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P and S wave tomography of Japan subduction zone from joint inversions of local and teleseismic travel times and surface-wave data

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ABSTRACT

We determined P and S wave velocity tomography of the Japan subduction zone down to a depth of 700 km by conducting joint inversions of a large number of high-quality arrival-time data of local earthquakes and teleseismic events which are newly collected for this study. We also determined 2-D phase-velocity images of fundamental mode Rayleigh waves at periods of 20–150 s beneath Japan and the surrounding oceanic regions using amplitude and phase data of teleseismic Rayleigh waves. A detailed 3-D S-wave tomography of the study region is obtained by jointly inverting S-wave arrival times of local and teleseismic events and the Rayleigh-wave phase-velocity data. Our inversion results reveal the subducting Pacific and Philippine Sea slabs clearly as dipping high-velocity zones from a 1-D starting velocity model. Prominent low-velocity (low-V) anomalies are revealed in the mantle wedge above the slabs and in the mantle below the Pacific slab. The distinct velocity contrasts between the subducting slabs and the surrounding mantle reflect significant lateral variations in temperature as well as water content and/or the degree of partial melting. The low-V anomalies in the mantle wedge are attributed to slab dehydration and corner flows in the mantle wedge. A sheet-like low-V zone is revealed under the Pacific slab beneath NE Japan, which may reflect hot upwelling from the deeper mantle and subduction of a plume-fed asthenosphere as well. Our present results indicate that joint inversions of different seismic data are very effective and important for obtaining robust tomographic images of the crust and mantle.

1. Introduction

The Japan subduction zone belongs to the Western Pacific trench–arc–backarc system, where the Pacific plate, the Eurasian plate, the Philippine Sea (PHS) plate and the Okhotsk plate strongly interact with each other (Fig. 1). The Pacific plate is subducting beneath the Okhotsk plate, the PHS plate, and the Eurasian plate along the Kuril–Japan–Izu-Bonin trench, whereas the PHS plate is subducting beneath the Eurasian plate along the Nankai trough and the Ryukyu trench. The strong interactions among these plates have resulted in many active arc volcanoes and large earthquakes, such as the 2011 Tohoku-oki earthquake (*Mw* 9.0) sequence (Fig. 1).

So far many researchers have studied the three-dimensional (3-D) velocity structure of the Japan subduction zone using abundant data recorded by the dense seismic networks installed on the Japan Islands (see a recent review by Zhao (2015)). Most of these studies focused on the velocity structure down to ~200 km depth, including the crust, mantle wedge, and the upper portion of the subducting Pacific slab. These previous studies have greatly improved our understanding of arc magmatism, forearc mantle serpentinization, seismotectonics and subduction dynamics of this region (e.g. Hasegawa et al. (2013), Liu and Zhao (2014, 2015), Zhao et al. (2016)). However, only a few studies investigated the fine deep structure of the Japan subduction zone, besides the large-scale regional and global tomography (e.g. Friederich (2003), Gorbatov and Kennett (2003), Zhao (2004), Huang and Zhao (2006), Koulakov (2011), Obayashi et al. (2013), Chen et al. (2015b), Wei et al. (2012, 2015)). Zhao et al. (1994) determined a 3-D P-wave velocity (Vp) model of the Japan subduction zone down to 500 km depth by conducting a joint inversion of travel-time data of local earthquakes and teleseismic events. They used 4211 travel-time residuals of 100 teleseismic events recorded by seismic stations in NE Japan. Later, Abdelwahed and Zhao (2007) adopted the same approach to obtain an improved 3-D Vp model down to 700 km depth beneath Japan. They used 34,148 relative residuals of 333 teleseismic events recorded by seismic stations on the Japan Islands. The teleseismic data used in these previous studies, however, were not sufficient in both quantity and quality, because

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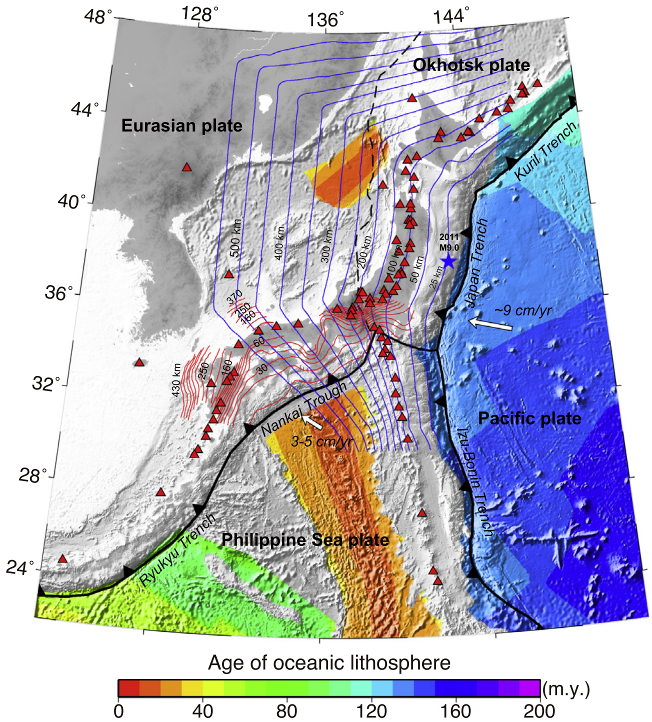

Fig. 1. Tectonic settings of the study region (after Liu et al. (2013a)). The red triangles denote the active and Quaternary volcanoes. The solid sawtooth lines and the black dashed line denote the plate boundaries. The blue and red lines denote the depth contours to the upper boundary of the subducting Pacific and Philippine Sea slabs, respectively, which are constructed based on several previous studies (e.g. Zhao et al. (1994, 1997a, 2012), Nakajima et al. (2009), Hasegawa et al. (2013), Huang et al. (2013), Asamori and Zhao (2015)). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the data were mainly recorded by the old and sparse seismic network, J-Array (Zhao et al., 1994; Abdelwahed and Zhao, 2007). Using all the previous teleseismic data recorded by the J-array and ∼11,500 data from 27 teleseismic events recorded by the High-Sensitivity Seismic Network (Hi-net) that covers the Japan Islands densely and uniformly (Okada et al., 2004), Zhao et al. (2012) determined a high-resolution Vp tomography of the crust and mantle down to 700 km depth beneath the Japan Islands. Recently, Asamori and Zhao (2015) presented a detailed shear-wave velocity (Vs) tomography of the Japan subduction zone down to 700 km depth using 34,122 S-wave arrival times of 51 teleseismic events recorded by the Hi-net. They also obtained an updated 3-D Vp model down to 700 depth using 5,878 P-wave arrival times they picked up from the Hi-net waveforms of 8 teleseismic events and ∼45,400 P-wave arrivals from 360 teleseismic events collected by the previous studies (Zhao et al., 1994, 2012; Abdelwahed and Zhao, 2007). These tomographic results show similar features of the deep structure beneath Japan. The subducting Pacific and PHS slabs were imaged as dipping high-velocity (high-V) zones, whereas low-velocity (low-V) anomalies are revealed in the surrounding mantle, in particular, in the mantle wedge above the slabs.

A simultaneous inversion of different sets of teleseismic arrival-time data recorded by separate arrays deployed in different areas (and perhaps in different periods) may result in a distorted tomography, because teleseismic tomography uses relative travel-time residuals of teleseismic events which mainly reflect the relative velocity anomalies beneath an array which recorded the teleseismic events (Zhao et al., 1994, 2012). Hence, it would be much better to use only the data from those teleseismic events which were recorded by a complete seismic network (such as the Hi-net) which covers the entire study region densely and uniformly.

Another problem of the previous studies (Zhao et al., 1994, 2012; Abdelwahed and Zhao, 2007; Asamori and Zhao, 2015) is that the teleseismic data used were much fewer than the local-earthquake data used in the tomographic inversion. Thus, the crust and upper mantle down to ∼200 km depth were densely sampled by both the local and teleseismic rays, whereas the deeper areas were much less sampled by the teleseismic rays alone. This problem would have also affected the quality of the previous tomographic models beneath Japan, in particular, for the areas deeper than ∼200 km.

In the present study, we have made great efforts to measure hundreds of thousands of high-quality P- and S-wave arrival-time data from many teleseismic events recorded by the Hi-net during the past 10 years. The number of the newly collected teleseismic data is even greater than that of the local-earthquake data used in this study. A joint inversion of both the local and teleseismic data results in robust Vp and Vs tomography of the crust and mantle down to 700 km depth of the entire Japan subduction zone. In addition, we also study the 3-D Vs structure beneath Japan by a joint inversion of the local and teleseismic S-wave arrival times and Rayleigh-wave phase-velocity data at periods of 20–150 s obtained by this study. Because we have collected and used much more body-wave and surface-wave data than all the previous tomographic studies in this region, we have obtained much more robust results, such as a clearly imaged Pacific slab with a thickness of ∼100 km from a 1-D starting velocity model. The present results shed important new light on the deep structure and dynamics of the Japan subduction zone.

2. Data

In this study we used 1852 seismic stations installed on the Japan Islands (Fig. 2a), which include 796 Hi-net stations (Fig. 2b), 74 F-net broadband stations (Fig. 2c), and 982 JMA (Japan Meteorological Agency) and Japanese national university stations (J-Array). We used three sets of data to conduct tomographic inversions. The first data set contains P- and S-wave arrival times of 2528 local earthquakes which occurred in and around the Japan Islands (Fig. 2d). The second data set contains P-wave relative travel-time residuals of 747 teleseismic events and S-wave residuals of 643 teleseismic events (Fig. 2e). The third data set consists of fundamental mode Rayleigh-wave amplitude and phase data in a period range of 20–150 s from 1030 teleseismic events (Fig. 2f).

Among the great number of local earthquakes recorded by the dense seismic network (Fig. 2a), we selected a best set of events for our tomographic study. The study area is divided into many cubic blocks with a size of $50 \times 50 \times 10\ km^3$. The local events are selected by a specific scheme of selection according to the maximum number of recording stations and the minimum formal uncertainty of the hypocenter locations. The shallow offshore events were removed from the data set because of their poor hypocentral locations. As a result, 2528 local events are selected (Fig. 2d), which generated 501,571 P-wave and 220,340 S-wave arrival times. The picking accuracy is estimated to be 0.05–0.10 s for P-wave data and 0.05–0.15 s for S-wave data. This data set contains more P- and S-wave arrivals than those released by the JMA Unified Earthquake Catalog, thanks to the great efforts made by the staff members of Tohoku University who picked up all the clear P and S arrivals from the original three-component seismograms. The uncertainty of hypocenter locations is <5 km for all the events and <3 km for the events beneath the seismic network.