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Letter

Imaging subducted slab structure beneath the Sea of Okhotsk with teleseismic waveforms

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ABSTRACT

The structure of subducted slabs is not well imaged in most global tomographic models with anomalies typically less than 1%. Synthetic waveforms for such models are not noticeably different from their 1D reference models. In contrast, we find that observed teleseismic waveforms sampling slabs in the down-dip direction display multipathing features indicative of substantial structure. Such waveform complexity patterns appear distinctly different for various source locations with outer-rise events generally displaying relatively simple waveforms. Here, we model these waveform patterns for a portion of the Kuril subduction zone. The best fitting slab models have relatively fast cores (∼5%) with smooth edges compatible with thermal modeling in shape. Complete seismograms for these 2D models indicate that multibounce *P* and *S* waves are slab-sensitive and can be used in refining models.

1. Introduction

Seismic images have revealed a complicated fate of subducted slabs, including penetrating into the lower mantle, stagnating in the transition zone, as well as shallow flat subduction (Fukao et al., 2009; Fukao and Obayashi, 2013). Approaches to derive these slab images are based mostly on travel times, and have evolved in the last decades with increasing data sets and progress in methodology (see Lay, 1994 for a review). In the 1960s and 70s, teleseismic *P*-wave travel-times from shallow nuclear explosions and earthquakes suggested the existence of subducted slabs as dipping high-velocity layers (e.g., Davies and Julian, 1972; Sleep, 1973). To test the hypothesis of whole-mantle convection, numerous studies applied the residual sphere method to teleseismic travel times from deep earthquakes, and found high-velocity (3–5%) slabs penetrating into the lower mantle in most of the west and northwest Pacific subduction zones (e.g., Jordan, 1977; Creager and Jordan, 1984, 1986; Fischer et al., 1988, 1991). To avoid biases from lower-mantle and station-side structures (e.g., Zhou et al., 1990), Ding and Grand (1994) applied the residual sphere method to differential travel times from shallow and deep earthquakes in the Kuril subduction zone. They reported high-velocity (∼5%) slab in the upper mantle, but complicated structure in the lower mantle. From the 1990s, with increasing quantity and quality of seismic data, global and regional travel-time tomography has been providing increasingly detailed images of subducted slabs (e.g., Zhou, 1990; van der Hilst et al., 1991; Zhao et al., 1992; Li et al., 2008; Simmons et al., 2012). Tomography models show that subducted slabs could have complex morphology (e.g., flat subduction, tearing), and could penetrate into the lower mantle or become stagnant in the transition zone. However, resolution of tomography is limited by data coverage, damping and accuracy of earthquake locations. For example, in most global tomography models, the velocity perturbations of slabs are on the order of 1%, much smaller than the earlier results (∼5%) from travel-time modeling mentioned above. It is unclear whether this discrepancy in perturbation is caused by smoothing/damping in tomography or possible systematic bias in the residual sphere method (e.g., see discussion in Lay, 1994). Resolving the absolute velocity perturbation is critical in the issue of thermally or chemically controlled slab structure, given the substantial uncertainty in seismic velocity dependence on temperature at high pressures (e.g., Anderson, 1988; Lay, 1994; Hacker et al., 2003a; Faul and Jackson, 2005; Schutt and Lesher, 2006).

Seismic waveforms have better sensitivities to velocity perturbations and sharpness than travel times alone. For example, Silver and Chan (1986) observed multipathing of teleseismic *S* waves from deep earthquakes beneath the Sea of Okhotsk, and explained them as evidence for slab extension in lower mantle.

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Using the Cagniard-de Hoop method, Mellman and Helmberger (1974) demonstrated that a thin high-velocity layer has similar effect as attenuation (elastic-wave tunneling effect). Vidale (1987) coupled 2D finite-difference method near the source with Kirchhoff method in the far field, and predicted waveform broadening at take-off angles sub-parallel with the slab. This broadening was confirmed latter by Cormier (1989) using the Gaussian beam theory. However, these predicted teleseismic waveform effects from earthquakes close to or within subducted slab have not been systematically tested due to the sparse global networks at that time (e.g., Vidale and Garcia-Gonzalez, 1988; Cormier, 1989). In recent years, with largely improved instrumentation, waveform modeling of slab has been performed in subduction zones with dense regional networks (e.g., Abers, 2000; Chen et al., 2007; Song et al., 2009; Savage, 2012). For example, by modeling two deep earthquakes' up-going waveforms recorded by Hi-Net, Chen et al., (2007) refined the slab model beneath Japan with about 4.5% high-velocity in the slab, and an elongated strong low-velocity layer on top to large depth. However, for many subduction zones without dense regional networks (e.g., Kuril), the teleseismic waveform modeling has not been applied to refine slab models. Furthermore, Beck and Lay (1986), Cormier (1989) pointed out another major difficulty with teleseismic waveform modeling that other deep-mantle heterogeneities or station-side structures could cause similar waveform distortions as subducted slabs. In this paper, we demonstrate that the difficulties with slab waveform modeling can be overcome given the much denser global network and the better numerical methods now available. In particular, with examples in the Kuril subduction zone, we find that the *P* wave velocity in the slab center is about 5% higher than the ambient mantle, and we also test the waveform sensitivity to slab sharpness and depth extent of subducted oceanic crust. In the following, we first introduce the waveform effects of a high-velocity slab using our 2D finite-difference method. Then, we analyze the teleseismic waveforms from two earthquakes in the Kuril subduction zone and invert for slab velocity perturbation and sharpness.

2. Waveform effects of a high-velocity slab

Waveform effects of a high-velocity slab have been studied by various techniques as outlined above. Here, we use an efficient GPU-based 2D finite-difference (FD) method to simulate the full global elastic wavefield with a high-velocity slab (Li et al., 2014). To make sure the simulated wavefield is accurate up to 1 Hz, we set the FD grid size to 1 km, and the time step to 0.01 s, which transfer to 10,240 × 4000 grid points and 160,000 time steps in each of our global wavefield simulations. With 2 Nvidia Tesla M2090 GPUs, it takes only about 30 min to finish one simulation. This speed allows the testing of many different kinds of slab models efficiently. In the following we will demonstrate slab's waveform effects with examples of a high-velocity slab embedded in a homogeneous background.

The first model consists of a homogeneous background with $V_p = 8$ km/s, and a 60 km thick, 500 km long slab (the black solid rectangle in Fig. 1A) with uniform velocity perturbation of 3%. These and the parameters in the following models are chosen to be somewhat realistic based on previous studies of oceanic plate and subducted slab structures (e.g., Chen et al., 2007; Tan and Helmberger, 2007). An isotropic explosion source is placed in the left end of the slab (the red star in Fig. 1A). The snapshot of the velocity field shows distorted *P* waves along directions sub-parallel with the slab, outlined by the wedge between the two red lines. In the right panel of Fig. 1A, we plot the synthetic *P* waveforms at a line of stations (small triangles in left panel of Fig. 1A) and align them on the theoretical travel times without the high-velocity slab. Waves arriving before the theoretical travel times (filled with red) have been speed up by the slab, and display waveform complexities (double arrivals). The first arrivals travel along the slab, and the second broader arrivals diffract around the slab (Vidale, 1987). Based on geometrical ray theory, the angular range of distorted waveforms can be approximated by

$$\sin\left(\frac{\pi}{2} - \theta\right) \approx \frac{1}{1+\delta},$$

where θ is the angle between the red lines and the slab in Fig. 1A and δ is the velocity perturbation of the slab. Note that larger velocity perturbation δ causes a wider range of waveform distortion (large θ angle), which is confirmed by our second example in Fig. 1B with increased slab velocity perturbation (6%). On the other hand, sharpness of slab controls the waveform shapes. In Fig. 1C, we set a triangular velocity profile across the slab with the highest perturbation in the slab center (6%), and drops in a constant gradient to the background velocity on both edges. The average velocity perturbation is 3%, similar to the first example in Fig. 1A. The simulated waveforms display distortions within similar range as in Fig. 1A, but are smoother without double pulses. This is because the waves traveling along or diffracted around the slab are not as distinct as in Fig. 1A. In Fig. 1D, a slab with triangular velocity profile and 12% perturbation at the center produces smooth waveforms as in Fig. 1C, but with a wide range of distortions as in Fig. 1B due to the similar average perturbation. Note that the areas of the pulses are essentially the same which is common in multipathing situations. To further benchmark our FD method, in Fig. S1, we consider another synthetic example which involves the well-known tunneling effect through a thin high velocity slab. The resulted wavefield is consistent with analytical solutions given by Mellman and Helmberger (1974).

In summary, these examples demonstrate consistent waveform effects of slabs as in previous studies (e.g., Vidale, 1987). In particular, we find that slab sharpness and perturbation control the waveform shapes and the angular range of distortions, respectively. In the next section, we present similar phenomena observed for earthquakes close to or within subducted slabs, and model these waveforms by applying perturbations and sharpness to slab structure.

3. Data

Although it is possible to treat the 3D slab problem with 2D propagation (e.g., Sun and Helmberger, 2011), we chose a naturally 2D section of the Kuril subduction zone as the study area (Fig. 2A). In this area, the relocated EHB catalog (Engdahl et al., 1998) shows that seismicity continues down to ~600 km depth, and has relatively little variation along strike (Fig. 2B). Therefore, the slab structure is close to a 2D problem along the down-dip direction, suitable for 2D waveform modeling (thick black line in Fig. 2A). We study two earthquakes (red beachballs in Fig. 2A), one on each side of the Kuril trench. The 2009/09/10, M_w 5.9 earthquake is a shallow-angle thrust event at a depth of 37 km located on the plate interface, while the 2007/01/13 M_w 6.0 earthquake is a shallow outer-rise event (depth ≈ 23 km). Both earthquakes have relatively simple source processes without obvious directivity. Fig. 3A shows the teleseismic *P* wave record-section of the 2009 interplate earthquake within 45° of the downdip azimuth (315°), aligned by the hand-picked P onsets (see Fig. S2 for a station map). While the P and sP pulses have durations of ~2 s at distances larger than 65°, the waveforms are significantly broader at distances less than 65°. The transition from narrow to broad pulses occurs between 70° and 60°, which correspond to only a ~3° difference in the take-off angles. Therefore, the observed distance-dependence of