Detection of ridge-like structures in the Pacific Large Low-Shear-Velocity Province

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A B S T R A C T

Waveform tomography is conducted for SH velocity structures of the entire mantle using approximately 3.5 times the data used for obtaining the previous model, SH18CE. The resultant new model, SH18CEX, exhibits a cluster of ridge-like low-velocity anomalies in the western part of the Pacific Large Low-Shear-Velocity Province (LLSVP). The location of the ridge-like anomalies is in good agreement with the location of the abrupt change in the topography of the D′ discontinuity. These results suggest that the LLSVP is associated with a cluster of ridge-like piles, rather than a single large pile spread over the entire region. The piles probably consist of intrinsically dense material; however, either their volume or density contrast may not be sufficiently large to develop large-scale domes.

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1. Introduction

As is well known, there exist two large low-shear-velocity provinces (LLSVPs) in the lowermost mantle beneath the Pacific and Africa. Ridge-like structures (low-velocity anomalies that are horizontally long and narrow) were detected in the African LLSVP via array analyses (e.g., Ni and Helmberger, 2003; Wang and Wen, 2007). Global tomography models also show generally consistent features (e.g., Grand, 2002; Takeuchi, 2007). It is important to verify whether such ridge-like structures are also observed in the Pacific LLSVP; if so, the ridge-like plume can be considered as the fundamental morphology of the upwellings.

Several array analyses were conducted in order to obtain regional structure models for the Pacific LLSVP. For instance, Takeuchi et al. (2008) suggested that the vertical extent of the low-velocity anomalies is approximately 400 km on the western side, whereas He and Wen (2009) suggested that it is approximately 740 and 340 km on the north-western and south-eastern ends, respectively. In these studies, the structure models were obtained by analyzing the data for event-station pairs on, or in the vicinity of, a particular great circle plane. Two-dimensional models were obtained by assuming that the structure is homogeneous in the direction perpendicular to the plane.

However, according to the global tomography model obtained by Schubert et al. (2004), the Pacific LLSVP consists of clusters of small-scale anomalies, and the validity of the aforementioned assumption is not evident. Furthermore, for some regions, such an assumption is clearly invalid; for example, Fig. 4 of Takeuchi and Obara (2010) shows a rapid variation in the Scs-S residuals (~8 s variation within 400–500 km) in the direction along which the structures are assumed to be homogeneous by He and Wen (2009). Therefore, further efforts to obtain three-dimensional models are required.

Takeuchi (2007) conducted global waveform tomography using three-dimensional Born kernels and obtained the three-dimensional SH velocity model, SH18CE. The tomography method adopted by Takeuchi (2007) utilizes all the phases in the waveform data (including ScsN and various major and multi-orbit body phases); thus, the resolution of the LLSVPs is improved significantly (see Fig. 2 of Takeuchi, 2007). This method is also advantageous in that it can recover smaller-scale structures by fully considering the finite-frequency effects (see Figs. 3 and 4 of Panning et al., 2009). In this study, we improve the resolution by using a larger data set than that used by Takeuchi (2007) and obtain a three-dimensional SH velocity model of the entire mantle. The obtained model, SH18CEX, exhibits ridge-like low-velocity anomalies in the western part of the Pacific LLSVP, where the resolution of the model is high. In addition, we discuss the plausibility of the obtained features.

2. Data and method

We invert the transverse component of the broadband waveform data from IRIS GSN and GEOSCOPE for 679 events (Fig. 1a). The data set used in this study is a combination of the data set of Takeuchi (2007) (hereafter, referred to as “Data Set 1”) and the new data set (hereafter, referred to as “Data Set 2”). Data Set 1 includes only data for large events (Mw ≥ 6.5), whereas Data Set 2 includes data for smaller events (the smallest Mw is 6.0). The event distribution for Data Set...
2 covers the area that had no or very few events in Data Set 1 (such as Hawaii, the East African rift zone, and mid-ocean ridges). We use a particularly large number of events in the western Pacific region, thereby improving the resolution of the western part of the Pacific LLSP. The entire data set used in this study consists of 54,790 traces (271,798 time windows), which is approximately 3.5 times the number of traces used by Takeuchi (2007). With the exception of the data set used, the methods and parameters employed in this study are exactly the same as those employed by Takeuchi (2007). The basic information required for further discussion is summarized below.

The periodic ranges of the data set are exactly identical to those of the data set used by Takeuchi (2007). The periodic ranges of the data set are exactly identical to those of the data set used by Takeuchi (2007). The data set consists of velocity waveforms with three different periodic ranges (200–400 s, 100–200 s, and 50–100 s). The methods for data selection are exactly identical to those adopted by Takeuchi (2007). We extracted time windows in which the residuals of the phase and the amplitudes between the observed and synthetic seismograms are reasonably small. These data selections were made to avoid the breakdown of the Born approximations used in the inversion in this study. The resultant data set for 200–400 s primarily consists of surface waveform data, whereas the data set for 50–100 s primarily consists of body waveform data.

The model parameters and the damping parameters are also identical to those of Takeuchi (2007). We expanded the perturbation of the elastic constants in terms of 14 radial functions (13 linear spline functions in the mantle and 1 box-

![Fig. 1. (a) Events used for obtaining SH18CEX in this study (left) and SH18CE [Takeuchi, 2007] (right). (b) Recovered models for checkerboard patterns of the heterogeneities when we use the data sets for SH18CEX (upper figures) and SH18CE (bottom figures).]
car function in the crust) for the vertically dependent part, and spherical harmonics with a maximum angular order of 18 for the horizontally dependent part. We defined the expansion coefficients as the model parameters. Appropriate scaling relations were assumed between the perturbation of N and L. The damping method and parameters are exactly identical to those of Takeuchi (2007). Therefore, we can directly compare the new model, SH18CEX, with the previous model, SH18CE.

3. Obtained model

3.1. Overall features, resolution, and variance improvements

The resolution of SH18CEX is considerably better than that of SH18CE (Fig. 1b). The resolution of SH18CEX for the western Pacific region is sufficient to recover the checkerboard pattern of heterogeneities whose scale mimics the scale of the structures observed in Fig. 5. Note that the checkerboard patterns exist in both horizontal and vertical directions. The S waves bottoming at various depths should primarily provide the vertical resolution.

The obtained model, SH18CEX, is shown in Figs. 2 and 3. First, we compare the lower mantle models of SH18CEX and SH18CE via visual inspection (Fig. 2). We see that the overall patterns, i.e., the long-wavelength features, of the two models are nearly invariant, but the significant differences between the models are the relatively small-scale anomalies observed only in SH18CEX (such as the features indicated by the green arrows in Fig. 2). This can probably be attributed to the resolution improvement in the new model.

Next, we compute the correlation coefficients between SH18CEX and SH18CE as a function of depth and degree (Fig. 4). The correlation coefficients fluctuate among degrees (Fig. 4a) partly because the heterogeneities are very small for some degrees. To clearly observe the overall features of the correlations, we plot the correlation coefficients for each degree bin (degrees 1–3, degrees 4–6, ..., degrees 16–18) (Fig. 4b). The thick black boxes denote the ranges where the correlation coefficients are less than 0.70. Although we have a few

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**Fig. 2.** Comparison between SH18CEX (upper figures) and SH18CE (lower figures) at various depths in the lower mantle. The SH velocity perturbations with respect to the initial model, PREM (Dziewonski and Anderson, 1981), are shown. The green arrows indicate examples of the prominent features observed only in SH18CEX.
exceptions, we can confirm that the primary ranges with lower correlation coefficients are higher degree components (degrees 16–18) in the lower mantle, showing that the small-scale features in the lower mantle are the primary differences between the models SH18CEX and SH18CE. The lowermost mantle is the region with lower coefficients for a larger degree range (degrees 10–18), and we will discuss their small-scale features in the next subsection.

The newly identified small-scale features appear to be constrained primarily by the body waveforms in Data Set 2. Table 1 summarizes the variance improvements due to SH18CE and SH18CEX. The variance improvement is defined by

\[ 1 - \frac{\int [u^{(i)}_{\text{obs}}(t) - u^{(i)}_{\text{final}}(t)]^2 dt}{\int [u^{(i)}_{\text{obs}}(t) - u^{(i)}_{\text{init}}(t)]^2 dt} \times 100\% , \]

where \( u^{(i)}_{\text{obs}} \) is the \( i \)-th time window of the observed seismograms, and \( u^{(i)}_{\text{init}} \) and \( u^{(i)}_{\text{final}} \) are the \( i \)-th time window of the synthetic seismograms.

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**Fig. 3.** SH18CEX at various depths in the upper mantle.

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**Fig. 4.** (a) Correlation coefficients between SH18CEX and SH18CE as a function of degree (horizontal axis) and depth (vertical axis). The discontinuities at 400 and 670 km are indicated by solid lines. (b) The same as (a) but showing the correlation coefficients for degree bins (degrees 1–3, 4–6, ..., 15–18). The thick black boxes denote the regions with correlation coefficients less than 0.70.
SH18CEX exhibits improvements comparable with those of SH18CE for the periodic ranges of 200–400 s and 100–200 s (Table 1, top). For the periodic range of 50–100 s, SH18CEX also exhibits comparable improvements for the existing data (34% for SH18CE and 31% for SH18CEX); on the other hand, it exhibits greater improvements for the incremental data (23% for SH18CE and 31% for SH18CEX) (Table 1, top). Improvements for the incremental data themselves are not surprising because they are included only in the inversion for SH18CEX, but note the larger improvements for the periodic range of 50–100 s compared with the other ranges. Considering that the data set of 50–100 s primarily consists of body waveforms, the results suggest that the incremental constraints on the Earth’s structures are primarily attributable to the body waveforms in the incremental data set.

For the periodic range of 200–400 s, the improvements for Data set 1 are greater than those for Data Set 2 (e.g., 44% and 32%, respectively, for SH18CEX) (Table 1, top). This is probably due to the fact that the signal-to-noise ratios of Data Set 2 are not adequate for longer periods because Data Set 2 includes data for smaller events. Indeed, for the periodic range of 200–400 s, variance improvements for larger events (Mw≥6.5) are significantly larger than those for the data for smaller events (Mw<6.5) (38% and 21%, respectively, for SH18CEX) (Table 1, bottom). However, note that this does not hold for the periodic range of 50–100 s (30% and 32%, respectively, for SH18CEX) (Table 1, bottom), which suggests that such problems

Table 1

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<tr>
<td>200–400 s</td>
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Fig. 5. Comparison between SH18CEX (upper figures) and SH18CE (lower figures) in the western Pacific region. The lines A–A' and B–B' denote the locations of the vertical sections shown in Fig. 6. The green dot denotes the relatively high-velocity region discussed in the text.
are not encountered in this periodic range. Therefore, we can conclude that the small-scale features in the lower mantle would be better constrained by the incremental data set.

3.2. Small-scale features in the western pacific region

We investigate the small-scale features observed in SH18CEX. We focus on the western Pacific region, where the resolution of SH18CEX was confirmed to be high in Fig. 1b. The enlarged figures (Fig. 5, top) indicate that the strong low-velocity anomalies are horizontally long and narrow in the vicinity of the core-mantle boundary (CMB). These ridge-like anomalies surround the relatively high-velocity region (represented by the green dot in Fig. 5), suggesting that the observed strong low-velocity anomalies are associated with the return flow of the downwelling at the center. Such features are not well observed in SH18CE (Fig. 5, bottom).

Part of the strong anomalies (those intersected by the line A-A’ in Fig. 5) extend to the shallower region. The vertical cross sections (Fig. 6, top) show that the extent of the anomalies is wide in the NW–SE direction, narrow in the NE–SW direction, and high upwards. These features are similar to those observed in the African LLSVP (e.g., Ni and Helmberger, 2003; Wang and Wen, 2007).

We can confirm some similarities between SH18CEX and several recent models. Fig. 6 shows a comparison of SH18CEX, HMLS-S06 (Houser et al., 2008) and S40RTS (Ritsema et al., 2011). In each section of A–A’ (Fig. 6, left), we can confirm tall and wide low-velocity anomalies; however, the anomalies in HMLS-S06 and S40RTS appear to be slightly less tall and slightly less wide, respectively, as compared to those in SH18CEX. In each section of B–B’ (Fig. 6, right), we can confirm two piles of low-velocity anomalies. The right pile is taller than the left in each model; however, the pile in SH18CEX appears to be the tallest. Therefore, we can say that the ridge-like anomalies are more pronounced in the model obtained in this study.

The observed ridge-like anomalies are not likely to be caused by resolution smearing. Fig. 7 shows the resolution kernels for the input anomalies having a point-wise distribution in the horizontal direction. The extents of the input anomalies in the vertical direction are different between Fig. 7a and b. The kernels are more or less isotropic in the horizontal direction, and few elongations are observed. Moreover, the smearing in the vertical direction is small. Therefore, we can conclude that the ridge-like anomalies are not due to the smearing effects.

4. Consistency with the travel time data

We confirm the plausibility of the obtained model by checking its consistency with the observed travel time data. We plot the distribution of the ScS-S travel time residuals observed by using Japanese broadband seismic arrays (Fig. 8a). 3469 residuals were measured between 45.3° and 80.7° using bandpass-filtered velocity seismograms with corner periods of 3.3 and 100 s. It should be noted that these residuals are independent of the data set used in the waveform tomography in that: (i) the former is data from the regional array, whereas the latter is data from global networks, (ii) the former is relatively
short-period data (around 3.3 s), whereas the latter is longer-period data (around 50 s), and (iii) the former is relative travel time data, whereas the latter only contains information regarding absolute travel times.

As in Fig. 4 of Takeuchi and Obara (2010) the measurements in this study indicate an 8 s variation in the residuals within a region of around 400–500 km (at the green line labeled P in Fig. 8a of this paper). Although the fluctuations are large, we also observe a variation of around 5 s in the residuals (at the green line labeled Q in Fig. 8a); the residuals of north-eastern part are approximately 5 s larger than those of the south-western part. These results intuitively suggest the existence of large velocity gradients in the NE-SW
direction. Other regions with relatively abrupt changes in the residuals (R and S in Fig. 8a) suggest the existence of velocity gradients in the NW–SE direction. These features are generally consistent with those reported previously (e.g., Fig. 1 of Schubert et al., 2004); however, the features in Fig. 8a appear to be clearer. This is probably because the results in Fig. 8a are obtained from a single regional array.

The low-velocity anomalies in SH18CEX effectively explain the observed distribution of the \( \text{ScS-S} \) residuals (Fig. 8b, left; see also Fig. 8d, left). By introducing a ridge-like structure, we can explain the abrupt change in the residuals at \( P, Q, \) and \( R \) in Fig. 8a and c. We can also explain the abrupt change at \( S \) by other low-velocity anomalies in the lowermost mantle. In contrast, SH18CE does not explain the observations (Fig. 8b, right and 8d, right). Larger residuals are observed in the region surrounded by the lines \( P, Q, \) and \( R \) (Fig. 8a and c), whereas the model SH18CE predicts smaller residuals (Fig. 8b, right and 8d, right). The results strongly suggest that the low-velocity anomalies in SH18CEX are more plausible than those in SH18CE.

The obtained low-velocity structures have good correlations with the \( D^* \) topography observed by Takeuchi and Obara (2010), who analyzed ScS-S\( \text{s} \) times for the Fiji-Tonga events. The sampling region extends across the ridge-like structure (Fig. 9a). The \( \text{ScS-S} \) residuals observed by Takeuchi and Obara (2010) were indeed large at the center of the ridge-like structure, and they linearly decreased with increasing distance from the center (Fig. 9b, left). The \( D^* \) discontinuity was deep at the center, became slightly shallower at the side, and abruptly became very shallow beyond the side of the ridge-like structure (Fig. 9b, right). The abrupt jump in the discontinuity suggests that the ridge-like structure is probably associated with a chemically distinct pile (Fig. 9c), as discussed by Takeuchi and Obara (2010).

5. Discussion and implications

In several previous studies, the LLSVPs have been interpreted as isolated piles of intrinsically dense materials (e.g., Ni and Helmberger, 2003; Ni et al., 2002; Wang and Wen, 2007). However, such piles are often expected to have larger-scale structures (e.g., Tackley, 1998; Tackley, 2002; McNamara and Zhong, 2005), which seems to contradict the cluster of small plumes observed in this study. In contrast, Schubert et al. (2004) proposed that LLSVPs are clusters of isochemical thermal plumes, which seems to contradict the abrupt change in the topography of the \( D^* \) discontinuity observed in this study. One solution for these contradictions may be as follows:
the piles consist of intrinsically dense materials; however, either the volume or the density contrast of the dense materials is small. Under these circumstances, the thermo-chemical plumes are expected to be similar to the isochemical thermal plumes (see, for example, the discussions by Bull et al., 2009).

The morphology of the plumes has long been debated, even for simple Rayleigh–Bénard convections. Bercovici et al. (1989), for example, suggested that the upwellings in the earth-like spherical shells are conduit-like, whereas Houseman (1990) and Yanagisawa and Yamagishi (2005) suggested that the upwellings are sheet-like. The most fundamental difference between these studies is the Rayleigh numbers that were considered. The existence of ridge-like structures suggests that the convection in the lower mantle is as vigorous as that for large Rayleigh numbers (more than, say, 1000 times the critical Rayleigh number).

In the new model, SH18CEX, we see ridge-like structures in both the African LLSP and the Pacific LLSP (Fig. 2, top). The structures in the African LLSP are similar to those obtained by Schubert et al. (2004). The results suggest that both the Pacific and the African LLSPs consist of clusters of chemically distinct piles. It is notable that piles are not spread over the entire region of the LLSPs, but confined only to the ridge regions. The recent high-P, T elasticity simulation of deep mantle minerals suggests that small volume fractions of mid-ocean ridge basalt (MORB) in the lowermost mantle are sufficient for explaining the amplitude of $V_p$ and $V_s$ anomalies observed in tomographic studies (Tsuchiya, 2011). The ridge-like pile clusters seem to be compatible with this mineralogical interpretation.

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