Seismic evidence for thermally-controlled dehydration reaction in subducting oceanic crust

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[1] We perform travel-time tomography to estimate detailed seismic velocity structures in the crust of the Pacific slab from northeastern (NE) Japan to the Kanto district, Japan, and reveal that the depth extent of the low-velocity (hydrated) oceanic crust varies along the arc. The low-velocity oceanic crust is subducting to depths of 120–150 km beneath Kanto, which is 40–70 km deeper compared to NE Japan. Such deeper preservation of the low-velocity oceanic crust beneath Kanto can be explained by lower-temperature conditions in the Pacific slab as a result of the subduction of the Philippine Sea slab immediately above it. These observations suggest that dehydration reactions accompanied by large velocity changes are controlled principally by temperatures, not by pressures. We also find spatial correspondence between intensive seismicity in the oceanic crust and the disappearance depth of the low-velocity oceanic crust, suggesting that breakdown of hydrous minerals triggers earthquakes in the oceanic crust.
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1. Introduction

[2] Subduction of oceanic plates at the trench carries water into the earth in the form of hydrous minerals. Hydrous minerals become unstable with increasing pressures and temperatures, and consequently dehydration reactions take place accompanied by the release of water to the surroundings. The water thus released is believed to trigger intraslab earthquakes and arc magmatism. Geodynamic modeling and experimental petrology [e.g., *Schmidt and Poli*, 1998; *Hacker et al.*, 2003] have constrained where the water is released and how it migrates from the slab to the mantle and have shown that dehydration reactions in the oceanic plate are dependent on pressure and temperature conditions as well as the distribution of hydrous minerals and petrological structures of the subducting plate.

[3] Seismological observations have detected the existence of a dipping low-velocity layer at the uppermost part of the subducting slab, which is interpreted as the hydrated oceanic crust [*Matsuzawa et al.*, 1986; *Zhang et al.*, 2004; *Abers*, 2005; *Kawakatsu and Watada*, 2007; *Rondenay et al.*, 2008; *Tsuji et al.*, 2008]. *Tsuji et al.* [2008] revealed the existence of a low-velocity layer at the top of the subducting Pacific slab beneath the central part of northeastern (NE) Japan, giving seismic evidence for the subduction of hydrated oceanic crust down to depths of 70–90 km. The low-velocity layer gradually disappears with increasing depths, and the oceanic crust shows higher velocity at deeper depths as a result of phase transformation from hydrous to anhydrous minerals. These observations demonstrate that breakdown of hydrous minerals in the subducting plate takes place with increasing pressures and temperatures. However, the effect of temperatures on dehydration reactions cannot be discriminated from that of pressures only from the depth variation in seismic velocities in the oceanic crust.

2. Low-Temperature Conditions in the Pacific Slab Beneath Kanto as a Result of Slab-Slab Contact

[4] The Kanto district in Japan, which surrounds the Tokyo metropolitan area, is known as one of the unique regions in the world in terms of plate tectonics. The region is located behind a trench-trench-trench triple junction with two obliquely subducting plates, the Philippine Sea and Pacific plates [*Seno et al.*, 1996] (Figure 1). An area of slab-slab contact, where the bottom of the Philippine Sea slab is in contact with the upper surface of the Pacific slab, is defined beneath Kanto on the basis of high-resolution seismic velocity structures [*Wu et al.*, 2007; *Nakajima et al.*, 2008] and distribution of slip vectors of interplate earthquakes [*Uchida et al.*, 2007]. The contact with the overlying Philippine Sea slab could hinder effective heat transfer to the Pacific slab from hot mantle wedge, and the Pacific slab beneath the slab contact zone can be expected to be colder than to the north where single subduction takes place. Actually, lower-temperature conditions in the Pacific slab have been argued on the basis of the distribution of interplate and intraplate [*Hasegawa et al.*, 2007; *Nakajima et al.*, 2008] as well as numerical simulation of subduction-induced flow [*Iwamori*, 2000].

[5] This tectonic framework provides us with the best opportunity through an actual subduction environment to evaluate the effect of temperatures on dehydration reactions independently of other parameters, since temperature conditions in the Pacific slab can vary along the arc as a result of slab-slab contact but the inherent nature of the subducting slab in terms of distribution of hydrous minerals and physical properties cannot vary much along it. Here, we extend our previous study by *Tsuji et al.* [2008] to a wider area from NE Japan to Kanto to investigate whether or not the depth extent of the hydrated crust of the Pacific slab varies along the arc.

3. Seismic Velocity Structures in the Crust of the Pacific Slab

[6] We divided the study area into four sub-regions and carried out double-difference tomography [*Zhang and Thurber*,

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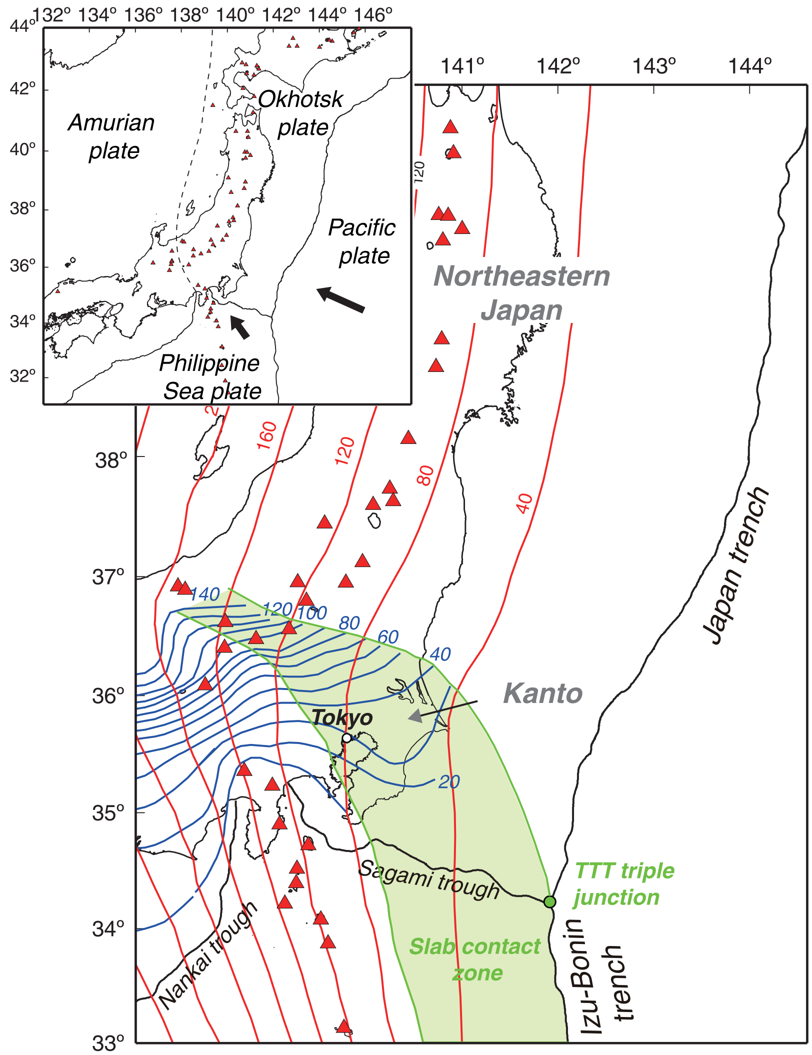

Figure 1. Tectonic settings of the study area. Iso-depth contours of the Pacific and Philippine Sea slab [*Nakajima et al.*, 2008] are shown by red and blue curves, respectively. An area of slab-slab contact where the bottom of the Philippine Sea slab is in contact with the upper surface of the Pacific slab [*Nakajima et al.*, 2008; *Uchida et al.*, 2007] is shaded by light green. Red triangles denote active volcanoes. Plate motions of Philippine Sea and Pacific plates [*Seno et al.*, 1996] are shown by black arrows in the insert map.

2003] for each region. In each region, grid intervals were set at 25 km in the along-arc direction, 10 km perpendicular to it, and 5 km in the vertical direction in a depth range of 0–160 km and 20 km at greater depths (Figure 2). We used P- and S-wave arrival-time data picked manually by Japan Meteorological Agency (JMA) and our institute. The distance between earthquake pairs was limited to 10 km. Distribution of stations and earthquakes are shown in Figure 2. We adopted a 1D velocity structure of the JMA2001 [*Ueno et al.*, 2002] as an initial velocity model and assigned 5% faster P- and S-wave velocities than those in the mantle to grid nodes within the subducting Pacific slab. Number of stations, earthquakes, and arrival-time data and root-mean-square of travel-time residuals for each region are summarized in Table 1. More details about the data are included in auxiliary material.[1]

[1]Auxiliary materials are available in the HTML. doi:10.1029/2008GL036865.

[7] Figure 3 shows that a layer of extremely low S-wave velocities (<4.5 km/s) with a thickness of ~10 km exists at the uppermost part of the Pacific slab. Earthquakes in the upper plane of the double seismic zone [*Hasegawa et al.*, 1978] occur mainly in the layer and S-wave velocities of <4.5 km/s are almost in agreement with those of oceanic crust composed of hydrous minerals [e.g., *Connelly and Kerrick*, 2002; *Hacker et al.*, 2003]. Therefore, we interpret the layer as the hydrated crust of the subducting Pacific slab as that of *Tsuji et al.* [2008]. The hydrated oceanic crust appear to be persisted down to a depth of ~80 km in line A-A′, ~150 km in line B-B′, and ~120 km in line C-C′. Results of checkerboard resolution tests show good recovery of checkerboard patters to a depth of ~140 km in line A-A′ (Figure S2 of the auxiliary material). We consider that the disappearance of the low-velocity oceanic crust at relatively shallower depths in line A-A′ can be resolved, which in turn shows much deeper penetration of the hydrated oceanic crust beneath Kanto. The low-velocity zone gradually disappears with increasing

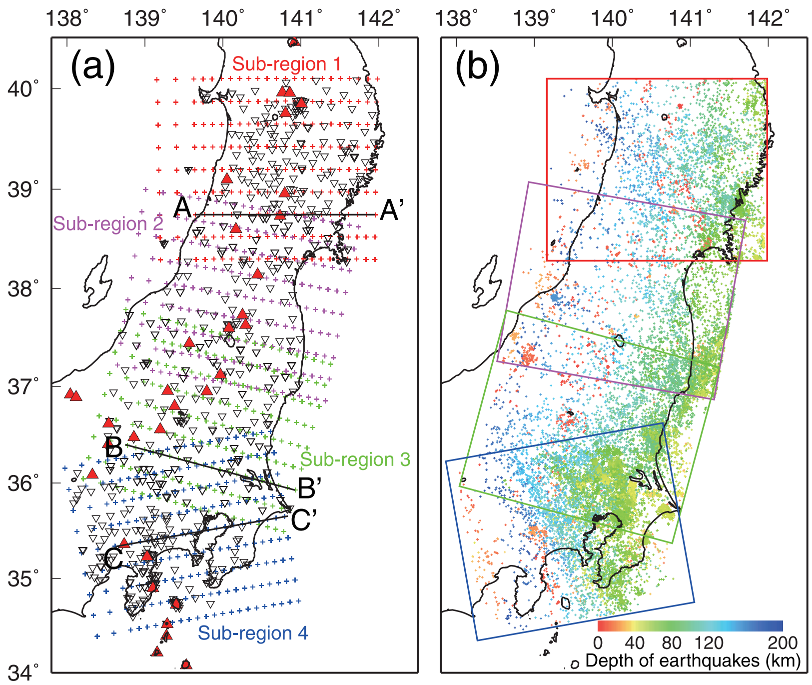

Figure 2. (a) Distribution of seismograph stations (reverse triangles) and configuration of grid nodes (crosses) adopted in the inversion. Colors of grid nodes indicate four sub-regions 1 to 4. Red triangles denote active volcanoes. Three lines, A-A′, B-B′, and C-C′, represent profiles for which vertical cross sections are shown in Figure 3. (b) Distribution of earthquakes used in this study. Colors represent depth of hypocenters. Four colored rectangles show each sub-region.

depths in lines A-A′ and C-C′. These features can be partly seen in P-wave velocity structures (auxiliary material).

4. Discussion

[8] To characterize velocity variation in the crust of the Pacific slab, we calculate S-wave velocity distribution along a curved surface 5-km-below the upper surface of the Pacific slab. It is apparent that seismic velocities in the oceanic crust show a striking spatial variation along and across the arc (Figure 4a). The oceanic crust with S-wave velocities of <4.5 km/s is observed down to a depth of ~80 km in NE Japan, whereas it obviously extends to depths of 120–150 km beneath Kanto. An important point to be addressed is that the oceanic crust retains lower velocities to greater depths only beneath the slab contact zone. The existence of the low-velocity oceanic crust beyond a depth of 100 km beneath Kanto was also pointed out by *Matsubara et al.* [2005]. This along-arc variation can be explained as follows. The Pacific slab is in contact with the overlying Philippine Sea slab beneath Kanto, and the upper surface of the Pacific slab cannot be heated by hot mantle wedge. Consequently, temperatures in the crust of the Pacific slab cannot increase enough to facilitate dehydration reactions, which could shift dehydration reactions to greater depths. The delay of dehydration underneath the slab contact zone can result in the deeper preservation of the low-velocity oceanic crust. These observations suggest that dehydration reactions accompanied by large velocity changes are dependent principally on temperatures rather than pressures.

[9] Dehydration reactions in the oceanic crust expected for intermediate to cold subduction zones can involve pressure-sensitive breakdown of amphibole at 2–3 GPa and temperature-sensitive breakdown of lawsonite at 3–6 GPa [e.g., *Schmidt and Poli*, 1998; *Okamoto and Maruyama*, 1999; *Hacker et al.*, 2003; *Forneris and Holloway*, 2003], and lawsonite-out reaction can be a likely candidate for the disappearance of the low-velocity oceanic crust for an intermediate temperature

Table 1. Data Sets Used in This Study and the Reduction of Travel-Time Residuals

		Sub-region			
	Wave Type	1	2	3	4
Number of events		6,643	4,840	11,150	11,861
Number of stations		191	125	120	179
Number of absolute travel times	P	204,228	100,921	259,790	264,385
	S	150,404	81,295	203,995	201,070
Number of differential travel times	P	832,489	426,798	1,293,493	1,275,486
	S	423,662	317,915	881,441	859,000
Root-mean-square reduction of travel times, s	P	0.20–>0.08	0.27–>0.11	0.27–>0.11	0.29–>0.12
	S	0.39–>0.14	0.48–>0.16	0.46–>0.17	0.51–>0.20

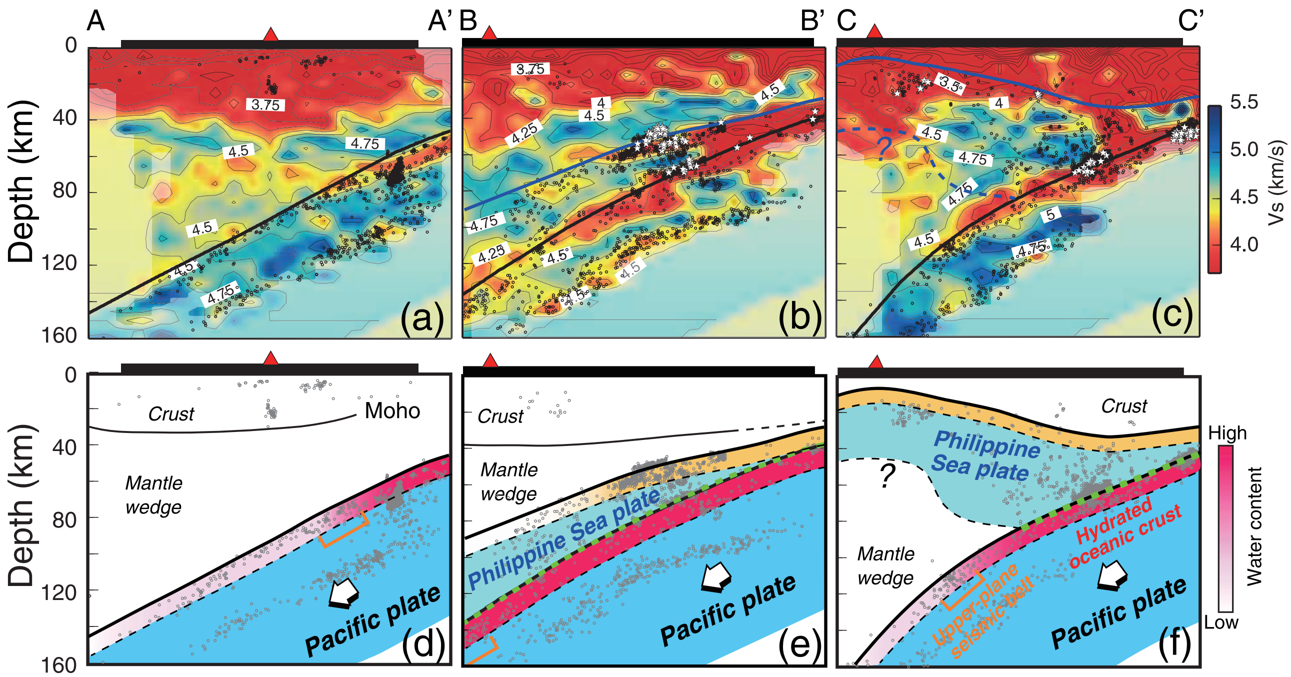

Figure 3. Vertical cross sections of S-wave velocity structures along lines (a) A-A′, (b) B-B′, and (c) C-C′ in Figure 2a. The upper surfaces of the Pacific and Philippine Sea slabs [*Nakajima et al.*, 2008] are shown by black and blue curves, respectively. Areas with values of derivative weighted sum (DWS) [*Thurber and Eberhart-Phillips*, 1999] of <500 are shaded by white. Red triangles and black bars on the top show active volcanoes and the land area, respectively. Earthquakes relocated with the final 3D velocity models are shown by black circles. White stars represent hypocenters of earthquakes with low-angle thrust-type focal mechanisms. Iso-velocity contours are shown with an interval of 0.25 km/s. Schematic illustration of interpretation along lines (d) A-A′, (e) B-B′, and (f) C-C′. Green dashed curves along the upper surface of the Pacific slab in Figures 3e and 3f denote the slab contact zone between the Philippine Sea and Pacific slabs. Locations of the upper-plane seismic belt [*Kita et al.*, 2006; *Hasegawa et al.*, 2007] are indicated by orange brackets. Colors of the oceanic crust represent qualitative water content.

subduction zone as suggested by *Connelly and Kerrick* [2002]. However, there are large uncertainties in breakdown temperatures of lawsonite from at <500°C [e.g., *Hacker et al.*, 2003] to at 600–700°C [e.g., *Schmidt and Poli*, 1998; *Forneris and Holloway*, 2003]. Since temperatures of 600–700°C are too high for the crust of the Pacific slab in NE Japan (250–450°C) [e.g., *Hacker et al.*, 2003; *Yamasaki and Seno*, 2003], we here assume that lawsonite-out reaction modeled by *Hacker et al.* [2003] is responsible for the disappearance of the low-velocity oceanic crust. As a result, temperatures in the crust of the Pacific slab in a depth range of 80–150 km would be estimated roughly to be ~200°C lower beneath Kanto compared to NE Japan. In any case, more precise phase diagram of the oceanic crust at temperatures of <500°C is required to conclude the cause of the along-arc variation in the velocity oceanic crust observed in this study.

[10] Figure 4b shows that the upper-plane seismic belt, a belt-like concentration of seismicity in the upper plane of the double seismic zone of the Pacific slab, is distributed sub-parallel to the iso-depth contours of the slab at depths of 80–100 km beneath NE Japan [*Kita et al.*, 2006] and at depths of 100–150 km beneath Kanto sub-parallel not to the iso-depth contours of the slab but to the down-dip (southwestern) limit of the slab contact zone [*Hasegawa et al.*, 2007]. A close relation between the depth range of the seismic belt and the disappearance depth of the low-velocity oceanic crust is direct evidence that breakdown of hydrous minerals is responsible for the triggering of earthquakes in the oceanic crust, as argued by *Abers et al.* [2006] in the Alaska subduction zone.

[11] *Kawakatsu and Watada* [2007] and *Tsuji et al.* [2008] detected a low-velocity layer immediately above the Pacific slab at depths deeper than 70–80 km and interpreted it as a hydrous layer composed of serpentine or chlorite, through which most of the water expelled from the slab is brought to greater depths. We obtain a similar low-velocity layer at the northernmost part of sub-region 1, but such a layer cannot be imaged clearly in other cross sections. Future work could involve an investigation of an along-arc variation in the low-velocity layer above the slab to deepen our understanding of water-circulation process in subduction zones.

5. Conclusions

[12] This study reveals an along-arc variation in the depth extent of the low-velocity crust of the Pacific slab. The low-velocity oceanic crust extends down to depths of 120–150 km beneath Kanto, whereas it is limited to a depth of ~80 km in NE Japan. Since the Pacific slab beneath Kanto can retain lower temperatures than beneath NE Japan due to the subduction of the overlying Philippine Sea slab, we infer that this variation may reflect an along-arc variation in temperatures of the Pacific slab. Results in this study will

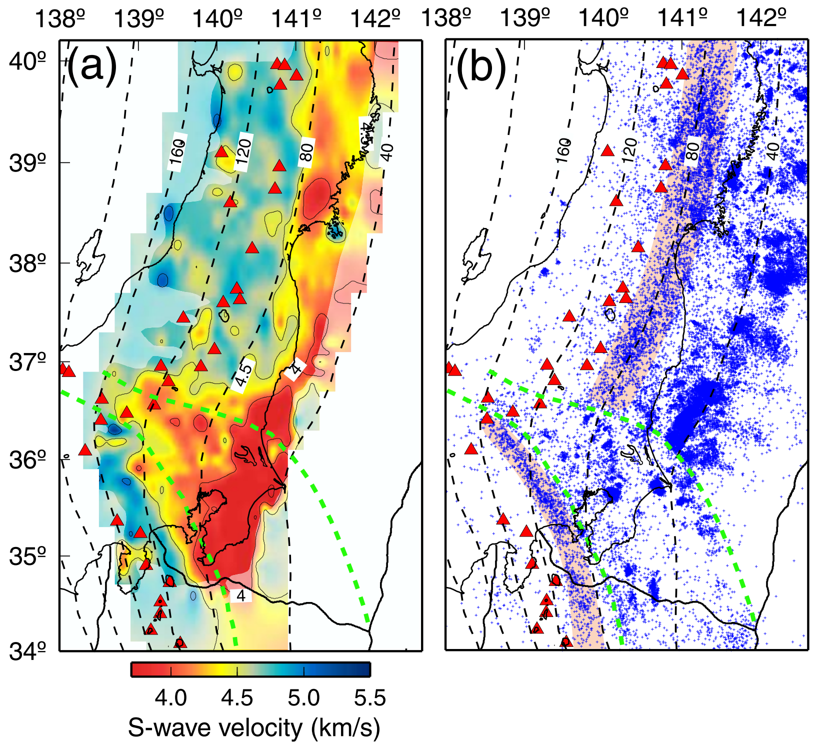

Figure 4. (a) S-wave velocity distributions in the oceanic crust, that is, along a curved surface 5-km-below the upper surface of the Pacific slab. Iso-depth contours of the Pacific slab are shown by dashed curves with an interval of 40 km. Iso-velocity contours are shown with an interval of 0.5 km/s. The northeastern and southwestern limits of the slab contact zone [*Nakajima et al.*, 2008; *Uchida et al.*, 2007] are indicated by green broken lines. (b) Hypocenter distributions of earthquakes that occurred in a distance range of 0–10 km from the upper surface of the Pacific slab. Light orange belts in Figure 4b denote locations of the upper-plane seismic belt.

provide practical constrains on the development of better phase diagrams of the oceanic crust, in particular for cold subduction environment.

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