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Observation of high-frequency PKiKP in Japan: Insight into fine structure of inner core boundary

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ABSTRACT

We observed clear PKiKP phases steeply reflected at the inner core boundary (ICB) in seismograms recorded by the dense short-period seismic network on the Japan Islands, and used 119 high-quality waveforms of the PKiKP phases to study the detailed structure of the ICB. The PKiKP phases are observed in seismograms band-pass filtered at 2–3 Hz from three deep earthquakes at epicentral distances of 7–20° at 105 seismic stations of High-Sensitivity Seismic Network (Hi-net) on the Japan Islands. After phase weighted stacking, the PKiKP waveforms exhibit some weak but clear phases that appear both before and after the PKiKP arrival, which could be explained by a transition zone with a few thin layers existing in the vicinity of the ICB. We used the reflectivity method to simulate the PKiKP waveforms and adopted a forward modeling approach to determine the optimal multi-layer model. Our results show that 8–17 km thick layers with higher density (0.1–1.0%) and higher P-velocity (0.1–1.5%) than the PREM model exist above a sharp ICB, while 10–32 km thick layers with lower density (0.4–2.2%) and lower P-velocity (0.4–2.5%) than PREM exist below the ICB. The big jump of density and velocity at ICB in our layered model (0.35–0.43 g/cm^3, 0.33–0.47 km/s) indicates that the ICB itself is still a sharp discontinuity. Our observations of the complex high-frequency PKiKP waveforms suggest that the sharp transition from the outer to inner core may be accompanied by laterally varying layering. The ICB stratification may reflect the gradual solidification process during the growth of the inner core.

1. Introduction

The structure and composition of Earth's solid inner core has long been the subject of geophysical studies. The age of the inner core cannot exceed 2.5 Ga and is most likely about 1 Ga in the case of absence of radioactive elements in the core (Labrosse et al., 2001). It is generally accepted that the inner core formed by crystallization of the liquid core. At the inner core boundary (ICB), the freezing of liquid iron alloy occurs with a depletion of light elements that are present in the liquid core. The ICB is thus an important place for chemical and energy exchanges. Determining the ICB structure is important for understanding how the inner core is solidifying from the liquid outer core. The process of solidification provides a source of compositional convection that may drive the geodynamo in the liquid outer core (e.g., Lister and Buffett, 1995).

Many scientific arguments arising from astronomical and geological observations, and theoretical developments concerning heat propagation, thermodynamics, geodesy, and mechanics led to propose a stratified model with a silicate mantle and an iron core, but the effective discovery of the core has relied on seismological observations (Souriau, 2007). To constrain the seismic structure near the ICB, the most useful phases include the PKIKP phase passing through the uppermost inner core and the PKiKP phase reflected at the ICB, which are called core phases. Engdahl et al. (1970) observed clear PKiKP phases and confirmed the previously estimated radius of the inner core. Since then, many studies have been made to constrain the physical properties of the ICB. For instance, Song and Helmberger (1992) analyzed the differential travel times and amplitude ratios of PKIKP and PKiKP and proposed a model containing a relatively low velocity gradient above the ICB based on the PREM model (Dziewonski and Anderson, 1981). Stroujkova and Cormier (2004) examined the structure of the uppermost 100 km of the inner core using PKIKP and PKiKP waveforms and found a regional variation in which the velocities in the eastern hemisphere are generally higher than in the western (Pacific) hemisphere below the ICB, which is similar to the hemispherical pattern of seismic attenuation (Cao and Romanowicz, 2004).

The amplitude ratios of PKiKP with respect to a reference phase (e.g., PcP) are considered to be more robust than the absolute amplitudes of PKIKP, because the ratios are relatively insensitive to variations in the shallow Earth structure and properties of the earthquake source (e.g., the precise hypocenter location, magnitude, and radiation pattern, see the pioneer work of Bolt and Qamar (1970)). Koper and Dombrovskaya (2005) combined data

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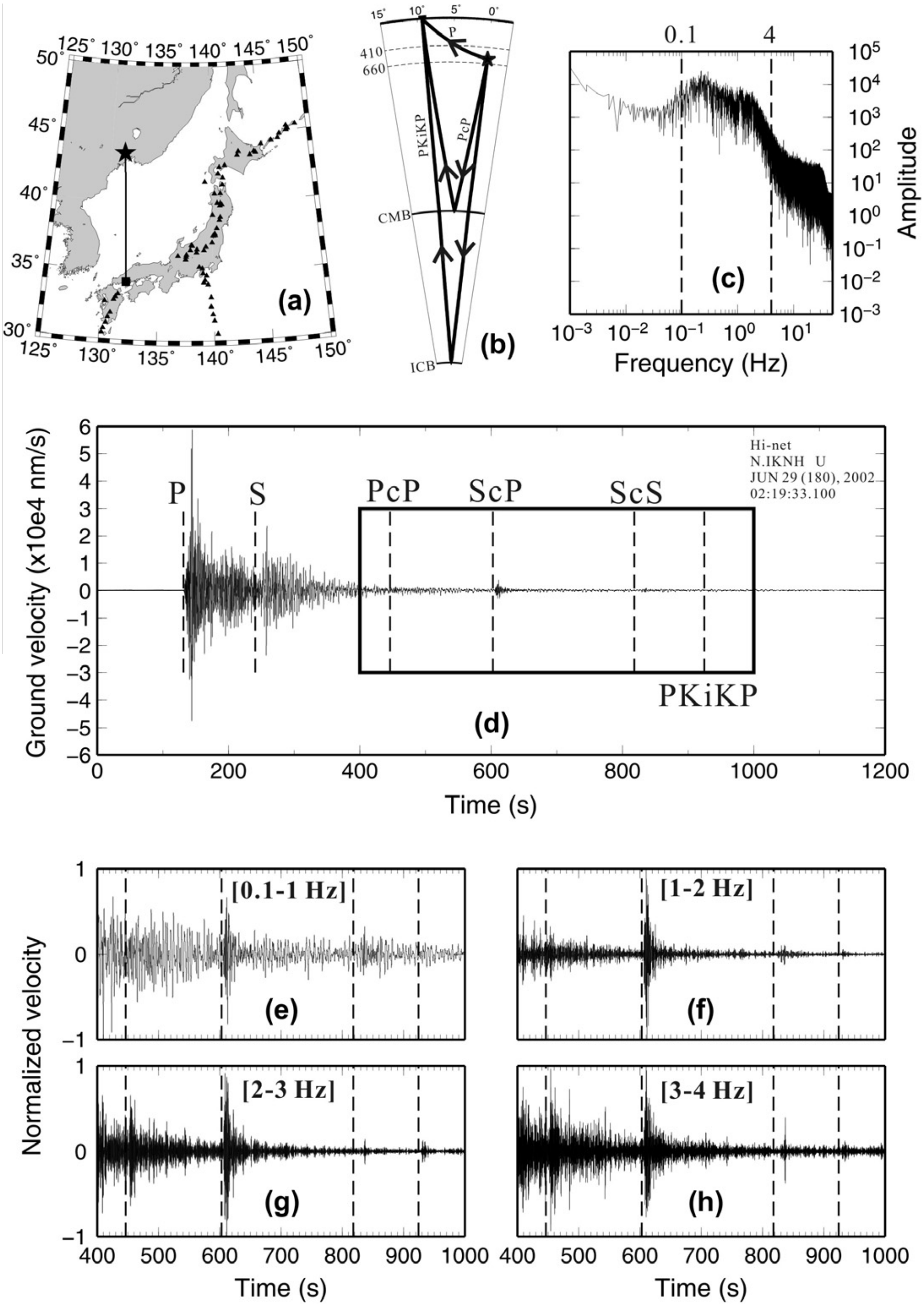

Fig. 1. An example of vertical-component seismogram (d) of a deep earthquake (focal depth: 589 km) recorded by a Hi-net seismic station. (a) Locations of the deep earthquake (star) and the seismic station (square). The black triangles represent active volcanoes. (b) Ray paths of P, PcP and PKiKP phases at an epicentral distance of 9.3° from the deep earthquake. (c) Amplitude spectrogram of the seismogram bracketed in the box shown in (d). The two dashed lines denote frequencies of 0.1 and 4 Hz, respectively. (d) The vertical dashed lines show the theoretical arrival times of P, S, PcP, ScP, ScS and PKiKP phases. The times are relative to the origin time of the earthquake shown in the upper-right corner. (e–h) The portion of seismogram bracketed in (d) during 400–1000 s is filtered in four frequency bands: 0.1–1, 1–2, 2–3, and 3–4 Hz, respectively.

of PKiKP/P amplitude ratios at distances of 50–90° with a data set of PKiKP/PcP amplitude ratios at distances of 10–50° and estimated the jumps of density and shear velocity at the ICB, respectively. Tkalčić et al. (2009) adopted PKiKP/PcP amplitude ratios from a nuclear explosion observed at epicentral distances of 10–20° and they estimated the upper bound of the ICB density contrast to be about 1.1 g/cm^3 that is similar to the result of Shearer and Masters (1990).

So far several models have been proposed concerning the ICB structure. Fearn et al. (1981) argued that a mushy layer may extend to the center of the Earth, which is supported by the works of Shimizu et al. (2005) and Deguen et al. (2007), but the thickness