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

Saeko Kita,[1] Tomomi Okada,[1] Junichi Nakajima,[1] Toru Matsuzawa,[1] and Akira Hasegawa[1]

Received 26 September 2006; revised 8 November 2006; accepted 14 November 2006; published 23 December 2006.

[1] We relocated microearthquakes using data obtained via a dense seismic network and systematically detected the characteristic distribution of the upper seismic plane seismicity within the Pacific slab beneath NE Japan. We found a seismic "belt" parallel to the iso-depth contour of the plate interface that is beneath the forearc area at depths of 70–100 km, indicating that the distribution of the upper plane earthquakes is non-uniform. The location of the deeper limits of this belt and seismicity of the upper seismic plane appear to correspond respectively to two facies boundaries where H_2O contents change in the slab crust. Events in the upper seismic plane have mainly down-dip compression-type focal mechanisms but several events have normal fault-type (NF-type) versions, whose spatial distribution appears to correspond to these boundaries. These NF events might be induced by the tensional stress field that is caused by volume reduction due to dehydration reactions.
Citation: 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.

1. Introduction

[2] In NE Japan, the Pacific plate subducts beneath the northeastern Japan arc in Tohoku and beneath the Kuril Arc in Hokkaido at a rate of 8.3 cm yr^{-1}(N39, 146E [*Gripp and Gordon*, 2002]) (Figure 1). Previous studies have revealed that intermediate-depth earthquakes within the subducting slab in this area form a double seismic zone and that the focal mechanisms of the upper seismic plane are of the down-dip compression (DC) type, whereas those of the lower seismic plane are of the down-dip extension (DE) type [*Umino and Hasegawa*, 1975; *Hasegawa et al.*, 1978a, 1978b; *Suzuki and Kasahara*, 1996]. The seismicity of the upper seismic plane is thought to be distributed uniformly in space, whereas that of the lower seismic plane is not uniform [*Hasegawa et al.*, 1994]. *Igarashi et al.* [2001] determined focal mechanisms of 1100 small intermediate-depth earthquakes beneath Tohoku using P and SH wave amplitude data, and found that normal fault (NF-) type events are distributed mainly in the uppermost portion of the slab, close to the plate interface, indicating that some parts of the double seismic zone in the NE Japan arc are not double-planed but triple-planed beneath the land area.

[3] Dehydration embrittlement and CO_2-bearing devolatization embrittlement hypotheses have been proposed as possible causes of intraslab earthquakes [e.g., *Peacock*, 2001; *Kirby et al.*, 1996; *Kirby*, 1995]. Some studies [*Hacker et al.*, 2003; *Yamasaki and Seno*, 2003] have compared the possible locations of facies fields of dehydration with the actual distribution of intraslab seismicity. As shown in these studies, the precise location of intraslab seismicity is needed to discuss its cause.

[4] A very dense nationwide seismic network (Hi-net) has recently been constructed by the National Institute for Earth Sciences and Disaster Prevention (NIED) in Japan. The Japan Meteorological Agency (JMA) routinely determines earthquake hypocenters by integrating data from Hi-net and other seismic networks operated by several universities and by the JMA. Integration of these networks by multiple institutions has created a network covering the whole of Japan with station separations of 15–20 km, leading to much improved earthquake detection capability. In this study, we relocated microearthquakes more precisely by using data obtained by this dense seismic network, and focused on the characteristic distribution of upper plane seismicity within the Pacific slab beneath Hokkaido and Tohoku, NE Japan.

2. Data, Method, and Results of DDLM-Relocation

[5] Development of Hi-net stations in Hokkaido was begun in 2002 by NIED. In the present study, we relocated events at depths of 20–300 km for the period from January 2002 to August 2005 from the JMA earthquake catalog. Hypocenter parameters and arrival time data in the JMA catalog were used as the initial hypocenters and data for relocations. We adopted a P- and S-wave velocity structure model used in the routine procedure of hypocenter locations in Tohoku University [*Hasegawa et al.*, 1978a].

[6] We applied the double-difference hypocenter location method (DDLM) by *Waldhauser and Ellsworth* [2000] to the arrival time data of the events. We selected event pairs with an epicentral separation of less than 15 km and epicentral distance between a station and a pair of events of less than 400 km. We also selected events having more than 8 arrival time differences with neighbors. We divided the study area into three sub-areas (Hokkaido, Northern Tohoku and Southern Tohoku) and relocated hypocenters of the events in each area (Figure 1). A total of 103,421 events (27,520 in Hokkaido, 30,860 in Northern Tohoku and 15,041 in Southern Tohoku) were relocated using DDLM

[1]Research Center for Prediction of Earthquakes and Volcanic Eruptions, Tohoku University, Sendai, Japan.

0094-8276/06/2006GL028239

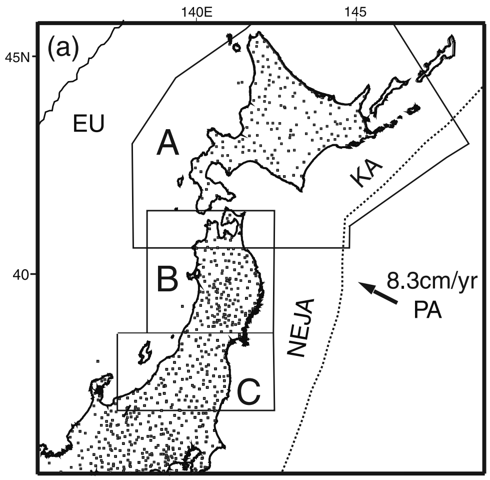

Figure 1. Tectonic view of NE Japan. The Pacific plate (PA) is subducting beneath the Kuril arc (KA) in Hokkaido and beneath the Northern Japan arc (NEJA) in Tohoku. Small dots show seismic stations used in this study. The areas surrounded by solid lines show the three sub-areas (A, B and C show Hokkaido, Northern Tohoku and Southern Tohoku, respectively) used in the DDLM-relocations (see text for details).

in and above the subducted Pacific slab. A total of 3,898,854 arrival time differences were obtained for P-waves (1,270,435 in Hokkaido, 1,881,996 in Northern Tohoku and 746,423 in Southern Tohoku), and 3,177,253 arrival time differences were obtained for S-waves (877,885 in Hokkaido, 1,712,610 in Northern Tohoku and 586,758 in Southern Tohoku). The average root mean square value of DDs for each event was reduced by this procedure from 0.23 s to 0.11 s in Hokkaido, 0.11 to 0.085 s in Northern Tohoku and 0.19 to 0.12 s in Southern Tohoku. The mean errors were estimated to be < 1.75 km in depth and < 1.18 km in horizontal. The relocated hypocenters are generally clustered more densely than before the relocation.

[7] We investigated the spatial distribution of upper plane events of the double seismic zone in detail using the following procedure. First, we estimated the depth distribution of the interface between the Pacific plate and the upper continental plate so that the plate interface estimated in this paper passes the locations of repeating earthquakes, which are expected to occur on the plate boundary [*Igarashi et al.*, 2003; *Uchida et al.*, 2003] and the uppermost part of the upper plane seismicity of the double seismic zone [*Matsuzawa et al.*, 1987; *Hasegawa et al.*, 1994]. The geometry of the estimated plate interface is shown in Figure 2a. The shape of the plate interface is similar to that observed in previous studies [*Hasegawa et al.*, 1994; *Zhao et al.*, 1997; *Katsumata et al.*, 2003] except for the arc-arc junction area between Hokkaido and Tohoku. By referring to the distance from the plate interface, we selected hypocenters below the plate interface and 0–14 km from it as events on the upper seismic plane of the double seismic zone.

[8] We also compared the locations of the upper plane seismicity to the western limit of interplate events, which probably corresponds to the deeper limit of the interplate coupling. In northeastern Japan, *Igarashi et al.* [2001] estimated the western limit of interplate earthquakes based on the focal mechanism distribution, shown in Figure 2a by a blue line. In Figure 2a, repeating earthquakes which are also interplate earthquakes are shown by yellow stars. In the present study, we estimated the western limit of interplate events in Hokkaido by using focal mechanisms from JMA and the location of the repeating earthquakes. The result is shown as a broken blue line in Figure 2a.

3. Spatial Distribution of Upper Plane Earthquakes: A Seismic Belt in the Upper Seismic Plane Extending in the Along-Arc Direction

[9] In the upper seismic plane (Figure 2a), we found a seismic belt (XX′ in Figure 2a) extending along the arc. It appears to be a group of concentrated events distributed along depth contours of about 70–90 km. This belt is parallel to the iso-depth contours of the plate interface and is also parallel to the volcanic front (Figure 2a). Figure 2a also clearly shows that the belt (XX′ in Figure 2a) extends further westwards than the western limit of interplate earthquakes (broken line in Figure 2a). This observation indicates that the belt (Figure 2a) consists mainly of intraslab earthquakes. Note that the high seismicity between the belt and the western limit at about 39°N is due to aftershocks of the 2003 Miyagi-Oki earthquake (M7.2) [*Okada and Hasegawa*, 2003].

[10] Figures 2b–2e show the frequency of events of the upper seismic plane and their depths. Two peaks are clearly seen in all the figures: one is at depths shallower than 60 km and the other is found at depths from about 80 to 90 km. The shallower peak is probably caused by the western limit of the interplate earthquakes. The deeper peak corresponds to the belt shown in Figure 2a. This observation suggests non-uniform distribution of the upper plane seismicity, although previous studies have reported it to be uniform [*Hasegawa et al.*, 1994; *Igarashi et al.*, 2001].

4. Relationship of the Seismic Belt in the Upper Seismic Plane to the Dehydration Embrittlement Hypothesis

[11] Figure 3a is a vertical cross-sectional view of the square in Figure 2a. In Figure 3a the earthquakes are projected within 60 km from the cross section line and this cross section is perpendicular to the depth counters of the plate interface. The seismic belt (XX′, in Figure 2a) can be seen at depths of 70–100 km (A, in Figure 3a).

[12] In general, facies boundaries are not the location of dehydration reactions in mafic rocks (e.g., the slab crust), but shows the boundary between two different groups of minerals. In other words, dehydration reaction occurs not exclusively along the facies boundaries in mafic rocks, but within facies fields involving H_2O as temperature increases. If dehydration embrittlement is the cause of intraslab earthquakes, the seismicity in the subducted crust at depths of 70–100 km may occur within the facies field with the dehydration reaction or CO_2-bearing devolatization reactions. For example, *Hacker et al.* [2003] mapped the locations of the metamorphic facies, based on calculated and experimentally determined phase diagrams, to the NE Japan arc. The facies boundary from jadeite lawsonite

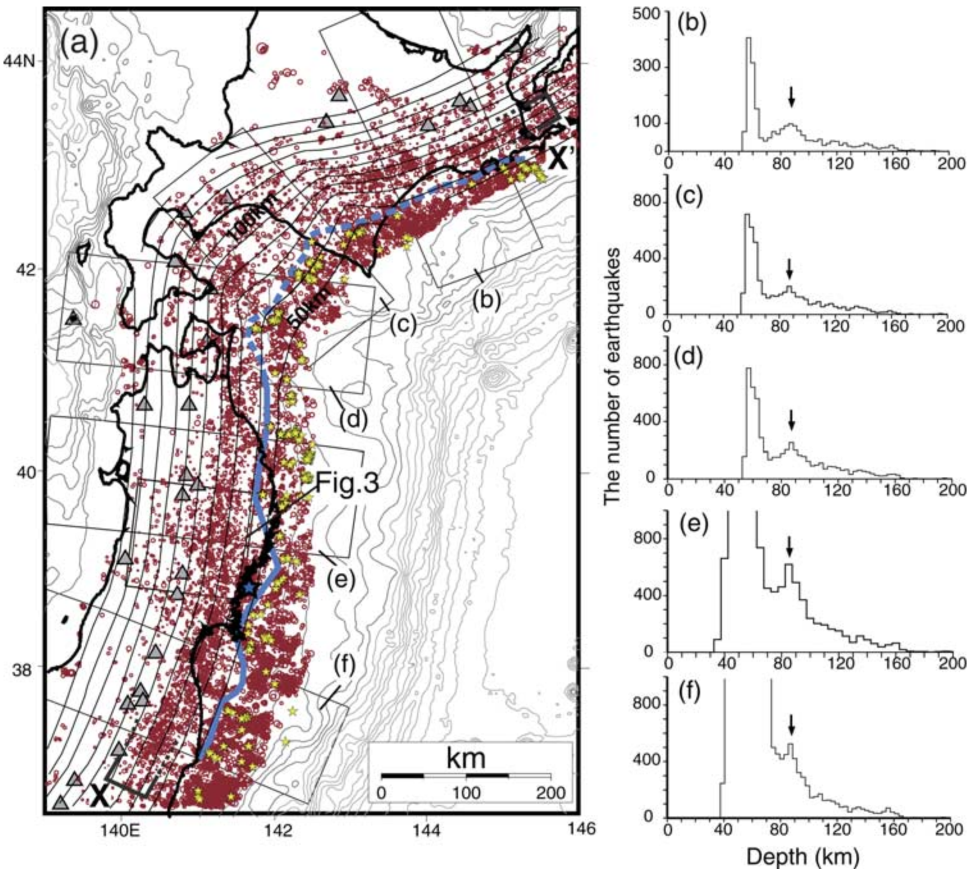

Figure 2. (a) Epicenter distribution of relocated events in the upper seismic plane. Red dots show events in the upper seismic plane. Gray triangles and black contours respectively show active volcanoes and the depth of the plate interface. The western limit of interplate-type events is shown as blue lines. The bold blue line is from *Igarashi et al.* [2001]. Yellow stars show the epicenters of the repeating earthquakes, which are thought to occur on the plate boundary. X-X′ shows a rough location of the seismic belt along depth contours of about 70–90 km. Blue star shows the epicenter of the 2003 Miyagi-Oki earthquake. (b–f) Frequency of events of the upper seismic zone with depth. Numbers of events are calculated for each 5 km. Black arrow shows the peak which corresponds to the seismic belt. We show this for events which occurred in the square in Figure 2a.

blueschist (H_2O content: 5.4 wt%) to lawsonite amphibole eclogite (3.0 wt%) is estimated to be at depths of about 80–130 km (Line B, in Figure 3a). The location of this phase boundary (Line B) roughly corresponds to the deeper limit of the seismic belt in the upper plane (A, in Figure 3a) found in the present study in Figure 2a. In this Figure we can see that the upper plane events are distributed in the whole crust at depths of 70–90 km (A, in Figure 3a), but they are only in the lower crust at depths of more than 90 km. This observation appears to be consistent with the location of the facies boundary (Line B). Another possible facies boundary correspondent with the location of the deeper limit of the seismic belt is suggested by *Yamasaki and Seno* [2003]. They indicate a facies boundary (from blueschist to lawsonite eclogite) at depths of about 75 km in the slab crust beneath NE Japan.

[13] We also checked the spatial distribution of the focal mechanisms of the events in the seismic belts and the surrounding upper seismic plane. We used focal mechanism solutions determined by *Igarashi et al.* [2001], which are shown in Figure 3a. We classified the events of the upper seismic zone by referring to the principal axis orientations of focal mechanisms, based on the triangle diagram [*Frohlich*, 1992] shown in Figure 3b. Most of the earthquakes show a down-dip compressional type focal mechanism. Several events marked by green circles, however, have P axes which are sub-vertical to the plate interface and they are classified into the normal fault [NF] type events in Figure 3b. The NF-type events appear to be located on the topmost part of seismicity, indicating that the belt revealed by this study is a part of the triple seismic zone beneath the NE Japan arc identified by *Igarashi et al.* [2001]. The NF-type events also seem to be located near this facies boundary (Line B). The volume reduction of the facies change (jadeite lawsonite blueschist to lawsonite amphibole eclogite) could induce the tension stress field [*Kirby*, 1995; *Igarashi et al.*, 2001].

[14] At depths of 100 to 150 km, the seismicity of the upper plane is confined to the lower crust, and it gradually decreases from the shallower portion and gives the impression of disappearing at depths of about 150 km. *Hacker et al.* [2003] also indicated that another facies boundary (lawsonite amphibole eclogite (H_2O content: 3.0 wt%) to eclogite (0.1 wt%)) should occur within the slab crust at

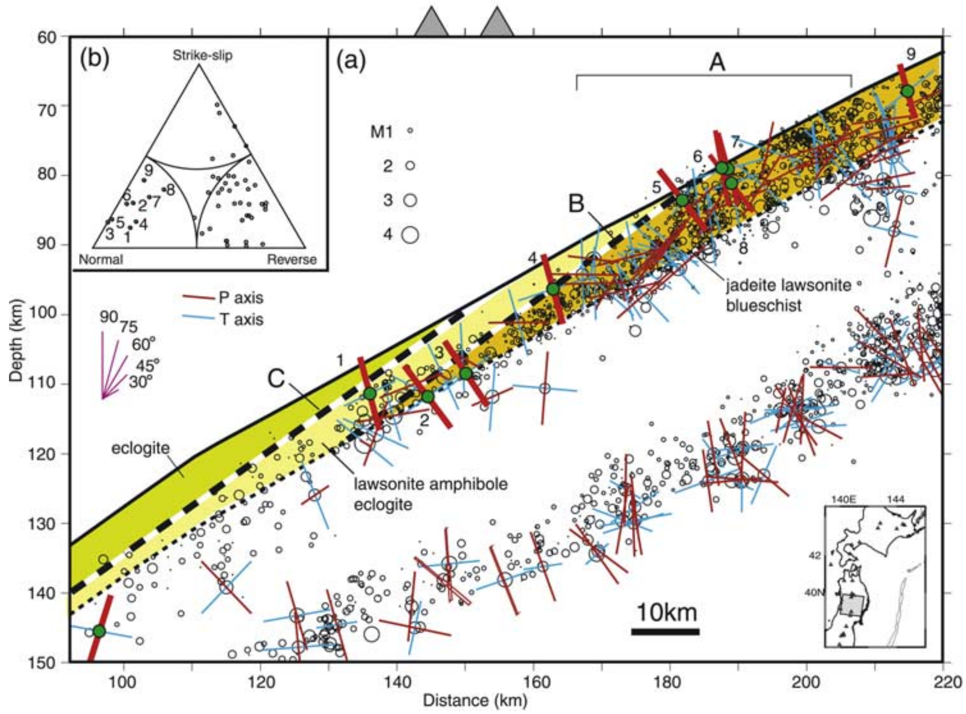

Figure 3. (a) Vertical cross-sectional view of the events in the square in the inserted map. Black circles and green circles with numerals show hypocenters and the normal fault [NF] type event shown on the triangle diagram (Figure 3b). Blue lines and red lines show respectively the T and P axes of events. The heavy red lines show the P axes of the NF. The heavy black solid line and dashed black line show the plate interface estimated by *Zhao et al.* [1997], the possible location of Moho (10 km deeper than the plate interface). Triangles show volcanoes. Metamorphic facies in the Tohoku subduction zone by *Hacker et al.* [2003] are shown in the yellow area (jadeite lawsonite blueschist), the orange area (lawsonite amphibole eclogite) and the green area (eclogite), respectively. Lines (B and C) show the location of the facies boundaries, respectively. (b) Triangle diagram [*Frohlich*, 1992] for the upper seismic plane events in Figure 3a. Circles with numerals show the NF-type events. Note that the coordinate system is based on the slab surface.

depths of 110–150 km (Line C, in Figure 3a). The location of this facies boundary also roughly corresponds to the deeper limit of seismicity of the upper seismic plane in the slab crust, which is also consistent with the suggestion by *Hacker et al.* [2003] that the earthquakes in a subduction slab should migrate from the upper crust to the lower crust because of the difference in grain size and hydration state of the upper and lower crust. The NF event appears to be located on the topmost part of seismicity and on this facies boundary in this depth range. This observation indicates that earthquakes do not occur in the slab crust within the eclogite stability field, which is expected because there should be virtually no dehydration within that field.

5. Conclusions

[15] In this study, we found a seismic belt at depths of 70–100 km in the upper plane of the double seismic zone beneath NE Japan. Its location of the deeper limit of the seismic belt appears to correspond to a facies boundary. The location of the deeper limit of seismicity of the upper seismic plane in the slab crust also appears to correspond to another facies boundary. These results indicate that the dehydration embrittlement hypothesis may explain the characteristic distribution of upper plane seismicity beneath NE Japan.

[16] **Acknowledgments.** Thanks to Stephen H. Kirby, Tetsuzo Seno and Eiji Ohtani for useful discussions, to Bradley R. Hacker and anonymous reviewer for detailed reviews, and to Aldo Zollo and associate editors for revising the manuscript. The data analyzed was provided by the seismic networks of national universities, JMA and NIED (Hi-net). This work was also supported by Tohoku University's 21st Century COE Program. In this analysis we used GMT by P. Wessel and W.H.F. Smith for preparing the figures. Saeko Kita is a Research Fellow of the Japan Society for Promotion of Science.

References

Frohlich, C. (1992), Triangle diagrams: Ternary graphs to display similarity and diversity of earthquake focal mechanisms, *Phys. Earth Planet. Inter.*, *75*, 193–198.

Gripp, A. E., and R. G. Gordon (2002), Young tracks of hotspots and current plate velocities, *Geophys. J. Int.*, *150*, 321–361.

Hacker, B. R., S. M. Peacock, G. A. Abers, and S. D. Holloway (2003), Subduction factory: 2. Are intermediate-depth earthquakes in subducting slabs linked to metamorphic dehydration reactions?, *J. Geophys. Res.*, *108*(B1), 2030, doi:10.1029/2001JB001129.

Hasegawa, A., N. Umino, and A. Takagi (1978a), Double-planed structure of the deep seismic zones in the northeastern Japan arc, *Tectonophysics*, *47*, 43–58.

Hasegawa, A., N. Umino, and A. Takagi (1978b), Double-planed deep seismic zone and upper-mantle structure in the northeastern Japan arc, *Geophys. J.R. Astron. Soc.*, *54*, 281–296.

Hasegawa, A., S. Horiuchi, and N. Umino (1994), Seismic structure of the northeastern Japan convergent margin: A synthesis, *J. Geophys. Res.*, *99*, 22,295–22,311.

Igarashi, T., T. Matsuzawa, N. Umino, and A. Hasegawa (2001), Spatial distribution of focal mechanisms for interplate and intraplate earthquakes associated with the subduction Pacific plate beneath the northeastern

Japan arc: A triple-planed deep seismic zone, *J. Geophys. Res.*, *106*, 2177–2191.

Igarashi, T., T. Matsuzawa, and A. Hasegawa (2003), Repeating earthquakes and interplate aseismic slip in the northeastern Japan subduction zone, *J. Geophys. Res.*, *108*(B5), 2249, doi:10.1029/2002JB001920.

Katsumata, K., N. Wada, and M. Kasahara (2003), Newly imaged shape of the deep seismic zone within the subducting Pacific plate beneath the Hokkaido corner, Japan-Kurile arc-arc junction, *J. Geophys. Res.*, *108*(B12), 2565, doi:10.1029/2002JB002175.

Kirby, S. H. (1995), Intraslab earthquakes and phase changes in subducting lithosphere, *Rev. Geophys.*, *33*(S1), 287–297.

Kirby, S. H., 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 (overview), in *Subduction: Top to Bottom*, *Geophys. Monogr. Ser.*, vol. 96, edited by G. E. Bebout et al., pp. 195–214, AGU, Washington, D. C.

Matsuzawa, T., N. Umino, A. Hasegawa, and A. Takagi (1987), Estimation of thickness of a low velocity layer at the surface of the descending oceanic plate beneath the northeastern Japan arc by using synthesized PS-waves, *Tohoku Geophys. J.*, *31*, 19–28.

Okada, T., and A. Hasegawa (2003), The M7.1 May 26, 2003 off-shore Miyagi prefecture earthquake in northeast Japan: Source process and aftershock distribution of an intra-slab event, NE Japan, *Earth Planets Space*, *55*, 731–739.

Peacock, S. M. (2001), Are the lower planes of double seismic zones caused by serpentine dehydration in subducting oceanic mantle?, *Geology*, *29*, 293–302.

Suzuki, S., and M. Kasahara (1996), Unbending and horizontal fracture of the subducting Pacific plate, as evidenced by the 1993 Kushiro-oki and the 1981 and 1978 intermediate-depth earthquakes in Hokkaido, *Phys. Earth Planet. Inter.*, *93*, 91–104.

Uchida, N., T. Matsuzawa, A. Hasegawa, and T. Igarashi (2003), Interplate quasi-static slip off Sanriku, NE Japan, estimated from repeating earthquakes, *Geophys. Res. Lett.*, *30*(15), 1801, doi:10.1029/2003GL017452.

Umino, N., and A. Hasegawa (1975), On the two-layered structure of a deep seismic plane in the northeastern Japan arc, *J. Seismol. Soc. Jpn.*, *28*, 125–139.

Waldhauser, F., and W. L. Ellsworth (2000), A double-difference earthquake location algorithm: Method and application to the northern Hayward Fault, California, *Bull. Seismol. Soc. Am.*, *90*, 1353–1368.

Yamasaki, T., and T. Seno (2003), Double seismic zone and dehydration embrittlement of the subducting slab, *J. Geophys. Res.*, *108*(B4), 2212, doi:10.1029/2002JB001918.

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.

A. Hasegawa, S. Kita, T. Matsuzawa, J. Nakajima, and T. Okada, RCPEV, Tohoku University, Aramaki Aza Aoba 6-6, Aoba-ku, Sendai 980-8578, Japan. (kita@aob.geophys.tohoku.ac.jp)