A Glassy Lowermost Outer Core

Vernon F. Cormier *(University of Connecticut)*

New theories for the viscosity of metallic melts at core pressures and temperatures, together with observations of translational modes of oscillation of Earth's solid inner core, suggest a rapid increase in the dynamic viscosity near the bottom of the liquid outer core. If the viscosity of the lowermost outer core (F region) is sufficiently high, it may be in a glassy state, characterized by a frequency dependent shear modulus and increased viscoselastic attenuation. In testing this hypothesis, the amplitudes of high frequency PKiKP waves are found to be consistent with an upper bound to shear velocity in the lowermost outer core of 0.5 km/sec at 1Hz. The fit of a Maxwell rheology to the frequency dependent shear modulus constrained by seismic observations at both low and high frequency favors a model of the F region as a 400 km thick chemical boundary layer. This layer has both a higher density and higher viscosity than the bulk of the outer core, with a peak viscosity on the order of 10^9 Pa-sec or higher near the inner core boundary. If lateral variations in the F region are confirmed to correlate with lateral variations observed in the structure of the uppermost inner core, they may be used to map differences in the solidification process of the inner core and flow in the lowermost outer core.

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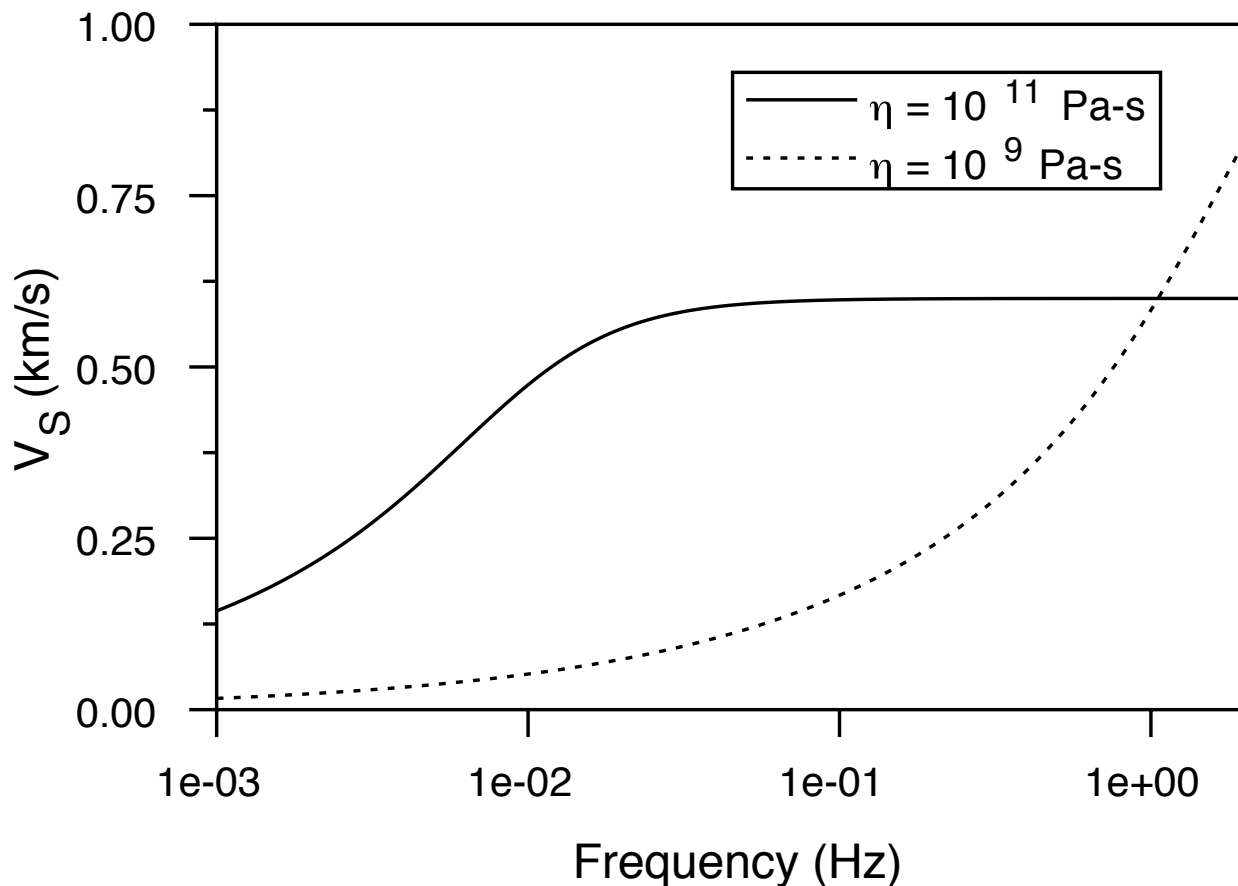
Shear velocity as a function of frequency for two different models of viscosity and in the lowermost outer core.

Localized Temporal Change of the Earth's Inner Core Surface

Lianxing Wen *(State University of New York at Stony Brook)*

The accumulation of seismic data recorded in the Global Seismographic Network (GSN) makes it possible for many discoveries to be made related to the Earth's inner core. One of these discoveries in recent years is the localized temporal change of the Earth's inner core surface. The discovery is made by comparing the seismic signals of an earthquake doublet, defined as earthquakes that occurred at different times but in almost exactly same location, recorded by the GSN stations.

Seismic phases used are the compressional waves reflected off the inner core surface (PKiKP) and propagating through the inner core (PKIKP) for an earthquake doublet occurring in South Sandwich on 12/01/1993 and 09/06/2003. Temporal changes of PKiKP travel time and waveform are observed at three GSN stations, ARU, AAK and OBN (Fig. 1), while no discernable temporal change at other seismic stations. The PKiKP and PKIKP phases recorded at station ARU arrives 0.11 s earlier and the PKIKP phase about 0.04 s earlier in event 2003 than in event 1993 (Fig. 1b). Moreover, the PKiKP-PKIKP differential travel time is about 0.07 s smaller in event 2003 than in event 1993 (Fig. 1c). The later portion of the AAK waveforms, with the energy primarily associated with the PKiKP phases, arrives about 0.07 s earlier in event 2003 than in event 1993, while the earlier portion of energy appears arriving at about the same time (Fig. 1d). The PKiKP waveforms observed at station OBN exhibit two characteristics: 1) the PKiKP main phase in event 2003 arrives about 0.07 s earlier than in event 1993; and 2) the PKiKP coda waves show waveform dissimilarities between the two events (Fig. 1e). These observations indicate a localized enlarged inner core radius by 0.98 to 1.75 km beneath middle Africa between the occurring times of the doublet.

The discovered localized temporal change of the inner core surface will have many implications to our understanding of the growth of the inner core, thermodynamic processes near the inner core boundary, convection in the outer core and driving forces for geodynamo. The GSN contributes uniquely to the discovery with its anchoring stations providing continuous open-access data, making it possible 1) to discover and locate many earthquake doublets, and 2) to confidently identify the subtle signals related to the temporal change of Earth's inner core surface between the doublets.

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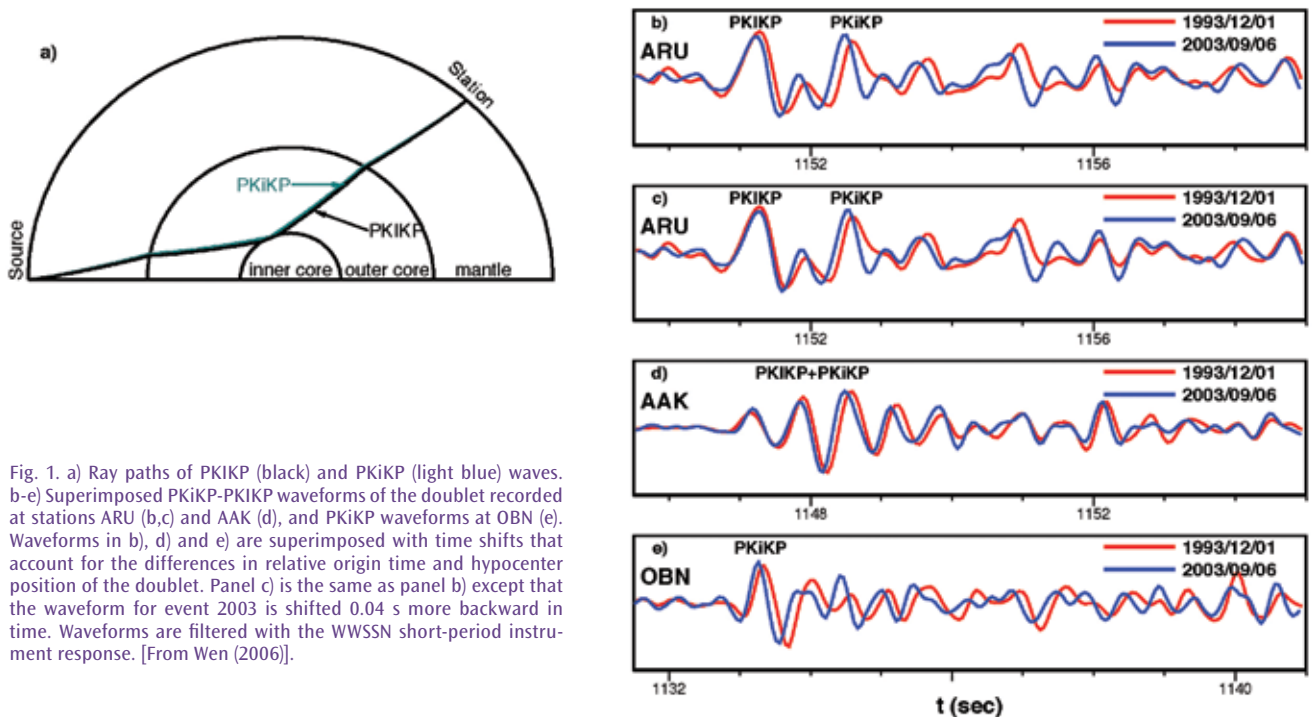
Fig. 1. a) Ray paths of PKIKP (black) and PKiKP (light blue) waves. b-e) Superimposed PKiKP-PKIKP waveforms of the doublet recorded at stations ARU (b,c) and AAK (d), and PKiKP waveforms at OBN (e). Waveforms in b), d) and e) are superimposed with time shifts that account for the differences in relative origin time and hypocenter position of the doublet. Panel c) is the same as panel b) except that the waveform for event 2003 is shifted 0.04 s more backward in time. Waveforms are filtered with the WWSSN short-period instrument response. [From Wen (2006)].

On the Inner-Outer Core Density Contrast from PKiKP/PcP Amplitude Ratios and Uncertainties Caused by Seismic Noise

Hrvoje Tkalčić *(The Australian National University),* **Brian L. N. Kennett** *(The Australian National University),* **Vernon F. Cormier** *(University of Connecticut)*

The inner core boundary of the earth is characterised by a discontinuous change in elastic properties between the liquid outer and solid inner core. In the ray theory approximation, a measure of the density contrast at the inner core boundary is given by the amplitude ratio of P waves reflected from the core-mantle boundary (PcP waves) and the inner core boundary (PKiKP waves), since that ratio conveniently appears in an explicit form in the transmission/reflection coefficient equations. The results for inner-outer core density contrast derived from direct amplitude picks of these waves in the time domain have varied significantly among different authors.

The transmission/reflection coefficients on the liquid-solid and solid-liquid boundaries derived from ground displacements enable a direct comparison between the amplitude measurements on displacement seismograms in the time domain and theoretical values. A new approach is proposed and applied to integrate effects of microseismic and signal-generated noise with the amplitude measurements, thus providing a direct maximal uncertainty measure [*Tkalčić et al., 2009*]. To suppress the effects of varying radiation pattern and distinctively different ray-paths at longer epicentral distances, this new method was applied to high-quality arrivals of PcP and PKiKP waves from a nuclear explosion observed at epicentral distances 10° to 20° from recording stations. The resulting uncertainties are high precluding precise estimates of the inner core boundary density contrast, but provide a robust estimate of an upper bound from body waves of about 1100 kg/m³. Median values of two amplitude ratios observed around 17° epicentral distance indicate a small density contrast of 200-300 kg/m³ and suggest the existence of zones of suppressed density contrast between the inner and the outer core, a density contrast stronger than 5000 kg/m³ at the core-mantle boundary, or a combination of both.

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Figure 14
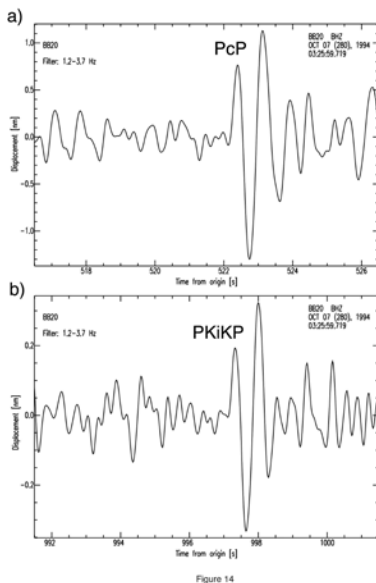
Bandpass-filtered ground displacements recorded at station BB20 using an optimal filter of 1.2-3.7 Hz for a nuclear event in China. Clear observations with similar waveforms of the PcP and PKiKP waves are visible.

Figure 15
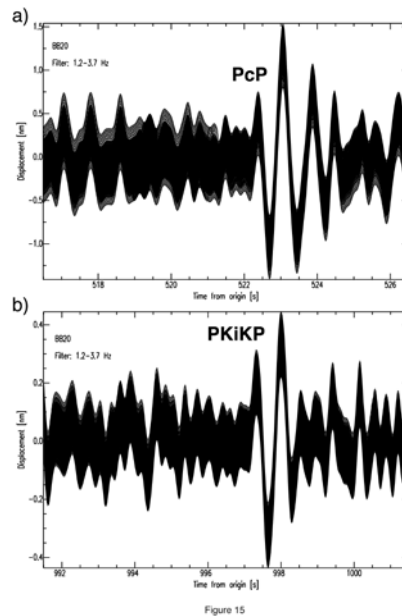
The subtraction of bandpass-filtered (1.2-3.7 Hz) seismic noise preceding the PKiKP waves from the PKiKP-wave signal recorded at station BB20 for the same event. 500 consecutive, 14 second long sliding windows of noise time series are calculated by shifting the time series by 1 sample toward earlier time and are then subtracted from the bandpass-filtered PKiKP-wave signal. Only 10 seconds of the time series are shown for clarity. Compare with Figure 1.

Figure 17
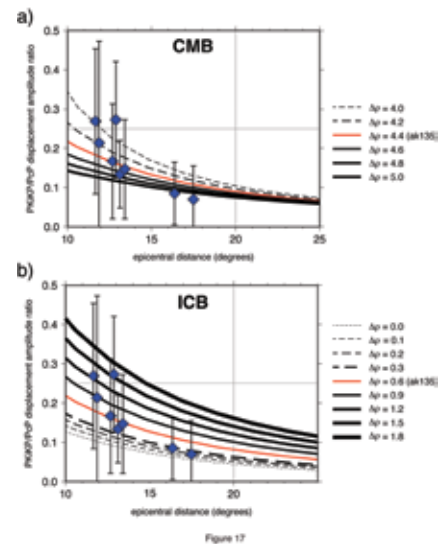
PKiKP/PcP amplitude measurements and their uncertainties (the median values are shown by diamonds, and the uncertainties are shown by error bars) plotted as a function of epicentral distance for: a varying density contrast at the ICB (top) and the CMB (bottom). Theoretical values (from ray theory) for different density contrast at the boundaries are shown with lines.

Core Structure Reexamined Using New Teleseismic Data Recorded in Antarctica: Evidence For, at Most, Weak Cylindrical Seismic Anisotropy in the Inner Core

Hrvoje Tkalčić *(The Australian National University),* **Daniel Leykam** *(The Australian National University),* **Anya M. Reading** *(University of Tasmania)*

We present a significant addition to the dataset of travel times of seismic PKP waves that sample the Earth's lowermost mantle and core along the Earth's rotation axis [*Leykam et al., 2010*]. Recorded at permanent Global Seismic Network (GSN) and temporary SSCUA deployment broadband seismographic stations in Antarctica, the new data improve the previously poor and biased coverage that underlies the seismic constraints on recent models of inner core structure and anisotropy. New differential PKP travel time measurements improve the sampling of predominantly the eastern inner core hemisphere. PKPab-df and PKPbc-df differential travel time residuals, with respect to the spherically symmetric model ak135, are consistently smaller than two seconds along the north-south paths sampled. Axially symmetric models of inner core seismic anisotropy with fast axis parallel to the Earth's rotation axis require only (0.4±0.1)% anisotropy to be consistent with our PKPbc-df observations. If only PKPbc-df observations from the top 200km of the quasi-eastern hemisphere are considered, this is reduced to (0.1±0.2)%, consistent with an isotropic layer. The dataset also increases constraints on D" structure beneath the South Pole. In contrast to previous inferences based on data from northern stations, we find no evidence of a velocity heterogeneity in the outer core near the inner core boundary associated with the cylinder tangent to the inner core in the southern hemisphere. Coverage of the quasi-western hemisphere along polar paths with differential travel times still needs improvement and may be biased by large anomalies in the mantle along the South Atlantic to Alaska path, as the new differential time residuals for polar paths from this study are consistently smaller than 2s.

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Locations of receiving stations in Antarctica. SSCUA stations are shown with black triangles.
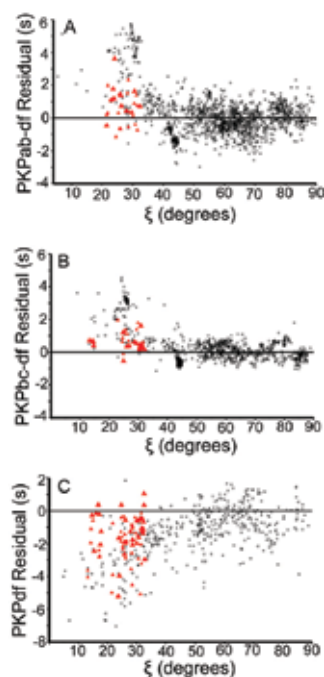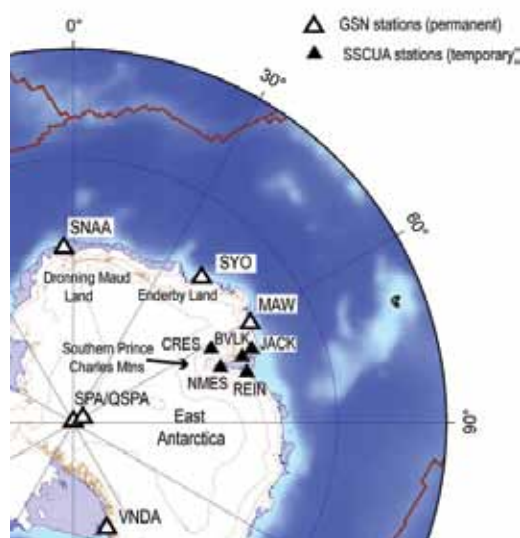
Travel time residuals with respect to the model ak135 plotted against angle between PKPdf in the inner core and Earth's rotation axis, ξ. A) Differential travel time residuals PKPab-df; B) Differential travel time residuals PKPbc-df; C) Absolute travel time residuals PKPdf. New data are in red triangles. Smaller triangles indicate lower quality data. Data from **Tkalčić** et al. [2002] are plotted with open circles.

On Iris Contribution to Deep Earth Studies

Satoru Tanaka *(IFREE, JAMSTEC)*

I have thankfully utilized the IRIS data for my deep Earth studies. This is a summary of my studies in recent 5 years.

A global data set consisting of 1211 SmKS (m≥2) waveforms collecting from IRIS database has been analyzed to investigate the radial seismic velocity structure around the core–mantle boundary (CMB). Although the thin low S-wave velocity at the base of the mantle is not conclusive, the possibility of a low P-wave velocity layer in the outermost core is remained because the waveform fitness for the part of S4KS is improved by the combination of the ULVZ and a 140 km thick layer with a 0.8% P-wave velocity reduction at the core top [*Tanaka, 2007*].

Combination of IRIS permanent observation and temporary seismic experiments reveals the mantle structure beneath South Pacific. Three-dimensional P- and S-wave velocity structures of the mantle beneath the South Pacific Superswell are determined through passive broadband seismic experiments on the ocean floor and islands between 2003 and 2005. First, we collect approximately 1500 relative times of long-period teleseismic P-waves. We analyze this data set with relative time tomography to depths of 2000 km. Our new tomographic images reveal that the large low velocity region rooted in the deep lower mantle is split into two sheets at 1200km depth and these terminate at approximately 800km depth [*Tanaka et al., 2009a*]. Second, we collect only approximately 800 long-period teleseismic SH-waves. We conduct relative time tomography to obtain a 3D structure to depths of 1600 km. The most prominent features are a large doughnut-shaped low-velocity region at 800 km depth, and an elongated large low-velocity region beneath the Society to Pitcairn hotspots at 1200 km depth. [*Tanaka et al., 2009b*].

P4KP-PcP differential travel times are examined to infer the core-mantle boundary (CMB) topography. A total of 362 P4KP-PcP times mainly collected from IRIS data are obtained. The resultant features indicate that the maximum amplitude of the CMB topography does not exceed }2 km, with an uncertainty of less than 0.5 km. A numerical test confirms that the pattern of degree 4 is more reliable with less amplitude recovery. The obtained degree 4 pattern shows an amplitude of less than }1 km and indicates the presence of depressions under the circum-Pacific, the central Pacific, and South Africa [*Tanaka, 2010*].

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Map of the CMB topography derived from P4KP]PcP travel times. Components of degrees 4 are used. The contour interval is 0.5 km.
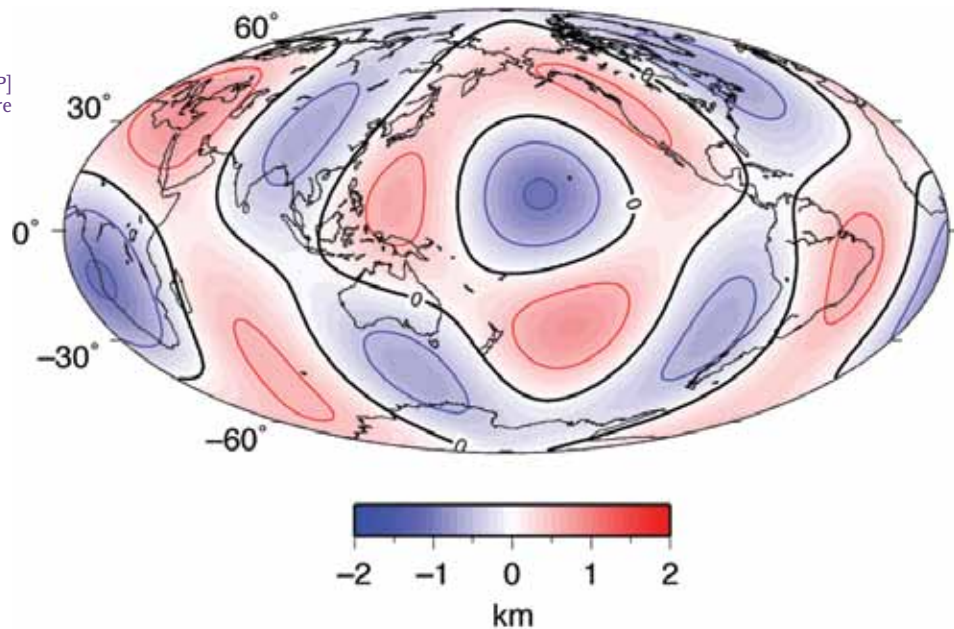
Large Variations in Travel Times of Mantle-Sensitive Seismic Waves from the South Sandwich Islands: Is the Earth's Inner Core a Conglomerate of Anisotropic Domains?

**Hrvoje Tkalčić** *(The Australian National University)*

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 [*Tkalčić, 2010*]. 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 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. 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. 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 inner core 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 inner core.

Normal modes observed at the Earth's surface integrate contributions over the entire depth range, and are less sensitive to local variations. Hence, if the inner core 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 anomalous splitting of free oscillations. The patchiness of anisotropic domains in the inner core reconciles observed complexities in travel times while preserving a net inner core anisotropy that is required by observations of Earth's free oscillations.

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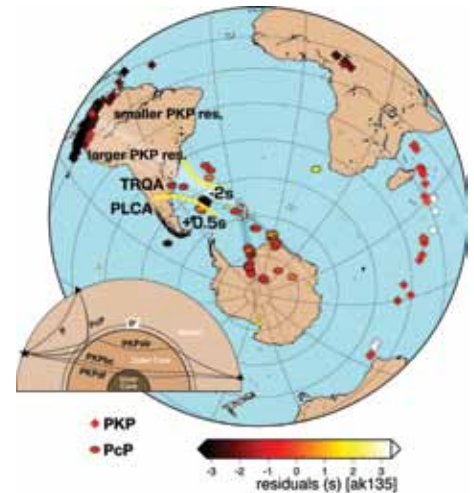
Map of locations of the SSI earthquakes used in this and in the previous study of PKP travel times (stars). Reflection points of PcP waves at the core-mantle boundary are projected to the surface (ellipses) in different colors corresponding to the observed PcP-P differential travel-time residuals. Piercing 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. 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.
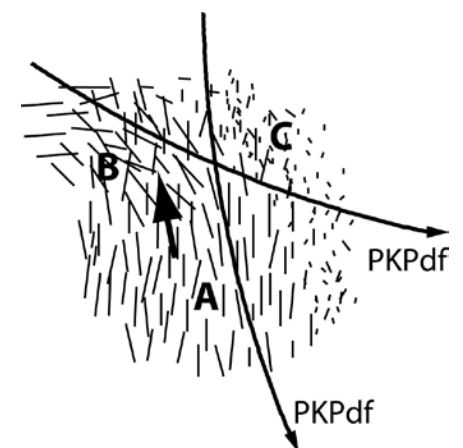
A schematic representation of three distinct anisotropic domains in the IC where the strength and orientation of fast crystallographic axes are shown as straight lines. Two different PKPdf ray paths are shown sampling different domains. "A" represents a semi-constant anisotropy domain with a predominant 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.

# Three-Dimensional Anisotropic Structure of the Earth's Inner Core

Xinlei Sun *(University of Illinois at Urbana-Champaign),* **Xiaodong Song** *(University of Illinois at Urbana-Champaign)*

Seismological studies have generally suggested that the Earth's inner core is strongly anisotropic and the anisotropy changes significantly both laterally and with depth. To image the complex structure, we have recently performed a non-linear tomographic inversion of the inner core anisotropy using three-dimensional (3D) ray tracing and a large collection of PKP differential travel times [*Sun and Song, 2008a,b*]. The data are mainly from IRIS global and regional networks up to 2006, and other local and regional networks around all over the world. The data are from various sources, including waveforms of global (WWSN, GSN, GEOSCOPE) and regional stations from various data centers (IRIS DMC, ORFEUS, GEOFON, NARS, and China Earthquake Network Center). Our 3D anisotropy model has the following major features. (1) The model has strong hemispherical and depth variation in both isotropic velocity in the topmost inner core and anisotropic velocity at deeper depth to about 600-700 km below the inner core boundary (ICB). (2) The anisotropy form changes sharply (over a depth range of about 150 km) at the radius of about 600 km, slightly less than half of the inner core radius, forming a distinct inner inner core (IIC). (3) Despite large variation of the anisotropy, the isotropic velocity (Voigt average) throughout the inner core is nearly uniform. The results suggest that the outer inner core (OIC) is likely composed of single iron phase with different degrees of preferred alignment, but the IIC may be composed of a different type of crystal alignment, a different iron phase, or a different chemical composition.

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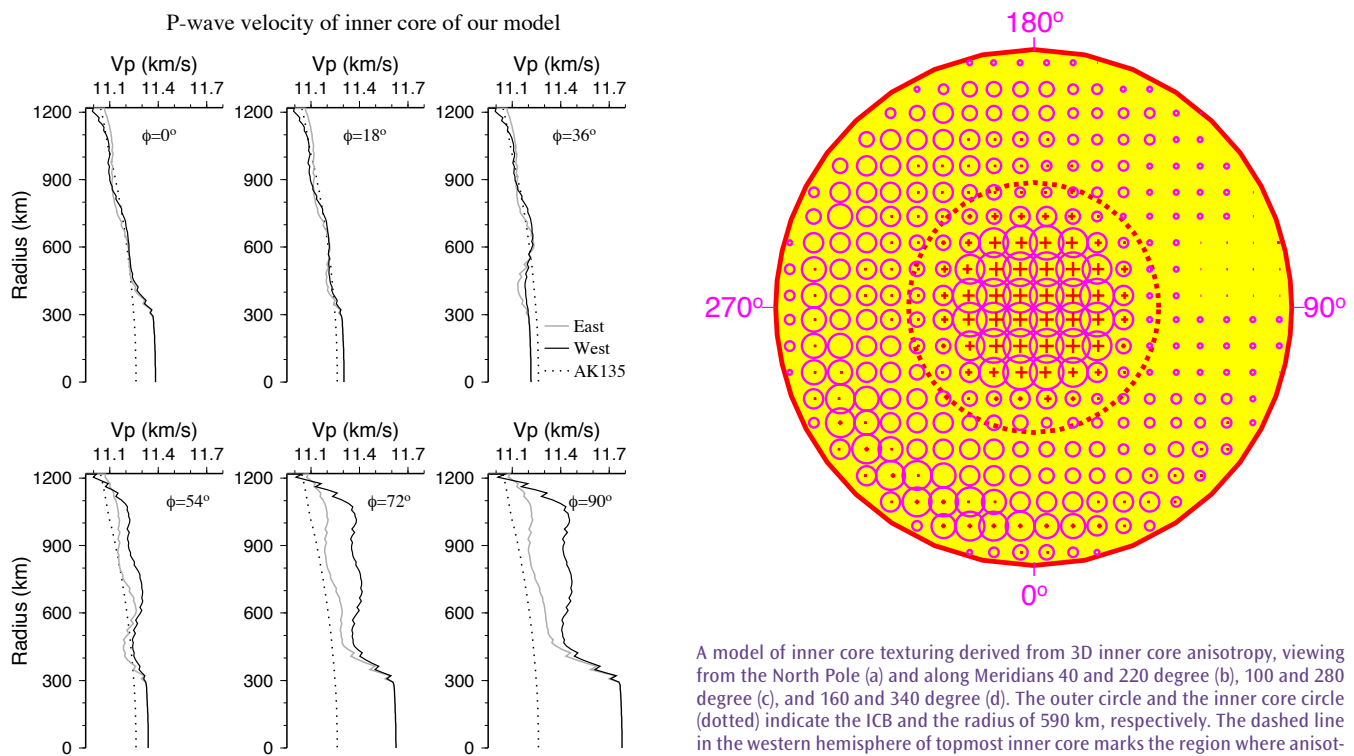
Averaged P-wave velocity of inner core for quasi-eastern hemisphere (gray) and quasi-western hemisphere (black) at different ray angle.

A model of inner core texturing derived from 3D inner core anisotropy, viewing from the North Pole (a) and along Meridians 40 and 220 degree (b), 100 and 280 degree (c), and 160 and 340 degree (d). The outer circle and the inner core circle (dotted) indicate the ICB and the radius of 590 km, respectively. The dashed line in the western hemisphere of topmost inner core marks the region where anisotropy increases sharply with depth. Note that the IIC part could also compose of different iron phase or different chemistry. (a) The circles and pluses indicate the fractions of polar alignment and equatorial alignment of the iron crystal's fast axis, respectively. The symbol size is proportional to the fraction. (b–d) The line segments indicate the fractions of polar and equatorial alignments.

Observations of Antipodal PKIIKP Waves: Seismic Evidence for a Distinctly Anisotropic Innermost Inner Core

Fenglin Niu *(Department of Earth Science, Rice University),* **Qi-Fu Chen** *(Institute of Earthquake Science, China Earthquake Administration)*

Studies of the seismic structure of the inner core using body waves that propagate through the inner core, such as PKIKP, are always hindered by contamination from mantle heterogeneities. A common approach in eliminating mantle anomalies is to use differential travel time or relative amplitude between PKIKP and a reference phase, which travels along a very close ray path to PKIKP in the mantle. Waves reflected at or refracted above the inner-core boundary (ICB), PKiKP and PKPbc, have been frequently employed to study the top ~400 km of the inner core [*e.g., Niu and Wen, 2001; Creager, 1992*]. On the other hand, no such reference phase has been identified as suitable for modelling the deeper part of the inner core [Breger et al., 2000]. As the result the seismic structure of the deeper ~800 km of the inner core is less constrained compared to the top ~400 km of the inner core. We found that PKIIKP is an ideal reference phase to PKIKP for deciphering seismic structure at the centre of the earth, as the two have very similar ray paths in the mantle (Figure 1a).

We found clear PKIIKP arrivals from two deep-focus earthquakes that occurred in Indonesia and Argentina, respectively. The Indonesia event was recorded by 61 sta-
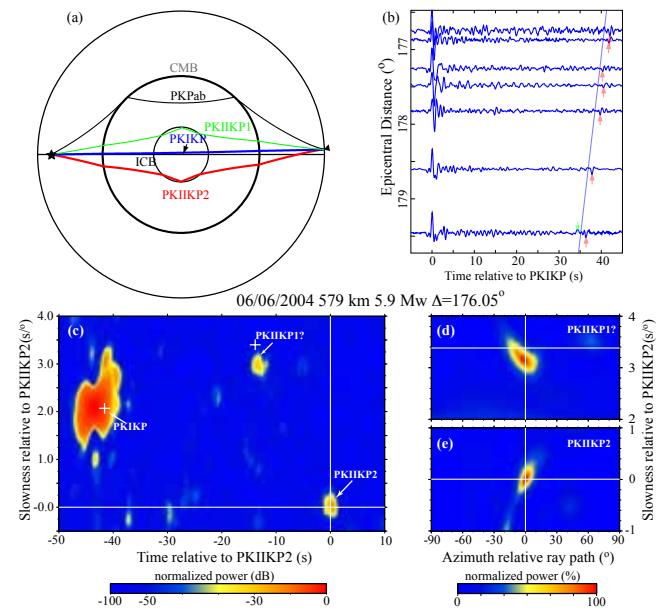

Figure 1. (a) Ray paths of the core phases: PKIKP (blue), PKPab (black), PKIIKP1 (green) and PKIIKP2 (red) at an epicentral distance of 178º. (b) Examples of seismograms recorded by the BOLIVAR array. (c) Color contour map of the vespagram stacked from the BOLIVAR data. Beam power showing the arrival direction and incident angle of the PKIIKP1 (c) and PKIIKP2 (e) phases.

tions of a temporary PASSCAL deployment in northern South America and the southern Caribbean known as the BOLIVAR array (Figure 1b), while the Argentina earthquake was recorded by 40 short-period and broadband mixed stations that belong to the China Digital Seismic Network (CDSN). We performed stacking (Figure 1d) and beam forming analysis (Figure 1e) with the array data. Both PKIIKP phases are clearly identifiable in the vespagrams of the two events with a positive and a negative slowness relative to PKIKP, respectively. We found that the Indonesia-Venezuela path exhibits a ~1.8 s positive differential travel-time residual while the Argentina-China path shows no significant anomaly with respect to PREM. As the Indonesia-Venezuela and Argentina-China paths are in the directions of ~8° and 28° from the equatorial plane, respectively, our observation suggests that the slowest direction of wave propagation is no longer in the east-west direction for the innermost inner core [*Ishii and Dziewonski, 2002*]. The Earth's centre has a distinct seismic anisotropy relative to the rest part of the inner core.

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# Inner-Core Shear-Wave Anisotropy and Texture from an Observation of PKJKP

James Wookey (*University of Bristol, UK*), **George Helffrich** (*University of Bristol, UK*)

Since the discovery of the Earth's core a century ago, and the subsequent discovery of a solid inner core (postulated to have formed by the freezing of iron) seismologists have striven to understand this most remote part of the deep Earth. The most direct evidence for a solid inner core is the observation of shear-mode body waves which traverse it, but these phases — for example, PKJKP — are extremely hard to observe. Two reported observations in short period data have proved controversial. Arguably more successful have been two studies in longer period data but such data somewhat limits the usefulness of the waveform beyond reported sightings. We present two observations of this phase at higher frequencies in stacked data from the Japanese High-Sensitivity Array, Hi-Net. From an analysis of timing, amplitude and waveform of PKJKP we derive constraints on inner core VP and shear attenuation at ~0.3 Hz which differ from standard isotropic core models. We can explain waveform features and can partially reconcile the otherwise large differences between core wavespeed and attenuation models that our observations apparently suggest if we invoke inner core shear-wave anisotropy. A simple model of an inner core composed of hcp-structured iron with its c-axis aligned perpendicular to the rotation axis yields anisotropy which is compatible with both the shear-wave anisotropy that we observe and the well-established 3% P-wave anisotropy.

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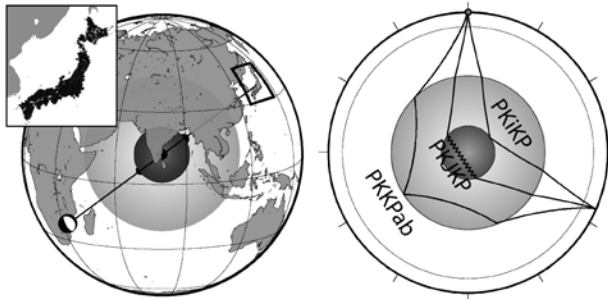
Source, raypath and receiver geometry. We search for evidence of PKJKP in records of the Mw=7.0 shallow (depth approx. 14 km) 22nd February 2006 event in Mozambique at the Japanese Hi-net array (inset). The epicentral distance to the centre of the array is 113.7 degrees. The right panel shows the raypaths for PKKPab, PKiKP and PKJKP at this distance (straight lines are P-wave segments, wiggly are S-wave).
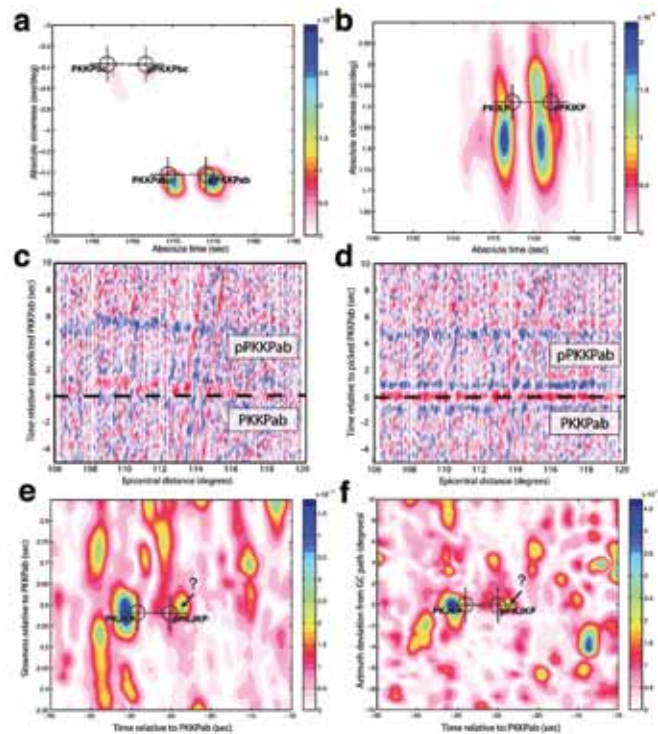
Seismic data. Panels a & b show vespagrams for the PKKPab and PKiKP time-slowness windows respectively. These vespagrams are computed using a phase-weighted slant-stack. Crosshairs denote predicted times and slownesses from ak135 for various core phases. Clear maxima associated with PKKPab, pPKKPab, PKiKP and pPKiKP arrivals are visible, with weaker maxima for PKKPbc and pPKKPbc. c, time window for PKKPab in the unstacked data. Since PKKPab is clearly visible we use it as reference phase to calculate a receiver side static time correction, and d shows this correction applied to PKKPab. e, time-slowness window (relative to the PKKPab reference phase) where PKJKP is predicted to arrive. A clear maximum can be seen 1.5 s before the prediction, at the correct slowness to within the resolution of the array (approx. 0.05 sec/deg). There is also energy near the time predicted for pPKJKP, though this is low amplitude (near the noise level) and poorly constrained in slowness. f, azimutha

Regional Variation of Inner Core Anisotropy from Seismic Normal Mode Observations

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The Earth's core, consisting of an iron alloy, makes up one third of our planet's total mass. As the Earth cools, the inner core grows by solidification of the fluid outer core. Solidification results in the release of light elements and latent heat, which drive the geodynamo generating the Earth's magnetic field. We studied inner core structure using long period normal mode splitting functions and made observations of regional variations in inner core anisotropy which are consistent with short period compressional body waves.

Previous seismic studies using compressional body waves had suggested hemispherical variation in the isotropic and anisotropic structure of the inner core. However, because of the limited distribution of earthquakes and receivers, the global extent of the hemispherical variations was poorly constrained. Normal mode observations have the potential to provide robust evidence, but so far had been elusive due to lack of theory and suitable data. Previous studies investigated isolated modes, which are only sensitive to even-degree structure, and showed strong evidence for inner core anisotropy. To investigate hemispherical variations, which is odd-degree structure, we take cross-coupling between pairs of modes into account.

To improve data coverage, we made a new long period data set for all large earthquakes from 1975 to 2009, including the 2004 Sumatra event and the 2008 Wenchuan China event. We measured splitting functions of odd-degree structure for pairs of coupled modes sensitive to the inner core in comparison with body wave observations. The observed odd-degree structure suggests more complicated regional variations than a simple Eastern versus Western hemispherical pattern. Our results open up possibilities for directly linking regional variations in inner core structure to the strength of the magnetic field and thermal evolution of the Earth's core. The similarity of the observed seismic pattern with Earth's magnetic field suggests freezing-in of crystal alignment during solidification or texturing by Maxwell stress as origins of the anisotropy. These observations also limit the amount of inner core super rotation, but would be consistent with oscillation.

References

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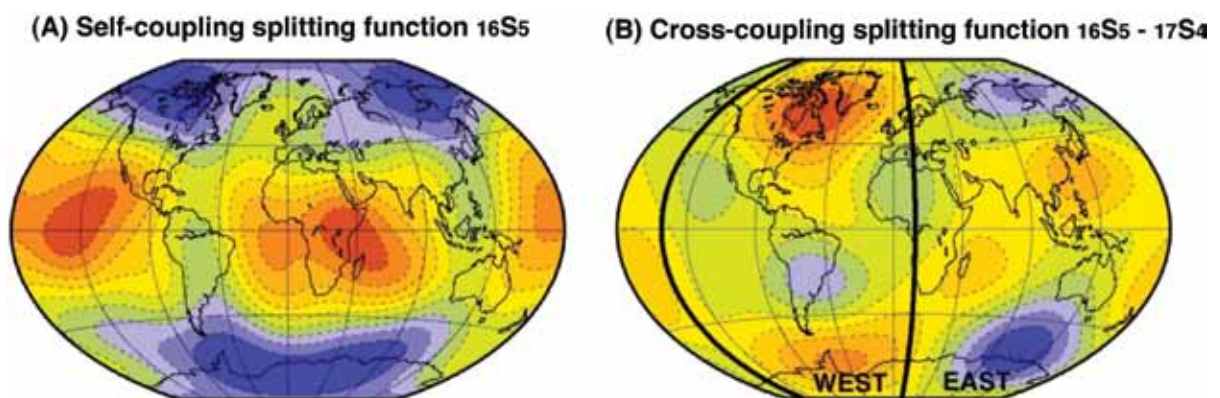
Observed and predicted splitting functions for the mode pair 16S5 and 17S4. (A) Observed splitting function using self-coupling only for 16S5 showing zonal splitting typical of inner core anisotropy. (B) Observed cross-coupled splitting function showing anti-symmetric splitting, which is characteristic of hemispherical variation (i.e. East versus West) in inner core anisotropy.

Inner Core Rotation and Its Variability from Non-Parametric Modeling

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We present a new approach to gain insight into the inner core rotation by separating the underlying inner core structure from its time evolution without any a priori constraints. This is achieved by fitting existing seismic travel time residual data with a smoothing spline analysis of variance model [*Gu, 2002*]. Our data are PKP BC-DF differential travel time measurements from South Sandwich Islands (SSI) earthquakes that were recorded at Alaskan stations (Fig. 1) dating back to as far as 1951 in case of the longtime College, Alaska station. We add our newly acquired seismic data from the recent PASSCAL experiment ARCTIC in northern Alaska, which increases our time resolution as well as lateral coverage of the inner core structure. Our method allows us not only to separate the time independent mantle contribution from the time dependent core contribution without any a priori constraints but also to estimate the error of the fit. In addition we are able to determine the average rotation rate of the inner core over a given period, assuming a rigid body motion. Synthetic tests support the applicability of our approach and when it is applied to the actual data enables us [*Lindner et al., 2010*] to:

- Unveil a clear spatial gradient of the inner core structure which and is non-linear.
- Determine the average rotation rate of the inner core to 0.39° per year to the East in agreement with previous studies.
- Rule out westward and no rotation.

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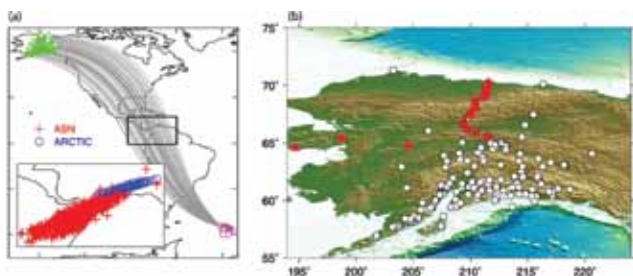
(a) Map of pathways from South Sandwich Islands (SSI) earthquakes to Alaska Seismic Network (ASN) and ARCTIC stations. The inset is an enlarged view of the PKP-DF ray turning points in the inner core beneath the Central America. The ARCTIC stations extend the inner core samples further to east. (b) Locations of stations used in this study, including ASN stations (circles) and ARCTIC stations (triangles) along the NS line. The ARCTIC stations along the EW direction are not used in this study.
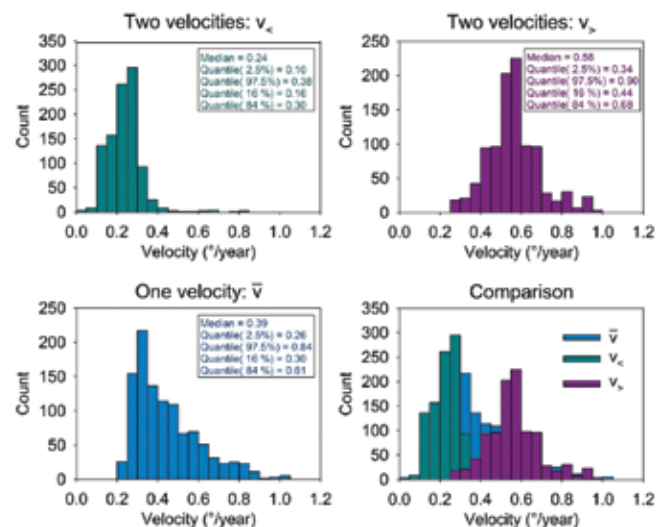

Figure 2. Histograms of inner-core rotation rates obtained in this study. Best average velocities $v_{<}=v(t<1990)$ (Top left), $v_{>}=v(t>1990)$ (Top right) $\bar{v}$ (Bottom left) over the whole study period from 1951 to 2007 (Bottom left). (Bottom right) Comparison between $\bar{v}$, $v_{<}$ and $v_{>}$.

Wide-Scale Detection of Earthquake Doublets and Further Evidence for Inner Core Super-Rotation

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The best evidence for a super-rotation of the Earth's inner core is provided by comparing the signals of earthquakes occurring years apart but in almost exactly the same location (doublets). The method was developed in the context of high-quality doublets by Li and Richards and has been used by many subsequent authors. *Zhang et al.* [2008] report on more than 100 earthquake waveform doublets in five subduction zones, including an earthquake nest in Bucaramanga, Colombia. Each doublet is presumed to be a pair of earthquakes that repeat at essentially the same location. These doublets are important for studying earthquake physics, as well as temporal changes of the inner core. In particular we have data for six different paths. They partition into three paths for which the travel time of PKIKP changes significantly and measurably (on the order of 0.01 s per year), and three paths that show little or no change (no more than 0.005 s per year, if any) of inner core travel-times. In the former set of three paths, there is a high angle between the ray path within the inner core, and the equatorial plane. In the latter set of ray paths, the path in the inner core is nearly parallel to the equatorial plane. Such a pattern of observations showing both presence and apparent absence of inner-core travel-time change can be explained by the geometry and relative directions of ray path, lateral velocity gradient and inner-core particle motion due to an eastward super-rotation of a few tenths of a degree per year.

References

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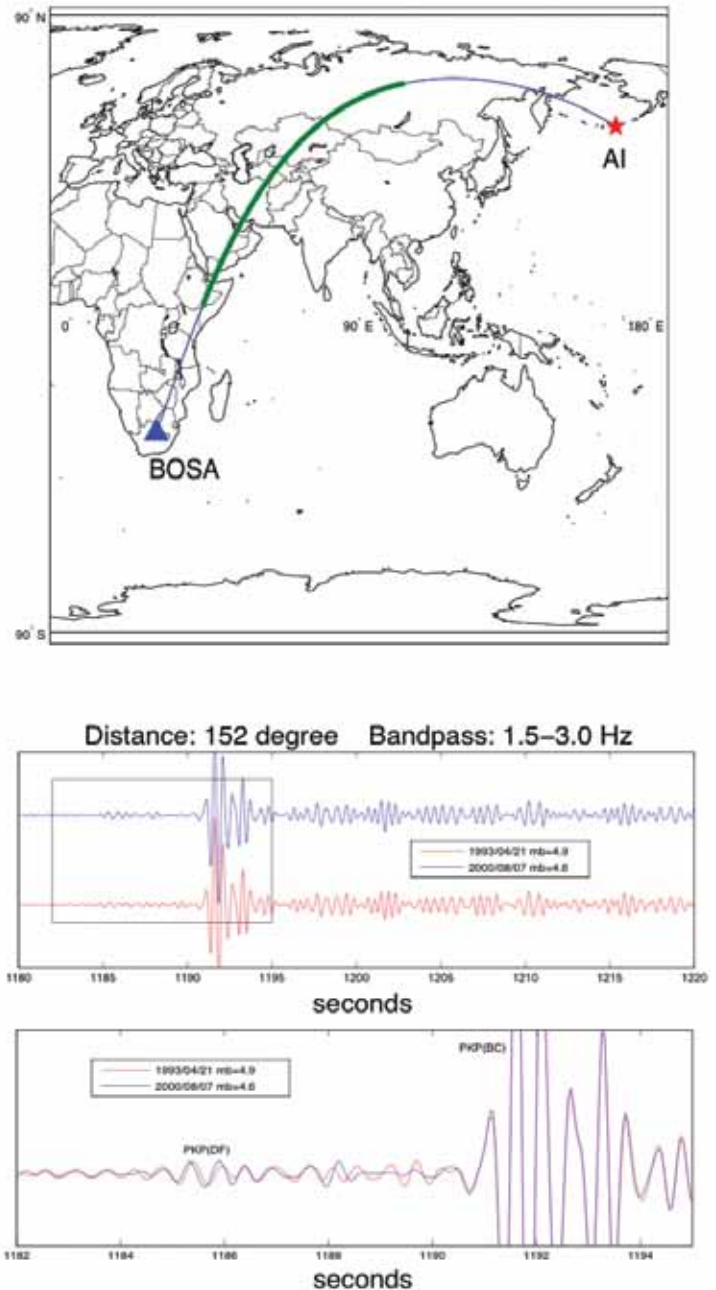
An apparent temporal change (about 0.1 s) of inner core travel-times observed from an Aleutian Islands doublet (about 7 yr apart in time) recorded at station BOSA. Top: Map view of the ray path projected on the Earth's surface. Star represents the doublet location. Triangle represents station BOSA. Blue curve represents the ray path projected on the Earth's surface. The green part of the curve represents the projected part of the ray path within the inner core. Bottom: Comparison of the highly similar waveforms of an Aleutian Islands doublet recorded at BOSA. PKP signals within the box in the upper panel are superimposed and enlarged in the lower panel, showing an apparent change of both inner core travel-times and PKP(DF) coda.