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Seismic anisotropy in the top 400 km of the inner core beneath the "eastern" hemisphere

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[1] Depth variation in seismic anisotropy at the top 400 km of the inner core beneath the "eastern" hemisphere is investigated by comparing the differential travel times of PKP phases recorded at distances from 127° to 160°. At distances less than about 150°, there is no noticeable difference in differential travel times for PKP phases sampling both the polar and the equatorial paths. At greater distances, however, PKIKP phases arrive systematically earlier (about 0 ~ 0.5 second) in the polar path than in the equatorial path. These observations suggest that, in the "eastern" hemisphere, seismic anisotropy exists only in depths greater than about 200 km below the inner core boundary (ICB) with seismic velocities along the polar paths (an average of 27.6° from the earth's spin axis) being 0.4% faster than those along the equatorial paths. *INDEX TERMS:* 7207 Seismology: Core and mantle; 7203 Seismology: Body wave propagation; 8115 Tectonophysics: Core processes (1507)

1. Introduction

[2] Both travel time analysis of core phases [*Morelli et al.*, 1986; *Shearer et al.*, 1988; *Su and Dziewonski*, 1995; *Creager*, 1992; *Song and Helmberger*, 1995] and splitting studies of core-sensitive modes [*Woodhouse et al.*, 1986; *Tromp*, 1993] suggest that the Earth's inner core has an axisymmetric anisotropic structure with P velocity being about 3% faster in the polar path than in the equatorial path. Recent studies, however, indicate that seismic structure at the top of the inner core is actually very complex. While more and more studies confirm a hemispherical variation of seismic structures at the top of the inner core [*Tanaka and Hamaguchi*, 1997; *Creager*, 1999; *Garcia and Souriau*, 2000; *Niu and Wen*, 2001; *Wen and Niu*, 2002], it remains unclear whether the top of the inner core is as anisotropic as the deeper part of the inner core [*Shearer et al.*, 1988; *Song and Helmberger*, 1995; *Garcia and Souriau*, 2000; *Niu and Wen*, 2001; *Ouzounis and Creager*, 2001]. If the Earth's inner core is indeed composed of an isotropic outer layer overlying an anisotropic inner part, then the depths and exact nature of these transitions will be of great importance to the understanding of both the dynamics and formation of the top of the inner core and the causes of anisotropy in the deep part of the inner core [e.g. *Wen and Niu*, 2002]. As important are the magnitudes and variations of the deeper anisotropy. *Song and Helmberger* [1998] and *Ouzounis and Creager* [2001] study such transition in the "western" hemisphere and conclude that the uppermost 50 ~ 150 km of the inner core beneath the "western" hemisphere is isotropic, although they still debate whether the transition from isotropy to anisotropy occurs through a broad depth region or not.

[3] The existence of an isotropic layer in the top of the inner core has not been established for the "eastern" hemisphere. Neither is the depth variation of anisotropy. In fact, because of the data coverage, previous estimates of anisotropy level in the "eastern" hemisphere have to rely on the assumption that anisotropy exists uniformly in the top 400 km of the hemisphere [e.g., *Creager*, 1999]. In this paper, we study the depth variation of anisotropy in the top 400 km of the inner core in the "eastern" hemisphere by comparing the differential travel times for various PKP phases sampling the polar and equatorial paths (whose ray angles from the equatorial plane are greater or less than 55° respectively). The seismic anisotropic structure in the top 80 km of the inner core is studied by comparing PKiKP-PKIKP differential travel times recorded at the distance range of 127° – 141° for both the polar and equatorial paths (whose ray angles from the equatorial plane are greater or less than 55°, respectively). The seismic structure in the deeper part of the inner core is constrained by PKPbc-PKIKP differential travel times recorded at the distance range of 147° – 160°, which sample 170 ~ 400 km deep of the inner core. PKIKP, PKiKP and PKPbc have similar raypaths in the mantle (Figure 1a). Their differential travel times minimize effects due to seismic heterogeneities in the mantle and uncertainties in source radiation pattern. We present and discuss seismic observations at both these distance ranges first, and explore seismic anisotropic structure in the top 400 km of the inner core for explaining the seismic data.

2. Seismic Observations

[4] The polar path data collected from two stations in Antartica, SYO and SPA. Based on signal to noise ratio and source simplicity, we select a total of 20 high quality PKiKP and 17 PKPbc data from more than one thousand seismograms recorded in the period of 1993 ~ 2000. We also use 9 PKPbc data collected by *Tanaka and Hamaguchi* [1997] from the recordings at station SYO before 1993. These selected polar paths are from earthquakes that occurred in Alaska and sample the "eastern" hemisphere of the inner core beneath Australia (Figure 1b). For the equatorial paths, we select a total of 60 high quality PKPbc seismograms from recordings of the IRIS Global Seismic Network (GSN), Graefenberg (GRF) array and the German Regional Seismic Network (GRSN). We choose the recordings for the intermediate and deep earthquakes occuring between 1990 and 1998 with simple sourcetime functions. For the equatorial PKiKP-PKIKP data, we use those collected in *Niu and Wen* [2001]. To avoid the possible lateral complex structure in the transition region between the two "hemispheres", we only use those seismograms with their PKIKP ray segments confined in the longitude range of 45°E ~ 170°E. The selected polar and equatorial data constitute a reasonably good sampling coverage for the "eastern" hemisphere of the inner core (Figure 1b). No difference is found between the polar and equatorial paths for all PKiKP-PKIKP differential travel times and the PKPbc-PKIKP differential travel times at distances less than about 150°. The

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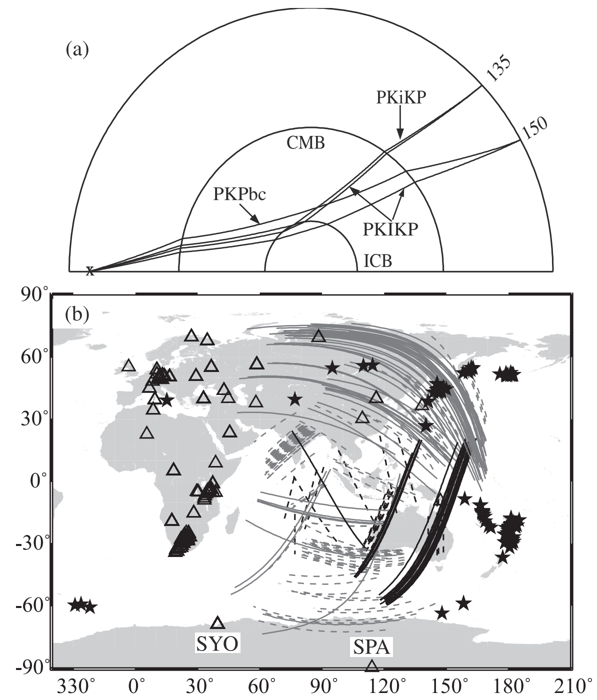

Figure 1. (a) PKP ray paths at distances of 135° and 150° for a source depth of 500 km. PKIKP is a P wave propagating through the inner core; PKiKP is the P wave reflected from the inner core boundary; and PKPbc is a PKP branch turning in the lower part of the outer core. (b) PKIKP ray segments in the inner core (lines), along with geographic distribution of seismic stations (open triangles) and earthquakes (stars) used. The polar and equatorial paths are shown by thick (dashed for distances ≤141° and solid for distances ≥147°) and thin (dashed for distances ≤141° and solid for distances ≥147°) lines, respectively.

difference of PKPbc-PKIKP travel time between the polar and equatorial paths grows gradually with distance as distances become larger than about 150°. We discuss the seismic data in detail in the following two subsections.

2.1. PKiKP-PKIKP Data

[5] The PKiKP-PKIKP time residuals of the polar paths (circles) shows no noticeable difference from those of the equatorial paths (triangles) (Figure 2a). There is no correlation between the PKiKP-PKIKP time residuals and PKIKP ray angles from the equatorial plane (Figure 2b). The differential travel times between PKiKP and PKIKP phases are determined by measuring the relative timing between their maximal amplitudes in the WWSSN short-period seismograms. This time picking method has been proven to be very accurate [*Niu and Wen*, 2001]. The uncertainty in picking the maximal amplitudes is ±0.10 sec. These observations are consistent with the result by *Niu and Wen* [2001] that the systematic positive travel time residuals observed in this distance range is caused by an isotropic velocity in the "eastern" hemisphere.

[6] The same travel time behaviors between the polar and equatorial paths are evident from the compilation of seismic waveforms of the PKIKP-PKiKP phases sampling these two paths. We show part of the PKiKP-PKIKP seismograms of the two paths in Figure 3. For both the polar (Figure 3a) and equatorial (Figure 3b) data, PKIKP waves arrive about 0.4 s earlier than PREM predictions (dashed lines). Both these polar and equatorial travel times can be explained by model E1 (heavy lines, Figures 3a, 3b), a model derived from fitting both the global and regional PKiKP-PKIKP waveform data sampling the "eastern" hemisphere of the top of the inner core [*Wen and Niu*, 2002].

2.2. PKPbc-PKIKP Data

[7] PKPbc-PKIKP travel time residuals show no noticeable difference between the polar and equatorial paths for PKIKP phases turning the top 200 km of the inner core (Figure 4). The polar PKPbc-PKIKP time residuals, however, become larger than the equatorial ones, as PKIKP phases sample the deeper part of the inner core (Figure 4). These differential travel times are determined by measuring the relative timing between the maximal amplitudes of short-period PKPbc and PKIKP phases. The above picking method is also demonstrated, from synthetic calculations, to have an accuracy of ±0.10 sec in the distance range studied.

[8] The polar-equatorial difference of differential travel times at larger distances is also evident from the collected seismic waveforms. We show some examples in Figure 5. A clear PKIKP travel time difference can be seen from two seismograms sampling the polar and equatorial paths at a similar distance of 150.1° (Figure 5a). The polar PKIKP (SYO) arrives about 0.2 s earlier than the equatorial one (GRB2) (Figure 5a). This polar and equatorial travel time difference is further evident from the seismic data recorded at larger distances, where we have a relatively good overlap of observations between the two paths. With both referenced to their PKPbc phases, the polar PKIKP

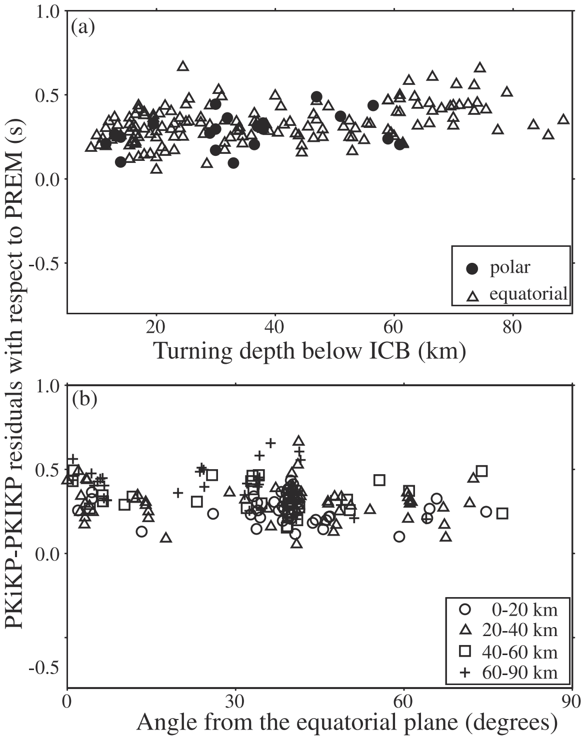

Figure 2. PKiKP-PKIKP travel time residuals (with respect to PREM) as a function of: (a) PKIKP turning depth below the ICB; (b) PKIKP ray angle from the equatorial plane at the turning point. Open triangles and solid circles in (a) represent those of equatorial and polar paths, respectively. Different symbols in (b) indicate observations with different PKIKP turning depths below the ICB (see legend in (b)). Note that there is no difference in travel time residual between those propagating in the polar paths and those traveling in the equatorial paths. See Figure 1b for the regions of the inner core sampled.

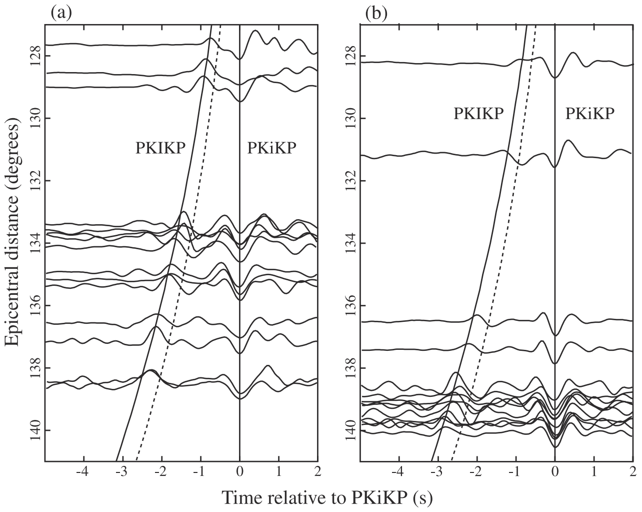

Figure 3. Examples of PKiKP + PKIKP phases sampling the polar (a) and the equatorial (b) paths. The polar data are collected from seismic stations SYO and SPA and the equatorial data are selected from the recordings at a Tanzania PASSCAL array for earthquakes occurring in the Fiji subduction zone. All seismograms are band-passed with the WWSSN short-period instrument response and aligned along the maximal PKiKP amplitudes ($t = 0$). Source depth corrections are made so that all seismograms are plotted at the distances equivalent to a common source depth of 600 km. Solid and dashed lines represent predicted PKIKP travel times based on models E1 and PREM, respectively. Note the same travel time characteristics for both the polar and equatorial data.

phases systematically arrive about 0.3 s earlier than the equatorial ones (Figure 5b).

3. Results and Discussion

[9] To investigate the depth variation in anisotropy, we first average the PKiKP-PKIKP travel time residuals at a binning depth interval of 10 km and the PKPbc-PKIKP travel time residuals at a binning depth interval of 20 km, for both the polar and equatorial paths (Figure 6a). We then calculate the difference between the polar and equatorial paths from their averaged travel time residuals at each depth interval (Figure 6b). The difference of residuals is around zero for those PKIKP waves turning within the top 200 km of the inner core. The residual difference between the polar and equatorial paths becomes evident and increases with turning depth as PKIKP rays bottom deeper than 200 km below the ICB (Figure 6b). These observations indicate that, in the “eastern” hemisphere, seismic structure is isotropic in the top 200 km of the inner core and becomes anisotropic at depths greater than 200 km below the ICB with the polar path being faster than the equatorial path.

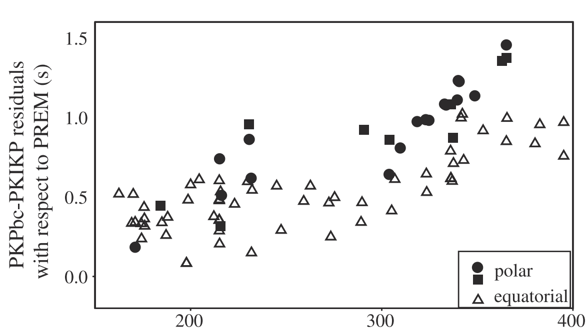

Figure 4. PKPbc-PKIKP travel time residuals as a function of PKIKP turning depth below the ICB. Open triangles and solid circles/rectangles represent those of the equatorial and polar paths, respectively. Solid rectangles are the polar path SYO data before 1993 collected by *Tanaka and Hamaguchi* [1997]. See Figure 1 for the regions of the inner core sampled.

[10] The difference of travel time residuals between the polar and equatorial paths can be used to place constraints on the magnitude of anisotropy in 200 ~ 400 km deep of the inner core beneath the “eastern” hemisphere. The polar-equatorial travel time difference can be explained by an anisotropic model with seismic velocities along the polar paths being 0.4% faster than those along the equatorial paths (solid line, Figure 6b) in depths ≥200 km below the ICB. This value is independent of the reference model we used, as only the difference of travel time residuals between the two paths

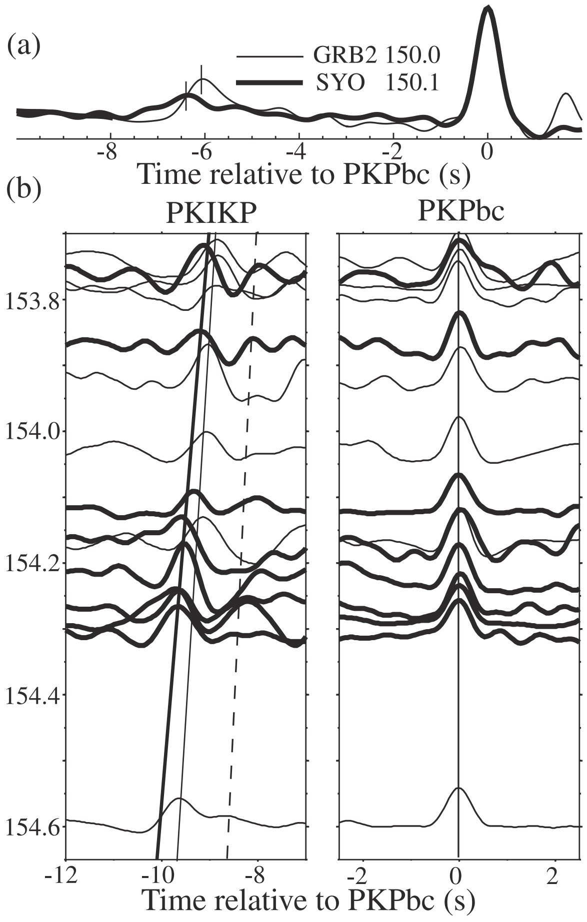

Figure 5. (a) An example of comparison between two recordings of PKP waves traveling in the polar (thick trace) and the equatorial (thin trace) paths, respectively. Two traces are aligned along their PKPbc phases and the vertical lines mark the PKIKP arrivals. Note that PKIKP arrive about 0.2 second earlier for the seismic wave propagating in the polar path (after the 0.1° distant correction). (b) Comparisons of a portion of seismograms recorded at SYO and SPA (thick traces; the polar path) and those recorded at GSN stations (thin lines, the equatorial path). Each trace is aligned along with PKPbc maximal amplitudes and plotted at an epicentral distance equivalent to a source depth of 600 km. The dashed line represents predicted arrivals based on PREM. The thick and thin lines in the left panel mark approximately the PKIKP arrivals for the polar and equatorial paths, respectively. Note that, at this distance range, PKIKP phases arrive systematically earlier for those traveling in the polar paths.

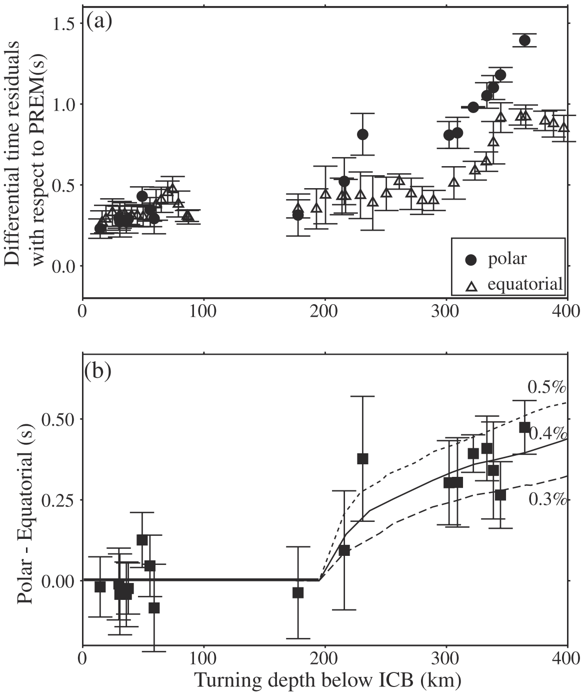

Figure 6. (a) Averaged PKPbc-PKIKP travel time residuals (with respect to PREM) as a function of PKIKP turning depth below the ICB. Notations are that same as in Figure 4. (b) Difference in PKPbc-PKIKP travel time residuals between the polar and equatorial paths as a function of PKIKP turning depth below the ICB. Also shown are the predicted residual time difference between the two paths by three anisotropic models. These three models have no anisotropy in the top 200 km of the inner core, and, an anisotropy deeper than 200 km below the ICB with the polar path velocity being 0.3% (dashed line), 0.4% (solid line) and 0.5% (dotted line) faster than the equatorial path velocity, respectively. Error-bars are also plotted in both panels.

is used. The PKIKP bottoming depths, however, will be slightly affected by the reference model used. The turning depths estimated based on E1 model [*Wen and Niu*, 2002] are about 10 km shallower than those calculated based on PREM. Since E1 and PREM likely bracket possible isotropic models in the top 400 km of the “eastern” hemisphere of the inner core, the uncertainty in estimating PKP turning depths using different reference models is about 10 km.

[11] Two issues remain unresolved because of the small magnitude of anisotropy and the limited data coverage in the polar path: 1) the sharpness of the transition from isotropy to anisotropy at about 200 km below the ICB; 2) the exact geometry of anisotropic structure in the deeper part of the inner core. Because of the small magnitude of anisotropy, the isotropy-anisotropy transitional boundary would generate little reflected energy, making it difficult to distinguish between a broad transition and a sharp discontinuity. The limited data coverage for the polar path makes it impossible to constrain the anisotropic axis. For a reference of comparison, if we assume the maximal anisotropic axis is parallel to the Earth’s spin axis, our anisotropic value of 0.4% would suggest a maximal magnitude of anisotropy of about 0.8% in the spin axis after taking into account the exact path directions of the data.

[12] Our results indicate that, rather than the anisotropy is distributed uniformly in the top 400 km of the “eastern” hemisphere of the inner core, the top 200 km of the inner core is actually isotropic and the anisotropy exists only about 200 km below the the inner core boundary. Such a layered structure of anisotropy is important to the understanding of the seismic structure and dynamics in the inner core as a whole. For example, *Wen and Niu* [2002] suggest the difference of velocity and attenuation between the “eastern” and “western” hemispheres may be explained by different geometric inclusions of melt between the two “hemispheres”. They also propose that different vigorousness of convection between the two “hemispheres” in the outer layer of the inner core could provide one possible mechanism to generate different geometric inclusions of melt. The vigorousness of convection is controlled by viscosity, heat resources, and the vertical extent of the layer. Our results, in combination with others, indicate that the depth extent of the outer isotropic layer is indeed different between the two “hemispheres”.

4. Conclusion

[13] We have investigated the seismic anisotropy in the uppermost 400 km of the inner core beneath the “eastern” hemisphere by comparing PKiKP-PKIKP and PKPbc-PKIKP differential travel times in the polar path to those in the equatorial path. At the distances less than about 150°, there is no noticeable difference in differential travel time for both the polar and equatorial paths. At larger distances, however, the polar PKIKP waves arrive systematically earlier than those in the equatorial paths. These observations suggest that the uppermost 400 km of the “eastern” hemisphere of the inner core is characterized by an isotropic 200 km layer overlying an anisotropic deeper interior with the velocity in the polar path being 0.4% faster than that in the equatorial path.

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