth's rotation axis (Bréger et al., 1999) as well as in the travel times of P'P' with polar orientations (Bréger et al., 2000a) that are not compatible with a smooth model of anisotropy. Although a background constant transverse isotropy model of 1-1.5% strength cannot be ruled out, strong local variations in the travel time trends imply either strong lateral variations in inner core anisotropy, or that the cause of these trends must be sought elsewhere, most likely in the deep mantle.

Because the distribution of polar PKP paths is very non-uniform (Figure 3), with a concentration of paths between events the South Atlantic (and more specifically the south Sandwich Islands) and stations in Alaska, the combination of complex, but organized D" structure and uneven sampling could lead to biases in the observations generally interpreted in terms of inner core anisotropy. We have shown that simple, realistic modifications of existing tomographic models, consisting, once again, in increasing the amplitude of heterogeneity in the deepest mantle while keeping the patterns constant (figure 4), can explain most of the trend of increasing PKP(AB-DF) differential travel time as a function of angle with respect to the rotation axis (Bréger et al., 2000b), generally attributed to inner core anisotropy. Only the very anomalous paths between South-Sandwich Islands and Alaska remain largely unexplained.

As the model constructed in the above study was not meant to fit any particular dataset and therefore may be considered as somewhat "adhoc", we have investigated this further by assembling a more complete global dataset of differential travel times of PKP(AB-DF) and combin-

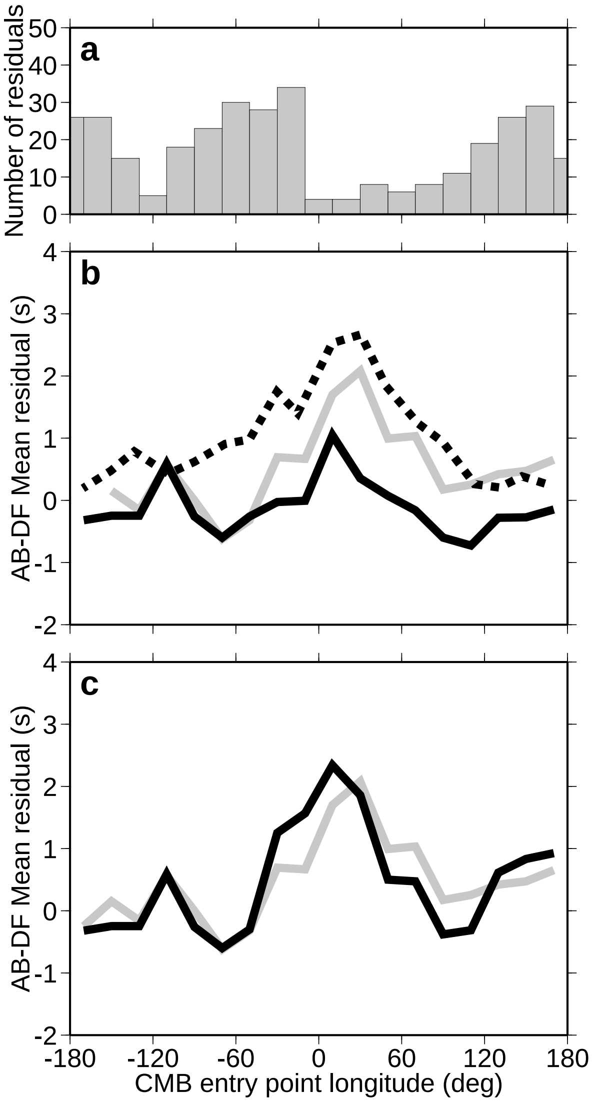

Figure 3: ((A) Number of AB-DF residuals as a function of the longitude λ of the point at which AB penetrates into the outer core. The largest anomalies are found where the sampling is the poorest (B)Mean observed AB-DF residuals (solid gray line) compared to predictions for Creager's (1992) constant transverse isotropy model of the inner core (dashed line) and by a tomographic model (solid black line), plotted as a function of λ. Creager's model, which has a strength of 3.5% slightly overpredicts the observations. (C) Same as (B) with observed residuals (gray line) compared to the prediction of the modified tomographic model, in which the strength of heterogeneity in D" has been increased (from Bréger et al, 2000b). The tomographic model is that of Grand et al. (1997) converted from S to P assuming $dlnV_s/dlnV_p = 2.$. The modified tomographic model shows good agreement with the observations.

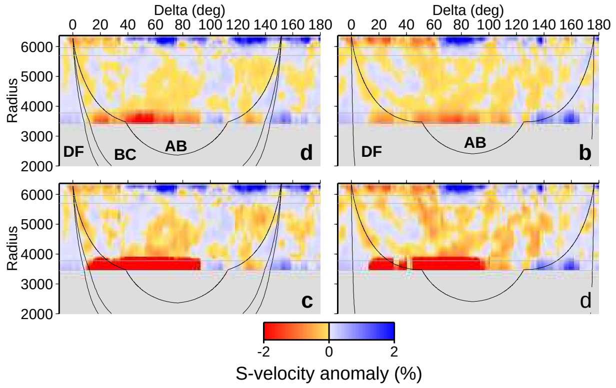

Figure 4: Vertical cross sections through a tomographic model (A)(B) and modified tomographic model (C)(D) for a path between south sandwich Islands and stations NRIL (A)(C) and SEY in Russia (B)(D). The raypaths of PKP(DF), PKP(AB) and PKP(BC) are shown. The tomographic model is that of Grant et al. (1997) converted to P assuming $dlnV_s/dlnV_p = 2$. In the modified model, all negative anomalies in D" greater than -0.8% have been increased to -2%. From Bréger et al., 2000b.

ing it with global measurements of PcP-P differential travel times. The PKP(AB-DF) dataset includes our own measurements and those of Creager, 1999; Souriau, personal communication; Wysession, personal communication). The PcP-P dataset is our own. This joint dataset, corrected for mantle structure above D" using the tomographic P velocity model which best fits our PKP and PcP travel time datasets (Karason and vanderHilst, 2000), has been inverted for P velocity heterogeneity in the lowermost mantle, using a block parametrization. A global dataset of PKP(BC-DF) differential travel times, combining our measurements with those of other studies (Tanaka and Hamaguchi, 1997;Creager, 1999; Souriau, personnal communication....), was used to provide constraints on the damping parameter used in the inversion. We have performed a series of experiments which involve the inclusion or exclusion of anomalous polar PKP data, and, when anomalous polar data are included, producing models that include or do not include corrections for simple inner core anisotropy (Tkalčić et al., 2000). We find that the models obtained without correction for inner core anisotropy (figure 5) are quite stable with respect to the subset of data used (except in regions, such as north America, where coverage is lost when a smaller dataset is used), resemble models previously obtained by independent studies (e.g. Karason and VanderHilst, 2000; Boschi and Dziewonski, 2000), and provide a good fit to all but the most anomalous data, which correspond to the now well identified paths between the south Sandwich Islands and Alaska. Moreover, the model obtained using the complete PKP(AB-DF) and PcP-P dataset explains over 40% of the variance in a global PKP(BC-DF)

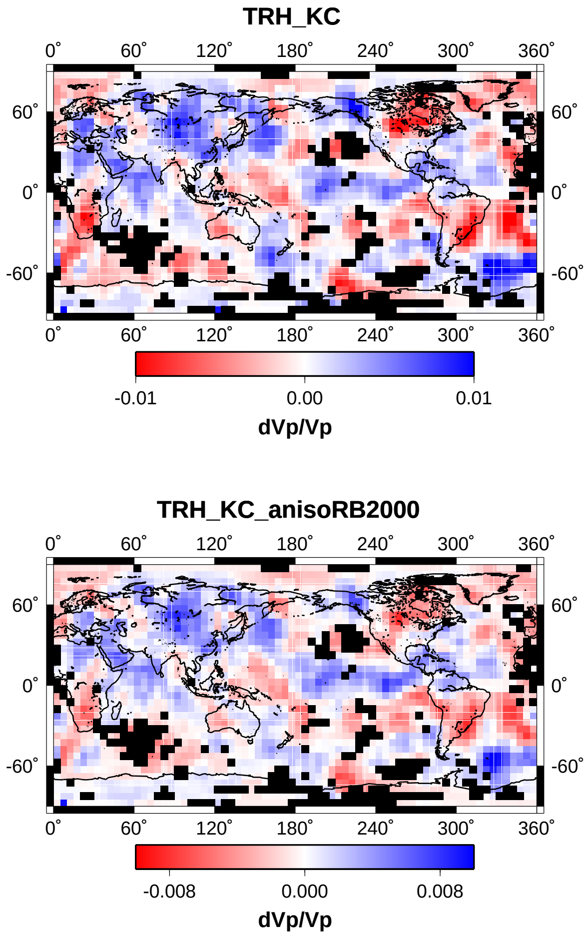

Figure 5: Maps of lateral variations in P velocity in D" obtained by tomographic inversion of the joint PKP(AB-DF) and PKP(PcP-P) dataset. Top: no correction for inner core anisotropy. Bottom: Data have been corrected for the inner core anisotropy model of Romanowicz and Brǵer (2000). The patterns in the two models are very similar. The correlation coefficient between them is 0.94. From Tkalčić et al. (2000).

dataset. While 80% of the variance in the PKP(AB-DF) data can be explained by the D" model obtained without correcting for inner core anisotropy, such a correction allows to explain an additional 3-5% of the variance, depending on the inner core anisotropy model used, and can account for up to an extra 2 s of anomaly for the south Sandwich to Alaska paths. The patterns in the D" model obtained in this case are however unchanged (figure 5).

We conclude that most of the variations in PKP(AB-DF) differential travel times can be explained by lateral variations of structure at the base of the mantle, and that there is no need to invoke a complex structure of anisotropy in the inner core. However, explaining the largest anomalies on south sandwich to Alaska paths requires either extreme heterogeneity in the mantle or a contribution from a simple model in the core. On the other hand, anomalous splitting of free oscillations cannot presently be explained by structure in the mantle (e.g. Romanowicz and Bréger, 2000). Therefore, if we seek a common cause to anomalous splitting ofmodes and unexplained PKP travel time observations, a contribution from the core cannot be ruled out.

Complex structure in the lowermost mantle needs to be documented in detail before the amount of signal coming from the core can be firmly established.

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