

Large variations in travel times of mantle-sensitive seismic waves from the South Sandwich Islands: Is the Earth's inner core a conglomerate of anisotropic domains?

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[1] Cylindrical anisotropy in Earth's inner core has been invoked to account for travel times of PKP core-sensitive seismic waves, such as from the South Sandwich Islands (SSI) earthquakes observed in Alaska, which depart from predictions. Newly collected travel-time residuals from seismic waves from the SSI region that sample only Earth's mantle (PcP and P waves) have a comparable range to the PKP differential travel-time residuals, yet they are insensitive to core structure. This observation suggests that mantle structure affects PKP travel time residuals more than previously acknowledged and challenges the existing conceptual framework of a uniform inner core anisotropy. The inner core could be a conglomerate of anisotropic domains, and the PKP travel times are most likely influenced by the geometry of inner core sampling and inhomogeneous mantle structure. This concept reconciles observed complexities in travel times while preserving a net inner core anisotropy that is required by observations of Earth's free oscillations. **Citation:** Tkalčić, H. (2010), Large variations in travel times of mantle-sensitive seismic waves from the South Sandwich Islands: Is the Earth's inner core a conglomerate of anisotropic domains?, *Geophys. Res. Lett.*, *37*, L14312, doi:10.1029/2010GL043841.

1. Introduction

[2] The conceptual framework of a uniform cylindrical anisotropy in Earth's inner core (IC) with the fast axis parallel to the Earth's spin axis has become widely accepted in the geophysical community during the last twenty-five years. Such a concept is appealing to researchers oriented to both body-wave and normal-mode studies because the predictions based on a simple model of cylindrical anisotropy can explain both the observed variations in the differential travel times of PKP waves and the anomalous splitting of normal modes. Namely, PKPbc-PKPdf differential travel times (for ray geometry see inset of Figure 1) for the ray paths traversing the IC nearly parallel to the Earth's spin axis (polar paths) were observed to be faster than those in the quasi-equatorial plane (equatorial paths) [e.g., *Poupinet et al.*, 1983; *Morelli et al.*, 1986; *Creager*, 1992; *Shearer*, 1994]. Core-sensitive normal modes exhibit more splitting of eigen-frequencies than predicted from Earth's rotation, shape and heterogeneity [e.g., *Woodhouse et al.*, 1986; *Tromp*, 1993]. Additionally,

because conditions are met for a material in the IC to form an anisotropic fabric, this became a subject of vigorous research in the field of mineral physics and geodynamics and a number of physical mechanisms have been proposed to explain simple and more complex models of anisotropy in the IC [*Jeanloz and Wenk*, 1988; *Karato*, 1993; *Stixrude and Cohen*, 1995; *Yoshida et al.*, 1996; *Romanowicz et al.*, 1996; *Bergman*, 1997; *Buffett and Wenk*, 2001]. When it was found that only one hemisphere of the IC is anisotropic [*Tanaka and Hamaguchi*, 1997], the IC anisotropy concept survived, with a paradigm shift toward a more complex pattern than what had been previously suggested. The observed average PKPbc-PKPdf travel time residuals of polar paths of 2.4 ± 0.8 s in the quasi-western hemisphere (from 183°W to 43°E) and 0.5 ± 0.4 s in the quasi-eastern hemisphere (from 43°E to 177°E) were interpreted as the existence of anisotropy only in the quasi-western hemisphere of the IC. The majority of data from *Tanaka and Hamaguchi* [1997] in the quasi-western hemisphere are from the SSI earthquakes. For the location of SSI, see stars in Figure 1 [also see *Tanaka and Hamaguchi*, 1997, Figure 1a and Table 2]. Even when a transition zone was proposed to separate the uppermost, isotropic, part from the rest of the IC [*Song and Helmberger*, 1998], the concept of IC anisotropy remained largely accepted by geophysicists, and inspired a number of further contributions. Most recently, the innermost IC concept was put forward [*Ishii and Dziewoński*, 2002] and consequent research confirmed that regardless of what additional features to the existing model are proposed, the backbone picture of prevailing elastic anisotropy in the IC remains undeterred.

[3] However, while some observed PKP differential travel times are predicted well, a uniform IC cylindrical anisotropy with the fast axis aligned with Earth's spin fails to explain all PKP travel times (Figure 2a) and is not uniquely required by the body-wave observations. Any model of uniform IC anisotropy does not predict well a scatter present in PKPbc-PKPdf travel time residuals (observed minus predicted differential travel times) associated with polar paths ($\xi < 35^\circ$) shown in Figure 2a. Two alternative concepts to that of the IC anisotropy with, *de facto*, much better fits to the observed scatter were proposed: 1) inhomogeneous structure in the Earth's lowermost mantle [*Bréger et al.*, 1999, 2000; *Tkalčić et al.*, 2002], and 2) inhomogeneous structure inside the Taylor cylinder in the outer core, tangent to the IC [*Romanowicz and Bréger*, 2000; *Romanowicz et al.*, 2003]. Due to the lack of an experimentally controlled environment in seismology of the deep Earth, it is currently not possible to scrutinize competitive hypotheses by a designed test. Recent observations of PKPbc-PKPdf differential travel times with polar geometries

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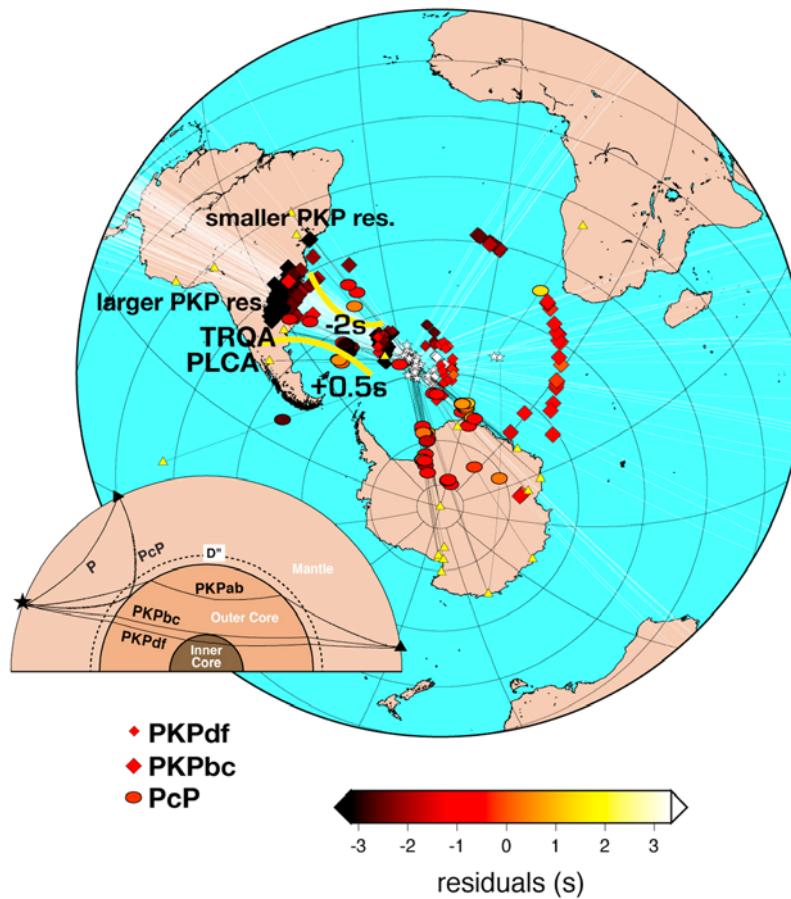


Figure 1. Map of locations of the SSI earthquakes used in this and in the previous study of PKP travel times (stars). Reflection points of PcP waves at the core-mantle boundary are projected to the surface (ellipses) in different colors corresponding to the observed PcP-P differential travel-time residuals. Piercing points of PKPdf and PKPbc waves in the IC are projected to the surface (small and large diamonds) with the corresponding PKPdf-PKPbc differential travel-time residuals using the same color scheme. Travel-time residuals are relative to the model ak135 by Kennett *et al.* [1995]. PKP and PcP ray-paths projected to the surface are shown in white and black lines. GSN stations PLCA and TRQA are highlighted. Yellow lines indicate a corridor in which some of the largest departures from theoretical predictions in PKPdf-PKPbc and PcP-P travel times are observed. A schematic representation of Earth's cross-section and ray-paths of seismic phases PKP, PcP and P waves used in the study is shown in the inset.

from Antarctic stations [Leykam *et al.*, 2010], however, illustrate that the average strength of anisotropy in the IC, in order to be consistent with all observations, has to be much smaller than previously proposed. If the data from SSI region earthquakes are omitted, the strength of anisotropy consistent with all other globally observed PKPbc-PKPpdf differential travel time data becomes only 0.7%.

2. South Sandwich Islands Earthquakes Anomaly

[4] The PKP travel times from earthquakes originating in the South Atlantic Ocean region are significant for IC anisotropy, yet they are not predicted well by simple models of IC anisotropy. Their residuals span a range between about zero and four seconds (Figures 2a–2c). When plotted as a function of the angle between PKPdf ray path in the IC and the Earth's rotation axis (Figure 2b), these travel time residuals do not increase with decreasing angle, which is predicted by the model of a uniform cylindrical anisotropy

parallel to the Earth's spin axis in the quasi-western hemisphere of the IC (Figure 2a). Moreover, there is a decreasing linear trend as a function of station longitude, the eastern stations having smaller residuals than the western (Figure 2c), which suggests lateral variation of elastic properties in Earth's mantle (for the analysis of absolute travel times see Romanowicz *et al.* [2003, Figure 9] or significant variation in inner core anisotropy. Since these earthquakes are special in the sense that they are the only earthquakes at extreme latitudes that produce polar paths in the western hemisphere, and since anisotropy- and hemisphericity-inferences rely on data associated with them, they need to be critically examined.

[5] Here we present a new data set of PcP-P differential travel times originating from the last twenty years of significant earthquakes in the SSI region recorded in Antarctica,

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South America and Africa. This is a complement to a global dataset of PcP-P travel times [Tkalčić and Romanowicz, 2002]. We analyzed vertical broadband waveforms from a total of 151 mb > 5.5 SSI earthquakes, which resulted in 1783 waveforms from 1990 to 2009. In addition, all South

Atlantic events with mb > 5.5, including the Bouvet Island were analyzed. The final data set consists of a selection of 75 PcP-P good-quality (A and B only, on the scale from A to D) travel time residuals measured by waveform cross-correlation. Table S1 of the auxiliary material is provided.¹ For a map of earthquake locations, PcP bouncing points and P and PcP ray-path projections see Figure 1. For the ray-path geometry see inset of Figure 1. Examples of PcP-P differential travel time measurements are shown in Figure 3. The new data set has values that span a similar range (four seconds) to that of the PKP residuals (Figure 2d), yet the new data is completely insensitive to IC structure, as both PcP and P waves sample only the Earth's mantle. Some of the largest PcP-P residuals occur in the same azimuthal corridor in which the largest PKPbc-PKPdf differential travel time residuals are observed (Figure 1). A sharp contrast in travel time residuals is present for the ray-paths observed in TRQA and PLCA stations in Argentina. Larger PcP-P residuals are also evident for the southern azimuths observed in Antarctica, and the smallest residuals are seen for the eastern azimuths.

[6] The observed range of PcP-P travel-time residuals must inevitably stem from the variations in mantle structure (heterogeneity or anisotropy), most likely from the upper mantle or from the lowermost mantle. For PcP and P waves from a 100 km deep earthquake observed at 30°, the difference in takeoff angles using ak135 model is 29°. At distances of 60°, this difference is reduced to only 13°, close to a typical difference in takeoff angles for PKPdf and PKPbc waves. It is perhaps a coincidence that some of the most anomalous PcP-P travel time data occur in the same corridor of azimuths in which the most anomalous PKP wave travel times are observed in Alaska, and that the smallest residuals are observed for the eastern azimuths for both PcP-P and PKPbc-PKPdf (Figure 1). Unfortunately, mantle structure in this part of the South Atlantic is not well constrained by current tomographic imaging due to the lack of receivers, volumetric coverage, and high-quality waveforms. Nonetheless, it is possible that shallow and intermediate depth earthquakes generate waves that can interact with the main slab or slab fragments. While mantle structure alone can account for the observed variations of about three to four seconds, more high-quality stations in South America and Africa are needed to increase constraints on the observed travel time patterns.

[7] The fact that mantle structure impedes the interpretation of differential travel times presents a serious challenge to a traditional view of cylindrical anisotropy in the IC with a fast axis parallel to the rotation axis of the Earth, which relies heavily on a significant number of polar paths originating from the SSI earthquakes. It requires that the inhomogeneous structure in the mantle is a significant trade-off effect to IC structure and can also reduce the difference between the two proposed hemispheric domains in the IC. The isotropic

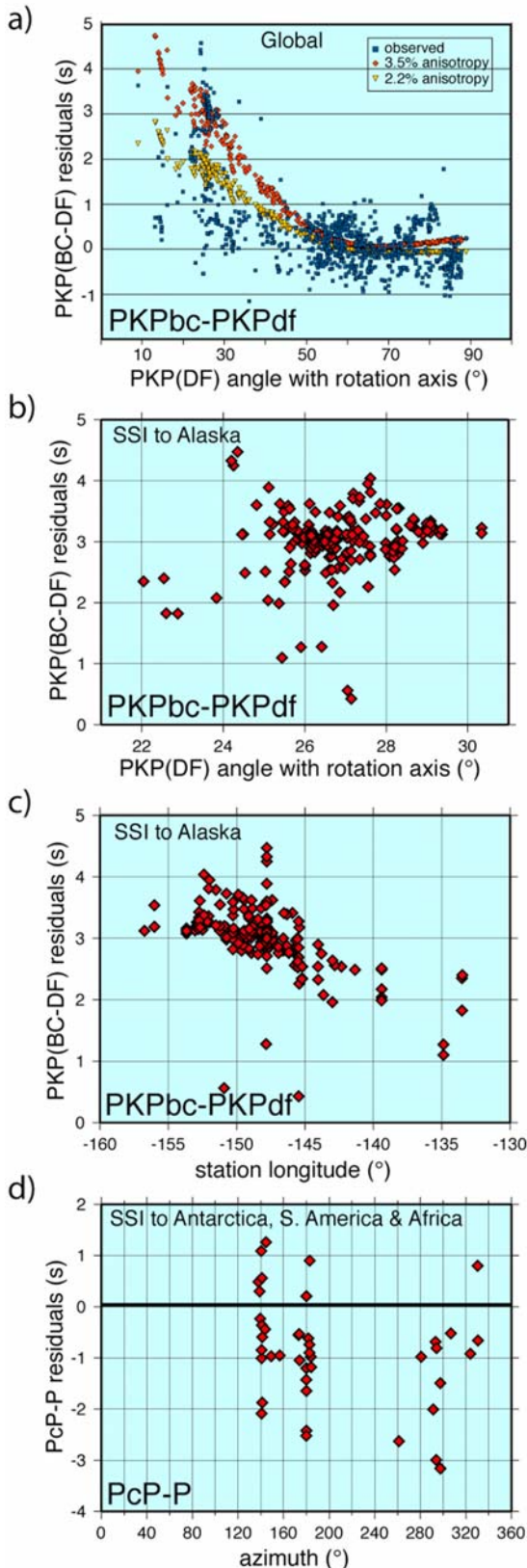


Figure 2. PKPbc-PKPdf differential travel time residuals, plotted as a function of the angle between PKPdf leg in the IC and the Earth's rotation axis for (a) the data set from *Leykam et al.* [2010] along with the 2.2% and 3.5% uniform cylindrical anisotropy predictions, and (b) only the SSI earthquakes observed in Alaska. (c) The data from Figure 2b plotted as a function of the Alaskan stations' longitude. (d) PcP-P differential travel times plotted as a function of azimuth towards recording stations.

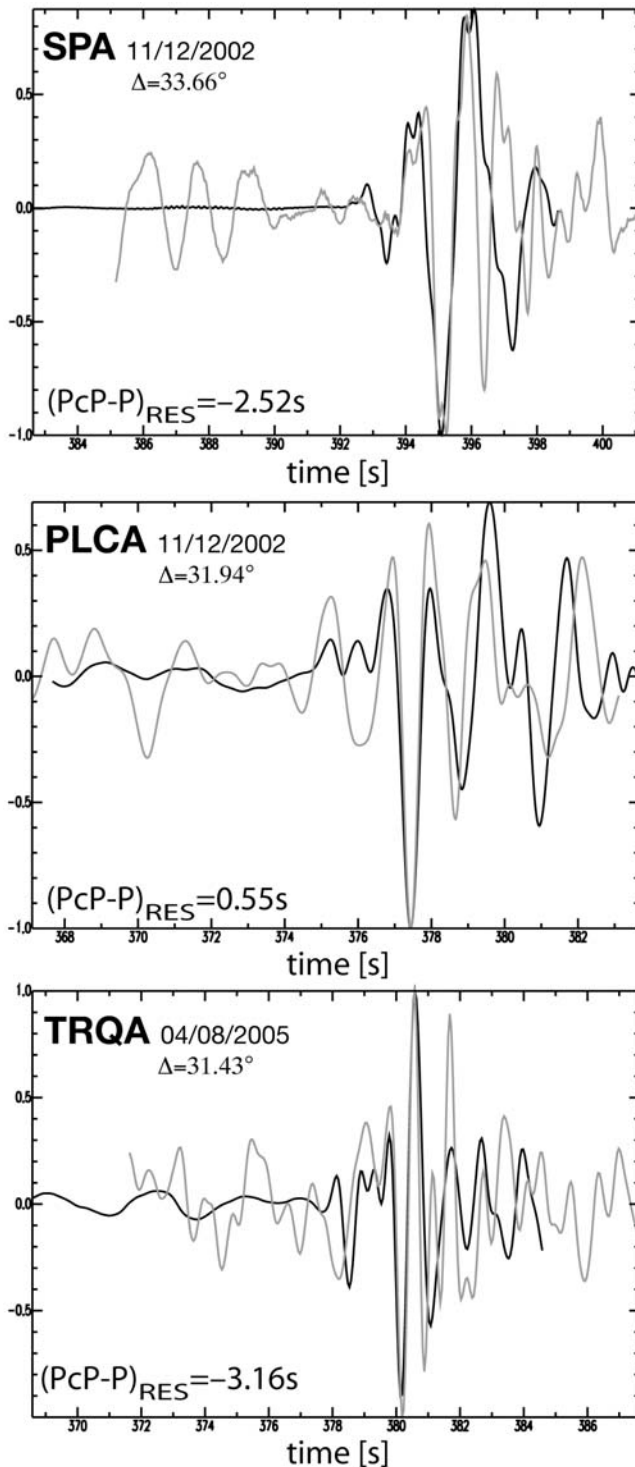


Figure 3. Examples of PcP-P differential travel time measurements. Vertical broadband components and differential travel time measurements using a cross-correlation time shift technique are shown for stations SPA (South Pole) located in Antarctica, PLCA (Paso Flores) and TRQA (Torquist) located in Argentina. Event dates and epicentral distances are shown in upper left. Differential travel time residuals in seconds with respect to ak135 model are shown in lower left.

seismic velocity of the quasi-eastern hemisphere at the top of the IC has been shown to be about 0.8% higher than that of the quasi-western hemisphere [e.g., *Niu and Wen, 2001*], whereas the region between about 100 and 400 beneath the inner core boundary (ICB) is anisotropic only in the quasi-western hemisphere [e.g., *Garcia and Souriau, 2000*]. The outstanding fact is that the concepts of hemispherical dependence of anisotropy (for depths between about 100 and 400 km beneath the ICB) and the consequent geographical delineation of two hemispheres in the IC are almost exclusively driven by the anomalous travel times observed from the SSI earthquakes in the quasi-western hemisphere. Without the cluster of the SSI events, it is not inconceivable from the remaining PKPbc-PKPdf travel-time residuals that such a simple IC hemisphericity is not required.

3. Is the Inner Core a Conglomerate of Anisotropic Domains?

[8] When mantle heterogeneities are completely ignored, the strength of IC anisotropy from body-wave studies is estimated from the contribution over the entire PKPdf ray path length in the IC. The small average value of 0.7% that is recently derived for anisotropy from a number of new PKP travel-time data observed in Antarctica, but without the inclusion of the SSI data [*Leykam et al., 2010*] (for rays sampling deeper than 100 km below the ICB) shows that elastically anisotropic fabric in the IC does not on average preserve the direction of fast axis of anisotropy over the entire IC volume. Thus, it is likely, with elastic anisotropy being strong in local patches, that the IC is a conglomerate of uniform and transitional domains with different net orientation of fast crystallographic axes and purely isotropic domains (Figure 4).

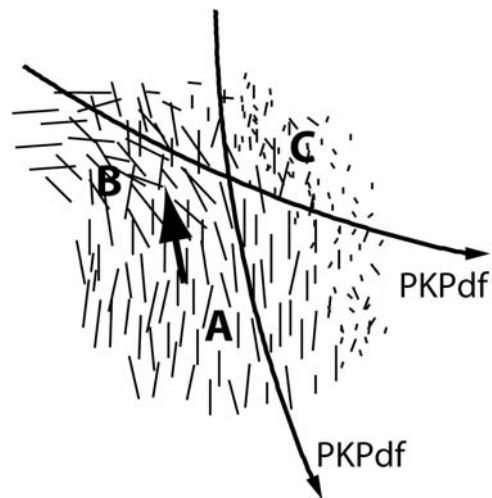


Figure 4. A schematic representation of three distinct anisotropic domains in the IC where the strength and orientation of fast crystallographic axes are shown as straight lines. Two different PKPdf ray paths are shown sampling different domains. **A** represents a semi-constant anisotropy domain with a predominant alignment of fast anisotropic axes; **B** is a transitional domain with a mixed orientation of fast anisotropic axes, and **C** is an isotropic or a weakly anisotropic domain. The arrow in the middle represents the net direction of the fast axis of anisotropy.

[9] A conglomerate-IC model is capable of reconciling complexities in the observed PKP travel times, while preserving considerable net elastic anisotropy in the IC that is required by the normal modes [e.g., *Tromp*, 1993]. Normal modes observed at the Earth's surface integrate contributions over the entire depth range, and are less sensitive to local variations. A similar effect can reconcile the discrepancies seen in the inner-outer core density contrast estimates from body waves and normal modes [*Gubbins et al.*, 2008]. Hence, if the IC is a conglomerate of anisotropic domains with variable strength, but with a net predominance in the direction of fast anisotropic axis, this will still produce an effect needed to explain an anomalous splitting of free oscillations.

[10] The quasi-eastern hemisphere of the IC can on average be faster for the equatorial PKP waves than the quasi-western hemisphere, likely due to the domain arrangement. The top 100 km of the IC is isotropic, and has a pronounced hemispherical pattern observed for isotropic velocities. This could be because the domains are smaller and erratic as a result of a more recent solidification. Spatial and temporal variations of the geomagnetic field and the lowermost mantle heterogeneity via the outer core can contribute to the complex structure of the IC. Columnar convection and convective heat flux in the outer core result in heat transfer variations, which influences IC growth and crystal alignment [e.g., *Yoshida et al.*, 1996], and this has been suggested through the observation of variations in crystal alignment [*Creager*, 1999], texture [*Cormier*, 2007] and modeling of randomly oriented anisotropic patches [*Calvet and Margerin*, 2008]. Thus, only for certain geometries of sampling, the accumulated travel time anomaly will be strong enough to be detected at the surface. Contrary, if elastic anisotropy in the IC is weak or cancels out in the domains sampled by body waves, then some very anomalous travel times with respect to spherically symmetric models of Earth for those ray paths are likely to be a result of inhomogeneous or anisotropic structure outside the Earth's core, such is probably the case for the SSI earthquakes.

[11] The lack of high-latitude earthquakes in the quasi-western hemisphere of the Earth is a serious drawback for further progress in this field, yet it is hoped that new observations and the concept presented in this manuscript will provoke discussion and ideas on how to direct future research and make further advances on this interesting topic.

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