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Inversion of seismic waveforms for shear wave velocity structure in the lowermost mantle beneath the Hawaiian hotspot

Kenji Kawai[a,b,*], Robert J. Geller[c]

[a] *Department of Earth and Planetary Sciences, Tokyo Institute of Technology, Ookayama 2-12-1, Meguro, Tokyo, Japan*
[b] *Institut de Physique du Globe de Paris, 1 Rue Jussieu-75238, Paris Cedex 05, France*
[c] *Department of Earth and Planetary Science, Tokyo University, Graduate School of Science, Hongo 7-3-1, Bunkyo, Tokyo, Japan*

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ABSTRACT

We perform waveform inversion for the radial profile of shear wave velocity in the lowermost mantle beneath the Hawaiian hotspot. The data used in this study are waveforms observed mainly at epicentral distances around 90°. The dataset includes waveforms from the CANOE (CAnadian NOrthwest Experiment) array and from the CNSN (Canadian National Seismographic Network). These data greatly enhance the resolution of the lowermost mantle as compared to earlier studies. We find a velocity decrease in the depth range from 2700 km to the core–mantle boundary (CMB), which is interpreted as probably due to a temperature increase. The results of the present paper, taken together with our previous results for other regions beneath the Pacific, suggest that there is a large amount of impurities such as aluminum and iron beneath Hawaii and that there is strong lateral heterogeneity in D'' beneath the Pacific.

1. Introduction

Many travel-time tomography studies over the past two decades have reported a large low velocity province (LLSVP) in the lowermost mantle beneath the Pacific (e.g., Grand, 2002). It is, however, still controversial whether this is due to temperature variation, chemical heterogeneity, or both. The vertical resolution of tomographic studies in the lowermost mantle is at best about 400 km. As the lowermost mantle is a thermal boundary layer for mantle convection, it is expected to be both vertically and horizontally heterogeneous (e.g., Maruyama et al., 2007; Kawai et al., 2009a). Hence, it is desirable to resolve the seismic velocity structure of the lowermost mantle in more detail using seismic waveform data in order to better understand geodynamics.

Most previous works that used seismic waveforms to study seismic structure in the lowermost mantle have used reflected waves associated with discontinuities of seismic velocity. Lay and Helmberger (1983) found evidence for the D'' discontinuity using forward modeling of seismic waves reflected at a discontinuity which was later inferred to be due to the phase change between perovskite (pv) and post-perovskite (ppv) (Murakami et al., 2004). While such studies can resolve sharp seismic velocity changes which cause reflected waves, it is difficult for forward modeling to resolve gradual velocity changes such those as associated with temperature variations or to determine absolute seismic velocity. Moreover, the incidence angle of seismic waves is close to horizontal in most studies of the lowermost mantle. It is, therefore, more difficult for forward modeling studies to resolve negative velocity discontinuities than positive ones. Finally, it is difficult for forward modeling studies to quantitatively estimate the resolution and uncertainty of the structure. On the other hand, seismic waveform inversion (e.g., Kawai et al., 2007a,b, 2009b) can quantitatively estimate the resolution and uncertainty of the model. In addition, since waveform inversion can analyze a large amount of observed data at many receivers for many events simultaneously, the effects of near-

* Corresponding author at: Tokyo Institute of Technology, Department of Earth and Planetary Sciences, Ookayama 2-12-1, Meguro, Tokyo 152-8551, Japan. Tel.: +81 3 5734 3936; fax: +81 3 5734 3538.
E-mail address: kenji@geo.titech.ac.jp (K. Kawai).

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source and near-receiver structure and the source time function can be minimized. Currently, as relatively long period waveforms (up to 8 s; Kawai and Geller, 2010) have been used for waveform inversion, the vertical resolution is nominally at best 80 km. As shorter period data are used, the resolution will further improve, but even at this point it is better than other methods.

The results of our previous waveform inversion studies are as follows. Kawai et al. (2007a) examined the structure of D'' beneath Central America and found a steep negative velocity gradient beneath the D'' discontinuity. Similar structure in D'' was also found beneath the Arctic (Kawai et al., 2007b) and beneath central Asia (Kawai et al., 2009b). This tends to suggest that such structure beneath the D'' discontinuity is ubiquitous in regions found to be fast by tomographic studies. In all of the above three cases the S-velocity in the upper half of D'' was found to be significantly faster than PREM (Dziewonski and Anderson, 1981), while the velocity in the lower half was roughly equal to PREM. This is broadly consistent with the "double crossing" hypothesis which proposes the existence of a reverse phase transition from ppv to pv within D'' due to rapid temperature increase in the thermal boundary layer (Hernlund et al., 2005). However, Kawai and Tsuchiya (2009) recently showed that if a "double crossing" phase transition were to exist, the S-velocity at the CMB would become too low (i.e., well below 7.0 km/s) and that the seismic velocity models obtained by the above three studies can be explained by thermal effects only without having to invoke a "double crossing." On the other hand, two waveform inversion studies investigated the shear wave velocity structure in D'' beneath the Pacific (Konishi et al., 2009; Kawai and Geller, 2010). Both found "S-shaped" shear wave velocity structure with a negative gradient in the depth range 400–300 km above the core–mantle boundary (CMB), a positive gradient in the depth range 200–100 km, and a negative gradient in the depth range 100 km – CMB. One implication of the "S-shaped" velocity structure is that there is a significant basaltic component in the lowermost mantle, which would cause two phase transitions with a negative velocity jump in SiO_2 (Karki et al., 1997) and in $MgSiO_3$ with impurities such as aluminum and iron (Tsuchiya and Tsuchiya, 2006). A simple thermal boundary can produce such an "S-shaped" velocity structure (Kawai and Tsuchiya, 2009). The seismic S-velocity in the lowermost mantle is, therefore, an important value to investigate whether or not there are impurities in a particular region. In this study we investigate shear wave velocity structure in the lowermost mantle beneath the Hawaiian hotspot and study the possible existence of chemical heterogeneity in the Pacific LLSVP.

2. Data analysis

A temporary seismic array, CANOE (CAnadian NOrthwest Experiment), was deployed in northwest Canada for two and a half years from 2003 to 2005. This array provides waveforms sampling the lowermost mantle beneath the Hawaiian hotspot. In this study we invert these data for shear wave velocity structure in the lowermost mantle beneath the Hawaiian hotspot.

The regions beneath which the structure of D'' can be studied in detail by waveform inversion are limited due to the source and receiver geometry. D'' beneath the Hawaiian hotspot is, despite its geophysical significance, difficult to examine in detail, since the distribution of permanent stations in western Canada is sparse. However, the CANOE array provides waveform data which sample D'' beneath the Hawaiian hotspot (Fig. 1). As the epicentral distances between Tonga-Fiji events and CANOE are, however, $85^\circ < \Delta < 95^\circ$, S and ScS phases are overlapped. It is difficult to pick the onset of phases sensitive to the lowermost mantle, but since waveform inversion can deal with such overlapped phases, we can use the CANOE data to investigate the structure of D'' beneath Hawaii.

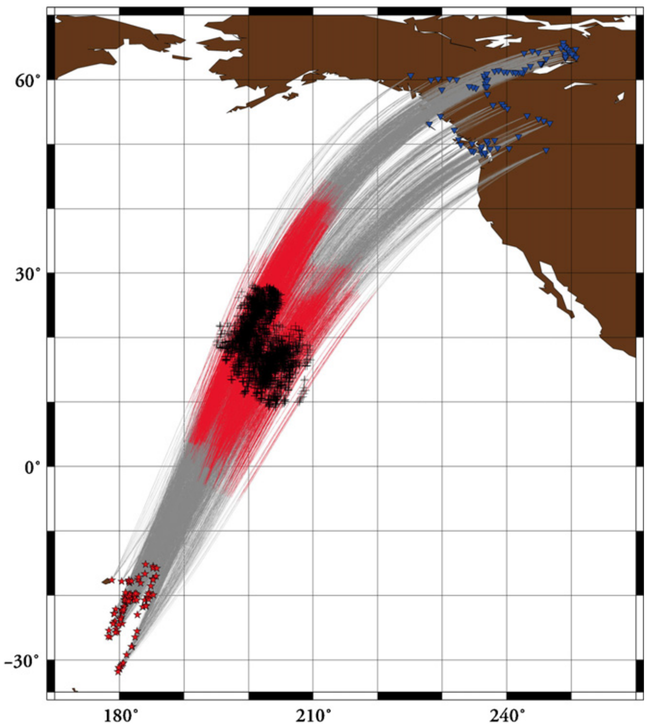

Fig. 1. Event-receiver geometry, with great circle ray paths. The ray paths are shown to indicate the coverage, but note that we do not use ray-theoretical approximations. The portions of the great circles which sample D'' are shown in red. Blue reversed triangles and red stars show the sites of stations used in our study and earthquakes studied, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

2.1. Waveform data

In this study, data from the CNSN (Canadian National Seismographic Network) and IRIS (Incorporated Research Institutions for Seismology) data centers as well as CANOE data are used (Fig. 1). The waveform data used are the transverse components of 88 events with $5.5 \leq Mw \leq 7.0$ between 1994 and 2008. 19 events are rejected, because we require events with high S/N waveforms at least four stations. We also reject stations that do not have acceptable records for at least four events. The CANOE stations recorded waveforms for 24 of the 88 events. We deconvolve the instrument response and apply a bandpass filter to the data and construct data sets for the passband 0.005–0.125 Hz (i.e., for the period range, 8–200 s). We then select records which include data for S, ScS and the other phases which arrive between them at epicentral distances $\Delta < 100^\circ$. We compute the ratio of the maximum amplitude of the data and the corresponding synthetic, and eliminate records for which the ratio is greater than 2 or less than 0.5. The dataset consists of 1437 records that satisfy the above criteria; 1203 records which did not satisfy the criteria were rejected. The data are velocity seismograms (after deconvolving the instrument response) with 1 Hz sampling. The reciprocal of the maximum amplitude of each record is used as the weighting factor in the inversion, so that all data have roughly the same importance.

2.2. Source time function and static correction

The source parameters (moment tensors and centroids) are fixed to the Global CMT solution. Kawai et al. (2007a) approximated the source time function as a δ-function at the centroid time for the period range 20–200 s, since its effect is small. As this study, however, uses data for the period range 8–200 s, we use box-