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New constraints on the structure of the inner core from P'P'

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Abstract.
We measured absolute P'P'df as well as differential P'P'bc-P'P'df and P'P'ab-P'P'df travel time residuals for earthquakes in Alaska and the Aleutians recorded at NORSAR array (Norway). For such paths, P'P'df samples two regions of the inner core which have been identified as strongly anisotropic ($\sim 3.5\%$), respectively beneath the Central Pacific and Africa, and should arrive some ~6s earlier than predicted by a standard model. Absolute and differential travel times do not appear to be anomalous. A very complex texture and/or heterogeneity of the top $\sim 400 km$ of the inner core, or a significant contribution from the strongly heterogeneous D", is required to explain this discrepancy.

Introduction

Inner core anisotropy was first proposed by *Morelli et al.* [1986] and *Woodhouse et al.* [1986] based on anomalous travel time and normal mode splitting data. The presence of an anisotropy reaching 1 to 3.5% in the inner core seems today widely accepted, although its exact strength and distribution remains the subject of debate [*Shearer et al.*, 1988; *Creager*, 1992; *Su and Dziewonski*, 1995; *Romanowicz et al.*, 1996; *Tanaka and Hamaguchi*, 1997; *Song and Helmberger*, 1998; *Durek and Romanowicz*, 1999]. PKPdf has been systematically used in body wave studies of the inner core, often associated to PKPbc and PKPab in order to reduce contamination by mantle structure. Unfortunately, due to imperfect path coverage, a large portion of the inner core remains unsampled by quasi-polar PKPdf, and models of anisotropy rely on a small number of measurements for rays quasi-parallel to the earth's spin axis. *Bréger et al.* [1999,2000] recently argued that the contamination of differential residuals by deep mantle structure for those paths could have been underestimated, yielding unrealistically large magnitude of inner core anisotropy. In the light of those studies, it has become critical to seek new observables that will provide additional constrains on the seismic structure of the deepest shell of the earth.

Data

Because of its two legs in the inner core, the P'P'df phase is very sensitive to structure below the Inner Core Boundary (ICB) (Fig. 1a). Earthquakes in the Aleutians recorded at the Norsar array in Norway, and in the South Sandwich Islands recorded at station CASY, correspond to paths for which the epicentral distance is between 50 and 65°, which is an appropriate distance to observe P'P', and for which the average angle ξ between the two legs of P'P'df in the inner core and the earth's spin axis is on the order of 16° (Fig. 1b). Models of inner core anisotropy derived from travel times of body waves have been so far based on datasets with very few observations for ξ smaller than about 25°. This particular source geometry is therefore well suited to provide critical additional constrains on the inner core anisotropic structure.

In Fig. 2a, we present the short-period vertical component data for an earthquake near Kodiak Island recorded at 23 stations of the NORSAR array. Three distinct arrivals are clearly visible around the arrival times of P'P'df, bc, and ab predicted by reference model ak135 [*Kennett et al.*, 1995]. We used the relocated earthquake parameters of [*Engdahl et al.*, 1998] (Table 1), and included ellipticity corrections [*Johnson*, 1989]. These three arrivals can be attributed to P'P'df, bc, and ab for several reasons. There is no other large enough teleseismic event that could be responsible for these arrivals. There is very little seismicity around the NORSAR array, and a small local event would generate waves with very different slownesses. The average observed amplitude ratio between P'P'bc and P'P'df and P'P'bc and P'P'ab is about 2.5 and 1.4 respectively, which is compatible with what is theoretically expected from model ak135 (2.3 and 1.2 respectively; considering the long pathlengh of the three branches of P'P' through the heterogeneous mantle, some differences should however not be surprising). Also, as expected, P'P'df and P'P'bc on the one hand, and P'P'ab and the Hilbert transform of P'P'df on the other hand, have similar waveforms (Fig. 2b-c). For an event of this type (Mb=6.1 Depth=17.3 km), the combination of a source duration of several seconds and of depth phases is expected to lead to a complex P coda. P'P'df should not critically affect P'P'bc because of the large P'P'bc/P'P'df ratio, which implies that the first arrival of P'P'bc has an amplitude which is well above that of the late P'P'df coda. However, P'P'bc could potentially perturb the P'P'ab waveform, yielding larger uncertainties in the measurements of P'P'ab travel times.

Measuring arrival slownesses is an important step in identifying phases. Using cross-correlation, we measured an average P'P'ab, bc, and df slowness of -3.2±1.0, -2.0±1.3, and -2.0±1.5 s/°, respectively, against -4.0, -2.5 and -1.6 s/° for model ak135. Errors were estimated by repeating the measurements on different subsets of stations. As the large uncertainties indicate, estimates of the slownesses are quite unstable, owing to the small aperture of the array (approximately 0.5°), the relatively small values of the slownesses measured, and also the very low amplitudes of the phases considered compared to the background noise. Our measurements are nevertheless compatible with expected theoretical slownesses. Scattering could, in principle, explain the presence of energy around the arrival time of P'P'df. However, it is highly unlikely to produce an

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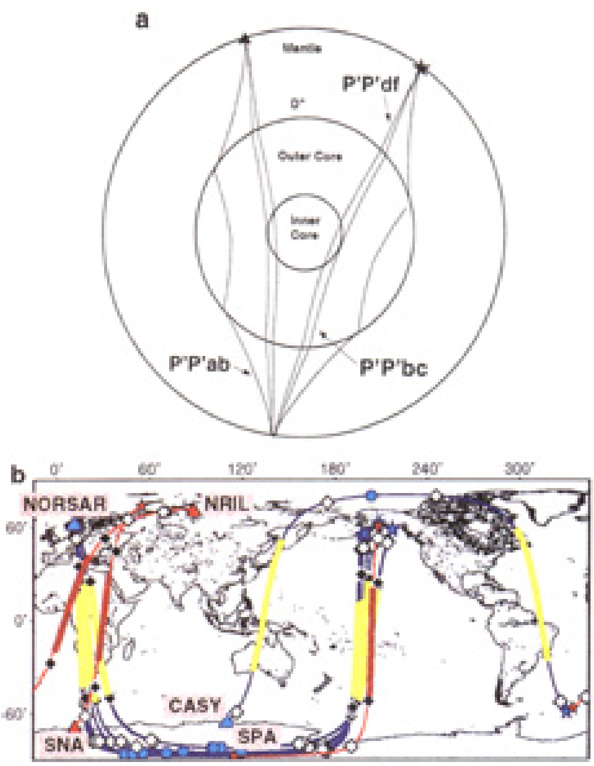

Figure 1. (a) P'P' raypaths discussed in this study. (b) Surface projections of P'P' wavepaths analyzed here (blue lines). Sources, stations, and P'P' bounce points are indicated by blue stars, triangles, and circles, respectively. Yellow thick lines correspond to the inner core legs of P'P'df. White (respectively black) diamonds represent the points where P'P'df (respectively P'P'ab) enters and exits the outer core. For comparison, we also plotted the surface projection (thin red lines) and the inner core leg (thick red lines) of PKPdf for paths between the South Sandwich Islands and station NRIL (149^o), between the Aleutians Islands and station SPA (149^o), and between Novaya Zemlya and SNA (146.5^o). PKPbc - PKPdf differential travel times were reported to be on the order of 2.5s [*Tanaka and Hamaguchi*, 1997], 2.5s [*Tanaka and Hamaguchi*, 1997], and 4.5s [*Li and Richards*, 1998], for these three paths, respectively.

arrival that would have a waveform similar to that of P'P'bc, and opposite in sign to the Hilbert transform of P'P'ab, and with an amplitude comparable to the expected amplitude of P'P'df. Precursors to PKPdf are also not observed at epicentral distances larger than 145^o, and we are here considering epicentral distances larger than twice 147^o.

Measuring travel time residuals on individuals seismograms with an accuracy less than 1s can be problematic, because P'P' first motions are usually hidden by noise. In order to reduce as much as possible the uncertainty on travel time measurements, we used a N^{th} root stacking method with N=3, after having aligned traces with respect to P'P'ab using cross-correlation. If $a_k(t_i)$ represents the amplitude at the k^{th} station at time t_i, the amplitude $S(t_i, \delta p)$ of the 3^{rd}-root stack for a given differential slowness δp can be written as:

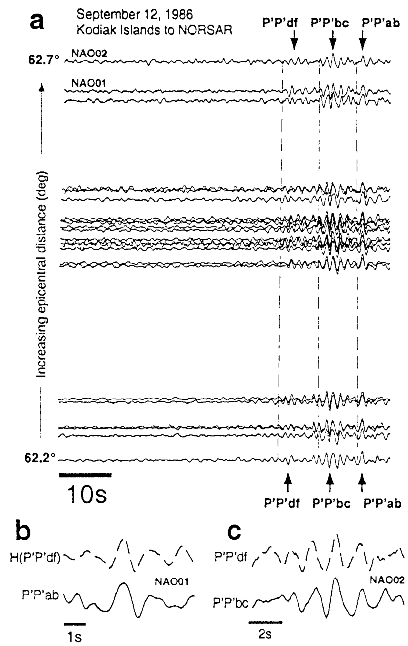

Figure 2. (a) 2s highpassed vertical short-period velocity records for the September 12, 1986 Alaska Peninsula magnitude 6.1 event at 23 NORSAR stations. This path corresponds to an epicentral distance of about 62.5^o. Three distinct arrivals interpreted as P'P'df, P'P'bc, and P'P'ab (see text), and outlined by arrows are clearly visible. The predicted arrival times of P'P'df, P'P'bc, and P'P'ab for model ak135 are given by dashed lines. (b) Comparison between P'P'ab and the Hilbert transform of P'P'df for station NAO01. (c) Comparison between P'P'bc and P'P'df for station NAO02. Note the similarity between waveforms in (b) and (c) respectively.

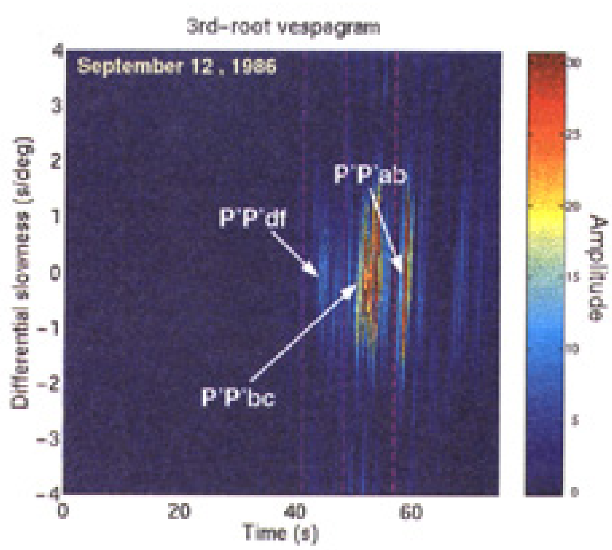

Figure 3. Absolute value of the third-root vespagram obtained by stacking the 23 traces presented in Fig. 2 aligned on P'P'ab. Vertical dashed lines indicate the arrival times of P'P'df, bc, and ab predicted by reference model ak135. Three distinct arrivals are clearly visible, with an amplitude well above the noise level. Unfortunately, the small aperture of the array does not allow to reliably resolve the slownesses of these arrivals.

$$S(t_i, \delta p) = |A(t_i, \delta p)||A(t_i, \delta p)|^2$$
$$\text{with } A(t_i, \delta p) =$$
$$\frac{1}{K}\sum_{k=1}^{K} sign[a_k(t_i + D_k\delta p)]|a_k(t_i + D_k\delta p)|^{1/3}$$

where D_k is the differential epicentral distance between the k^{th} station and the center of the array. The 3rd-root vespagram for the Kodiak Island earthquake of September 12, 1986, is presented in Fig. 3. There is compelling evidence for three sharp arrivals which have an amplitude well above the noise level, and which can be picked with an accuracy of a few tenths of a second. We verified that the differential times obtained from the slant-stack were within a few tenths of a second of those determined using waveform cross-correlation of P'P'df and P'P'bc, and P'P'ab and the Hilbert transform of P'P'df.

We were also able to measure P'P'df and P'P'bc - P'P'df residuals for an event in the South Sandwich Islands recorded at station CASY (-66.28°N,+110.53°E), which corresponds to an average angle ξ of about 14.6°. There were again two clear arrivals on the vertical short-period component record around the expected arrivals of P'P'df and P'P'bc, that are unlikely related to any other local or teleseismic event. P'P'df/P'P'bc is about 1.5, which is compatible with the prediction of ak135 (1.8), and P'P'df and P'P'bc have comparable waveforms (Fig. 4). P'P'df and bc are delayed by 8.2±0.5 and 6.8±0.6 s with respect to the predictions of ak135; such large absolute residuals should actually not be surprising, considering that the pathlength of the PKP phase through the heterogeneous mantle is long, and that absolute P and PKP residuals of a few seconds are routinely observed. We obtained a P'P'(bc-df) differential residual of 1.3±0.1 s using waveform cross-correlation.

Discussion

Absolute and differential travel time residuals for the earthquakes listed in Table 1 are plotted as a function of epicentral distance in Fig. 5a, and as a function of the mean angle between the earth's spin axis and PKPdf legs in the inner core in Fig. 5b. Except in the case of station CASY, where the vertical record is exceptionally clean, measurements were all performed using the 3rd-root stacking procedure illustrated above, using at least 5 stations of the Norsar array. Note that while the first P'P'df arrival is usually easy to identify, it was not always possible to measure P'P'bc - P'P'df and P'P'ab - P'P'df, which explains the smaller number of differential residuals.

The very long path length of P'P'df through the heterogeneous mantle and its sensitivity to mislocation effects make P'P'df absolute residuals delicate to use to infer inner core structure. We note, however, that the two particular source/receiver geometries discussed in this study yield P'P'df residuals which, on average, tend to be positive, while axisymmetric models of inner core anisotropy tend to predict negative residuals (Fig. 5). The P'P'ab - P'P'df average value is also close to zero (Fig. 5), but again, this should be interpreted with cau-

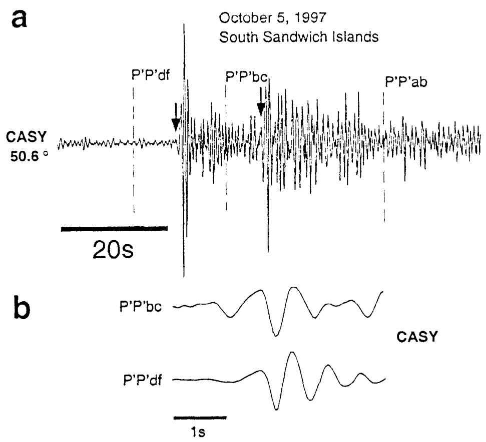

Figure 4. (a) 1s highpassed vertical short-period velocity record at station CASY for the October 5, 1997, South Sandwich Islands event. The epicentral distance is 55.6°. Two prominent arrivals are visible respectively 8.2 and 6.8s after the arrival of P'P'df and P'P'bc predicted by ak135. P'P'ab is, on this record, harder to identify. (b) Comparison between P'P'df and P'P'bc, showing the similarity of waveforms.

Table 1. Paths and residuals discussed in this study.

Date Time	Lat. Long. Dep. (°) (°) (km)	M_b	Sta.	df (s)	(bc-df) (s)	(ab-df) (s)
86/09/12 23:57	56.18 -153.44 17.3	6.1	NOR.	1.8	-0.6	-1.4
87/06/21 05:46	54.18 -162.64 34.8	6.1	NOR.	-4.5	-1.3	-2.1
87/11/30 19:23	58.83 -142.60 15.0	6.6	NOR.	0.8	-1.1	1.3
88/03/06 22:35	57.26 -142.74 6.8	6.7	NOR.	1.8	-2.1	0.2
89/09/04 13:14	55.59 -156.86 6.3	6.3	NOR.	1.6	-2.1	
91/05/01 07:18	62.55 -151.51 113.9	6.2	NOR.	6.5		-2.0
91/05/30 13:17	54.51 -161.71 28.5	6.3	NOR.	2.3	-0.1	2.0
92/08/07 18:19	57.57 -142.86 2.4	6.3	NOR.	-0.9	3.1	1.4
93/05/13 11:59	54.93 -160.48 34.8	6.4	NOR.	-0.9	-1.3	1.3
97/10/05 18:04	-59.66 -29.20 272.7	6.1	CASY	8.4	-1.4	

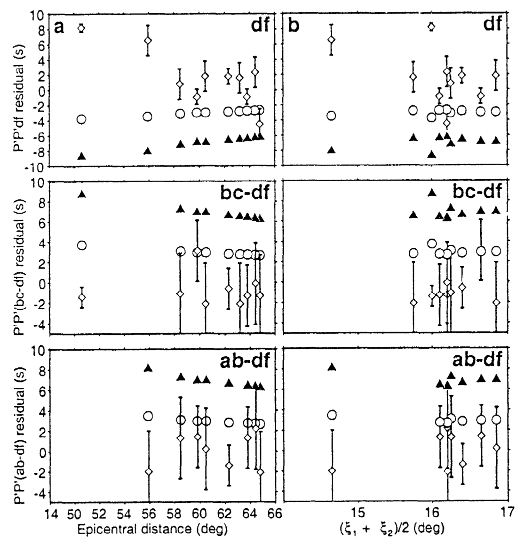

Figure 5. (a) Observed travel time residuals with respect to reference model ak135 plotted as a function of epicentral distance (gray diamonds). For comparison, we plotted the residuals predicted by a uniform axisymmetric anisotropy of 3.5% (black triangles) and 1.5% (white circles). The average observed P'P'df are slow while the models of inner core anisotropy predict arrivals which should be early by at least 2.5s. Note how observed P'P'(bc-df) residuals are between -1 and 2s, whereas inner core anisotropy models of 1.5 and 3.5% predict residuals of about 3 and 7s respectively. (b) Same as (a) for residuals plotted as a function of the average angle $\xi = (\xi_1 + \xi_2)/2$, where ξ_1 and ξ_2 are the angles between the earth's spin axis and the first and second PKPdf inner core branch of P'P'df.

tion because of the large sensitivity of P'P'ab to mantle and especially D" structure [*Bréger et al.,* 2000].

P'P'bc - P'P'df differential travel time residuals are, in principle much less sensitive to mislocation effects and mantle structure. For events in the Aleutians Islands region, the two legs of P'P'df in the inner core are in regions which have previously been identified as anisotropic. The path over the Central Pacific (Fig. 1b) corresponds to reported PKPbc - PKPdf residuals which are on the order of 3s, for epicentral distances of about 149^o [*Tanaka and Hamaguchi*, 1997]. Similarly, events in the South Sandwich Islands recorded at station NRIL (Fig. 1b) yield PKPbc - PKPdf residuals of 2 to 3s [*Tanaka and Hamaguchi*, 1997], and PKPab - PKPdf residuals on the order of 5s [*Bréger et al.*, 2000]. PKPbc - PKPdf in excess of 4s have also been reported [*Li and Richards*, 1997] for nuclear tests at Novaya Zemlya recorded at Antarctica station SNA (Fig. 1b). According to these PKP differential observations, P'P'bc - P'P'df, and P'P'ab - P'P'df should be larger than about +5s. However, our measurements show unambiguously 'normal' P'P'bc - P'P'df residuals, with an average value less than +1.0s. In Fig. 5 we compare our observations with two simple axisymmetric models of inner core anisotropy, with strength of 1.5 and 3.5%, respectively. Both models clearly overpredict the P'P'bc - P'P'df observations. Our P'P' observation for the South Sandwich Islands event of October 5, 1997 recorded at station CASY, corresponds to two PKPdf legs that sample the inner core beneath the Atlantic ocean, and beneath the western circum Pacific ring. The first leg propagates roughly through a region of the inner core for which large PKPab - PKPdf (~5s) have been observed [*Bréger et al.*, 2000]. The second PKP leg corresponds to polar paths which have been reported as not anomalous, which led *Tanaka and Hamaguchi* [1997] to propose that only one quasi-hemisphere of the inner core was anisotropic. P'P'bc - P'P'df should therefore be on the order of a few seconds. We measured a differential residual of about 1s.

It seems difficult to reconcile P'P' and PKP differential travel times if these observations are interpreted solely in terms of an effect of a relatively simple anisotropy model on the df branch. We proposed recently that the effect of the strongly heterogeneous D" could have been severely underestimated, and that a very large part of PKPab-PKPdf residuals could be explained with an inner core anisotropy significantly weaker than 3.5% [*Bréger et al.*, 2000]. We also documented complex short-scale variations in the behavior of PKPbc-PKPdf residuals for several quasi-polar paths [*Bréger et al.*, 1999], and proposed D" as a complementary, or even alternative explanation to a complex inner core anisotropy and/or heterogeneity. The P'P' paths, which we here report as 'normal', sample regions of the inner core along paths which are very close to paths previously identified as anisotropic. The apparent discrepancy between P'P' and PKP observations could stem from an exceptionally complex inner core structure, with very sharp anisotropic gradients and lateral contrasts [*Bréger et al.*, 1999], and possibly produced by a complex pattern of convection [*Wenk et al.*, 2000] associated with a strong intrinsic anisotropy [*Mao et al.*, 1998]. PKP and P'P' sample similar parts of the inner core, but different regions of D". Following *Bréger et al.* [1999,2000], a strong contribution of D" could also explain the discrepancy between P'P' normal travel times and anomalously fast PKPdf.

To conclude, P'P' seems a very promising tool to investigate the structure of the inner core. Preliminary results are in apparent disagreement with earlier reports of PKP travel times, unless we invoke an extremely complex inner core, or a significant effect of the deep mantle.

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