Anomalous deepening of a belt of intraslab earthquakes in the Pacific slab crust under Kanto, central Japan: Possible anomalous thermal shielding, dehydration reactions, and seismicity caused by shallower cold slab material

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[1] A belt of intraslab seismicity in the Pacific slab crust parallel to iso-depth contours of the plate interface has been found beneath Hokkaido and Tohoku. Hypocenter relocations have shown that this seismic belt does not run parallel to but obliquely to the iso-depth contours beneath Kanto, deepening toward the north from ~100 km to ~140 km depth. The depth limit of the contact zone with the overlying Philippine Sea slab is located close to and parallel to this obliquely oriented seismic belt, suggesting that the deepening of the seismic belt there is caused by the contact with the overlying slab. The contact with this cold slab hinders the heating of the Pacific slab crust by hot mantle wedge, which would cause delay of eclogite-forming phase transformations and hence deepening of the seismic belt there. The depth limit of the subducting low-velocity crust also deepens toward the north, supporting this idea. **Citation:** Hasegawa, A., J. Nakajima, S. Kita, T. Okada, T. Matsuzawa, and S. H. Kirby (2007), Anomalous deepening of a belt of intraslab earthquakes in the Pacific slab crust under Kanto, central Japan: Possible anomalous thermal shielding, dehydration reactions, and seismicity caused by shallower cold slab material, *Geophys. Res. Lett.*, *34*, L09305, doi:10.1029/2007GL029616.

1. Introduction

[2] The genesis of intermediate-depth intraslab earthquakes remains enigmatic, because lithostatic pressure at such depths becomes too high to allow brittle faultings. Therefore, some special weakening mechanism is required for the occurrence of intermediate-depth earthquakes. Dehydration embrittlement has been proposed as a possible mechanism for decreasing effective normal stress and so triggering intermediate-depth earthquakes [e.g., *Kirby et al.*, 1996; *Seno and Yamanaka*, 1996].

[3] Precise relocation of intermediate-depth earthquakes recently made for Hokkaido and Tohoku, NE Japan, has demonstrated a characteristic fine-structure of the hypocenter distribution that supports the dehydration embrittlement hypothesis [*Kita et al.*, 2006]. Intermediate-depth events in the Pacific (PAC) slab beneath this area form a double seismic zone: upper-plane events occur in the subducting crust and lower-plane ones in the middle of the slab mantle [*Hasegawa et al.*, 1978, 1994; *Suzuki and Kasahara*, 1996; *Matsuzawa et al.*, 1990]. *Kita et al.* [2006] have applied the DD location method [*Waldhauser and Ellsworth*, 2000] to intraslab events observed in the dense nationwide seismic network that was recently deployed in Japan and found a belt-like concentration of seismicity in the upper plane of this double seismic zone. This seismic belt is located at depths of 70–90 km in the subducting crust of the PAC slab and trends parallel to iso-depth contours of the plate interface in the fore-arc side of the volcanic front over a length of about 1000 km from Hokkaido to Tohoku (a long pink belt in Figure 1). Its deeper end coincides well with the location of metamorphic facies boundary in mafic oceanic crust from jadite lawsonite blueschist (JLB) to lawsonite amphibole eclogite (LAE) estimated from a thermomineralogical model by *Hacker et al.* [2003b] for Tohoku, although many sources of uncertainty are involved in the estimation [*Hacker et al.*, 2003a, 2003b]. If the seismic belt is caused by dehydration associated with the phase transformation from JLB to LAE in the subducting crust, it should also exist beneath Kanto, south of Tohoku. However, we cannot find a similar seismic belt that is parallel to iso-depth contours of the plate interface there. Instead, a conspicuous NW-SE-trending linear alignment of earthquakes, running obliquely to the iso-depth contours, has been found in the uppermost portion of the slab.

[4] *Nakajima and Hasegawa* [2006] detected a narrow low-velocity (low-V) zone distributed along this linear seismicity, and suggested a possibility that it might be caused by a reactivation of subducted fracture zone. The Philippine Sea (PHS) plate is also subducting beneath Kanto from the south, and it directly comes in contact with the PAC slab located below it. The contact with the cold overlying plate would hinder the conductive heating of the PAC slab by the hot mantle wedge, which should result in lower temperatures in the slab there [*Noguchi et al.*, 2004]. Since temperatures within the slab affect the formation depth of the seismic belt assuming that the seismic belt is caused by the dehydration reaction from JLB to LAE, the seismic belt beneath Kanto, if it exists, should have a different spatial distribution compared to that beneath Tohoku and Hokkaido. Therefore, more detailed investigation is necessary for accurate understanding of the cause of the seismic belt.

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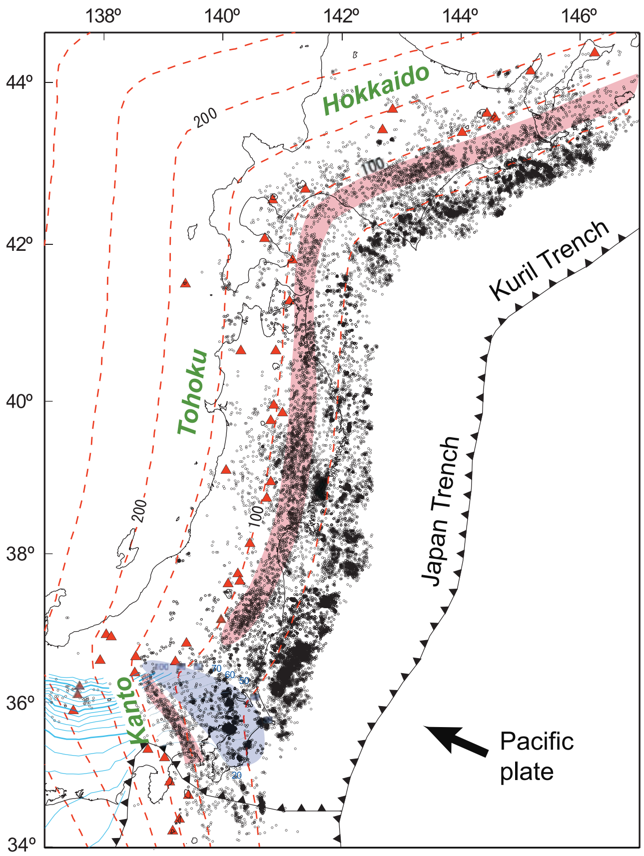

Figure 1. Epicenter distribution of relocated earthquakes in the distance range of 0–15 km below the upper surface of the PAC slab. Events in Hokkaido and Tohoku are those relocated by *Kita et al.* [2006]. The seismic belt in Kanto detected in this study and that in Hokkaido and Tohoku previously found by *Kita et al.* [2006] are shown by pink belts. The contact zone between the Pacific slab and overlying slab material is shaded in purple. Red broken lines and blue solid lines show the depth contours of the upper surface of the PAC slab estimated by the distribution of slab earthquakes [*Nakajima and Hasegawa*, 2006] with a interval of 50 km and the PHS slab estimated by the velocity structure and focal mechanisms with a interval of 10 km (F. Hirose et al., Three-dimensional velocity structure in southwestern Japan, and configuration of the Philippine Sea slab estimated by double-difference tomography, submitted to *Journal of Seismological Society of Japan*, 2007) (alternatively, the PAC slab fragment beneath Kanto [*Toda et al.*, 2005]), respectively. Red triangles denote active volcanoes.

[5] In the present study, we investigate how the PAC slab contacts with the overlying PHS slab and how it affects the depths of the dehydration reaction.

2. Hypocenter Distribution of Upper-Plane Events

[6] *Kita et al.* [2006] relocated earthquakes beneath Hokkaido and Tohoku by the DD location method [*Waldhauser and Ellsworth*, 2000]. In the present study, we also relocated earthquakes beneath Kanto for the period of 2002–2005 yielding a precise hypocenter distribution of earthquakes within the PAC slab over a wide area from Hokkaido to Kanto including the two arc-arc junctions. Figure 1 shows epicenter distribution of relocated upper-plane earthquakes. It should be noted that many events located trenchward of the 50-km (about 70-km in case of Kanto) contour line of the plate interface are not upper-plane events but interplate events. A seismic belt similar to that detected by *Kita et al.* [2006] beneath Tohoku and Hokkaido is also seen beneath Kanto, but it is rather sharper and extends in the NW-SE direction at depths of 90–140 km obliquely to the iso-depth contours.

3. 3D Seismic Velocity Structure Beneath Kanto

[7] *Nakajima and Hasegawa* [2006] obtained the 3D seismic velocity structure beneath Kanto by applying the seismic tomography method of *Zhao et al.* [1992]. Data used are 363,354 P- and 234,571 S-wave arrival times at 697 stations from 4,698 earthquakes that occurred during the period from 1997 to 2005. The dense nationwide seismic network enabled us to image the complicated plate structure beneath this region in detail. We use the results of this tomographic inversion in the present study. Details of the tomographic inversion are described by *Nakajima and Hasegawa* [2006].

3.1. Contact Zone With the Overlying Slab

[8] Underneath Kanto the PHS plate subducts to the north on top of the westward subducting PAC plate. Tomographic inversion using data obtained by the dense seismic network in this region clearly imaged the mantle portions of the subducted PHS slab and the PAC slab as inclined P- and S- wave high-velocity (high-V) zones. Based on this tomography result, we investigate where the PAC slab is in contact with the overlying PHS slab. Figure 2 shows the distribution of P-wave velocity perturbations along a surface 10 km above the upper surface of the PAC slab. Epicenters of upper-plane events in the PAC slab are shown by dots. We can see a prominent high-V zone extending in the NW-SE direction obliquely to the iso-depth contours of the PAC slab surface. It is located just south of the kink or cusp in the iso-depth contours. Comparison with hypocenter distribution of events associated with the subducting PHS slab shows that this NW-SE-trending high-V zone corresponds to the mantle portion of the PHS slab. (*Toda et al.* [2005] have, instead of the PHS slab, proposed the existence of a separate microplate, a dislodged block of the PAC slab, in this region. If this interpretation is correct, this high-V zone corresponds to a PAC slab fragment.) Consequently, the NW-SE-trending high-V zone shown in Figure 2 would indicate the location and the extent of the contact area between the PAC slab and the mantle portion of the overlying slab. The crustal portion of the overlying slab is also in contact with the PAC slab and its contact area should be located just northeast of the NW-SE-trending high-V zone, which can be estimated from hypocenter distribution of earthquakes [e.g., *Hori*, 2006; *Noguchi*, 2007].

[9] Our present estimate of the position of the contact zone with the overlying slab is shown in Figures 1 and 3 by the blue shaded area. The southwestern edge of the zone

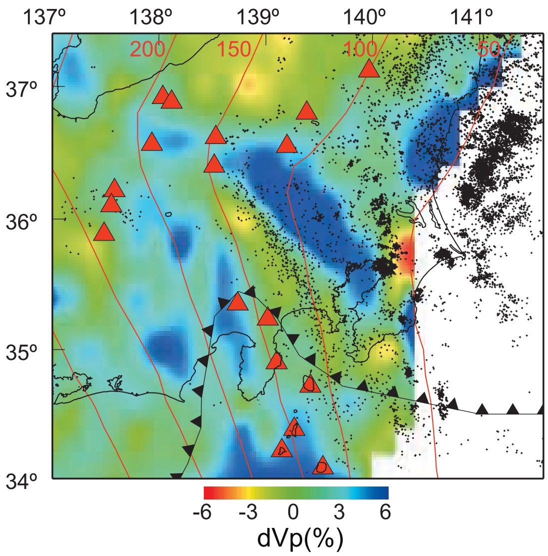

Figure 2. P-wave velocity distribution on a surface 10 km above the upper surface of the PAC slab. P-wave velocity perturbation from the average value at each depth is shown by color scale at the bottom. Upper-plane earthquakes in the PAC slab are shown by dots. Red lines and triangles denote iso-depth contours of the upper surface of the PAC slab and active volcanoes, respectively.

indicates the depth limit of the slab contact zone. Figures 1 and 2 show that the linearly-aligned seismicity in the crust of the PAC slab is located to the southwest of the depth limit of the contact zone. This correspondence indicates that the portion of the PAC slab crust with this linearly-aligned seismicity is in direct contact with the hot mantle wedge above it. This observation strongly suggests that the contact with the cold overlying slab reaches down to 75–125 km depth in this region and therefore causes this unusual intraslab seismic belt where the linearly-aligned seismicity is oblique to the depth contours of the PAC slab surface. The contact with the cold slab right above it evidently hinders the heating of the Pacific slab by the hot mantle wedge, and probably delays the phase transformation from JLB to LAE, causing the shift of the seismic belt to greater depth, instead of extending parallel to the iso-depth contours of the plate interface as it does in Hokkaido and Tohoku.

3.2. Depth Limit of Low Velocity Crust

[10] If the above interpretation is correct, then the depth limit of the low-V zone in the subducting crust of the PAC slab should increase toward the north as the depth limit of the contact zone deepens. This is because P-wave velocity in the crust is estimated to be lower (~7.5–7.6 km/s at 100–150 km depth) than that in the surrounding mantle before the phase transformation of JLB to LAE [*Hacker et al.*, 2003a]. Figure 4 shows vertical cross sections of P-wave velocity along lines A through C. A low-velocity zone is visible around the top of the slab nearby the belt of intraslab earthquakes. Moreover, the depth limit of this low-V zone deepens toward the north from ~100 km along A to ~150 km along C. This supports the idea that the contact with the overlying slab hinders the heating of the Pacific slab by the mantle wedge and thus causes the shift of the seismic belt to greater depth, indicating that the linearly-aligned seismicity detected beneath Kanto is identical in cause with the seismic belt found beneath Hokkaido and Tohoku [*Kita et al.*, 2006]. Moreover, the observed narrower width of the seismic belt beneath Kanto compared to Tohoku and Hokkaido (Figure 1) could be explained by the abrupt heating of the PAC slab that started after passing through the contact zone. This abrupt heating would allow the dip of the facies

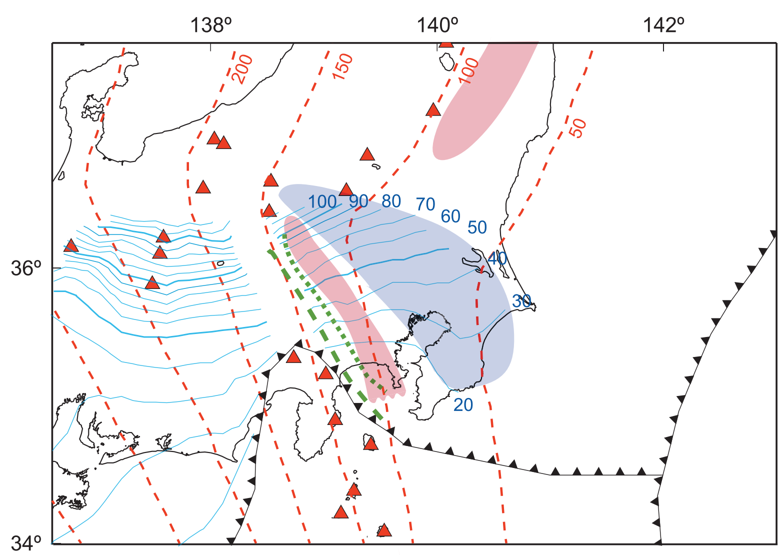

Figure 3. Configuration of the upper-plane seismic belt (shaded in pink) in the PAC slab and the contact zone with the overlying slab material (shaded in purple). Green broken and dotted lines indicate estimated location of facies boundary from JLB to LAE in the mafic crust of the PAC slab. Red broken and blue solid lines show iso-depth contours of the upper surface of the PAC slab and PHS slab, respectively.

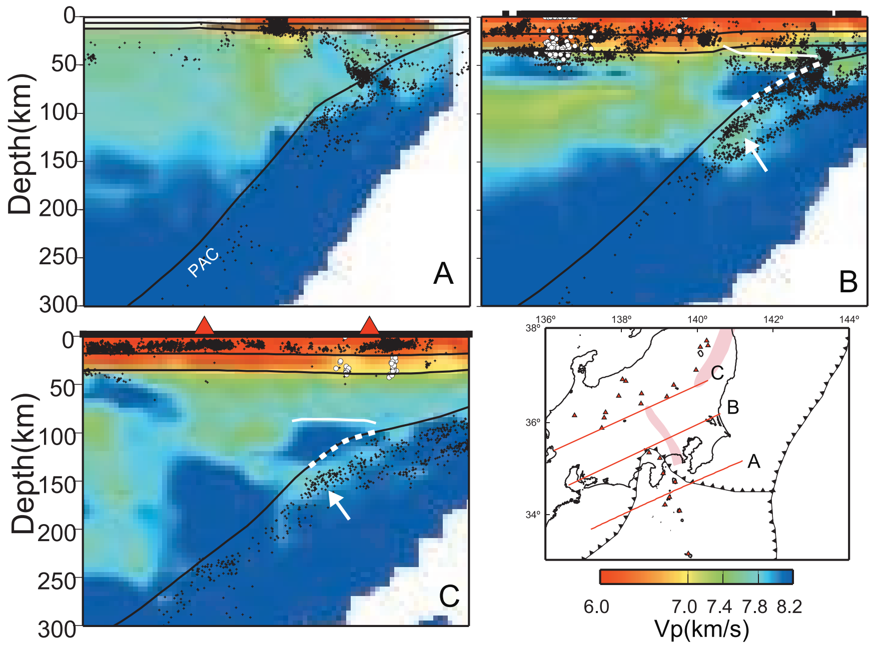

Figure 4. Vertical cross sections of P-wave absolute velocity along lines A through C shown in the inset map. P-wave velocity is shown by color scale. Hypocenters of earthquakes and low-frequency earthquakes are shown by dots and open circles, respectively. Thick lines and red triangles on the top denote land areas and active volcanoes. White arrows represent the cluster of earthquakes that forms upper-plane seismic belt. The upper interface of the Philippine Sea slab beneath Kanto is indicated by white lines and the contact zone of the Pacific slab with the overlying slab is shown by white broken lines, respectively. Solid lines from top to bottom show the Conrad and Moho discontinuities and the upper surface of the PAC slab, respectively.

boundary from JLB to LAE in the PAC slab crust beneath Kanto to be steeper than that beneath Tohoku and Hokkaido (B in Figure 3 of *Kita et al.* [2006]), probably causing the formation of the narrower seismic belt. Note that the absence of a thin low-velocity layer corresponding to the oceanic crust at the top of the PAC slab is due to the lack of resolution of tomographic images.

4. Discussion

[11] Figure 4 shows the P-wave low-V zone in the subducting PAC slab crust that persists down to depths of 100–150 km, with its depth limit deepening toward the north. If we plot P-wave velocity perturbations instead of P-wave velocity, only the deepest portion of the low-V zone having an anomalously deep depth limit could be regarded as a low-V zone since the average velocities of the surrounding mantle at shallower depths are probably as low as those in the low-V zone. This is the reason why we were able to image the narrow low-V zone along the seismic belt in the PAC slab that trends obliquely to the iso-depth contours [*Nakajima and Hasegawa*, 2006]. The present reinvestigation and reinterpretation revealed that the NW-SE-trending narrow low-V zone in map view [*Nakajima and Hasegawa*, 2006, Figure 3] is an apparent one and caused by the deepening of the depth limit of the subducting low-V crust toward the north.

[12] According to the phase diagram and the thermal model for Tohoku estimated by *Hacker et al.* [2003a, 2003b], P-wave velocity of the crust would amount to about 7.9 km/s after completion of the phase transformation from JLB to LAE at depths deeper than ~90 km under the assumption that the entire crust is composed of fully hydrated MORB. Although the thermal structure of the Pacific slab beneath Kanto could be slightly different from Tohoku, the P-wave velocity of the crust after the phase transformation completion would be approximately the same as that estimated for Tohoku by *Hacker et al.* [2003a, Figure 8a]. Thus we infer that a P-wave velocity of 7.9 km/s for the subducting crust gives a rough estimation for finding the location where the entire crust completes the phase transformation from JLB to LAE. Green broken line in Figure 3 shows the location where the P-wave velocity of the crust estimated by the tomographic inversion reaches the value of 7.9 km/s. We can see that the seismic belt in the crust (shaded by pink color) is located just above this line and nearly parallel to it, being consistent with the expectation from the dehydration embrittlement hypothesis for the genesis of such intraslab earthquakes.

[13] The above discussion is based on the assumption that the entire crust consists of MORB composition, which is not correct for the lower oceanic crust [*Hacker et al.*, 2003a; *Dick et al.*, 2000]. If we assume, as an extreme case, that the upper crust is composed of metamorphosed MORB and the lower crust of unmetamorphosed gabbro and both have the same thickness, the average P-wave velocity of the entire crust becomes 7.7 km/s after completion of the phase transformation from JLB to LAE in the upper crust. The green dotted line in Figure 3 shows the location where the observed P-wave velocity in the crust attains a velocity of 7.7 km/s. The seismic belt in the crust detected in this study

is again located right above this estimated line of the phase-transformation completion, being nearly parallel to it.

5. Conclusions

[14] We have shown the existence of a linear prominent seismic belt in the upper plane of the double seismic zone in the Pacific slab beneath Kanto by precisely relocating hypocenters of intraslab earthquakes. It extends in the NW-SE direction obliquely to the iso-depth contours of the plate interface, indicating that the location of this seismic belt in the crust anomalously deepens toward the north. A detailed investigation of the slab structure in this region based on seismic tomography imaging has shown that the depth limit of the contact zone with the overlying slab is located next to and parallel to this seismic belt, suggesting that the northward deepening of the seismic belt is caused by the shielding effect of the cold slab material above from conductive heat transport. The P-wave velocity in the subducting crust estimated from the tomographic inversion has also shown a characteristic depth variation consistent with this interpretation.

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