Short wavelength topography on the inner-core boundary

Aimin Cao, Yder Masson, and Barbara Romanowicz*

Berkeley Seismological Laboratory, University of California, Berkeley, CA 94720

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Constraining the topography of the inner-core boundary 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 postcritically at the short-period Yellowknife seismic array (YK), which occurred in the South Sandwich Islands within a 10-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 $\approx 0.1\text{--}0.15^\circ$ per year. In the absence of inner-core rotation, decadal scale temporal changes in the inner-core boundary topography would provide an upper bound on the viscosity at the top of the inner core.

PKiKP | super rotation | doublet

The inner-core boundary (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). Although 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 also is 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 10–200 km laterally. Because their data were obtained at subcritical distances, these authors could not constrain the precise nature of the variability in the measured *PKiKP* amplitudes. Although 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 by using *PKP*(*DF–BC*) differential travel times on paths to Alaska stations in the epicentral distance range $147\text{--}155^\circ$ (15), Zhang *et al.* (16) found several high-quality earthquake doublets in the South Sandwich Islands (SSI) 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 (December 1, 1993/September 6, 2003, see also *SI Text*). 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 <1.0 km horizontally.

Data, Results, and Discussion

We found that this doublet also was 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 postcritically 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° , 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 18 of the 19 YK stations. In a 50-s 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 of >0.97 [Fig. 2; see also [supporting information \(SI\) Figs. 7 and 8](#)]. The amplitudes of *PP* for both events differ only by a factor of 1.05. The above observations provide 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. 3*A*). For the 2003 event, the waveforms of *PKiKP* are simply reversed in polarity with respect to those of *PKIKP*, as theoretically predicted for postcritical reflections (Fig. 3*D*) (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. 3*B*) so that reversed waveforms of *PKiKP* are similar to those of *PKIKP* for both events (Fig. 3 *B* and *C*). In this frequency range, where the amplitude ratios can be determined more robustly, the amplitudes of *PKiKP* for the 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 0.5–2 Hz (*SI Figs. 7 and 8*) and the other evidence for the quality of the doublet (16), 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. 3*D*). This amplitude ratio is therefore 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

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Abbreviations: ICB, inner-core boundary; SSI, South Sandwich Islands; YK, Yellowknife Seismograph Array.

*To whom correspondence should be addressed. E-mail: barbara@seismo.berkeley.edu.

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Fig. 3. Waveform analyses. (A) Original waveform profile of *PKIKP* and *PKiKP* phases. For each event, waveforms are highly similar at most of stations, except the 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. In addition, 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° as predicted theoretically (7). (C) Linearly stacked waveforms of *PKIKP* and the reversed *PKiKP* phases after bandpass filtering (1–2 Hz) showing the similarity of shape. The vertical broken line indicates where the *PKiKP* waveform has been cut and reversed. The amplitude of *PKIKP* for the 2003 event is 1.5-times larger than that for the 1993 event; the amplitude of *PKiKP* for the 2003 event is 7.2-times larger than that for the 1993 event. Amplitude ratios of *PKIKP* to *PKiKP* are 2.3 (1993) and 0.7 (2003). (D) Theoretical phase shifts of *PKiKP* with respect to *PKIKP* based on PREM (red), IASPEI91 (blue), and AK135 (green) reference models (25–27). In this study, the phase shift is $\approx 145^\circ$. (E) Theoretical amplitude ratios of *PKIKP* to *PKiKP*. Dashed lines show ratios resulting from the assumption that the inner core $Q_\alpha = \infty$ (i.e., no seismic attenuation in the inner core), which is based on the above three reference models. Solid lines show ratios resulting from the assumption that $Q_\alpha = 445$, which is 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.

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 300–500 m, which is compatible with dynamical considerations.

Two other high-quality doublets from SSI were found in the study of Zhang *et al.* (16) (see SI Table). For one of these doublets (1997/1999), 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. 6A and B). Considering the time separation and the location of the

theoretical *PKiKP* reflection points at the ICB of the three doublets considered (Fig. 6C) 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 ≈ 0.12 – 0.15° per 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 time scale of decades (4), or it could be sustained by small-scale convection in the top layers of the inner core (22).

Fig. 4. Wavelet analysis of the seismograms of the 1993 and 2003 earthquakes. Both records have been analyzed three times by using different mother wavelets. Each line corresponds to the analysis performed with one of the three mother wavelets. The leftmost graphs show the real and imaginary parts of the mother wavelet used for the analysis. The two central graphs show the wavelet amplitude spectra 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. The rightmost panels show comparisons between the wavelet phases of both time series. Solid lines correspond to the times when 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. This analysis shows that the difference between the *PKiKP* and *PKiKP* waveforms between the 1993 and 2003 events is mostly in the amplitudes, with imperceptible difference in the phase.

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 subcritical distances (13), and the changes in

the envelope of *PKiKP* on decadal time scales (23). 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 (24). In this scenario, the

Fig. 5. 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 toward the YK. The sizes of the bumps are grossly exaggerated both laterally and vertically.

Fig. 6. Other doublets. (A) *PKiKP* and *PKiKP* waveforms for April 4, 1997 ($m_b = 4.8$, $\Delta = 138.1^\circ$) and May 14, 1999 ($m_b = 4.7$, $\Delta = 138.2^\circ$) doublets 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 normalization. (B) *PKiKP* and *PKiKP* waveforms for December 30, 1993 ($m_b = 5.0$, $\Delta = 139.0^\circ$) and January 29, 2001 ($m_b = 4.8$, $\Delta = 138.9^\circ$) 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 the *PKiKP* phases are identical after normalization. (C) Reflection points of three doublets at the ICB. Black thin lines are the ray paths of the *PKiKP* phases. The distance between the 1993/2003 and 1997/1999 reflection points is ≈ 8 km; the distance between the 1993/2003 and 1993/2001 reflecting points is ≈ 30 km.

viscosity at the top of the inner core would need to be $<10^{16}$ Pa (4) to allow time variability on the time scale of a decade.

Materials 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 postcritically reflected phases at the ICB (Fig. 3D) (7), implying that the reflection coefficients of *PKiKP* at the ICB for both events are not significantly different from 1. According to current reference one-dimensional seismic models [Preliminary Reference Earth Model (PREM) (25), International Association of Seismology and Physics of the Earth's Interior (IASPEI) (26), and AK135 (27)], the *PKIKP*/*PKiKP* amplitude ratio cannot be >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, the *PKIKP*/*PKiKP* theoretical amplitude ratio is ≈ 1.0 ; based on our recent estimate ($Q_\alpha = \approx 370$) (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 <0.05 sec for the *PKiKP* and 0.1 s for the *PKIKP* phases, 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 (SI

Fig. 11) indicates that they do not significantly depart from the theoretical predictions.

Constraints on a Possible Rate of Inner Core Super Rotation. 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. 5). For the 1997/1999 doublet, for which the ICB reflection points of *PKiKP* is located at a distance of ≈ 5 km (projected in the direction of rotation) west from the 1993/2003 doublet, the *PKIKP*/*PKiKP* amplitude ratios are not anomalous (0.9 and 1.1, respectively, for the two events) (Fig. 6). On the other hand, for the 1993/2001 doublet, for which it is located at a distance of ≈ 20 km west of the 1993/2003 doublet, both amplitude ratios are anomalous (3.2 and 2.4, respectively) (Fig. 6). A wavelength of ≈ 10 km for the topography is compatible with the projected distance between the 1993/2001 and 1993/2003 doublet reflection points of ≈ 20 km, both of which need to be near a topographic maximum in 1993. For the 1993/2001 doublet reflection point to be near a topographic maximum in 2001, the rotation rates should be 10/8, 20/8, and 30/8 km/year. The 1997/1999 reflection point is near a topographic minimum in 1993 and needs to be near one in 1997/1999. The observation implies rotation rates of 10/4, 20/4, and 30/4 km/year. The 1993/2003 reflection point is near a topographic maximum in 1993 and a minimum in 2003, which implies rotation rates of 5/10, 15/10, and 25/10 km/year. Therefore, the minimum compatible rate for all these conditions to be satisfied is ≈ 2.5 km/year or 0.12° per year. Multiples of this rate cannot be excluded.

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- Glatzmeier GA, Roberts PH (1995) *Nature* 377:203–209.
- Fearn DR, Loper DE (1985) *Phys Earth Planet Inter* 39:5–13.
- Lister JR, Buffett BA (1995) *Phys Earth Planet Inter* 91:17–30.
- Buffett BA (1997) *Nature* 388:571–573.
- Niu F, Wen L (2001) *Nature* 410:1081–1084.
- Garcia R (2002) *Geophys J Int* 150:651–664.
- Cao A, Romanowicz B (2004) *Earth Planet Sci Lett* 228:243–253.
- Souriau A, Souriau M (1989) *Geophys J Int* 98:39–54.
- Koper DK, Pyle MK, Franks JM (2003) *J Geophys Res* 108:2168.
- Poupinet G, Kennett BLN (2004) *Phys Earth Planet Inter* 146:497–511.
- Vidale JE, Earle PS (2000) *Nature* 404:273–275.
- Cormier VF, Li X (2002) *J Geophys Res* 107:2362.
- Krasnoshechikov DN, Kaazik PB, Ovtchinnikov VM (2005) *Nature* 435:483–487.
- Earle PS, Shearer PM (1997) *Science* 277:667–670.
- Song X, Richards PG (1996) *Nature* 382:221–224.
- Zhang J, Song X, Li Y, Richards PG, Sun X, Waldhauser F (2005) *Science* 309:1357–1360.
- Advanced National Seismic System (April 2002) ANSS Earthquake Catalog, available at <http://www.ncedc.org/anss>. Accessed May 20, 2006.
- Daubechies I (1990) *IEEE Trans Inf Theory* 36:961–1005.
- Neuberg J, Wahr J (1991) *Phys Earth Planet Int* 68:132–143.
- Emmerich H (1993) *Phys Earth Planet Int* 80:125–134.
- Laske G, Masters G (1999) *Nature* 402:66–69.
- Wen L, Niu F (2002) *J Geophys Res* 107:2273.
- Vidale JE, Earle PS (2005) *Geophys. Res. Lett.* 32:L01309.
- Sumita I, Yoshida S, Kumazawa M, Hamano Y (1996) *Geophys J Int* 124:502–524.
- Dziewonski AM, Anderson DL (1981) *Phys Earth Planet Inter* 25:297–356.
- Kennett BLN, Engdahl ER (1991) *Geophys J Int* 105:429–465.
- Kennett BLN, Engdahl ER, Buland R (1995) *Geophys J Int* 122:108–124.