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Key Points:
- We estimate seismic velocity in the subducting crust beneath eastern Hokkaido by using guided waves
- Observed V_p and V_s are lower than those expected for the hydrated MORB at depths of 50–100 km
- The amount of fluids channeled in the crust would contribute to the facilitation of crustal seismicity

Supporting Information:
- Supporting Information S1

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Depth variations in seismic velocity in the subducting crust: Evidence for fluid-related embrittlement for intermediate-depth earthquakes

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Abstract We investigated seismic wave velocity in the subducting crust of the Pacific slab beneath eastern Hokkaido, northern Japan. To detect depth-dependent properties of the seismic velocities in the crust, we analyzed guided waves that propagate in the crust and estimated *P* wave velocity (V_p) of 6.5–7.5 km/s and *S* wave velocity (V_s) of 3.6–4.2 km/s at depths of 50–100 km. The results show that the obtained V_p and V_s are 10–15% lower than those expected for the fully hydrated mid-ocean ridge basalt, suggesting the existence of aqueous fluids by ~1 vol % in the crust at this depth range. Our observations suggest that overpressurized fluids channeled in the subducting crust plays as a dominant factor for facilitating the genesis of crustal earthquakes at intermediate depths.

1. Introduction

The subducting crust located at the uppermost part of the oceanic lithosphere involves a large amount of fluids in the form of hydrous minerals [e.g., *Hacker et al.*, 2003]. It is considered that fluids released by dehydration reactions of hydrous minerals are related to the genesis of earthquakes in subduction zones [e.g., *Kirby et al.*, 1996]. Additionally, released fluids that migrate to the overlying mantle wedge are thought to contribute to arc magmatism [e.g., *Kimura and Nakajima*, 2014]. Thus, the investigating the amount and distribution of fluids in the subducting crust is important for understanding the seismogenesis and fluid circulation in subduction zones.

Distinct later phases, such as mode-converted waves [e.g., *Matsuzawa et al.*, 1986; *Kawakatsu and Watada*, 2007; *Audet et al.*, 2009] and guided waves [e.g., *Hori et al.*, 1985; *Martin et al.*, 2003; *Takemura and Yoshimoto*, 2014], are useful tools for investigating seismic properties of the subducting crust because such waves propagate at longer distance in the crust and are very sensitive to heterogeneity in the crust. *Shiina et al.* [2013] estimated *P* wave velocity in the crust of the Pacific slab beneath Tohoku district, northeastern Japan, with high spatial resolution by analyzing arrival times of *PS*-converted waves and showed clear correlations between areas with marked low-velocity anomalies and concentrated seismicity at depths of 70–100 km [*Kita et al.*, 2006]. *Shiina et al.* [2013] suggest that overpressurized fluids coexist with hydrous minerals in the subducting crust, facilitating seismic activity by reducing the effective normal stresses.

In Hokkaido, northern Japan, the low-velocity subducting crust is identified at depths of ~100–150 km [e.g., *Abers*, 2005; *Nakajima et al.*, 2009; *Nakanishi et al.*, 2009]. However, spatial variations in seismic velocity in the crust are poorly understood because previous studies used only direct waves or small amount of later phase data. On the other hand, it is discussed that the oblique subduction of the Pacific slab beneath Hokkaido drives differences in stress regimes of the slab [e.g., *Kita et al.*, 2010a] and mantle convection patterns [e.g., *Nakajima et al.*, 2006; *Wada et al.*, 2015] from those beneath Tohoku where the normal subduction of the Pacific slab occurs. These differences would affect seismic properties in the subducting crust. Thus, detailed investigation of the velocity structure in the crust beneath eastern Hokkaido will improve understanding of the generation mechanism of intraslab earthquakes.

A guided wave that propagates in the subducting crust is often observed when earthquakes occur beneath eastern Hokkaido [*Abers*, 2005; *Shiina et al.*, 2014]. Because guided waves propagate at long

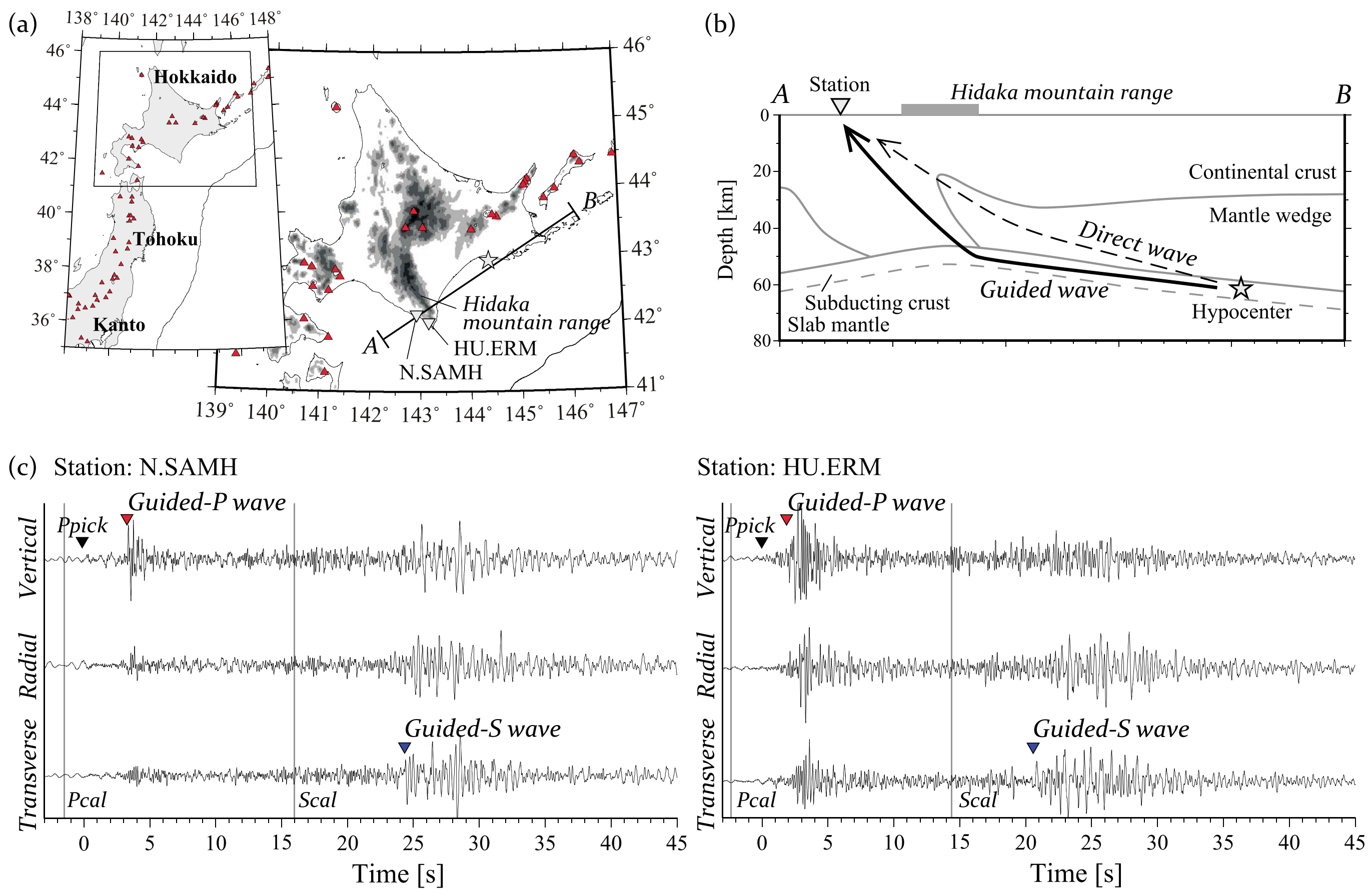

Figure 1. (a) Tectonic settings and topography of Hokkaido. Red triangles denote volcanoes. (b) A schematic illustration of a propagation path of the guided wave from an intraslab earthquake (star) to a station (inverted triangle) along the A–B cross section in Figure 1a. (c) Examples of band-pass filtered (1 to 12 Hz) three-component seismograms containing guided waves. Locations of hypocenter and stations (N.SAMH and HU.ERM) are plotted as a star and inverted triangles in Figure 1a. Vertical bars indicate theoretical arrival times of *P* and *S* waves for the JMA2001 1-D velocity model [*Ueno et al.*, 2002]. Inverted triangles denote arrivals of direct *P* (black), guided-*P* (red), and guided-*S* (blue) waves.

distances along the crust [*Shiina et al.*, 2014], we can resolve the depth-dependent seismic properties of the subducting crust by analyzing guided waves. In this study, we measured arrival times of guided-*P* and guided-*S* waves and then estimated *P* wave (V_p) and *S* wave (V_s) velocities in the crust beneath eastern Hokkaido. Moreover, we discuss seismic activity and the amount of fluids channeled in the crust based on the estimated V_p and V_s.

2. Data and Method

2.1. Observations of Guided Waves

At the western side of the Hidaka mountain range in Hokkaido, guided waves propagating in the subducting crust [*Abers*, 2005; *Shiina et al.*, 2014] are frequently recorded for earthquakes occurring near the upper surface of the Pacific slab (Figure 1a). In addition to guided-*P* waves reported by *Shiina et al.* [2014], we detected another later phase in seismograms with a clear guided-*P* wave and interpreted it as a guided-*S* wave. Amplitudes of the later phases are dominant in horizontal components (Figures 1c and S1 in the supporting information), and the later phases arrive at stations 3–15 s after a theoretical arrival time of the direct *S* wave calculated for the JMA2001 1-D velocity model [*Ueno et al.*, 2002] (Figure 2). The characteristics of later phases are similar to those of the guided-*P* waves [*Shiina et al.*, 2014] and guided-*S* waves reported in previous studies [e.g., *Hori*, 1990; *Abers*, 2005]. Therefore, we interpreted the later phases observed in Hokkaido as guided-*S* wave propagating in the crust. Fundamental features of the guided-*P* and guided-*S* waves observed in this study are described in the supporting information (Text S1).

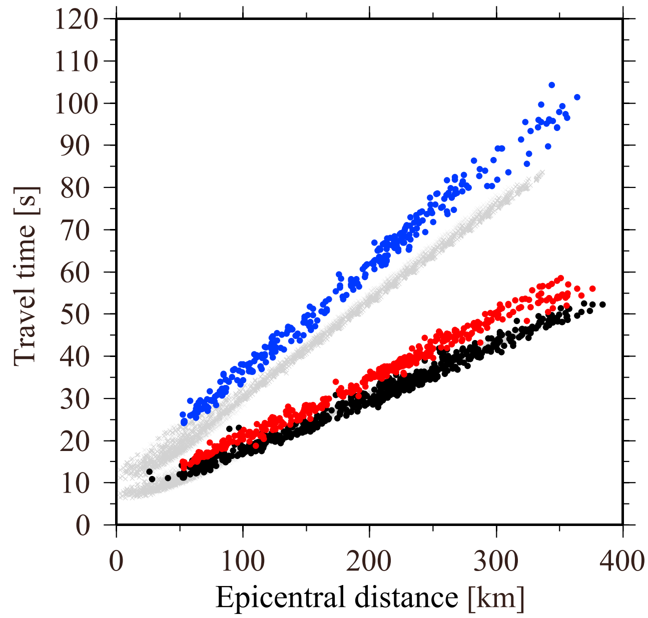

Figure 2. Travel times of direct and guided waves with respect to epicentral distance. Red and blue dots represent guided-*P* and guided-*S* waves, respectively. Black dots show direct *P* waves. Gray crosses represent direct *P* and direct *S* waves calculated with the JMA2001 1-D velocity model [*Ueno et al*., 2002] for earthquakes located at the uppermost part of the Pacific slab beneath eastern Hokkaido.

2.2. Estimations of Interevent Seismic Velocity

The ray path of a guided wave discussed by *Shiina et al*. [2014] is schematically shown in Figure 1b. It is thought that the energy of a guided wave trapped along the low-velocity subducting crust is efficiently leaked when the crust contacts a low-velocity body above the crust [e.g., *Martin et al*., 2003; *Miyoshi et al*., 2012]. Beneath the Hidaka mountain range in Hokkaido, a prominent low-velocity body with V_p of $<$7.5 km/s and V_s of $<$4.2 km/s (comparable to continental crustal material velocity) overlies the subducting crust to a depth of ~80 km [e.g., *Kita et al*., 2010b, 2012]. This unique tectonic setting facilitates efficient leakage of guided wave energy to the overlying plate [*Shiina et al*., 2014]. When guided waves are observed at a station for two earthquakes with similar azimuths, propagation paths are likely to overlap in a region from the leakage point to the station [*Shiina et al*., 2014], suggesting that structural effects above the subducting crust on travel times of the guided waves can be removed by taking the travel time difference of guided waves for the two earthquakes. Based on this idea, we estimate an average seismic velocity of the crust between the two earthquakes, as carried out by *Shiina et al*. [2014].

In this study, we visually picked arrival times of the guided-*P* and guided-*S* waves from 315 and 275 earthquakes (magnitude range of 2.0–4.0), respectively, that occurred from March 2003 to February 2011. For earthquakes with clear guided waves, we selected a pair of earthquakes based on following criteria in order to estimate reliable values of V_p and V_s in the subducting crust: (1) an interevent distance of $>$100 km, (2) a difference in azimuth from the two earthquakes to a common station of $<$5°, and (3) a difference in focal depths of the two earthquakes of $<$10 km. Based on these criteria, we obtained the number of earthquake pairs of 286 and 208 for identifying V_p and V_s in the subducting crust, respectively, for five stations located at the west of the Hidaka mountain (Figure 3). The number of earthquake pairs of 286 for *P* waves is about twice that in *Shiina et al*. [2014], and the third criterion is a new condition to improve the resolution of seismic velocity imaging. The larger number of data and stricter criterion for earthquake pairs probably contributes to higher resolution in depth variations in seismic velocity of the subducting crust. The maximum picking errors in arrival times of guided-*P* and guided-*S* wave were about 0.3 s and 0.5 s, respectively. The total amount of possible errors in differential travel times, which include uncertainties in the origin time and location of an earthquake, are calculated to be less than 1.0 s and 1.5 s. These uncertainties yield errors of less than 5–8% in the estimates of V_p and V_s in the subducting crust (Figure S2).

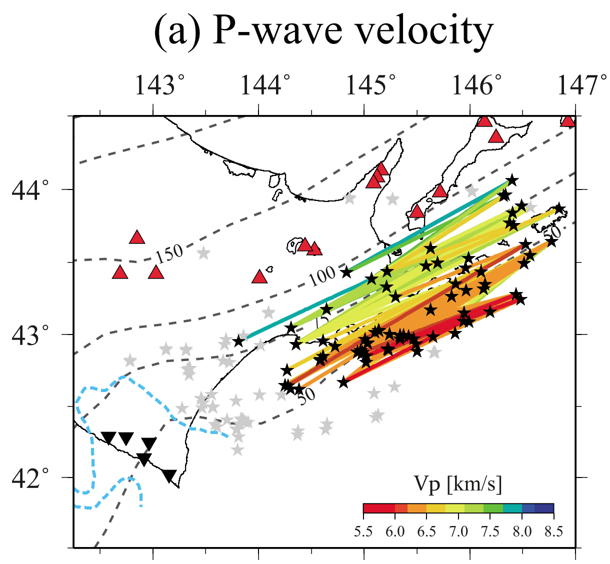

Figure 3. (a) *P* wave and (b) *S* wave velocities in the subducting crust beneath eastern Hokkaido. Stations used in this study are plotted as inverted triangles. Earthquakes with clear guided waves are denoted by gray stars, and earthquakes adapted to the analysis are denoted by black stars. Black broken lines represent isodepth contours of the Pacific slab [*Kita et al.*, 2010b], and a light blue broken line shows the contacting area between the subducting crust and the low-velocity materials beneath the Hidaka mountain range [*Kita et al.*, 2010b]. Red triangles denote volcanoes.

3. Results

We identify guided-*P* and guided-*S* waves for earthquakes located at depths of 40–150 km beneath eastern Hokkaido (Figure 3), but earthquakes pairs used for estimating V_p and V_s in the subducting crust are located only at depths of 50–100 km. Therefore, we here focus on depth variations in seismic velocity in the subducting crust at depths of 50–100 km.

We obtained V_p and V_s of 6.5–7.5 km/s and 3.6–4.2 km/s, respectively, in the subducting crust at depth of 50–100 km beneath eastern Hokkaido (Figures 3 and 4). These values are consistent with previous estimates of V_p and V_s in the crust beneath this region [e.g., *Abers*, 2005; *Nakajima et al.*, 2009; *Nakanishi et al.*, 2009]. Furthermore, we reveal remarkable low-velocity anomalies, with V_p of 6.5–6.8 km/s and V_s of 3.6–3.8 km/s at depths of 50–70 km (Figures 4a and 4b), and the velocities increase to ~7.3 km/s for *P* wave and ~4.2 km/s for *S* wave at depths of >80 km. The increase in seismic velocity in the crust with depth is supported by a change in apparent velocities of guided waves derived from shot gathers for many earthquakes at a single station; apparent velocities vary from ~7.0 km/s to ~7.3 km/s for guided-*P* wave and from ~4.0 km/s to ~4.2 km/s for guided-*S* wave when focal depths of earthquakes shift deeper (Figures S3 and S4).

The obtained V_p values at depths of 50–70 km are lower by about 0.5 km/s than those estimated by *Shiina et al.* [2014]. This probably results from the analysis with the new criterion of the focal-depth difference for earthquake pair selections, which would result in higher resolutions of V_p variation with depth than that in *Shiina et al.* [2014], in which V_p values are more or less averaged in the depth direction because of no criterion on focal-depth differences. Although we obtained an average V_p/V_s value of 1.81 at depths of 50–100 km from earthquake pairs identified both guided-*P* and guided-*S* waves, it is difficult to quantify the depth variation in V_p/V_s because of larger 1 sigma uncertainty in V_p/V_s. Quantification of V_p/V_s variation with depth remains left for future studies.

4. Discussions

The V_p and V_s observed at a depth range of 50–70 km are lower than those obtained from experimental studies that measure elastic velocities of subducting crustal rock [e.g., *Fujimoto et al.*, 2010] and expected for fully hydrated (about 5 wt%) mid-ocean ridge basalt (MORB) materials [e.g., *Hacker et al.*, 2003; *Kimura and Nakajima*, 2014]. One explanation of the low-velocity anomalies at depths of 50–70 km may be seismic

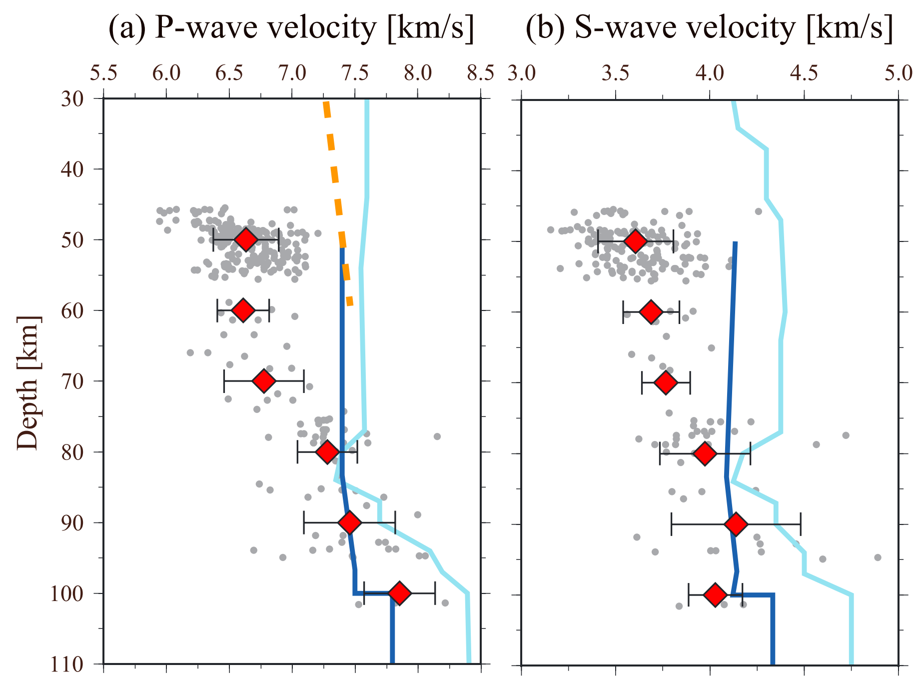

Figure 4. Velocity profiles of (a) P wave and (b) S wave velocities in the subducting crust. Values estimated for each pair of earthquakes are plotted as gray dots. Red diamonds show averaged velocities within 10 km depth bins with error bars of one standard deviation. Blue and light blue lines indicate velocities expected for fully hydrated MORB by *Hacker et al.* [2003] and *Kimura and Nakajima* [2014], respectively. An orange broken line shows an experimentally derived P wave velocity of lawsonite blueschist obtained by *Fujimoto et al.* [2010].

anisotropy in the subducting crust, which can be created by the alignment of bending-related faults formed at the trench outer slope [e.g., *Faccenda et al.*, 2008]. However, the seismic anisotropy would have minor effects on travel times of the guided waves used in this study because propagation paths of the guided waves are subparallel to the strike of fault orientations [*Shiina et al.*, 2014].

The remarkable low V_p in the subducting crust at depths of 50–70 km beneath eastern Hokkaido is comparable to that observed beneath the forearc region of Tohoku [*Shiina et al.*, 2013] (Figure 5a). As dehydration reactions of the hydrous minerals mainly occur at depths of 80–100 km beneath Hokkaido [e.g., *Abers et al.*, 2013; *Kimura and Nakajima*, 2014], dehydrated fluids would exist in the crust at depths of <100 km. Thus, we interpret that aqueous fluids are distributed and coexist with hydrous minerals in the crust at depths of 50–70 km, as is suggested in Tohoku [e.g., *Shiina et al.*, 2013]. In this case, a fluid-filled pore of ~1 vol % with an equivalent aspect ratio of ~0.01 [*Takei*, 2002] can explain the observed reductions in V_p and V_s in the crust.

The lowered V_p in the subducting crust beneath eastern Hokkaido increases to ~7.3 km/s at a depth of ~80 km, which is shallow by 20 km compared to Tohoku. Consequently, the V_p at depths of 80–100 km in eastern Hokkaido is ~0.5 km/s faster than in Tohoku (Figure 5a). As this feature is also suggested by tomographic studies [e.g., *Tsuji et al.*, 2008; *Nakajima et al.*, 2009], we consider that the difference in seismic velocities at the depths of 80–100 km between eastern Hokkaido and Tohoku is a robust feature and represents regional differences in thermal and hydrological properties of the subducting crust beneath the two regions.

Belt-like distributions of concentrated seismicity in the subducting crust, so called the upper plane seismic belt, are observed at depths of 70–100 km beneath eastern Hokkaido and Tohoku [*Kita et al.*, 2006]. Dehydration reactions of hydrous minerals in the crust and dehydration-derived fluids are considered to generate crustal earthquakes [e.g., *Abers et al.*, 2013; *Okazaki and Hirth*, 2016]. Because the depths of dehydration reactions depend largely on temperature [e.g., *Hacker et al.*, 2003], depths of concentrated crustal seismicity would shift to shallower depths if temperature recovery in the subducting crust is faster beneath eastern Hokkaido resulting from a small thermal parameter due to the oblique subduction of the Pacific slab [e.g., *Kita et al.*, 2010a; *Abers et al.*, 2013]. However, crustal seismicity patterns at depths of 50–100 km does not

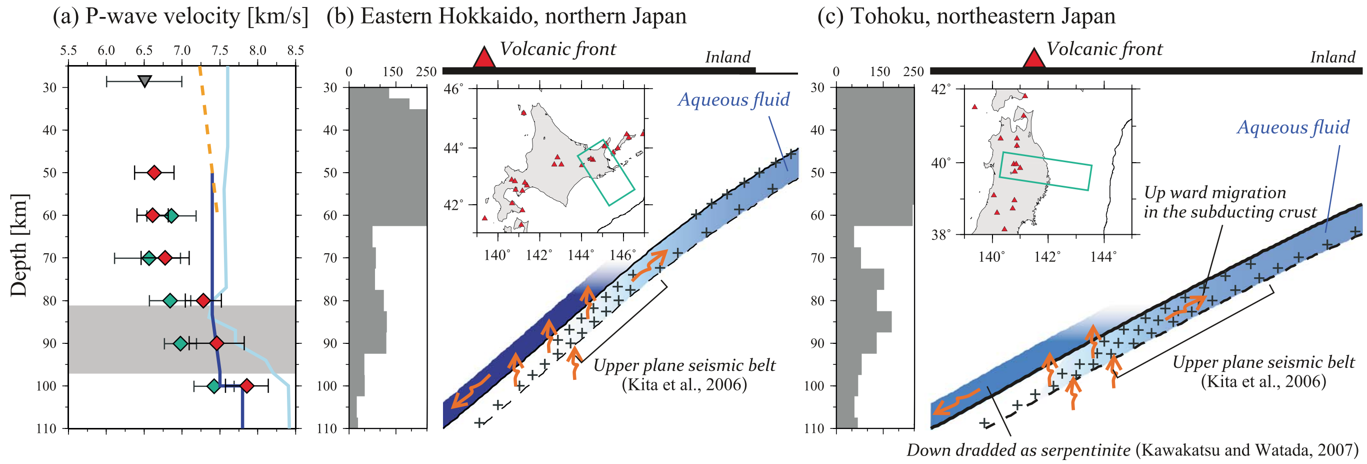

Figure 5. (a) Comparisons of *P* wave velocity in the subducting crust beneath eastern Hokkaido (red diamonds) and Tohoku (green diamonds) [*Shiina et al.*, 2013]. A gray inverted triangle shows range of *P* wave velocity observed by seismic refraction survey [e.g., *Nakanishi et al.*, 2009]. The shaded area denotes depth ranges where major dehydrations of hydrous minerals occur in the crust [*Abers et al.*, 2013]. Other symbols are the same as Figure 4a. (b and c) (left) Number of earthquakes (magnitude of ≥1) located within 10 km from the upper boundary of Pacific slab in green boxes shown in the inset maps and (right) schematic models for fluid distributions in and above the crust beneath eastern Hokkaido and Tohoku.

show marked differences between eastern Hokkaido and Tohoku [*Kita et al.*, 2006] (Figures 5b and 5c), suggesting that dehydration depths of hydrous minerals in the crust do not change substantially between the two regions. Thus, it is expected that temperature recovery in the crust to depths of ~100 km may not be fast enough to shift the dehydration depths to shallower beneath eastern Hokkaido.

According to *Kita et al.* [2006], the number of earthquakes in the subducting crust at associated with the upper plane seismic belt at depths of 80–100 km is smaller in eastern Hokkaido than in Tohoku (Figures 5b and 5c). In contrast, seismic activities in the crust between eastern Hokkaido and Tohoku appears to be comparable at depths of 60–70 km (Figure 5), although it is difficult to discuss crustal seismicity at depths of shallower than 60 km because of the occurrence of thrust-type earthquakes at the plate interface. Correspondingly, the amount of aqueous fluids in the crust is ~1 vol % at depths of 50–70 km beneath the both regions (this study and *Shiina et al.* [2013]). These variations in seismicity around the upper plane seismic belt beneath eastern Hokkaido and Tohoku are not due to difference in detection capability of crustal earthquakes because we confirmed the lower threshold of magnitude of ≥1 for crustal earthquakes at depths of 60–100 km for the both regions. We infer that the faster V_p in the crust at depths of 80–100 km beneath eastern Hokkaido than those beneath Tohoku could be explained by a small amount of fluids in the crust. These spatial variations in seismic activity linked to the seismic velocity reductions in the crust suggest that the amount of overpressurized fluids channeled in the subducting crust may control the facilitation of crustal seismic activity, supporting the fluid-related embrittlement that high pore-fluid pressures reduce the effective normal stress and waken the shear strength of a fault [e.g., *Kirby et al.*, 1996].

We observe that V_p in the subducting crust at depths of 80–100 km is higher by ~0.5 km/s in eastern Hokkaido than in Tohoku, suggesting the small amount of fluids channeled in eastern Hokkaido, given that thermal regimes and petrological properties in the slab do not show substantial differences between the two regions. One possible cause for the smaller amount of fluids in eastern Hokkaido is an effective leakage of fluids from the subducting crust to the overlying mantle wedge, because of a decrease in the dihedral angles for the olivine-fluid system above the Pacific slab [e.g., *Mibe et al.*, 1999] and grain size growth in the mantle wedge [e.g., *Wada et al.*, 2011] as a result of higher thermal structure in the mantle wedge beneath eastern Hokkaido [e.g., *Wada et al.*, 2015], both of which can promote fluid escape from the slab to the mantle wedge. It is noted that we infer that the differences in thermal regimes in the subducting crust could be too small to make dehydration depths shallower, and hence, seismicity patterns in the subducting crust change little for the both regions. If fluid leakage to and temperatures in the mantle wedge are really different beneath eastern Hokkaido and Tohoku, the differences could be resolved by high-resolution imaging of seismic structures above the subducting slab. Therefore, the estimation of detailed heterogeneous structures above the slab will improve our interpretation of fluid migration processes from the subducting crust to the mantle wedge.

5. Conclusions

We estimated seismic velocity in the subducting crust beneath eastern Hokkaido by using guided-*P* and guided-*S* waves which propagate in the crust and revealed the depth-dependent variations in V_p and V_s at depths of 50–100 km. The estimated V_p and V_s marked 6.5–7.5 km/s and 3.6–4.2 km/s, respectively, which were 10–15% lower than expected values for fully hydrated MORB materials. This observation suggests that aqueous fluids of ~1 vol % coexist with the hydrous minerals in the subducting crust at the depths of 50–100 km beneath eastern Hokkaido. The obtained V_p in the subducting crust at depths of 80–100 km in eastern Hokkaido which is slightly faster than that in Tohoku appears to be correlated with difference in crustal seismic activity in two regions. This correlation suggests a close link between amount of overpressurized fluids and facilitation of crustal earthquakes, supporting the fluid-related embrittlement for seismic activity in the subducting crust at intermediate depths.

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