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Evidence from high frequency seismic waves for the basalt–eclogite transition in the Pacific slab under northeastern Japan

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ABSTRACT

Seismic multi-pathing effects, attributed to a contrast in seismic attenuation between the back-arc mantle wedge and subducted crust, are detected in central Honshu, northeastern Japan. We observe an initial broadened P-wave which is followed by a delayed higher frequency P-wave signal. Their discrepant frequencies are best explained by attenuation effects: delayed P-wave signals travel in the low-attenuation oceanic crust and therefore contain more high frequency components. The time separation between the initial broadened P-waves and the delayed P-wave signals are affected by the seismic velocity in the subducted oceanic crust. We observe systematic variation in the delay times of the later waves indicating an increase in seismic velocity in the oceanic crust (relative to the mantle wedge) at ∼130–150 km depth. High-frequency seismic simulations incorporating mineral-physics derived models show that a 4% Vp increase due to the blueschist decomposition and a 9% Vp increase associated with the (lawsonite, talc)–eclogite transition replicate the observed delay time variation. The blueschist breakdown may occur at a depth of ∼100 km and the (lawsonite, talc)–eclogite transition might be linked with the reduced seismicity level at depths greater than 150 km. Distinct from traditional guided waves, the multi-pathing effects in this study are mainly controlled by attenuation contrast and therefore may not require the oceanic crust to have low velocity and any special decoupling mechanism. The multi-pathing effects offer us another important tool to image subducted oceanic crust below back-arc mantle wedges, especially where guided waves are not observable. In this study, we demonstrate the value of observing and simulating high frequency seismic waves (>20 Hz) in advancing our understanding of subduction zones.

1. Introduction

The upper parts of subducted slabs, including the oceanic crust and the slab's uppermost mantle, are believed to be highly hydrated, with water present in form of hydrous minerals and/or free water. As slabs subduct into higher temperature and pressure environments, a series of metamorphic reactions dehydrate slabs and turn most of the water bound in hydrous mineral into aqueous fluid (Hacker et al., 2003) (Fig. 1). This free water migrates through the mantle wedge and feeds arc volcanic activity, while some amount of mineralogically bound water might remain in the slabs as they descend to their ultimate fate in the deep Earth (Hacker, 2008). However, the spatial evolution of water content in slabs during subduction and the specific path of water migration within a mantle wedge are still not fully constrained. Additionally, the genesis of intermediate-focus earthquakes in the subduction context has been proposed to be linked with dehydration embrittlement (Kirby et al., 1996), but other hypotheses, for example plastic instabilities (Hobbs and Ord, 1988) and transformational faulting (e.g. Green and Burnley, 1989), exist. Thus, a detailed understanding of slab dehydration and metamorphic reactions is critical for understanding both the water cycle within the solid Earth and the physical mechanism for the intermediate-focus seismicity.

Metamorphic reactions in slabs usually lead to changes of seismic properties and therefore could be detected by seismic waves. Thanks to dense, high quality seismic networks such as the High-sensitivity seismograph network (Hi-net, Okada et al., 2004; Obara et al., 2005), the subducting slab beneath Japan is arguably the best imaged on the Earth. Seismic tomography, including velocity and attenuation imaging (for example Matsubara et al., 2008; Nakajima et al., 2013a), has been applied to the slab beneath Japan and provides unprecedented images. However, even under Japan, the seismic tomographic resolution is still limited by ray path coverage and smoothing constraints and is therefore not able to resolve sharp or small scale structure, such as on the scale of oceanic crust

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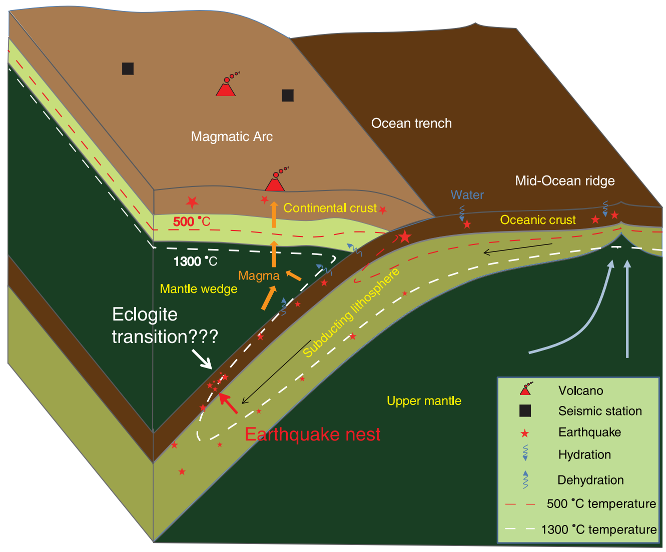

Fig. 1. Cartoon showing the tectonic setting of a subducting slab (not to scale). The earthquake nest may be related to the eclogite transition.

which has a thickness of ∼7 km. Higher spatial resolution of seismic imaging is critical to address many questions about subduction context. For example, Nakajima et al. (2013b) found three earthquake nests at depth of around 150 km in the subducted oceanic crust beneath central Honshu, northeastern Japan (Fig. 2) and indicated that the nests' likely origin is due to dehydration embrittlement caused by eclogitization. Such eclogitization of subducted oceanic crust could only be detected by seismic imaging with high spatial resolution.

Seismic waves trapped in oceanic crust, a form of guided waves, travel along slab interfaces and are therefore sensitive to the oceanic crust's velocity. Observations of guided waves in various slabs, including under Northern Japan, have confirmed the ubiquitous existence of low-velocity (LV) oceanic crust in slabs with old lithosphere (Abers, 2000; Martin et al., 2003; Shiina et al., 2017), although the depth range of where the LV crust is present may vary among different slabs. However, Furumura and Kennett (2005) proposed an alternative model of elongated heterogeneities parallel to the plate margin to explain dispersed guided waves, in which an LV oceanic crust is not necessary. In this study, we find multi-pathing phenomena from intermediate-focus earthquakes beneath central Honshu, northeastern Japan and attribute it to the attenuation and velocity differences between mantle wedge and oceanic crust. Distinct from traditional guided waves, the multi-pathing effects in our study are mainly controlled by the remarkably different attenuations present, and therefore not limited to the scenario of LV oceanic crust. Using SPECFEM2D (Komatitsch and Tromp, 1999), we compute the sensitivity kernels of the direct P-waves and the delayed high frequency signals, which clearly illustrate their different travel paths and explain the multi-pathing effects well. After testing different crust models, comparison of the synthetic seismograms with observations indicates a likely velocity increase in the oceanic crust at a depth of ∼138 km.

2. Data and observations

Here we use high frequency seismic waves, recorded at Hi-net stations, generated by intermediate-focus earthquakes to investigate the structure of the oceanic crust.

2.1. Hi-net seismograms

The Hi-net stations contain borehole seismometers with a natural frequency of 1 Hz and high sensitivity in the high frequency range (their sampling frequency is 100 Hz, Okada et al., 2004; Obara et al., 2005). Fig. 3 shows seismograms from five Hi-net stations corresponding to an earthquake at a depth of 155 km. After removing the instrument responses, we identify the onsets of the direct P-waves, on which the seismograms are aligned in Fig. 3a. It is difficult to clearly identify the onset at NMEH due to the low Signal to Noise Ratio (SNR). While there are more Hi-net stations in this region, they are not used here due to either low SNR or raypaths which deviate from the up-dip direction. By analyzing the waveforms, we find apparent multi-pathing effects: multiple signals traveling with different raypaths. In the first few seconds after the onsets, there are two distinct P-wave signals with different travel times and frequency contents. A broad direct P-wave is followed by a signal containing high frequency components. After applying a high frequency filter (>20 Hz), the delayed signals are clearer (Fig. 3b).

We collect data for 312 earthquakes in the period 2004–2013 from the JMA earthquake catalog. The horizontal locations of the 312 events (Fig. 4a) are within 20 km of the up-dip projected

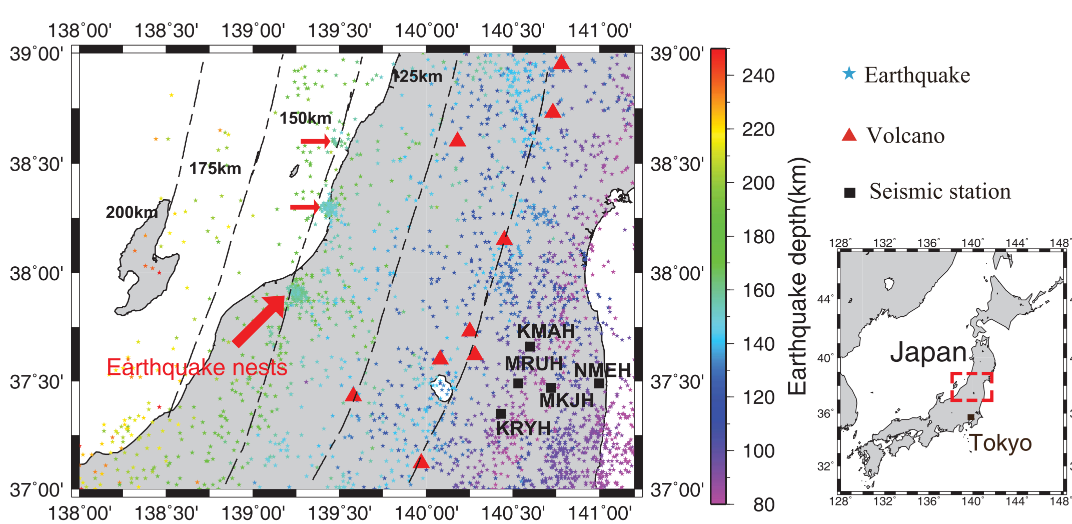

Fig. 2. Map of central Honshu, northeastern Japan (left figure) and location of this region (red box, right). Colored stars represent earthquakes between 2004–2013 (catalog from Japan Meteorological Agency). The black dashed lines are contours corresponding to the estimated geometry of the top interface of the subducted Pacific plate (Zhao et al., 1997; Nakajima et al., 2013b). The three red arrows point out the concentrated seismic clusters. All of the three clusters, or earthquake nests, are located below the top interface of the slab which has a depth of ∼150 km. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)