Three Types of Earth's Inner Core Boundary

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1. Introduction

The Earth's inner core boundary (ICB) is the site where the inner core grows from the solidification of the liquid outer core. The solidification process releases latent heat and expels light elements, providing driven forces for the outer core convection and the geodynamo, which is responsible for the Earth's magnetic field. Thus, the fine-scale structure of the Earth's inner core boundary is important for our understanding of the thermo-compositional state of the Earth's core.

In this study, we employ seismological observations to constrain the fine-scale structure of the Earth's ICB. We collect a large set of seismic records with high-quality pre-critical PKiKP and PcP phase pairs, recorded by two dense seismic arrays, Hi-net and USArray. This dataset samples the ICB regions beneath East Asia, Mexico and the Bering Sea. We will show that the sampled ICB regions exhibit laterally varying seismic structures, which can be grouped into three types based on their seismic characteristics: simple ICB, bumpy ICB and mushy ICB.

2. Method & Data

We use pre-critical PKiKP phases in the distance of 0° to 90° to study the topography and fine-scale structure of the ICB. We also adopt PcP phase as a reference phase, to minimize the effects of shallow Earth's structure, uncertainties in source origin time, location, and source time function.

PKiKP-PcP differential travel time residuals, defined as

$$dt = (PKiKP_{obs} - PKiKP_{pre}) - (PcP_{obs} - PcP_{pre})$$

are used to constrain the ICB topographic height changes, while PKiKP-PcP waveform differences are used to determine the fine-scale ICB structure.

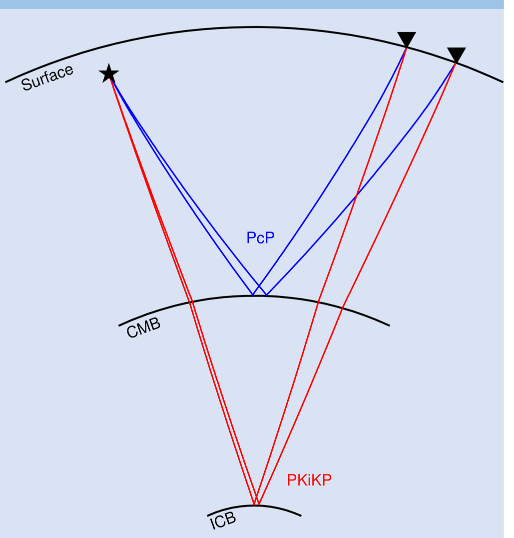


Fig. 1. Raypaths of PKiKP (red) and PcP (blue) phases from a seismic source at a depth of 300 km (black star) to receivers (black triangles) at two example epicentral distances of 30° and 35°.

In this study, we perform a systematic search of seismic waveforms recorded by two dense arrays, Hi-net in 2004–2014 and USArray in 2004–2015, for all events with focal depths greater than 30 km and magnitudes greater than Mw 5.8, which yield over 1,430,000 potential PKiKP-PcP pairs. After eye-checking data quality of each seismogram, we are able to retain a total of 2630 pairs of high-quality PKiKP and PcP waveforms. These PKiKP observations sample the ICB regions beneath East Asia, Mexico and the Bering Sea.

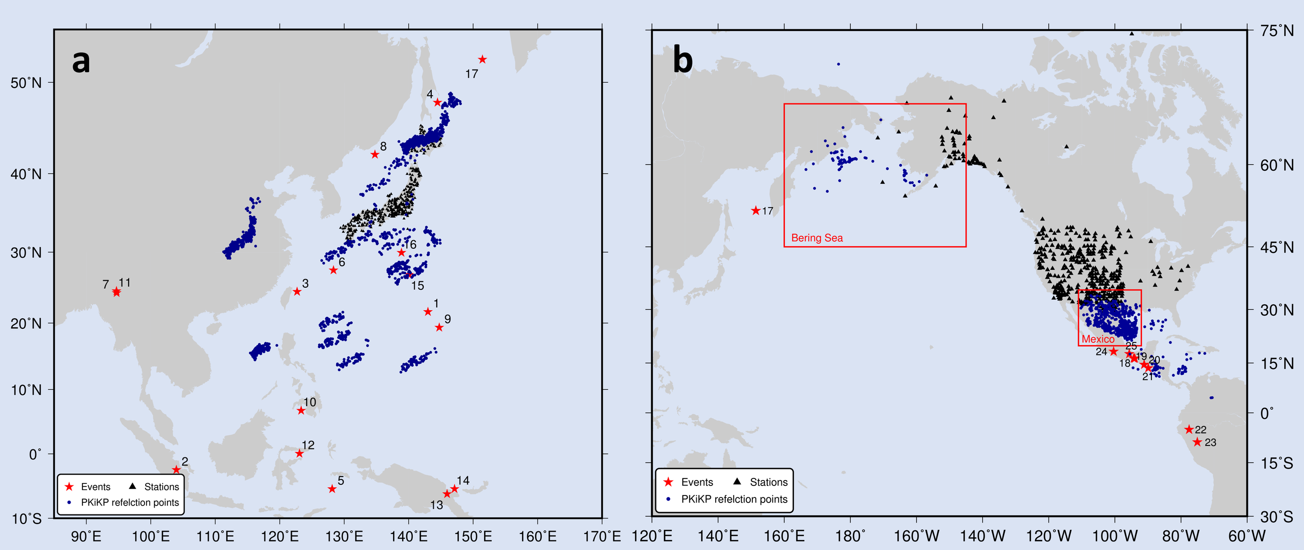


Fig. 2. Map view of seismic events (red stars) with high-quality PKiKP-PcP phase pairs recorded by two dense seismic arrays, **(a)** Hi-net and **(b)** USArray. The PKiKP reflection points at the ICB are plotted as dark blue dots. The ICB beneath East Asia, Mexico and the Bering Sea are well sampled.

3. PKiKP-PcP Differential Travel Time Residuals

PKiKP-PcP differential travel time residuals are sensitive to ICB topography. Small lateral variations indicate a flat ICB, while large lateral variations suggest a possible ICB topographic change in small horizontal distances.

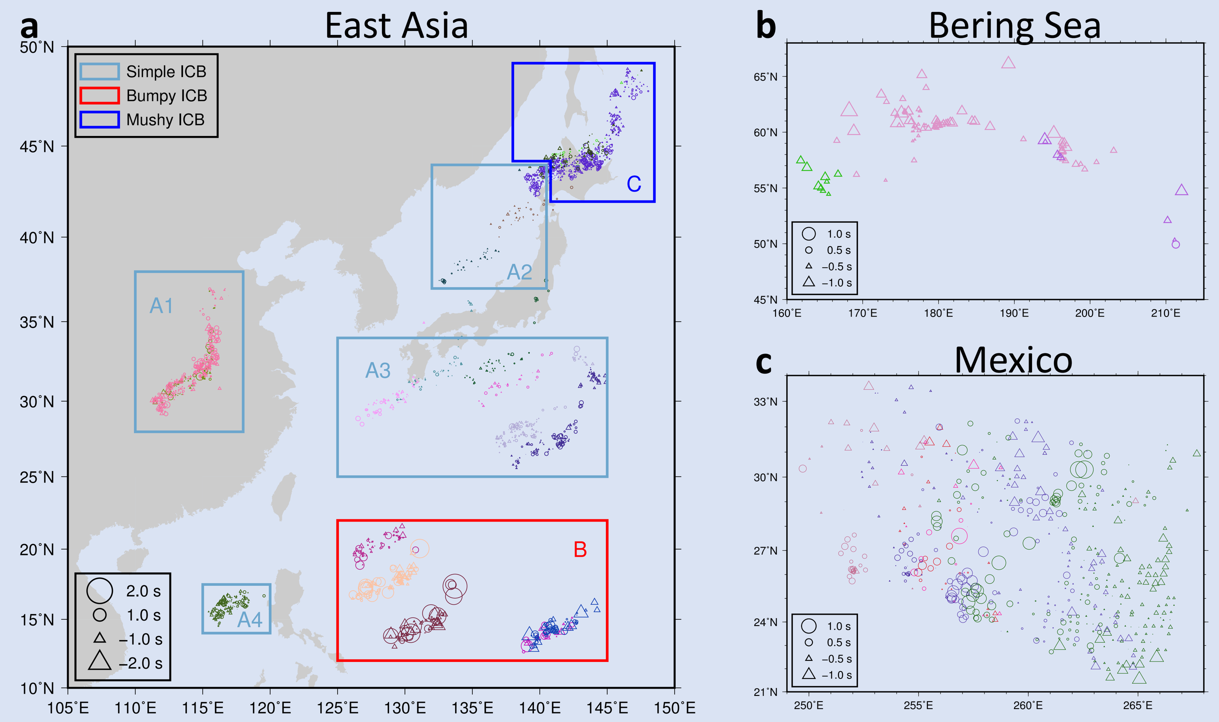
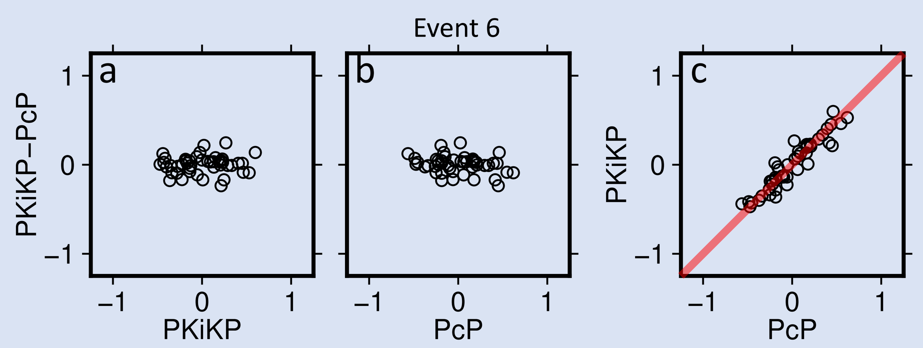


Fig. 3. PKiKP-PcP differential travel time residuals with respect to PREM, plotted at the PKiKP bouncing points of the ICB. Circles denote records with positive residuals, while triangles negative. Events are coded using different colors.

4. Simple ICB

For most sampled ICB regions, the PKiKP-PcP differential travel time residuals exhibit very small variations, and PKiKP and PcP phases have very similar waveforms, indicating a simple, flat and sharp ICB.



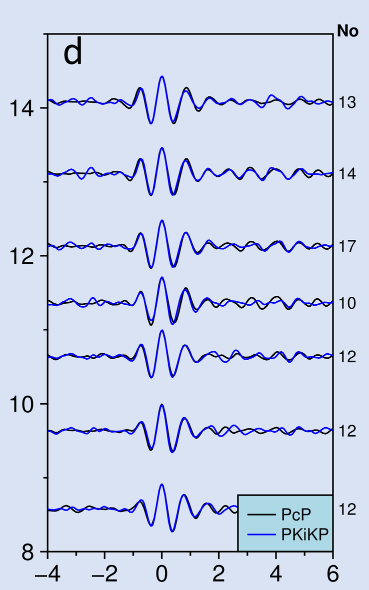


Fig. 4. (a-c) Relationship among PKiKP-PcP differential travel time residuals, PKiKP travel time residuals and PcP travel time residuals for event 6. **(d)** Comparisons of stacked observed PKiKP (blue) and PcP (black) waveforms for event 6.

5. Bumpy ICB

For the ICB regions beneath southwest of the North Pacific Ocean and Mexico, PKiKP-PcP differential travel time residuals exhibit large variation in small horizontal distances (Figs. 2 and 3), which suggest possible ICB topographic height changes. However, these variations can be attributed to CMB structure or ICB structure or both. Effects of CMB structures are small in the studied regions, based on differences of PcP travel time residuals between two neighboring events, suggesting that the observed 2 s variations of PKiKP-PcP differential travel time residuals can be attributed to the ICB topographic height changes of ~10 km.

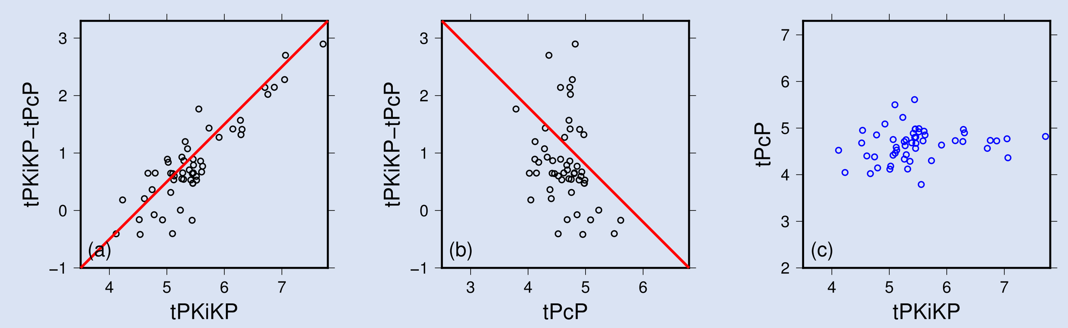


Fig. 5. Relationship among PKiKP-PcP differential travel time residuals, PKiKP travel time residuals and PcP travel time residuals for event 5. Note the large variations of PKiKP travel time residuals and small variations of PcP travel time residuals.

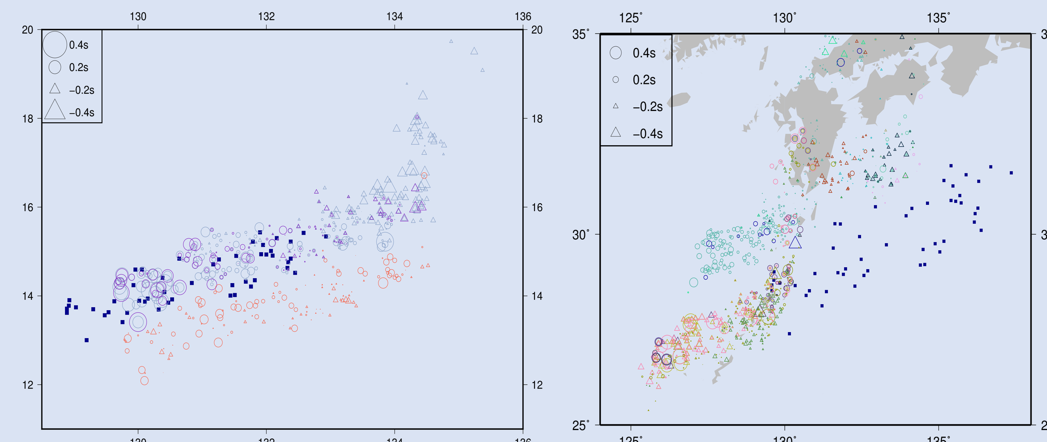


Fig. 6. Differences of PcP travel time residuals between two neighboring events, which sample **(a)** the PcP reflected region and **(b)** PKiKP exit points at CMB for the raypaths from event 5 to Hi-net array.

6. Mushy ICB Beneath Southwest Okhotsk Sea

PKiKP waves sampling the ICB region beneath southwest Okhotsk Sea exhibit small variations of PKiKP-PcP differential travel time residuals of no more than 0.3 s, indicating a flat ICB. However, the PKiKP phases exhibit complex waveforms with respect to simple PcP waveforms (Fig. 8a). The two energy pulses in the PKiKP waveforms have a time separation of about 0.9 s, with the relative amplitudes of the second pulses decreasing gradually with increasing epicentral distances. The observed PKiKP waveforms can be explained by a mushy ICB model with laterally varying thicknesses of 4–8 km and P wave velocity jumps of ~30% to ~50% (Figs. 8b-d).

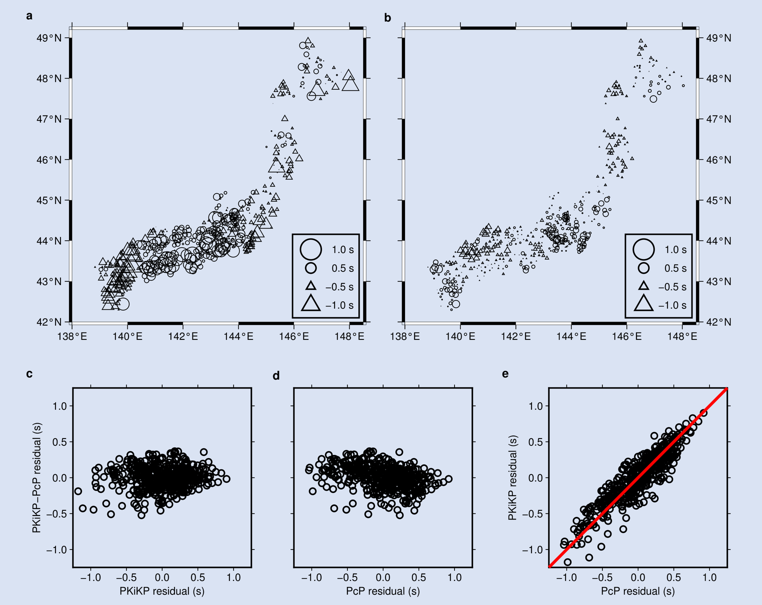


Fig. 7. Travel time residuals of event 17. a-b, Geographic distribution of **(a)** PKiKP travel time residuals and **(b)** PKiKP-PcP differential travel time residuals. All residuals are plotted at the PKiKP reflected points at the ICB, with positive and negative residuals denoted by circles and triangles respectively, and the size of the symbol proportional to the absolute value of travel time residual. **c-d**, Relationship between PKiKP-PcP differential travel time residuals and **(c)** PKiKP travel time residuals and **(d)** PcP travel time residuals. **e**, Relationship between PKiKP travel time residuals and PcP travel time residuals. Note that PKiKP travel time residuals exhibit a linear relationship with PcP travel time residuals.

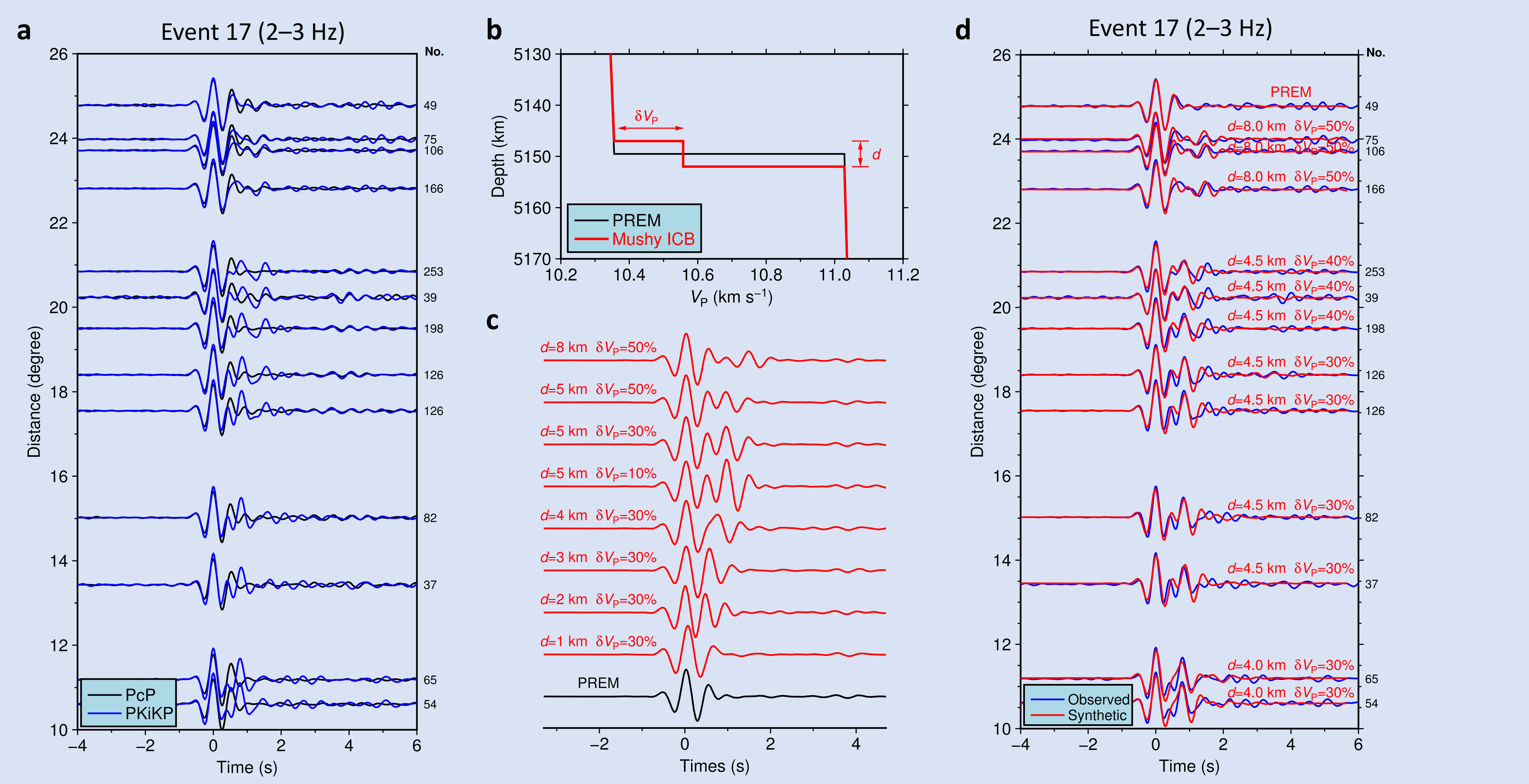


Fig. 8. Localized localized mushy ICB beneath southwest Okhotsk Sea. (a) Comparisons of stacked PKiKP (blue traces) and PcP (black traces) waveforms of the event sampling southwest Okhotsk Sea. Stacked PcP and PKiKP waveforms are bandpass filtered in a frequency range of 2–3 Hz. The number of waveforms used in each stacking is indicated at the right of each trace. **(b)** P wave velocity profile of the mushy ICB, represented by two parameters: *d* the thickness of the mushy zone, δV_P percentage P wave velocity jump of the top layer with respect to PREM velocity jump at ICB, along with PREM (black line). **(c)** Synthetic seismograms in a frequency range of 2–3 Hz for a series of mushy ICB models (red traces, labeled accordingly with two model parameters) and for PREM (bottom black trace). **(d)** Comparisons of stacked observed PKiKP waveforms (blue traces) and synthetic seismograms (red traces) of the best-fitting models. The number of waveforms in each stacking is labeled at the right of each trace, while the thickness *d* and percentage P wave velocity jump of the top layer δV_P of the best-fitting models are labeled above the red traces.

7. Conclusions

1. We collected a large dataset of pre-critical PKiKP phases, which sample of the ICB regions beneath East Asia, Mexico and the Bering Sea.
2. The sampled ICB can be grouped into three types:
   - a simple ICB with a flat and sharp boundary
   - a bumpy ICB with topographic height change of ~10 km
   - a mushy ICB with laterally varying thickness of 4–8 km
3. The laterally varying fine-scale structure of the ICB indicates a laterally varying solidification process of the inner core due to lateral variations of thermo-compositional condition near the ICB.

Tian, D., & Wen, L. (2017). Seismological evidence for a localized mushy zone at the Earth's inner core boundary. *Nature communications*, **8**, 165. doi:10.1038/s41467-017-00229-9