Localized Temporal Change of the Earth’s Inner Core Boundary

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Compressional waves of an earthquake doublet (two events occurring in the South Sandwich Islands on 1 December 1993 and 6 September 2003), recorded at three seismic stations in Russia and Kyrgyzstan and reflected off Earth’s inner core boundary, arrived at least from 39 to 70 milliseconds earlier in the 2003 event than in the 1993 event. Such changes indicate that Earth’s inner core radius enlarged locally beneath middle Africa by 0.98 to 1.75 kilometers between the times of these two events. Changes of the inner core radius may be explained by either a differential motion of the inner core, assuming that irregularities are present at the inner core boundary and fixed to the inner core, or a rapid growth of the inner core by this amount.

Earth’s inner core grows from the solidification of the outer core (1). The growth of the inner core releases latent heat and dissipates light elements, providing driving forces for the outer core convection (2) and power for generating the geodynamo (3, 4). The inner core growth process is thought to be geologically slow (5–10) and geographically uniform because of the presumed extremely small variation in temperature in the outer core (11). Here, I used PKIKP [a compressional wave reflected off the inner core boundary (Fig. 1A)] waveforms of an earthquake waveform doublet discovered by Zhang et al. (12) to study temporal change of the inner core boundary. Earthquake waveform doublets are earthquakes occurring at different times but in almost exactly the same location and generating similar waveforms (12–18). Because the relative travel time and waveform difference between the waveform doublets is sensitive only to the relative change of event location and/or the temporal change of seismic properties, it is powerful to use waveform doublets to study high-resolution relative locations of the earthquakes (13–15) and to detect temporal change of seismic properties (12, 16–18). The similarities of the doublet waveforms also allow accurate travel time measurement to be made. Zhang et al. (12) reported the existence of 19 waveform doublets in the South Sandwich region over a period of 35 years and showed that the PKP(DF) (PKIKP) phases [a compressional wave propagating through the inner core (Fig. 1A)] are in misalignment to each other between the doublets. Their study provided compelling evidence for the reported temporal changes in PKIKP travel time (19–21). They further proposed that the observed temporal changes can be explained by an inner core differential motion over a lateral velocity gradient in the inner core (20).

I used the best doublet reported in Zhang et al. (12) (table S1). The doublet consists of two events occurring on 1 December 1993 (event 93) and 6 September 2003 (event 03). I used the observed difference in absolute arrival time of various seismic phases that are not associated with the inner core (non-IC phases) between the doublet to determine the relative location and origin time of the two events. I used event 93 as the master event [i.e., fixed its origin time and location to those reported in the earthquake catalog (table S1)] and searched for the best-fitting relative location and origin time for event 03 that minimize the travel time residuals of the non-IC phases between the two events. I then studied the temporal changes of travel time and waveform of the PKIKP-PKIKP waves between the two events occurring on 1 December 1993 (event 93) and 6 September 2003 (event 03). I used the observed difference in absolute arrival time of various seismic phases that are not associated with the inner core (non-IC phases) between the doublet to determine the relative location and origin time of the two events. The PKIKP waveforms were superimposed on the basis of the relative arrival times of these phases between the doublet, estimated using the best-fitting relative location and origin time of the two events. The PKIKP travel time residuals between the doublet were further calculated by subtracting the predicted relative arrival times of the seismic phases from the measured arrival time differences between the doublet. If the superimposed waveforms are in misalignment between the doublet, or if a travel time residual is larger than the relocation error bar, it would mean that the arrival times of the seismic phases between the doublet cannot be explained by the relative origin time and hypocenter location of the doublet, and these phases exhibit temporal change in time.

The detailed relocation analysis places the doublet within 0.37 km in horizontal space and 0.7 km in depth (22). The inferred best-fitting relative origin time and hypocenter location between the doublet yield, for the non-IC phases,
a minimal root mean square travel time residual of 0.016 s and a maximal travel time residual of 0.031 s in the individual stations (Fig. S1B) (22). The maximal travel time residual in the individual stations (0.031 s) is considered as the relocation error bar.

Superimposed PKiKP-PKIKP waveforms and PKiKP waveforms observed at stations ARU (Arti, Russia), AAK (Ala Archa, Kyrgyzstan), and OBN (Obninsk, Russia) reveal that the PKiKP phases observed at these stations are in misalignment and that they arrived earlier in event 03 than in event 93, even after the travel time differences due to the relative hypocenter position of the two events are taken into account (Fig. 1, B to E). The PKiKP and PKIKP phases recorded at station ARU arrived 0.11 s earlier and the PKIKP phase about 0.04 s earlier in event 03 than in event 93. Moreover, the PKiKP-PKIKP differential travel time was about 0.07 s smaller in event 03 than in event 93 (Fig. 1C). Station AAK is closer, and the separation of the PKiKP and PKIKP phases is not clear, but the later portion of the waveforms (energy primarily associated with the PKiKP phases) is clearly in misalignment and arrived about 0.07 s earlier in event 03 than in event 93, whereas the earlier portion of energy appears to have arrived at about the same time (Fig. 1D). The PKiKP waveforms observed at station OBN exhibit two characteristics: (i) the PKiKP main phases are evidently in misalignment between the two events, with the phase in event 03 arriving about 0.07 s earlier than in event 93 and (ii) the PKiKP coda waves show waveform dissimilarities between the two events (Fig. 1E).

The observed smaller differential PKiKP-PKIKP travel times of about 0.07 s at stations ARU and AAK in event 03 further confirm that the PKiKP travel time residuals were not caused by relative event location or origin time of the doublet but by temporal changes of PKiKP travel time between the occurrences of the two events (22). The temporal changes in PKiKP travel time are at least 0.07 s at ARU and AAK, using their PKiKP arrival times as reference, and 0.039 s at OBN taking into account the maximal possible error of relocation, with the PKiKP phases arriving earlier in event 03 than in event 93.

No discernible temporal change of PKiKP travel time is observed for other stations. Superimposed PKiKP-PKiKP or PKiKP waveforms of the doublet recorded at other stations show excellent agreements in both absolute arrival time and differential travel time of the two phases (Fig. 2, A and B). The best-fitting relative location and origin time of event 03, obtained using the arrival times of the non-IC phases, also reduce the travel time residuals of the PKiKP and PKIKP phases within the relocation error bar for all other stations (Figs. 2 and 3). For the data available, the temporal changes in the PKiKP travel times are only observed for the phases recorded at ARU, AAK, and OBN, which sampled a localized region of the inner core boundary beneath middle Africa (Fig. 3).

The temporal changes of travel time for the PKiKP phases recorded at stations ARU, AAK, and OBN between the doublet are not likely to have been caused by temporal changes of seismic properties near the hypocenters or in the mantle (22). They indicate a localized change of the inner core radius beneath middle Africa between the occurrences of the doublet. A larger radius would produce an earlier PKiKP arrival, because the PKiKP phase would be reflected at a shallower depth. An inner core radius enlarged by 0.98 to 1.75 km between the occurrences of the doublet, either in the PKiKP sampling points (Fig. 4C) or in a regional scale beneath middle Africa (Fig. 4D). The position of the inner core boundary is controlled by the temperature and the outer core composition (iron and its companion light elements) (10). The localized growth may be caused by something unknown (for example, Earth’s magnetic field) or by a regional perturbation of temperature and/or composition near the inner core boundary through mechanisms such as a heterogeneous heat-flow flux at the bottom of the outer core induced near the core-mantle boundary (23) or small-scale compositional convection in the top of the inner core (24).

Both interpretations indicate that the inner core boundary has irregular topography and that the growth of the inner core and the energy release associated with the growth are not geo-
graphically uniform. Furthermore, the existence of irregular topography of the inner core boundary would require the existence of small-scale variations of temperature or/and outer core composition near the inner core boundary. Because the time scale of the outer core convection is short, the required existence of small-scale variations of temperature and/or outer core composition would suggest that the rapid localized growth of the inner core is a plausible interpretation for the observed localized enlarged inner core radius. If the temporal change of the inner core boundary position is caused by rapid localized growth of the inner core, it would further suggest that the growth of the inner core and the energy release due to the solidification of the outer core are rapid and episodic. To maintain a geologically slow growth rate, the inner core growth process would also be required to be constructive for some localized regions in some time periods and destructive in other regions or in other time periods.

The above inference of the conditions near the inner core boundary would have considerable implications for the convection in the outer core and geodynamo. The inner core region with the enlarged radius corresponds to where the anomalously strong small-scale magnetic field changes in the top of the outer core are inferred at the present time (25) and where most of Earth’s reversed magnetic polarity field has been produced in the past 400 years (26).

References and Notes
Transcrystalline Melt Migration and Earth’s Mantle

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Plate tectonics and volcanism involve the formation, migration, and interaction of magma and gas. Experiments show that melt inclusions subjected to a thermal gradient migrate through olivine crystals, under the kinetic control of crystal-melt interface mechanisms. Exsolved gas bubbles remain fixed and eventually separate from the melt. The dashed line in (B) is the equilibrium position of the inner core boundary. (C and D) The inner core boundary is changed by rapid localized inner core growth.

Fig. 4. Illustration of possible scenarios to change the inner core boundary at PKIKP reflected points between the occurring times of the doublet. (A and B) The inner core boundary has irregular topography and is changed by a differential inner core rotation. The doublet. (C and D) The inner core boundary is changed by rapid localized inner core growth.

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References

22. Materials and methods are available as supporting material on Science Online.
27. Time shifts in Fig. 1, B, D, and E, and Fig. 2, and travel time residuals in Fig. 3, are defined as T_{93-91} and T_{91-91} in (22), respectively. They are estimated using the best-fitting relative origin time (6 September 2003, 15:47:00.205) and hypocenter position of event 03 (fig. S2A).
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Supporting Online Material

www.sciencemag.org/cgi/content/full/1131692/DC1 Materials and Methods
Figs. S1 to S3 Table S1 References

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