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Intricate heterogeneous structures of the top 300 km of the Earth's inner core inferred from global array data: I. Regional 1D attenuation and velocity profiles

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We apply a waveform inversion method based on simulated annealing to complex core phase data observed by globally deployed seismic arrays, and present regional variation of depth profiles of attenuation and velocity for the top half of the inner core. Whereas measured attenuation parameters exhibit consistent trends for data sampling the eastern hemisphere of the inner core, for the western hemisphere, there is a remarkable difference between data sampling the inner core beneath Africa (W1) and beneath north America (W2). Obtained attenuation profiles suggest that intricate heterogeneities appear to be confined in the top 300 km. The profile for the eastern hemisphere has a high attenuation zone in the top 150 km that gradually diminishes with depth. Conversely, for the western hemisphere, the profile for W1 shows constant low attenuation and that for W2 represents a gradual increase from the inner core boundary to a peak at around 200 km depth. Velocity profiles, obtained from differential traveltimes between PKP(DF) and PKP(CD, BC) phases, for the eastern and western hemispheres are respectively about 0.8% faster and 0.6% slower than the reference model at the top of the inner core, and the difference nearly disappears at about 200 km depth. Our result suggests the presence of intricate quasi-hemispherical structures in the top ∼200–300 km of the inner core.

1. Introduction

The structure of the inner core has been studied primarily by analyzing seismic core phases (Fig. 1a). PKP(DF) which passes thorough the inner core, and PKP(BC, AB) which passes thorough the outer core or PKP(CD) which is reflected at the inner core boundary (ICB) contain information about the inside and outside of the inner core, respectively. These phases, however, are also affected by the structure of the crust, mantle and strongly heterogeneous D'' layer at the base of the mantle. We usually, therefore, utilize the differential traveltime and amplitude between PKP(DF) and PKP(CD, BC, AB) for structural analyses of the inner core, assuming that the effects from outside of the inner core cancel out each other due to the closeness of ray paths therein.

One of the most peculiar and puzzling seismological properties of the inner core is the presence of the hemispherical heterogeneity in the outermost part of the inner core first reported by Tanaka and Hamaguchi (1997) and later confirmed by many researchers (e.g. Creager, 1999; Niu and Wen, 2001; Cao and Romanowicz, 2004; Yu and Wen, 2006; Tanaka, 2012). It is generally agreed that the eastern (western) hemisphere is characterized by a high (low) velocity and high (low) attenuation shallow layers, which may provide an important clue to constrain the growth processes of the inner core (e.g. Monnereau et al., 2010; Alboussière et al., 2010). There exist, however, considerable discrepancies in the detail of the attenuation and velocity structures among previous studies; for example, by analyzing PKP(DF) and PKP(Cdiff; a diffracted wave along ICB) that globally sampled the inner core, Tanaka (2012) suggested that fast and slow velocity anomalies gradually merge to their average at about 400 km and 250 km depths from ICB, and high attenuation ($Q_P \approx 180$) and low attenuation ($Q_P \approx 300$) layers exist top 250 km and 450 km in the eastern and western hemisphere, respectively. Yu and Wen (2006) reported larger Q_P values than Tanaka (2012) both in the eastern hemisphere and in the western hemisphere. On the other hand, Cao and Romanowicz (2004) obtained similar hemispherical features, but only in the top 85 km of the inner core.

In terms of regional studies, Kaneshima et al. (1994) showed a velocity model beneath the northeastern Pacific (VMOI velocity

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model) which is about 0.6% slower than PREM (Dziewonski and Anderson, 1981) at the ICB and linearly merges to the PREM at 300 km depth, and Ohtaki et al. (2012) represented a similar western hemisphere like velocity structure beneath the Antarctica. As to the attenuation structure, the pioneering work of Doornbos (1974) suggested largest attenuation at the top of the inner core and a gradual decrease with depth beneath the northwestern Pacific, while the existence of a high attenuation zone at depths of 200–300 km below the ICB is suggested beneath the northeastern Pacific (Morita, 1991; Kazama et al., 2008; Iritani et al., 2010).

Systematic analyses of globally available waveform data may help to resolve these discrepancies (e.g. Li and Cormier, 2002; Cormier and Li, 2002; Garcia et al., 2006). Particularly, the waveform inversion method based on simulated annealing (SA) adopted by Garcia et al. (2004, 2006) is effective in extracting information about the inner core structure from complicated core phases (Fig. 1). In our earlier study (Iritani et al., 2010), we modified and applied the waveform inversion method for Japanese Hi-net array data, and obtained a continuous 1D attenuation profile beneath the northeastern Pacific that shows a gradual increase of attenuation from ICB with a peak at 200 km depth. While this result is consistent with the previous result for the same region (Morita, 1991; Kazama et al., 2008), it is not so with other studies that show generally low attenuation for the western hemisphere. In this study, we extend the treatment of Iritani et al. (2010) to a large number of globally available broadband seismic array data, and obtain continuous depth profiles of attenuation and velocity structures in various regions of the inner core to systematically investigate the hemispherical heterogeneity. We also note that Iritani (2013) extended the waveform inversion method to discuss the frequency dependence of attenuation and its hemispherical variation to infer the growth process of the inner core.

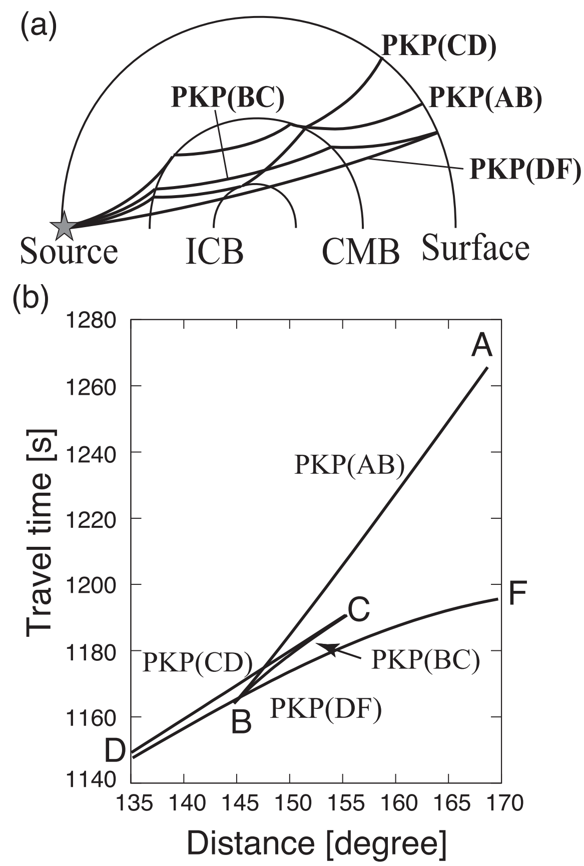

Fig. 1. (a) Illustration of ray paths of core phases. (b) Traveltime curve of core phases for the AK135 model.

2. Data

We analyze the vertical component of broadband velocity seismograms observed by globally expanded seismic arrays that record high-quality core phases. The distribution of stations and events are illustrated in Fig. 2. The waveform data are collected from Japanese F-net, NECESSArray (NorthEast China Extended SeiSmic Array, from Sep. 2009 to Aug. 2011), permanent European stations, USArray and PASSCAL arrays deployed in a number of places in the world for events that occurred from May 1997 to March 2012 with Mw greater than 5.8 (Table 1). Collected core phases sample regions beneath eastern Pacific, North America and Africa in the western hemisphere and almost all areas of the eastern hemisphere of the inner core (Fig. 2). The angle of the ray paths with respect to the earth's rotation axis is greater than 40° (i.e., equatorial paths) for all data sets used in this study, and the effect of anisotropy of the inner core is not significant (Creager, 1999). Each waveform is filtered by a second order zero-phase Butterworth band-pass filter with corner frequencies of 0.35 and 2 Hz,

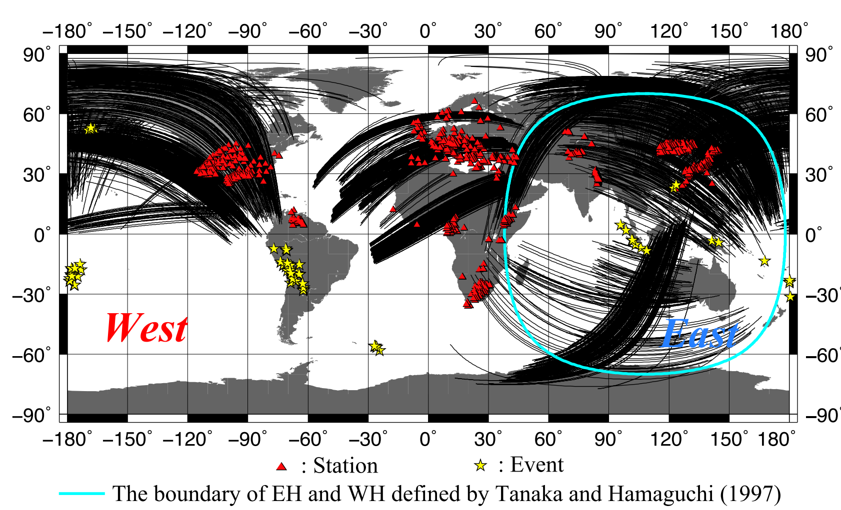

Fig. 2. Distributions of stations (red triangle), events (yellow star) and ray paths (black line) that are used in this study. Ray paths are plotted only for the inner core. The blue line indicates the boundary between the eastern and western hemispheres defined by Tanaka and Hamaguchi (1997). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)