Short Wavelength Topography on the Inner Core Boundary

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Constraining the topography of the ICB is important for studies of core-mantle coupling and the generation of the geodynamo. We present evidence for significant temporal variability in the amplitude of the inner core reflected phase PKiKP for an exceptionally high quality earthquake doublet, observed post-critically at the short period Yellowknife seismic array (YK), which occurred in the South Sandwich Islands within a ten year interval (1993/2003). This observation, complemented by data from several other doublets, indicates the presence of topography at the inner-core boundary, with a horizontal wavelength on the order of 10 km. Such topography could be sustained by small scale convection at the top of the inner core, and is compatible with a rate of super-rotation of the inner core of ∼0.1-0.15 deg/year. In the absence of inner core rotation, decadal scale temporal changes in the ICB topography would provide an upper bound on the viscosity at the top of the inner core.

Inner Core | Topography | PKiKP | Super Rotation

The ICB separates the liquid outer core from the solid inner core and is the site of important dynamical processes, as the core freezes and light elements are expelled to power convection in the outer core (1-3). Significant long wavelength topography of the ICB is ruled out by dynamical considerations (4). While hemispherical variations in the seismic properties at the top of the inner core have been documented (5-7), seismological investigations indicate that the ICB is, to a good approximation, quite spherical (8). However, the observation of significant PKiKP coda, likely due to multiple scattering (9) (10) indicates that the structure of the ICB is more complex at short wavelengths. There is also evidence for significant scattering near the top of the inner core (11) (12). Recently, in a study of amplitudes of ICB reflected phases (PKiKP), Krasnoshchekov et al. (13) have proposed that the ICB is "patchy" in its reflective properties at scales of 10-200km laterally. Because their data were obtained at sub-critical distances, these authors could not constrain the precise nature of the variability in the measured PKiKP amplitudes. While short wavelength topography has been proposed for the core-mantle boundary (14), there has not been any such evidence for the ICB.

In their efforts to constrain the rate of differential rotation of the inner core previously estimated using PKP(DF-BC) differential travel times on paths to Alaska stations in the epicentral distance range $147 - 155^o$ (15) , Zhang et al. (16) found several high quality earthquake doublets in the South-Sandwich region, separated in time by a decade or more. The high waveform similarity at many stations indicates that the two sources are located within a wavelength for compressional waves. One of the earthquake doublets reported in the Zhang et al. (16) study is of exceptional quality (Dec 1, 1993/ Sep 6, 2003, see also *Supporting Information*). Highly similar waveforms for both events were recorded at 102 stations with a broad coverage of epicentral distances and azimuths, and the hypocenter separation of the two events was inferred to be 100 m vertically and less than 1.0 km horizontally.

We found that this doublet was also well recorded on the short-period Yellowknife Seismograph Array (YK) in northern Canada, which is located in an optimal position for the study of mantle phases PP as well as both refracted (PKIKP) and post-critically reflected (PKiKP) core phases. Indeed, these phases are emitted near the maximum in the lobe of the doublet's radiation pattern (Fig. 1), at an epicentral distance of 137.8^o, where the two core phases are well separated and where the PKiKP undergoes total reflection. High signal-to-noise seismic waveforms were recorded for both events at eighteen of the nineteen YK stations. In a 50-second time window around the PP phases of the doublet, unfiltered waveforms are very highly similar at all stations of the array, with cross-correlation coefficients larger than 0.97 (Fig.2, see also Fig. 7,8 in *Supporting Information*). The amplitudes of PP for both events differ only by a factor of 1.05. This provides strong additional confirmation of the high quality of this doublet. We therefore expect the waveforms of other phases to be very similar in shape and amplitude for this special doublet.

However, the first two arrivals (PKIKP and PKiKP) in the individual unfiltered YK seismograms, which are well separated for both events, have significantly different waveforms (Fig. 3A). For the 2003 event, the waveforms of PKiKP are simply reversed in polarity with respect to those of PKIKP, as theoretically predicted for post-critical reflections (Fig. 3D) (7). For the 1993 event, the amplitudes of PKiKP are much reduced (by a factor of 3.0). The later part of the PKIKP waveform also shows some change. In the frequency range 1-2 Hz, PKIKP and PKiKP waveforms of both events are simpler (Fig. 3B), so that reversed waveforms of PKiKP are similar to those of PKIKP for both events (Fig. 3B,3C). In this frequency range, where the amplitude ratios can be determined more robustly, the amplitudes of PKiKP for 2003 and 1993 events differ by a factor of 7.2. Given the striking similarity of the PP waveforms and their coda in the frequency range 0.5 to 2 Hz (Fig. 7,8 in *Supporting Information*) and the other evidence for the quality of the doublet (15), we infer that both phases (especially the PKiKP phase) have undergone temporal changes within 10 years.

PKIKP/PKiKP amplitude ratios, which are not affected by the slight difference in magnitude, are 2.3 and 0.7 for the 1993 and 2003 events, respectively (Fig. 3C). This amplitude ratio is thus also significantly different for the two events. Further analysis of PKIKP/PKiKP amplitude ratios indicates that the anomaly is primarily in the amplitude of the PKiKP phase for the 1993 event (*see Materials and Methods*). In addition, our wavelet analysis demonstrates that in the frequency range of 0.2-3 Hz there is not any interfering phase (Fig. 4). We now discuss possible causes for this anomaly. Apparent temporal changes in the waveforms could be due to small differences in 1) the earthquake source mechanism and time function, 2) interference with another local, regional or teleseismic event, 3) slightly different paths causing different scattering from local heterogeneities near the stations or the sources or along the path. The PP waveforms are ex-

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tremely similar, so we rule out possible differences in the source time functions. We also verified that PKiKP waveforms for the 1993 event were not affected by any local, regional, or teleseismic event. Half an hour before and after the origin times of the doublet, there were no teleseismic events of $m_b > 3.0$ reported in the composite ANSS catalog (17). If, on the other hand, there was an interfering local or regional event, there would be a time delay of at least 1.5 seconds across the YK seismic array, which would cause detectable changes in waveform. An undetected, but large enough teleseismic event arriving at YK simultaneously with PKiKP for the 1993 event would have an effect on the waveforms within 50 sec of the PP arrivals, which is not seen (Fig. 2, see also Fig. 7,8 in *Supporting Information*). We note that the raypaths of PKIKP and PKiKP are very close near the doublet sources and throughout the upper mantle, where they remain within a wavelength of the P wave at the period of observation ($< 5km$). The difference of their take-off angles is only $\sim 0.8^o$ and both phases are emitted near the maxima of the lobe of the source radiation pattern (Fig. 1A). In order to investigate whether hidden scattered phases may be present within the 1993 PKiKP waveform, we performed a wavelet decomposition of the waveforms (18). This analysis shows that the phases of both PKiKP and PKIKP are very stable from one event to the other in the band pass of sensitivity of the YK network, and that the only detectable differences are in the amplitudes (Fig. 4, see also further discussion in *Supporting Information*). Since differential travel times measured with respect to PP are not significantly different, given measurement uncertainty (0.05 sec for PKiKP's and 0.1 sec for PKIKP's), we infer that the cause of the anomalous amplitudes is defocusing or attenuation by a heterogeneity located most likely near the ICB reflection point of the 1993 PKiKP phase.

Because the PKiKP phase is post-critically reflected at the distance considered (Fig. 3C), the large amplitude differences within the doublet are most likely due to short wavelength topography on the ICB. As shown in Fig. 9 in *Supporting Information*, the presence of an anomalous laterally varying layer above the ICB (13) would not affect the reflection coefficient at the post-critical distance of our observations. A laterally varying, highly attenuating layer above the ICB would be incompatible with the absence of significant travel time differences in PKiKP within the doublet. However, defocusing can be produced by a "bump" on the ICB (Fig. 6). The amplitude deficiency of the 1993 PKiKP phase is most clear in the frequency range 1-2Hz (Fig. 4, see also Fig. 9 in *Supporting Information*). Based on the width of the corresponding fresnel zone, we therefore estimate the wavelength of an anomalous "bump" on the ICB to be on the order of 10 km. Because there is no significant difference in the relative PKiKP travel times for the doublet, and no other study has detected topography on the ICB using travel times, these considerations provide a conservative upper bound on the height of the topography (3-5km). However, since an aspect ratio of 0.02 is enough to generate reflected wave amplitude ratios of a factor of 2 (19) (20),we estimate that the height of the detected topography could be as small as 300-500m, compatible with dynamical considerations.

Two other high quality South Sandwich Islands doublets were found in the study of Zhang et al. (16) (see *Supporting Information*). For one of these doublets (1997/1998), there is no significant anomaly in the amplitude ratio PKIKP/PKiKP, whereas for the other (1993/2001), this amplitude ratio is anomalous for both events (Fig. 5A,5B). Considering the time separation and the location of the theoretical PKiKP reflection points at the ICB of the three doublets considered (Fig. 5C), and the 10 km wavelength of the topography, our observations are in agreement with an eastward rotation of the inner core with respect to the mantle at a rate of $\sim 0.12 - 0.15^o/year$ (see *Materials and Methods*), compatible with scattered wave and normal mode based estimates (11) (21). The viscosity at the top of the inner core would have to be large enough to sustain such topography over a timescale of decades (4), or it could be sustained by small scale convection in the top layers of the inner core (22).

The presence of corrugations at the ICB not only explains our observations, but also the variability in the PKP(DF) coda previously observed (16), and may also account for the PKiKP coda previously reported (9) (10), the amplitude variability observed at sub-critical distances (13), as well as the changes in the envelope of PKIKP on decadal time scales (27). An alternative explanation, which we cannot completely rule out, involves time varying topography, which could be due to dynamic processes related to inner core growth (23). In this scenario, the viscosity at the top of the inner core would need to be lower than 10^{16} Pas (4), to allow time variability on the time scale of a decade.

Material and Methods. **Which phase is the most anomalous?** Amplitude ratios are measured by peak-to-peak amplitudes of PKIKP, PKiKP and PP, respectively, between two linearly stacked traces of the doublet. For the 1993 event, the PKiKP amplitude is 3.0 times smaller than that for the 2003 event in the raw records. The similarity of filtered waveforms of PKIKP and reversed PKiKP is compatible with the theoretical prediction for post-critically reflected phases at the ICB (Fig. 3D) (7). This implies that the reflection coefficients of PKiKP at the ICB for both events are not significantly different from 1. According to current reference 1D seismic models (PREM (24), IASPEI (25), and AK135 (26)), the amplitude ratio of PKIKP to PKiKP cannot be larger than 1.9 even if we assume that there is no attenuation ($Q_\alpha = \infty$) in the inner core (Fig. 3E). Based on the compressional quality factor ($Q_\alpha = 445$) in the PREM reference model, the theoretical amplitude ratio of PKIKP to PKiKP is ~ 1.0; based on our recent estimate, ($Q_\alpha =\sim 370$) *(7)*, the predicted amplitude ratio is ~ 0.8, which is very compatible with the observed amplitude ratio for the 2003 event. Therefore, we infer that the PKiKP of the 1993 event is the most anomalous phase. We note however, that the amplitude ratio of the two PKIKP phases (1.5) is slightly larger than that of PP (1.05), indicating that some changes are also detected in the amplitudes of PKIKP, although much more subtle than for PKiKP. Differential travel times, referenced to the phase PP, differ by less than 0.05 sec for the PKiKP's and 0.1 sec for the PKIKP's, which is within the uncertainty of the location of the two events. Further examination of these phases in the field of slowness and back-azimuth (Fig. 11 in *Supporting Information*) indicates that they do not significan tly depart from the theoretical predictions.

Constraints on possible rate of super-rotation of the inner core. Let us assume that the ICB can sustain short scale topography and that the inner core is rotating eastward with respect to the mantle (Fig. 6). For the 1997/99 doublet, which is located at a distance of $\sim 5km$ (projected in the direction of rotation) west from the 1993/03 doublet, the PKIKP/PKiKP amplitude ratios are not anomalous (0.9 and 1.1 respectively for the two events, Fig. 5). On the other hand, for the 1993/01 doublet, which is located at a distance of $\sim 20km$ west of the 1993/03 doublet, both amplitude ratios are anomalous (3.2 and 2.4 respectively, Fig. 5). A wavelength of $\sim 10km$ for the topography is compatible with the projected distance between the 93/01 and 93/03 doublets of about $\sim 20km$, both of which need to be near a topographic maximum in 1993. In order for the 93/01 doublet to be near a topographic maximum in 2001, the rotation rates should be 10/8, 20/8, 30/8 km/yr... The 1997/99 reflection point is near a topographic minimum in 1993, and needs to be near one in 1997/99. This implies rotation rates of 10/4, 20/4, 30/4 km/yr... The 93/03 reflection point is near a topographic maximum in 1993 and minimum in 2003. This implies rotation rates of 5/10 km/yr, 15/10 km/yr, 25/10km/yr... The minimum compatible rate for all these conditions to be satisfied is therefore $\sim 2.5 km/yr$ or $0.12^o/yr$. Multiples of this rate cannot be excluded.

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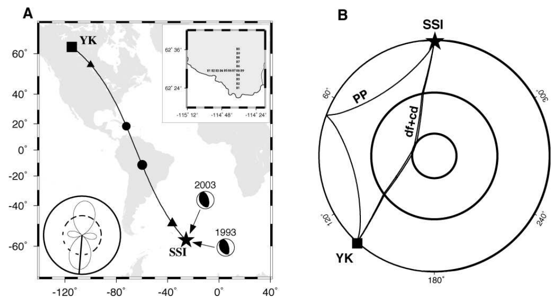

Fig. 1. (A) Yellowknife Seismic Array (YK) and the doublet. The 19 stations of the array form two arms, one along a lake (shore indicated) and one orthogonal to it. Its aperture is 25 km with a station interval of 2.5 km (upper-right inset). The doublet consists of two South Sandwich Islands (SSI) events at an epicentral distance of 137.8^o : Dec 1, 1993, m_b=5.5, depth=33 km according to the PDE catalog; and Sept. 6, 2003, m_b=5.6, depth=33 km according to the PDE catalog. According to Harvard CMT (http://www.seismology.harvard.edu), scalar moments and depths are (M_o=3.53x1024 dyne-cm, h= 45 km) and (M_o=4.02x1024dyne-cm, h= 44km), respectively. The lower-left inset is the P-wave radiation pattern of the doublet based Harvard CMT moment tensors. Black triangles and dots are entry (exit) points of PKIKP at the ICB and the CMB, respectively. (B) Ray paths of PP, PKIKP(df), and PKiKP(cd) phases used in this study.

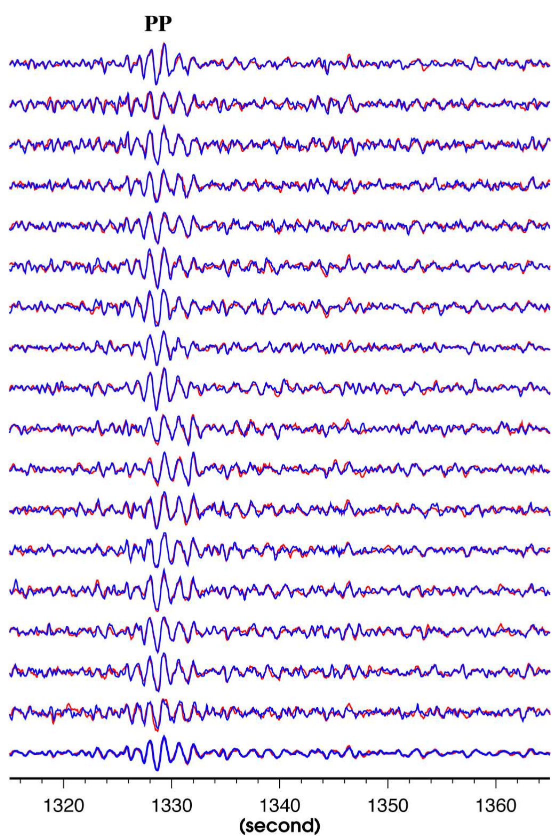

Fig. 2. Original waveform profile of PP phases, for the 1993 event (red) and for the 2003 event (blue). The station YKR8 did not work correctly for the 1993 event, and so we removed this station in this study. We choose YKR7 as the reference station to align individual PP waveforms. The last trace is the linearly stacked trace after the alignment. Cross-correlation coefficients of waveforms in this time window are larger than 0.97. The amplitudes of the PP phase are nearly identical (less than 5% difference).

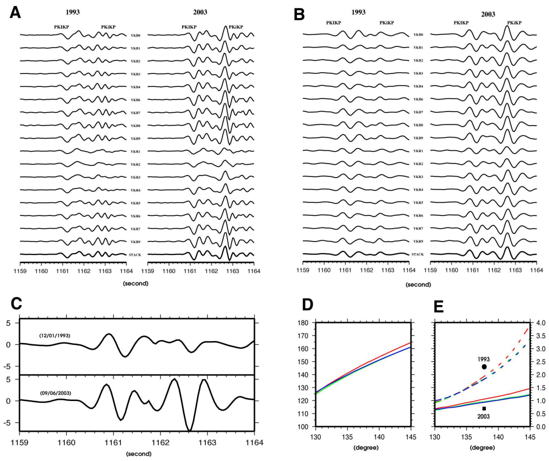

Fig. 3. (A) Original waveform profile of PKIKP and PKiKP phases. For each event, waveforms are highly similar at most of stations except YKR1, YKR2, and YKR3 stations. These three stations are close to the lake (Fig. 1A) and they have a common feature for both events: site-related filtering of higher frequencies. (B) Bandpass filtered waveform profile of PKIKP and PKiKP phases (from 1.0 to 2.0 Hz). In this frequency range, waveforms of PKIKP and PKiKP are highly similar at all stations (including YKR1, YKR2, and YKR3) for each event. Also, waveform shapes of PKIKP and PKiKP for the 1993 event are more similar to those of the 2003 event. In this profile, it is obvious that phase shifts between PKiKP and PKIKP are close to 180^o as predicted theoretically (7). (C) Linearly stacked waveforms of PKIKP and the reversed PKiKP phases after bandpass filtering (1-2Hz) showing the similarity of shape. Vertical broken line indicates place where the PKiKP waveform has been cut and reversed. The amplitude of PKIKP for 2003 event is 1.5 times larger than that for 1993 event; the amplitude of PKiKP for 2003 event is 7.2 times larger than that for 1993 event. Amplitude ratios of PKIKP to PKiKP are 2.3 (1993)and 0.7(2003) event. (D) Theoretical phase shifts of PKiKP with respect to PKIKP based on PREM (red), IASPEI91 (blue), and AK135 (green) reference models (24-26). In this study, the phase shift is $\sim 145^o$. (E) Theoretical amplitude ratios of PKIKP to PKiKP. Dashed lines are assuming that the inner core $Q_\alpha = \infty$ (i.e., no seismic attenuation in the inner core) based on the above three reference models. Solid lines are using $Q_\alpha = 445$ provided in PREM model. The black dot and square are observed amplitude ratios of PKIKP to PKiKP (Fig. 3C) for the 1993 and 2003 events, respectively.

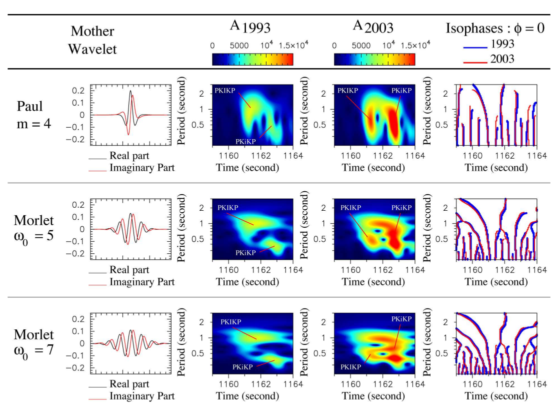

Fig. 4. Wavelet analysis of the seismograms of the 1993 and 2003 earthquakes. Both records have been analysed three times using different mother wavelets. Each line in the figure corresponds to the analysis performed with one of the three mother wavelets. Left panels : real and imaginary parts of the mother wavelet used for the analysis. Two central panels : wavelet amplitude spectrum of the 1993 (left) and 2003 (right) seismograms. Color intensity corresponds to the coefficient magnitude of a wavelet with a particular period at a particular time. The x-axis is the wavelet location in time. The y-axis is the wavelet time period corresponding to the wavelet scale. Left panels : Comparaison between the wavelet phases of both time series. Solid lines corresponds to the times where the phase takes the value zero (i.e : each time the phase has completed a 2π radian cycle). Blue and red lines have been computed from the 1993 and 2003 seismograms respectively. The x-axis is the wavelet location in time. The y-axis is the wavelet period in seconds.

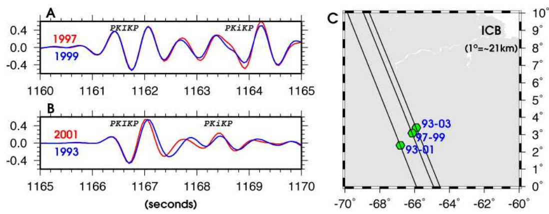

Fig. 5. (A) PKIKP and PKiKP waveforms for 04/04/1997 (m_b=4.8, $\Delta = 138.1^o$) and 05/14/1999 (m_b=4.7, $\Delta = 138.2^o$) doublet at SSI. Amplitude ratios of PKIKP to PKiKP are 0.9 and 1.1, respectively, which is not incompatible with theoretical predictions. PKIKP phases for the doublet completely match after normalisation. (B) PKIKP and PKiKP waveforms for 12/30/1993 (m_b=5.0, $\Delta = 139.0^o$) and 01/29/2001 (m_b=4.8, $\Delta = 138.9^o$) doublet at SSI. Amplitude ratios are 3.2 and 2.4, respectively. Both of them are anomalous (e.g. Fig. 3E). The beginning parts of PKIKP phases are identical after normalization. (C) Reflection points of three doublets at the ICB. Black thin lines are the raypaths of PKiKP phases. The distance between 93-03 and 97-99 reflection points is $\sim 8km$; the distance between 93-03 and 93-01 reflecting points is $\sim 30km$.

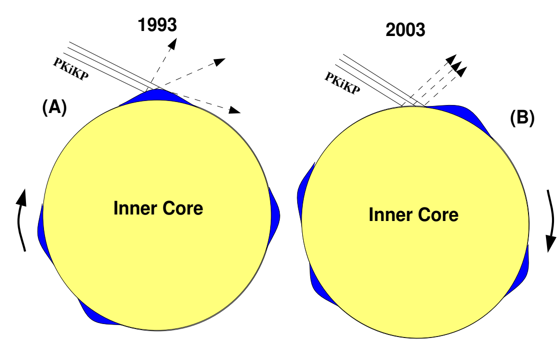

Fig. 6. Cartoon illustrating how bumps on the ICB may interact with PKiKP, as a function of time, assuming inner core super rotation. (A) The PKiKP phase from the 1993 event encounters a bump and its energy is dispersed, resulting in reduced amplitude observed at the YK seismic array. (B) By 2003 the bump has rotated away from the PKiKP reflection point, so all of the energy is reflected towards the YK. The size of the bumps is grossly exaggerated both laterally and vertically.