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Depth-dependent attenuation structure of the inner core inferred from short-period Hi-net data

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ABSTRACT

Depth-dependent attenuation structure in the inner core below the northeast Pacific is studied utilizing the short-period Hi-net data. The commonly used method of estimating inner core attenuation (differential spectral slope analysis) is not suitable because it is too sensitive to the presence of small amplitude phases. Instead, we found that the method of relative and differential amplitudes is more robust estimator of inner core attenuation. We use the relative amplitude of PKIKP (DF) to PKPs (BC or AB) around 1.0 Hz to estimate t^* as a function of the epicentral distance. Geometrical ray theory was employed to correct the source and propagation effects except that of inner core attenuation. The resulting t^* for South American events shows a clear peak around an epicentral distance of 152°, whose corresponding bottoming depth is about 300 km below the inner core boundary (ICB). This pattern can be explained by a low Q_P (<200), high attenuation region in a depth range of 200–300 km. We also found that, in this depth range, there exists positive correlation between attenuation and velocity, indicating seismic scattering due to anisotropic structure of iron crystals at the intermediate depth of the inner core.

1. Introduction

The solid inner core's structure has been revealed by observations of core phases, which pass through the Earth's core as compressional body waves (Fig. 1). PKIKP, or DF phase passes through the inner core, whereas PKPs (BC and AB phases) turn in the liquid outer core.

The observed DF phase is more attenuated than BC and AB (Doornbos, 1974), indicating significant anelasticity in the inner core. The cause of the seismic attenuation in the inner core has been attributed to the presence of partial melt; Loper and Fearn (1983) suggested a mushy zone in the inner core, or Singh et al. (2000) suggested spheroidal inclusions of liquid iron. And inner core attenuation has been characterized through its heterogeneity (Cormier and Choy, 1986), anisotropy (Helffrich et al., 2002) and its hemispherical structure (Wen and Niu, 2002; Cao and Romanowicz, 2004) in the inner core.

On the depth dependency of inner core attenuation, several studies have disagreement. Doornbos (1974) showed that the seismic attenuation becomes highest at the top of the inner core and grows lower at deeper depth. In contrast, Morita (1991) found that the attenuation is highest at 200–300 km depth below the ICB. It must be resolved whether these differences come from variations of analysis methods or inner core heterogeneity (Cormier and Choy, 1986).

In this paper, we studied the depth profile of inner core attenuation. Amplitude analysis method was used, which can estimate inner core attenuation robustly. Our result is consistent with Morita (1991); attenuation is highest at 200–300 km depth below the ICB, not at the uppermost inner core, suggesting attenuation heterogeneity by complex structures in the inner core.

2. Methods of analysis

If a seismic P wave, with the initial amplitude A_0, passes through a medium with the seismic quality factor Q_P, the amplitude spectrum becomes

$$A(f) = A_0 \exp(-\pi f t^*), \tag{1}$$

where

$$t^* = \int_{\text{path}} \frac{dt}{Q_P} \tag{2}$$

is the attenuation factor integrated along the ray path.

2.1. Differential spectral slope method

Assuming that ray paths of core phases in the mantle are similar and that the outer core attenuation is negligible (Buchbinder, 1971),

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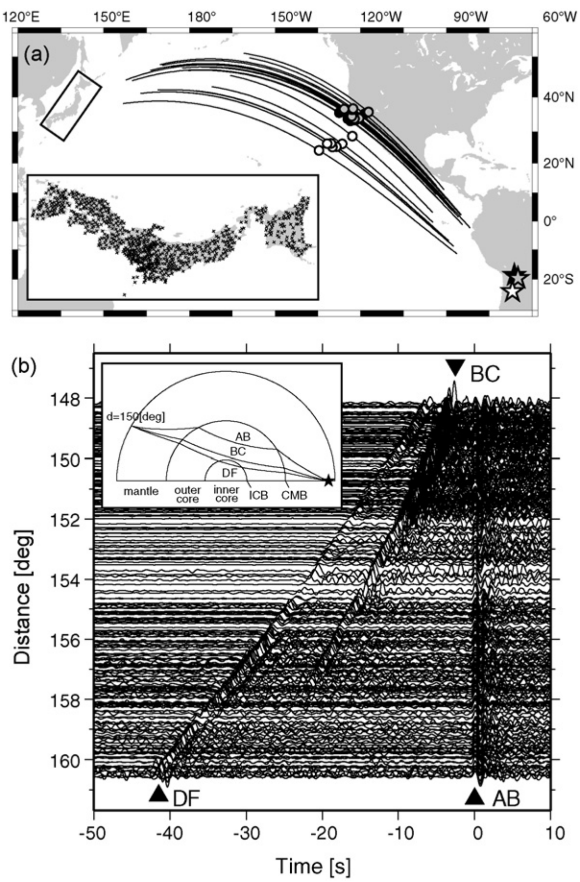

Fig. 1. Core phases. (a) DF ray paths in the inner core (bold lines) with bottoming points (circles). Stars and crosses show hypocenters and Hi-net stations, respectively. Solid, gray and open symbols indicate events 1, 2 and 3 (Table 1), respectively. (b) Core phase waveforms with 1.0 Hz low-pass filter, recorded at Hi-net stations. Each waveform is normalized by AB amplitude and aligned with AB's travel time. Solid curves in the semicircle show ray paths of core phases. Note that waveforms and ray paths are for event 1 (Table 1).

amplitude ratios of core phases can be written as

$$\frac{A_{\mathrm{df}}}{A_{\mathrm{ref}}} \propto \exp(-\pi f t^{*}_{\mathrm{df/ref}}), \quad (3)$$

where $t^{*}_{\mathrm{df/ref}}$ represents the attenuation in the inner core along the DF path, and the subscript ref indicates a reference phase (AB or BC). Assuming further that Q is independent of frequency, the slope of the logarithmic of spectral ratios gives $t^{*}_{\mathrm{df/ref}}$. This is the most commonly used method of estimating inner core attenuation (e.g., Bhattacharyya et al., 1993; Tseng et al., 2001; Helffrich et al., 2002). Here, we applied this method to the DSM synthetic seismograms (Takeuchi et al., 1996), calculated for the IASP91 velocity model (Kennett and Engdahl, 1991) and the PREM Q-model (Dziewonski and Anderson, 1980). Note that in the modeling, the low velocities of crustal layers are replaced by the velocities of the uppermost mantle to avoid crustal reverberations, and that the source depth and mechanism of the synthetics are based on event 1 (Table 1). Fig. 2 a shows the result of t^*. In this figure, source depth is not corrected, and C-cusp position is located at 155.0°. Both $t^{*}_{\mathrm{df/bc}}$ and $t^{*}_{\mathrm{df/ab}}$ are highly oscillatory and noisy due to the existence of the small PKiKP (CD) phase. The slope analysis is largely affected by phases having small amplitudes, and is not suited for estimating attenuation structure precisely.

Table 1
Source parameters reported by USGS

	Events		
	1	2	3
Year	2001	2003	2005
Date	June 29	July 27	June 2
UTC	18:35:51	11:41:28	10:55:58
Latitude	−19.473	−19.841	−24.202
Longitude	−66.182	−64.942	−66.863
Depth	276	348	191
Mw	6.1	6.0	6.1
Obs.	383	634	697

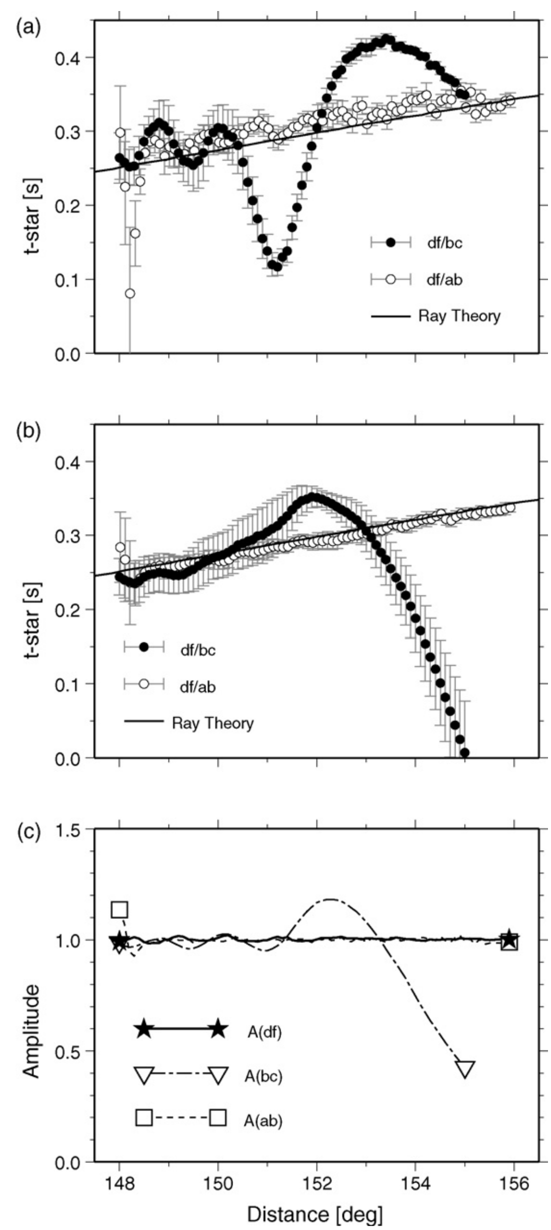

Fig. 2. Synthetic tests for DSM waveforms. (a) Slope analysis t^*. (b) Amplitude analysis t^*. In (a) and (b), black and white circles show $t^{*}_{\mathrm{df/bc}}$ and $t^{*}_{\mathrm{df/ab}}$, respectively. (c) Corrected amplitudes of core phases. All of ray theoretical effects, including inner core attenuation, are corrected in this figure. Note that in these figures, source depth is not corrected to 0 km, and that C-cusp is located at 155.0°.