

Tomographic evidence for hydrated oceanic crust of the Pacific slab beneath northeastern Japan: Implications for water transportation in subduction zones

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[1] We estimate detailed seismic-velocity structure around the Pacific slab beneath northeastern Japan by double-difference tomography. A remarkable low-velocity zone with a thickness of ~ 10 km, which corresponds to much hydrated oceanic crust, is imaged coherently along the arc at the uppermost part of the slab. The zone gradually disappears at depths of 70–90 km, suggesting the occurrence of intensive dehydration reactions there. The concentration of intraslab earthquakes at these depths supports dehydration-embrittlement hypothesis as a mechanism for generating intraslab earthquakes. A low-velocity zone imaged immediately above the slab at depths >70 km probably reflects a hydrous layer that absorbs water expelled from the slab and carries it to deeper depths along the slab. Our observations suggest that an along-arc variation in arc volcanism might be related to that in the development of the hydrous layer above the slab.

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1. Introduction

[2] When the oceanic plate subducts at the trench, the hydrated oceanic crust carries water into the earth in the form of hydrous minerals. Hydrous minerals in the oceanic crust become unstable with increasing pressure and temperature, and consequently dehydration reactions occur accompanied by the release of water to the surroundings. Hydrated oceanic crust, which is expected to be lower seismic velocity compared to the surrounding mantle, has been detected in various subduction zones as a low-velocity layer at the top of the subducting plate [e.g., Matsuzawa *et al.*, 1986; Bostock *et al.*, 2002; Abers, 2005; Rondenay *et al.*, 2008], but seismological observations have poorly constrained where metamorphic fluids are released from the slab and how they migrate into the mantle wedge.

[3] Dehydration reactions in the subducting slab are also important for the occurrence of intraslab earthquakes in terms of dehydration-embrittlement hypothesis [e.g., Kirby *et al.*, 1996; Jung *et al.*, 2004]. Kita *et al.* [2006] found the ‘upper-plane seismic belt’, a belt-like concentration of seismicity at depths of 70–90 km in the upper plane of

the double seismic zone beneath northeastern (NE) Japan that is distributed sub-parallel to iso-depth contours of the Pacific slab, and interpreted it to be associated with dehydration reactions near a facies boundary modeled by Hacker *et al.* [2003]. Detailed seismic velocity structure of the oceanic crust will provide an additional constraint on the verification of dehydration-embrittlement hypothesis.

[4] This paper estimates three-dimensional (3-D) seismic velocity structure in and around the subducting Pacific slab beneath NE Japan to reveal where water is released from the slab and how it migrates into the mantle wedge. High-quality arrival-time data obtained at dense seismograph network of Japan enable us to resolve the 3-D seismic velocity structure around the slab. A better knowledge of this issue is important to understand ongoing whole processes in subduction zones in terms of the triggering mechanism of intraslab earthquakes and arc magmatism.

2. Data, Method, and Resolution Test

[5] In this study, we applied double-difference tomography method [Zhang and Thurber, 2003, 2006] to a large number of arrival-time data of 311,280 for P waves and 267,828 for S waves from 14,032 earthquakes that occurred in the period from 2001 to 2006. Arrival-time data were taken from the catalogue of the Japan Meteorological Agency (JMA). The distance between earthquake pairs was limited to 10 km, yielding 570,000 (P wave) and 457,038 (S wave) differential travel-time data at 145 stations. Grid intervals were set at 25 km in the along-arc direction, 10 km perpendicular to it, and 5–10 km in the vertical direction (Figure 1). The 1D velocity structure of Hasegawa *et al.* [1978] was adopted as an initial P-wave velocity model. An initial S-wave velocity model was calculated by assuming a constant V_p/V_s value of 1.73. In the initial model, we assigned P- and S-wave velocities within the subducted Pacific slab to be 5% faster than those in the mantle on the basis of the plate model of Nakajima and Hasegawa [2006], which is determined from the upper envelope of intermediate-depth earthquakes (see auxiliary materials¹). It is noted that *tomofDD* [Zhang and Thurber, 2006] is adopted in this study, which uses a finite-difference travel-time algorithm taking the curvature of the earth into consideration, because a lateral extent of the study area is $240 \text{ km} \times 240 \text{ km}$ and hence the curvature of the Earth is not negligible. The final results were obtained after 18

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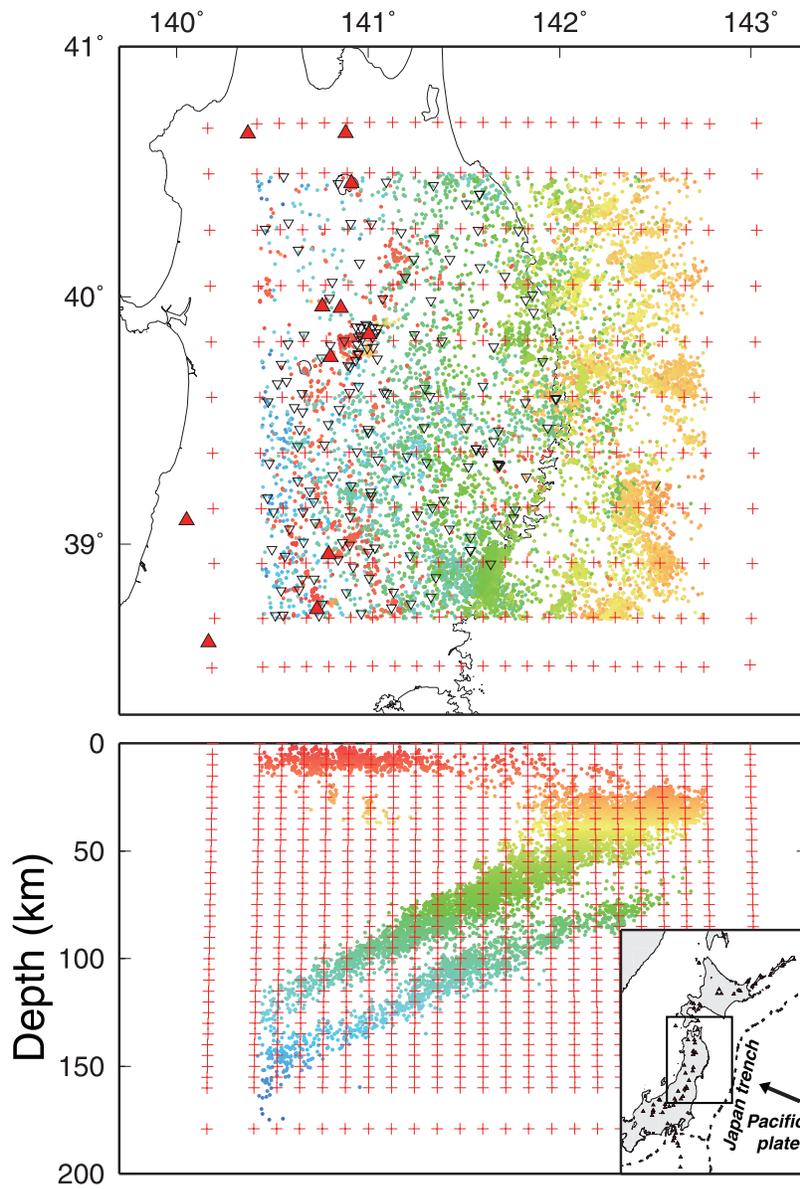


Figure 1. Distribution of earthquakes (colored circles), stations (reverse triangles), and grid configurations (red crosses) used in this study. Colors of circles represent the depths of hypocenters. Red triangles denote active volcanoes.

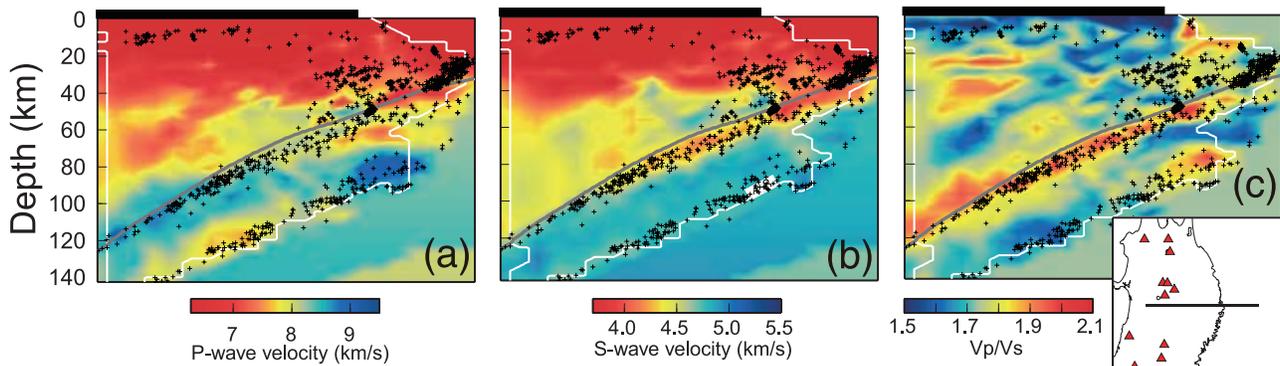


Figure 2. Across-arc vertical cross sections of (a) P- and (b) S-wave velocities and (c) V_p/V_s ratio. Crosses denote hypocenters relocated in this study. Black bar on the top of each figure represents the land area. Contours with $DWS = 500$ are shown by white lines. Gray curves represent the upper surface of the Pacific slab (Nakajima and Hasegawa, 2006) corrected for the effect of 3D velocity models on the relocated hypocenters (see auxiliary materials for details).

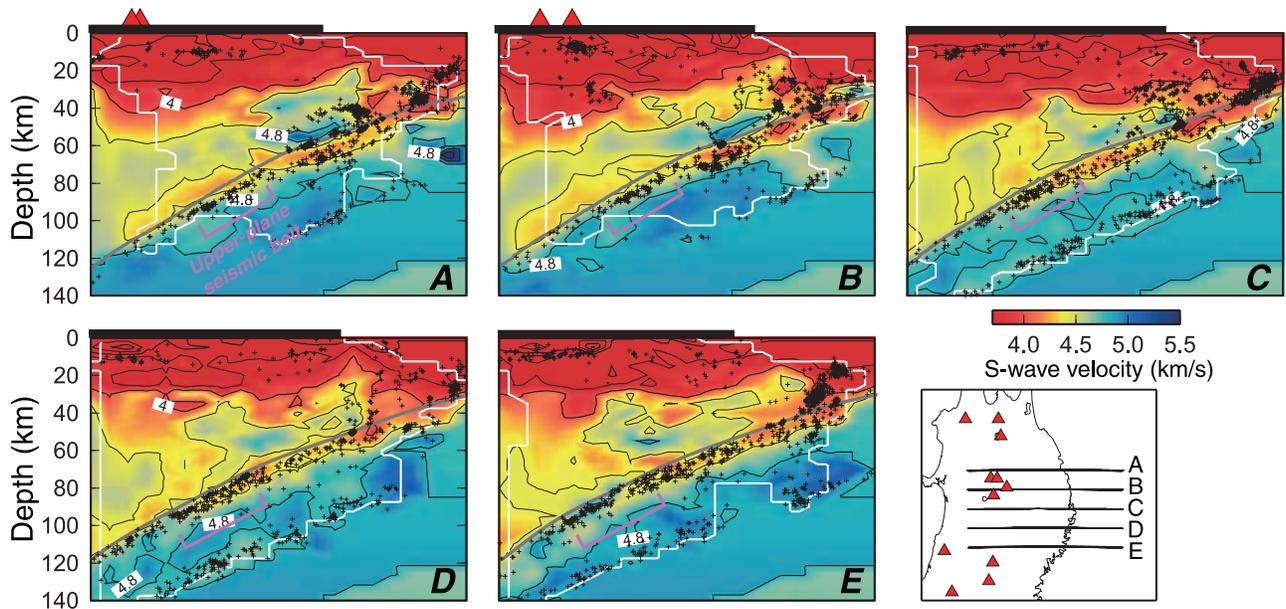


Figure 3. Across-arc vertical cross sections of S-wave velocity along five lines in the inset map. Contours indicate absolute-velocity values with an interval of 0.4 km/s. Red triangles on the top of each plot represent active volcanoes. Pink mark in each plot indicates the location of the upper-plane seismic belt (Kita *et al.*, 2006; Hasegawa *et al.*, 2007). Other symbols are the same as in Figure 2.

iterations, which reduces travel-time residuals from 0.38 s to 0.11 s for P wave and from 0.61 s to 0.16 s for S wave.

[6] We carried out three resolution tests, a checkerboard resolution test (CRT) and two reconstruction tests specialized for hydrated (hence low-velocity) oceanic crust and low-velocity layer above the slab, to assess the reliability of obtained results (auxiliary materials). The result of the CRT shows that checkerboard patterns are well recovered around the upper surface of the Pacific slab down to a depth of ~ 90 km. The reconstruction tests demonstrate that hydrated oceanic crust and the low-velocity layer above the slab are well resolved at least down to a depth of 100–110 km if they exist. We also refer to values of derivative weighted sum (DWS) [Thurber and Eberhart-Phillips, 1999], and contours with $DWS = 500$ are shown in Figures 2 and 3 inside which the checkerboard patterns are recovered and hence the obtained velocity structures are reliable.

3. Results and Discussion

[7] Figure 2 shows across-arc vertical cross sections of P- and S-wave velocities and V_p/V_s ratio along line in the inset map. The most striking feature is the existence of a layer with slightly low V_p , low V_s , and high V_p/V_s at the uppermost part of the Pacific slab down to depths of 70–90 km. Since the resolution of P-wave is good in the subducting slab down to a depth of ~ 100 km, S-wave velocity may be more sensitive to hydrous minerals or water than P wave and hence anomalous structures around the slab can be imaged clearly in S-wave velocity structure [e.g., Shelly *et al.*, 2006a, 2006b]. We thus consider that S-wave velocity structure is preferred to characterize the features around the slab.

[8] Across-arc vertical cross sections of S-wave velocity are shown in Figure 3. A prominent low-velocity zone with

a thickness of ~ 10 km exists in all cross sections at the uppermost part of the Pacific slab down to depths of 70–90 km. At these depths, a low-velocity zone emerges immediately above the Pacific slab sub-parallel to the dip of the subducting slab in lines A and B, though it is not clear in lines C, D, and E. This low-velocity zone extends downward along the upper surface of the Pacific slab to a depth of ~ 120 km. We confirmed that the obtained results are not sensitive to initial models of inversions and the characteristic features described above are still robust when we assume a different plate model by Zhao *et al.* [1997], which is estimated by converted phases at the plate boundary (see Figures S3 and S4 in auxiliary materials).

[9] We here describe in detail the low-velocity zones below and above the upper surface of the Pacific slab. Since the thickness of the low-velocity zone at the top of the slab is ~ 10 km and seismicity in the upper plane of the double seismic zone [Hasegawa *et al.*, 1978] is distributed in the zone, we interpret it to be hydrated oceanic crust. The oceanic crust is classified into two regions on the basis of the obtained velocity structure. The oceanic crust with prominent low-velocity anomaly (< 4.4 km/s) gradually disappears at depths of 70–90 km, whereas that with S-wave velocity of 4.4–4.8 km/s continues to deeper depths. This result leads to an idea that breakdown of hydrous minerals takes place in the oceanic crust at depths of 70–90 km. Actually, experimentally-derived phase diagrams of mid-ocean ridge basalt (MORB) involves dehydration reactions at depths of 60–120 km for possible thermal structures of the slab for NE Japan [e.g., Schmidt and Poli, 1998; Okamoto and Maruyama, 1999; Hacker *et al.*, 2003]. The gradual termination of the prominent low-velocity anomaly can be accounted for by continuous decrease in water contents due to the existence of solid solutions in most of the facies, so that resultant reactions taking place over

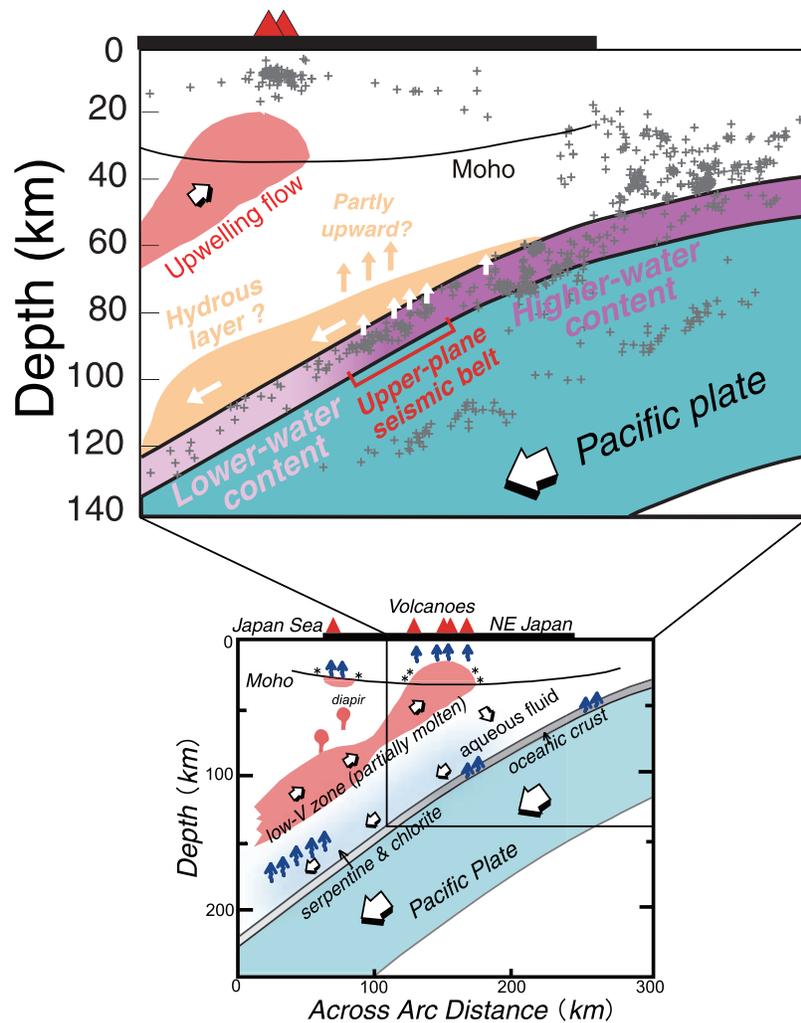


Figure 4. A cartoon showing water-transportation paths in and around the subducting slab inferred from this study for the region shown in the inset map. The inset map shows a schematic illustration of fluid-transportation paths in NE Japan (after Hasegawa and Nakajima, 2004).

extended temperature and pressure intervals. Oblique facies boundary of MORB relative to the plate interface [e.g., Kita *et al.*, 2006, Figure 3] can also contribute to the gradual increase in seismic velocity in the oceanic crust.

[10] The termination depths of the prominent low-velocity zone in the oceanic crust are in agreement with the depth range of the upper-plane seismic belt in NE Japan (Figure 3) [Kita *et al.*, 2006; Hasegawa *et al.*, 2007]. In addition, seismicity in the lower plane of the double seismic zone appears to be distributed in a low-velocity zone as shown in lines C and D, which was partly pointed out by Zhang *et al.* [2004], though the resolution in such regions is not so good. These observations suggest the triggering of intraslab earthquakes as a result of dehydration embrittlement.

[11] The existence of the oceanic crust with S-wave velocity less than 4.8 km/s beyond depths of 70–90 km indicates that the oceanic crust can still involve hydrous minerals there [e.g., Hacker *et al.*, 2003]. It is known that a low-velocity layer at the top of the subducting slab persists at least down to depths of 130–150 km beneath NE Japan [e.g., Matsuzawa *et al.*, 1986; Kawakatsu and Watada, 2007]. Abers [2005] showed from analysis of guided

seismic waves in the oceanic crust that a low-velocity channel with several-km thick at the top of the subducting slab probably has not transformed to eclogite to depths greater than 150 km in cold subduction zones. Our results support the interpretation that water is brought with the oceanic crust to deeper depths (Figure 4).

[12] It has been argued that water released by dehydration reactions in the oceanic crust migrates into the mantle wedge. Our results can give tomographic constraints on the path of water transportation. From the depths of 70–90 km where the prominent low-velocity zone in the oceanic crust gradually disappears, the low-velocity zone appears immediately above the slab and extends at least to depths of 100–120 km along the slab in lines A and B. Kawakatsu and Watada [2007] revealed from receiver function analysis that a similar low-velocity layer exists above the slab from 80 km to 130 km depths along a cross section that is nearly identical to line A in this study. As is interpreted by Kawakatsu and Watada [2007], the low-velocity zone probably corresponds to a hydrous layer composed of serpentine or chlorite, through which most of the water expelled from the subducting slab is brought

down to deeper depths as predicted by *Iwamori* [1998] (Figure 4). It is noted that resolution tests demonstrate that the low-velocity zone just above the slab may not be well resolved beyond a depth of ~ 100 km because of the lack of crossing rays and hence needs further confirmation.

[13] The hydrous layer above the slab is developed well in lines A and B where active volcanoes are formed at the surface, whereas it is ambiguous in lines C, D, and E where no volcanoes exist. Interestingly, a sub-vertical low-velocity zone is distributed in the mantle wedge from 80 km to 40 km depths in lines C and D, which probably reflects that water released from the slab can partly migrate upward due to buoyancy (Figure 4). These observations suggest that a larger volume of water can be carried to deeper depths through the hydrous layer above the slab along lines A and B and then can be released to the mantle wedge in the back-arc side with increasing temperature and pressure. Consequently, a larger amount of melts can be generated in the mantle wedge in such regions [*Nakajima et al.*, 2001]. Actually, *Hasegawa and Nakajima* [2004] pointed out that velocity distributions in the mantle upwelling flow show an along-arc variation with an interval of 50–80 km and velocity reduction rates are locally larger in regions where active volcanoes exist at the surface. An along-arc variation in arc volcanism [e.g., *Tamura et al.*, 2002] might be related to that in the development of the hydrous layer above the slab.

4. Conclusions

[14] This study reveals the existence of low-velocity layers at the uppermost part of the subducting Pacific slab and above the slab beneath NE Japan, giving seismic evidence for the preservation of much hydrated oceanic crust down to depths of 70–90 km and the formation of hydrous layer above the slab. A distinct belt-like seismicity in the upper plane of the double seismic zone at depths of 70–90 km is distributed in regions where intensive dehydration reactions are expected to occur in the oceanic crust, suggesting the validity of dehydration-embrittlement hypothesis as a mechanism for generating intraslab earthquakes.

[15] Tomographic imaging of hydrated oceanic crust for a wider area as well as the improvement of resolution for the lower plane of the double seismic zone are required for a better understanding of water-circulation process and the occurrence of intraslab earthquakes in subduction zones. The detailed analyses of these and other possible subjects are left open for future studies.

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References

- Abers, G. A. (2005), Seismic low-velocity layer at the top of subducting slabs beneath volcanic arcs: Observations, predictions, and systematics, *Phys. Earth Planet. Inter.*, *149*, 7–29.
- Bostock, M. G., R. D. Hyndman, S. Rondenay, and S. M. Peacock (2002), An inverted continental Moho and serpentinization of the forearc mantle, *Nature*, *417*, 536–538.
- Hacker, B. R., G. A. Abers, and S. M. Peacock (2003), Subduction factory: I. Theoretical mineralogy, densities, seismic wave speeds, and H₂O contents, *J. Geophys. Res.*, *108*(B1), 2029, doi:10.1029/2001JB001127.
- Hasegawa, A., and J. Nakajima (2004), Geophysical constraints on slab subduction and arc magmatism, in *The State of the Planet: Frontiers and Challenges in Geophysics*, *Geophys. Monogr. Ser.*, vol. 150, edited by R. S. J. Sparks and C. J. Hawkesworth, pp. 81–94, AGU, Washington, D. C.
- Hasegawa, A., N. Umino, and A. Takagi (1978), Double-planned structure of the deep seismic zone in the northeastern Japan arc, *Tectonophysics*, *47*, 43–58.
- 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.
- Iwamori, H. (1998), Transportation of H₂O and melting in subduction zones, *Earth Planet Sci. Lett.*, *160*, 65–80.
- Jung, H., H. W. Green II, and L. F. Dobrzinetskaya (2004), Intermediate-depth earthquake faulting by dehydration embrittlement with negative volume change, *Nature*, *428*, 545–549.
- Kawakatsu, H., and S. Watada (2007), Seismic evidence for deep-water transportation in the mantle, *Science*, *316*, 1468–1471.
- Kirby, S., E. R. Engdahl, and R. Denlinger (1996), Intermediate-depth intraslab earthquakes and arc volcanism as physical expressions of crustal and uppermost mantle metamorphism in subducting slabs, in *Subduction: Top to Bottom*, *Geophys. Monogr. Ser.*, vol. 96, edited by G. E. Bebout et al., pp. 195–214, AGU, Washington, D. C.
- Kita, S., T. Okada, J. Nakajima, T. Matsuzawa, and A. Hasegawa (2006), Existence of a seismic belt in the upper plane of the double seismic zone extending in the along-arc direction at depths of 70–100 km beneath NE Japan, *Geophys. Res. Lett.*, *33*, L24310, doi:10.1029/2006GL028239.
- Matsuzawa, T., N. Umino, A. Hasegawa, and A. Takagi (1986), Upper mantle velocity structure estimated from PS-converted wave beneath the north-eastern Japan arc, *Geophys. J.R. Astron. Soc.*, *86*, 767–787.
- Nakajima, J., and A. Hasegawa (2006), Anomalous low-velocity zone and linear alignment of seismicity along it in the subducted Pacific slab beneath Kanto, Japan: Reactivation of subducted fracture zone?, *Geophys. Res. Lett.*, *33*, L16309, doi:10.1029/2006GL026773.
- Nakajima, J., T. Matsuzawa, A. Hasegawa, and D. Zhao (2001), Three-dimensional structure of V_p, V_s, and V_p/V_s beneath northeastern Japan: Implications for arc magmatism and fluids, *J. Geophys. Res.*, *106*, 21,843–21,857.
- Okamoto, K., and S. Maruyama (1999), The high-pressure synthesis of lawsonite in the MORB + H₂O system, *Am. Mineral.*, *84*, 362–373.
- Rondenay, S., G. A. Abers, and P. E. van Keken (2008), Seismic imaging of subduction zone metamorphism, *Geology*, *36*, 275–278.
- Schmidt, M. W., and S. Poli (1998), Experimentally based water budgets for hydrating slabs and consequences for arc magma generation, *Earth Planet. Sci. Lett.*, *163*, 361–379.
- Shelly, D. R., G. C. Beroza, H. Zhang, C. H. Thurber, and S. Ide (2006a), High-resolution subduction zone seismicity and velocity structure beneath Ibaraki Prefecture, Japan, *J. Geophys. Res.*, *111*, B06311, doi:10.1029/2005JB004081.
- Shelly, D. R., G. C. Beroza, S. Ide, and S. Nakamura (2006b), Low-frequency earthquakes in Shikoku, Japan, and their relationship to episodic tremor and slip, *Nature*, *442*, 188–191.
- Tamura, Y., Y. Tatsumi, D. Zhao, Y. Kido, and H. Shukuno (2002), Hot fingers in the mantle wedge: New insights into magma genesis in subduction zones, *Earth. Planet. Sci. Lett.*, *197*, 105–116.
- Thurber, C. H., and D. Eberhart-Phillips (1999), Local earthquake tomography with flexible gridding, *Comput. Geosci.*, *25*, 809–818.
- Zhang, H., and C. H. Thurber (2003), Double-difference tomography: The method and its application to the Hayward fault, California, *Bull. Seismol. Soc. Am.*, *93*, 1875–1889.
- Zhang, H., and C. H. Thurber (2006), Development and applications of double-difference seismic tomography, *Pure Appl. Geophys.*, *163*, 373–403.
- Zhang, H., C. H. Thurber, D. R. Shelly, S. Ide, G. C. Beroza, and A. Hasegawa (2004), High-resolution subducting-slab structure beneath northern Honshu, Japan, revealed by double-difference tomography, *Geology*, *32*, 361–364.
- Zhao, D., T. Matsuzawa, and A. Hasegawa (1997), Morphology of the subducting slab boundary and its relationship to the interplate seismic coupling, *Phys. Earth Planet. Inter.*, *102*, 89–104.

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