# Subduction zone dynamics:
# role of $H_2O$ in generation of earthquakes and magmas

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## Subduction zone

New oceanic plates are produced at the mid-ocean ridges by the upwelling of mantle materials. The production of new oceanic plates does not cause the expansion of the earth's surface, since an equal amount of material returns downward back into the mantle. Generally, this consumption of oceanic plates is made at "subduction zones", where oceanic plates plunge downward into the mantle. At a subduction zone, two plates collide with each other. One plate must ride over the other, forcing the heavier one back into the mantle. Thus the heavier oceanic plate subducts beneath the lighter continental plate. This subduction of the oceanic plate causes high seismic activity along the zone. Indeed, most of world's large earthquakes occur in subduction zones. The plate subduction also causes volcanic activity along the zone, forming belt-like volcanic chains distributed along ~100-km depth contour lines of the upper surface of the subducted plates. In terms of understanding the earth as a system, subduction zones are the sites where oceanic plates are recycled back into the mantle, being the locations for material flux back into the mantle. The subduction of the oceanic plate in the shallow mantle beneath a volcanic arc and the ultimate fate of a plate as it sinks downward into the deeper mantle plays an important role in the recycling of chemical elements in the earth's interior.

Japanese Islands are located at this subduction zone where many disastrous earthquakes have repeatedly occurred, causing extensive damages to the inhabitants. One typical example is the recent 2011 Mw9.0 Tohoku-Oki earthquake that occurred along the plate interface off the east coast of Tohoku, NE Japan. This great earthquake caused severe damage to eastern Japan: especially huge tsunami excited by this event killed many people near the Pacific coast of eastern Japan. Before the earthquake, a dense nationwide seismic network covering the whole country of Japan has been constructed. This spatially dense seismic network and high seismic activity there provide large volume of high-quality seismic data, enabling the high-resolution imaging of deep seismic structures of the Japanese subduction zones. Many studies have been done in this region using data acquired by the dense seismic network. These studies have revealed the detailed structure of the subducting plates and the associated mantle wedges and overlying crust, and have contributed to the understanding of the mechanism of earthquake generation in the subduction zones, especially for their shallow portions. In this presentation, these studies in the Japanese subduction zones are summarized as a typical example, and the inferred mechanisms, particularly roles of $H_2O$, for generating earthquakes and magmas are discussed.

**Plate subduction**

Recent studies on seismic tomography, hypocenter locations, and focal mechanisms using data from the dense nationwide seismic network have allowed the identification of the complex structure of the oceanic plates subducting beneath the Japanese Islands. The configuration of the subducting Pacific plate was determined by precisely relocating earthquake hypocenters and by using focal mechanism information for those earthquakes (Nakajima et al., 2009a; Kita et al., 2008). The configuration of the subducting Philippine Sea plate beneath SW Japan remains poorly understood, primarily because only limited seismic activity is associated with subduction of this plate. A recent double-difference tomography study clearly imaged the crust portion of the Philippine Sea plate as a layer with low S-wave velocity and high Vp/Vs located immediately above a region of intraslab seismicity (Hirose et al., 2008a, b), enabling the determination of the location of the Philippine Sea plate at depths of 20–60 km. The deeper portions (60–200 km) of the plate were determined based on seismic tomography-derived upper envelope of the high-seismic-velocity slab (Nakajima and Hasegawa, 2007). The geometry of the subducting Pacific and Philippine Sea plates thus estimated is shown as contours in Fig. 1.

The estimated configuration shows that the Philippine Sea slab subducting underneath SW Japan has an undulatory configuration down to a depth of 60–200 km, and is continuous from Kanto to Kyushu without disruption or splitting, even within areas north of the Izu Peninsula. The contact zone between the Pacific and Philippine Sea plates estimated from seismic tomography and focal mechanism studies (Uchida et al., 2009; Nakajima et al., 2009a) indicates that the contact zone is present across a wide area beneath Kanto, with a correlation with the location of the Kanto Plain. This broad contact zone beneath the Kanto Plain causes anomalously deep interplate and intraslab earthquake activities due to the low-temperature conditions there as a result of the subduction of the Philippine Sea slab immediately above the Pacific slab.

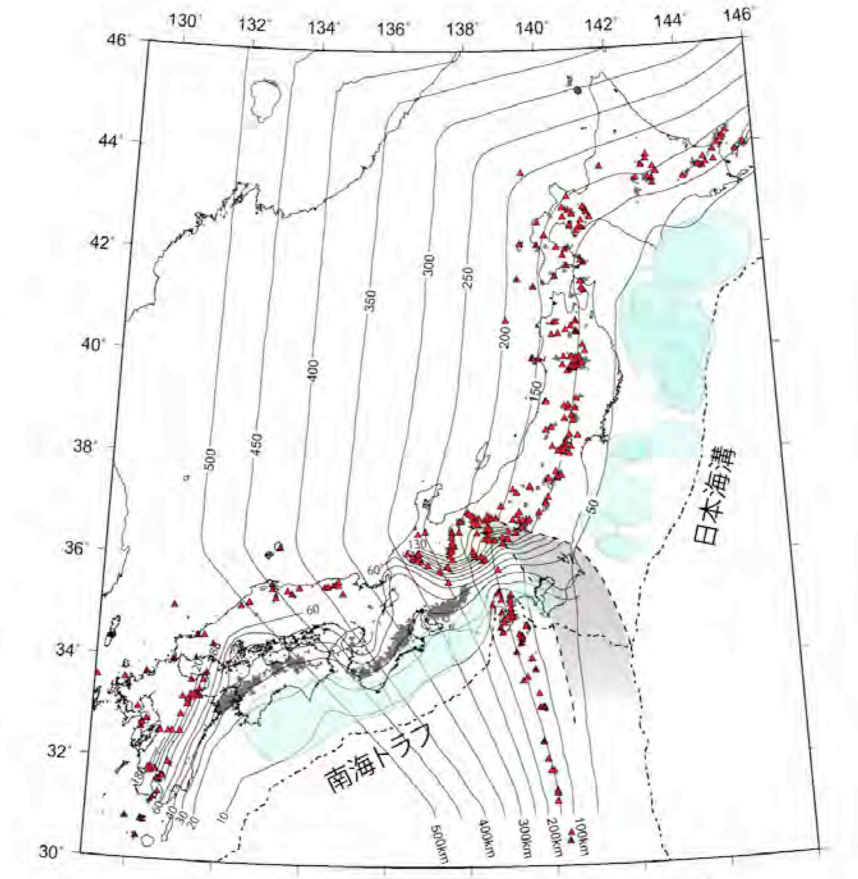


Fig. 1 Map showing isodepth contours of the upper surfaces of the Pacific and Philippine Sea plates. The contact zone between the Philippine Sea and overlying Pacific plates is shaded in gray and enclosed by two broken curves.

## Slip pattern along the plate interface and fault strength

Shallow portions of the plate interface in subduction zones (megathrust) host the world's largest earthquakes and the majority of seismic energy on the earth is released from them. It is known that seismic coupling coefficients are not 100% and vary with locations on the megathrust, which suggests that some amount of the interplate slip is accommodated by aseismic slip. Detailed analyses of seismic waveforms in the NE Japan subduction zone revealed that large slip areas of successive ruptures by large interplate earthquakes occurred in the same location on a given section of the plate interface, showing asperities (locked areas) are persistent features (e.g., Yamanaka and Kikuchi, 2003). What causes asperities? Of course, the problem has not been resolved yet, but there exist some observations suggesting that $H_2O$ might play a role. Seismic tomography studies show that P-wave velocities in the mantle wedge right above the asperity patches on the megathrust have normal values whereas those right above the non-asperity (stably sliding) areas have anomalously low values which indicates the existence of serpentinized mantle wedge there (Yamamoto et al., 2007). This suggests serpentinized mantle wedge materials immediately above the plate interface, formed by the supply of slab-derived $H_2O$, contribute to the determination of the frictional properties on the megathrust. Pore fluid pressure on the megathrust might more directly contribute to it: locked areas at depth in the Hikurangi subduction zone are considered to be formed by overpressured fluids on the megathrust which are caused by low-permeability upper plate materials right above (Fagereng & Ellis, 2009; Reyners & Eberhart-Phillips, 2009).

Stress field change after a large earthquake, if exists, provides a unique opportunity to estimate deviatoric stress magnitude. Because of its extremely large earthquake size and a dense broadband seismic network deployed in the Japanese Islands, temporal change in the stress field after the 2011 Tohoku-Oki earthquake was clearly observed by stress tensor inversions of earthquake focal mechanisms (Hasegawa et al., 2011). The maximum compressive stress ($\sigma_1$) axis before the earthquake has a direction toward the plate convergence, dipping oceanward at an angle of 25–30 degrees. Its dip angle significantly increased by 30–35 degrees after the earthquake (Fig. 2). The ratio of mainshock stress drop to the background deviatoric stress was estimated to be 0.7–1.0 from the observed rotation of $\sigma_1$ axis (Fig. 3). This shows that the deviatoric stress causing the Mw 9.0 earthquake was mostly released by the earthquake, or the stress drop during the earthquake was nearly complete. Adopting the average stress drop obtained by GPS observation data (Iinuma et al., 2011), the deviatoric stress magnitude is estimated to be 8–13 MPa. This suggests the plate interface is very weak. If we assume that the weak fault is caused by overpressured fluids, pore pressure ratio on the megathrust is estimated to be ~0.94.

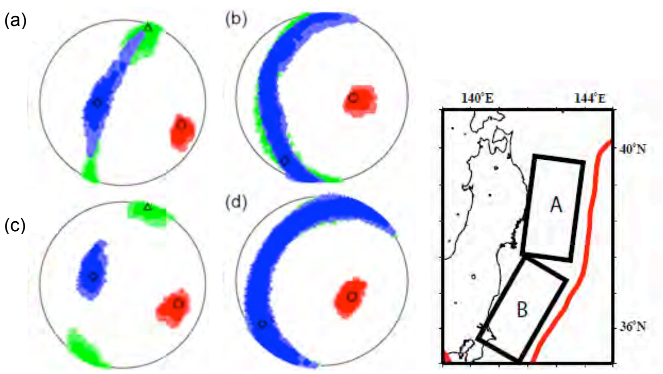

Fig. 2 Best fit principal stress $\sigma_1$ (red circle), $\sigma_2$ (green triangle) and $\sigma_3$ (blue square) (a) before and (b) after the Tohoku-Oki earthquake in region A. (c) and (d) show those for region B. Principal stresses falling within 68% and 95% confidence levels are shown by lighter colors.

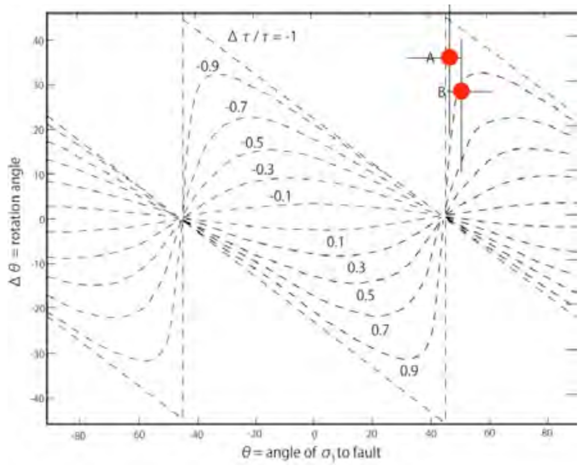


Fig.3 Rotation of $\sigma_1$ axis ($\Delta\theta$) as a function of angle of $\sigma_1$ axis to the fault plane ($\theta$) for various values of $\Delta\tau/\tau$ , the ratio of stress drop to the deviatoric stress (Hardebeck and Hauksson, 2001). Estimated rotation angles for regions A and B are plotted by red circles with the confidence ranges.

**Intraslab earthquakes**

Yamasaki and Seno (2003) estimated the dehydration loci of metamorphosed slab crust and serpentinized slab mantle using experimentally derived phase diagrams for six subduction zones. Their estimation showed that the lower plane seismicity of the double-planed deep seismic zone in the slab is located at the lower dehydration loci of serpentine, whereas the upper plane seismicity is located at dehydration loci of metamorphosed crust, which supports the hypothesis that intraslab seismicity is caused by dehydration embrittlement. Concentration of earthquakes along the dehydration loci of serpentine, i.e., the lower boundary of a hydrated slab mantle, is considered to be the main cause for the formation of the double-planed deep seismic zone. This further implies that dehydration reaction is greater when materials reach the facies boundary in the slab mantle.

The recent resolution of the detailed hypocenter distribution and seismic velocity structure of subducted slabs by the dense nationwide seismic network has provided further evidence supporting the dehydration-related embrittlement hypothesis for the generation of intermediate-depth intraslab earthquakes. Kita et al. (2006) detected a pronounced seismic belt in the upper plane of the double seismic zone, nearly parallel to the ~80 km isodepth contour of the upper surface of the Pacific slab beneath Hokkaido and Tohoku (Fig. 4a). This pronounced seismic belt, termed an ‘upper-plane seismic belt’, is located within the oceanic crust at a depth near a metamorphic facies boundary in the crustal material, suggesting that this belt was associated with intraslab earthquakes generated by dehydration-related embrittlement. Seismic tomography imaging indicates that low-seismic velocity slab crust persists down to the depth of this upper-plane seismic belt, but not below (Tsuji et al., 2008), suggesting that a phase transformation and eclogite formation occur in the slab crust at this depth (Fig. 4b). The depth at which this phase transformation takes place is thought to be dependent on the temperature within the slab; if this is the case, the local low-temperature conditions in the Pacific slab immediately beneath the slab contact zone beneath Kanto should cause a delay in phase transformation. As expected, both the upper-plane seismic belt and the low-seismic-velocity oceanic crust deepen beneath the slab contact zone in the Kanto area. Hasegawa et al. (2007) showed that the upper-plane seismic belt beneath the Kanto area is oblique to the ~80 km isodepth contour, deepening toward the north from a depth of ~100 km to 140 km along a trend nearly parallel to the downdip edge of the slab contact zone (Fig. 4c). A seismic tomography study by Nakajima et al. (2009b) indicated that the low seismic-velocity region in the slab crust extends to the uppermost depths where the obliquely trending upper-plane seismic belt is observed (Fig. 4d).

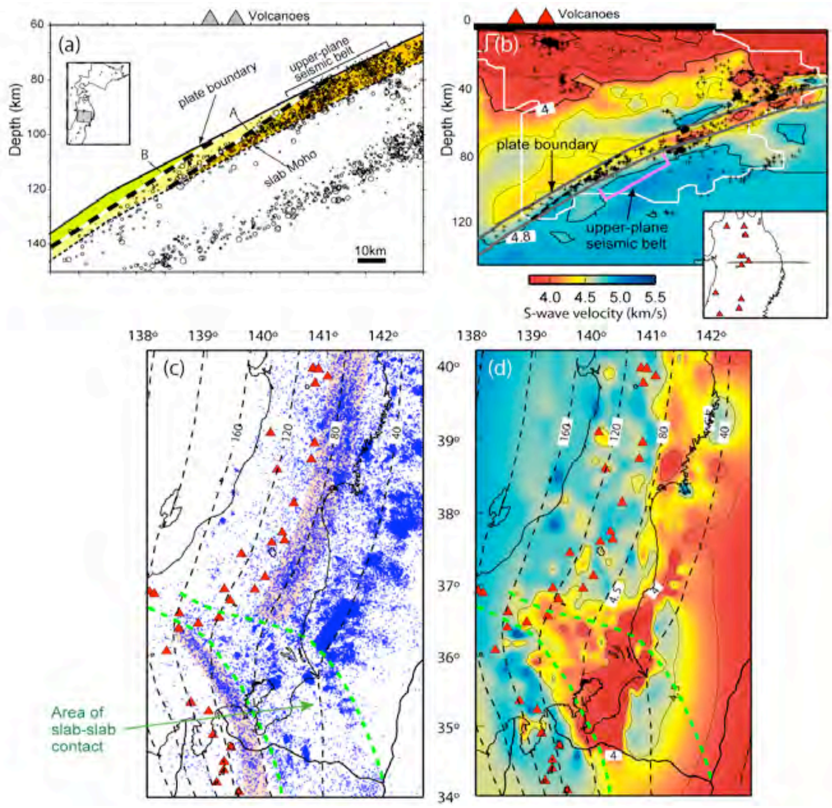


Fig. 4. Across-arc vertical cross-sections (a) showing intraslab earthquakes and (b) showing variations in S-wave velocity in central Tohoku. (c) Distribution of earthquake epicenters within the crust of the Pacific slab. The contact zone between the Philippine Sea and Pacific slabs beneath Kanto is delineated by two broken green curves, with solid curves and red triangles showing isodepth contours of the upper surface of the Pacific slab and the location of active volcanoes, respectively. (d) S-wave velocity distribution in the crust of the Pacific slab on a curved plane 5 km below the upper plate surface.

These observations strongly support an interpretation where low-temperature conditions associated with the slab–slab contact zone beneath the Kanto area cause a delayed onset of eclogite-forming phase transformations.

## Transportation of aqueous fluids from slab to arc crust and formation of volcanic front

$H_2O$ liberated from the slab during dehydration rises up to the mantle wedge right above the slab, where it reacts with mantle materials to form hydrated minerals such as serpentine, chlorite and amphibole (Davies and Stevensen, 1992; Iwamori, 1998). In old plate subduction zone, such as Tohoku, this hydrated layer is formed right above the slab, and is thought to be dragged downward by the slab to a depth of 150-200 km, where it undergoes a further dehydration (Iwamori, 1998). This hydrated layer formed directly above the slab has been detected both by seismic receiver function analyses and seismic tomography study (Kawakatsu and Watada, 2007; Tsuji et al., 2008).

As the hydrated layer directly above the slab reaches a depth of 150-200 km due to entrainment with the subducting slab, dehydration releases $H_2O$, which is presumed to rise vertically as aqueous fluid. It has been predicted that the entrainment of mantle material with slab subduction results in the migration of mantle material on the back-arc side to fill the enclosed space (McKenzie, 1969). Seismic tomography studies seem to detect this return flow portion of the secondary convection associated with slab subduction as a clear inclined sheet-like seismic low-velocity, high-attenuation layer oriented sub-parallel to the subducted slab (Hasegawa et al., 1991; Zhao et al., 1992, 1994; Nakajima et al., 2001, 2013).

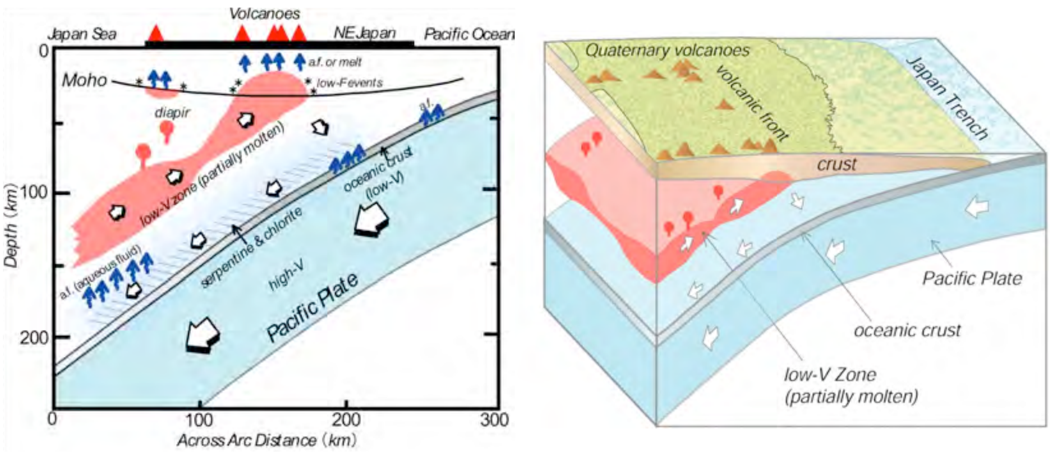


Fig. 5 Schematic illustration showing the inferred pathway of $H_2O$ transportation. (a) Cross-arc vertical cross-section of crust and upper mantle in Tohoku. (b) Three-dimensional expression.

This inclined sheet-like low-velocity layer in the mantle wedge has along-arc variation in terms of the velocity reduction within it: very low-velocity areas periodically occur about every 80 km or so along the strike of the arc (Hasegawa and Nakajima, 2004). The along-arc variation of velocity reduction in the inclined low-velocity layer in the mantle wedge is spatially correlated with the distribution of low-frequency earthquakes in the lower crust, the distribution of Quaternary volcanoes and the distribution of topographic elevation running from the backbone range to the back-arc region at the surface. Transportation paths of aqueous fluids from slab to arc crust including mantle upwelling flow in NE Japan estimated from seismic observations are shown schematically in Fig. 5. The volcanic front, which runs through the middle of the arc nearly parallel to the trench axis, is formed above the region where the inclined upwelling flow reaches the Moho.

**Deformation of the arc crust and inland crustal earthquakes**

The inclined low-velocity, high-attenuation zone is considered to correspond to the upwelling flow portion of the subduction-induced convection. It reaches the Moho immediately beneath the volcanic front, or the Ou Backbone Range, suggesting that the volcanic front is formed by this hot upwelling flow. Aqueous fluids supplied by the subducted slab are probably transported upward through this upwelling flow to reach shallow levels beneath the Backbone Range where they are expelled from solidified magma and migrate further upward. The existence of aqueous fluids may weaken the surrounding crustal rocks, resulting in local contractive deformation and uplift along the Backbone Range under the compressional stress field of the volcanic arc. A strain-rate distribution map generated from GPS data reveals a notable concentration of east–west contraction along the Backbone Range, consistent with this interpretation (Miura et al., 2004). Shallow inland earthquakes are also concentrated in the upper crust of this locally large contraction deformation zone. Based on these observations, a simple model is proposed to explain the deformation pattern of the crust and the characteristic shallow seismic activity beneath the NE Japan arc (Hasegawa et al., 2005). Seismic tomography using dense temporary seismic networks deployed in the source areas of recent large inland crustal earthquakes have provided further evidence of the important role of $H_2O$ in earthquake generation (Hasegawa et al., 2009; Fig. 6). Prominent low-velocity zones can be readily identified in the lower crust immediately below the fault planes of all of these large earthquakes. These low-velocity zones in the lower crust are inferred to be caused by $H_2O$ of slab origin.

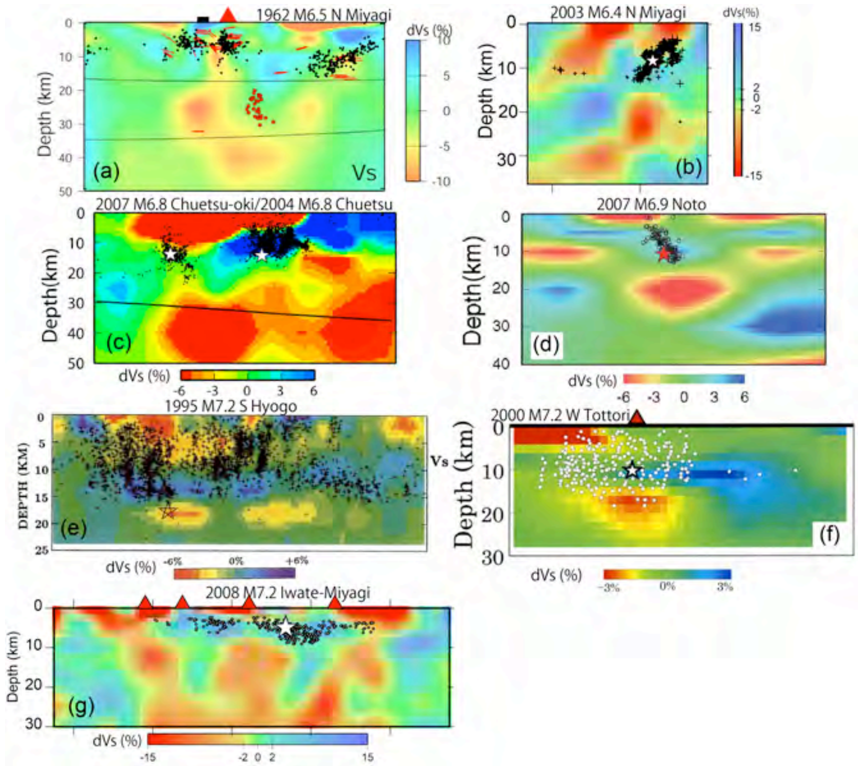


Fig. 6 Seismic velocity structure in the source areas of recent large inland crustal earthquakes in Japan. (e), (f), and (g) are vertical cross-sections along the mainshock faults, and other figures are vertical cross-sections across the mainshock faults. Mainshock and aftershocks are denoted by stars and circles or crosses, respectively.

After the 2011 Tohoku-Oki earthquake, stress fields seem to have changed in some areas in the inland of NE Japan, where the orientations of the principal stresses became approximately the same as the orientations of the static stress change associated with the earthquake (Yoshida et al., 2012). If this is the case, deviatoric stress magnitudes in these areas before the earthquake were extremely small. A recent study on stress field in NE Japan using many focal mechanism data shows that highlands are characterized by strike-slip stress regime while the lowlands by thrust fault stress regime (Yoshida et al., 2013). This suggests that gravity effect by topography is reflected in the present stress field, which means that the deviatoric stress magnitudes in the inland of NE Japan are as small as ~10 MPa or so. Since earthquakes are actually occurring under such small stress magnitudes, fault strengths are estimated to be weak in the inland area as well. The weak faults are probably due to overpressured fluids there.

All of these observations suggest that $H_2O$ expelled from the subducting slab play an important role in the generation of earthquakes and magmas in subduction zones.

**References**


Davies, J.H., Stevenson, D.J., 1992. Journal of Geophysical Research 97, 2037–2070.
Fagereng, A. and S. Ellis, 2009. Earth Planetary Science Letters, 278, 120-130.
Hardebeck, J. and E. Hauksson, J. Geophys. Res., 106(B10), 21859–21882, 2001.
Hasegawa, A., Nakajima, J., 2004. AGU Geophysical Monograph,150, vol.19. IUGG, pp. 81–94.
Hasegawa, A., Zhao, D., Hori, S., Yamamoto, A., Horiuchi, S., 1991. Nature 352, 683–689.
Hasegawa, A., Nakajima, J., Umino, N., Miura, S., 2005. Tectonophysics 403/1–4, 59–75.
Hasegawa, A., Nakajima, J., Kita, S., Okada, T., Matsuzawa, T., Kirby, S., 2007a. Geophysical Research Letters 34, L09305. doi:10.1029/2007GL029616.
Hasegawa, A, K. Yoshida , and T. Okada, 2011. Earth Planets Space, 63, 703-707, doi:10.5047/eps.2011.06.007.
Hasegawa, A., J. Nakajima, N. Uchida, T. Okada, D. Zhao, T. Matsuzawa, and N. Umino, 2009. Gondwana Research, 16, 370-400.
Hirose, F., Nakajima, J., Hasegawa, A., 2008a. Journal of the Seismological Society of Japan 60, 123–138.
Hirose, F., Nakajima, J., Hasegawa, A., 2008b. Journal of Geophysical Research 13, B09315. doi:10.1029/2007JB005274.
Iinuma, T., R. Hino, M. Kido, D. Inazu, Y. Osada, Y. Ito, M. Ohzono, H. Tsushima, S. Suzuki, H. Fujimoto, and S. Iwamori, H., 1998. Earth and Planetary Science Letters 160, 65–80.
Kawakatsu, H., Watada, S., 2007. Science 316, 1468–1471.
Kirby, S.H., 1995. U.S. National Report to International Union of Geodesy and Geophysics 1991–1994. American Geophysical Union, Supplement to Reviews of Geophysic 33, 287–297.
Kita, S., Okada, T., Nakajima, J., Matsuzawa, T., Hasegawa, A., 2006. Geophysical Research Letters 33. doi:10.1029/2006GL028239.
McKenzie, D.P., 1969. Geophysical Journal of the Royal Astronomical Society 18, 1–32.
Miura, M., Sato, T., Hasegawa, A., Suwa, Y., Tachibana, K., Yui, S., 2004. Earth Planets Space 56, 1347–1355.
Nakajima, J., Hasegawa, A., 2007a. Journal of Geophysical Research 112, B08306. doi:10.1029/2006JB004770.
Nakajima, J., Hasegawa, A., 2007b. Earth and Planetary Science Letters 254, 90–105.
Nakajima, J., Matsuzawa, T., Hasegawa, A., Zhao, D., 2001. Journal of Geophysical Research 106, 843–857.
Nakajima, J., Tsuji, Y., Hasegawa, A., 2009a. Geophys. Res. Lett. 36, L03303. doi:10.1029/2008GL036865.
Nakajima, J., Hirose, F. and Hasegawa, A., 2009a. Journal of Geophysical Research, 114, B08309, doi:10.1029/2008JB006101.
Reyners, M. and D. Eberhart-Phillips, 2009. Earth Planetary Science Letters, 282, 299-305.
Tsuji, Y., Nakajima, J., Hasegawa, A., 2008. Geophysical Research Letters 35, L14308. doi:10.1029/2008GL034461.
Uchida, N., Hasegawa, A., Nakajima, J., Matsuzawa, T., 2009. Earth and Planetary Science Letters 283 (1-4), 111–121.
Yamamoto, Y., Hino, R., Nishino, M., Yamada, T., Kanazawa, T., Hashimoto, T., Aoki, G., 2006. Geophysical Research Letters 33, L10308. doi:10.1029/ 2005GL025619.
Yamanaka, Y., Kikuchi, M., 2003. Earth Planets Space 55, e21–e24.
Yamasaki, T., Seno, T., 2003. Journal of Geophysical Research 108. doi:10.1029/2002JB001918.
Yoshida, K., A. Hasegawa, T. Okada, T. Iinuma, Y. Ito, and Y. Asano, 2012. Geophys. Res. Lett., 39, doi:10.1029/2011GL049729.
Zhao, D., Hasegawa, A., Horiuchi, S., 1992. Journal of Geophysical Research 97,19909–19928.
Zhao, D., Hasegawa, A., Kanamori, H., 1994. Journal of Geophysical Research 99, 22313–22329.