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REVIEW
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Localized extensional tectonics in an overall reverse-faulting regime, Northeast Japan

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Abstract
In Northeast Japan, it has been recognized that trench-normal compressional stresses, aligned in the approximate direction of plate convergence, tend to dominate stress fields over a broad region. However, a particularly notable event was the shallow, normal-faulting earthquake swarms with a T-axis oriented in the E–W or NW–SE directions that occurred immediately after the 2011 Tohoku-Oki earthquake near the Pacific coast in the Southeast Tohoku district. The stress tensor inversion represents the pre-Tohoku-Oki earthquake stress field in this area as a normal-faulting stress regime with the minimum principal horizontal stress oriented in a roughly NW–SE direction. Additionally, the stress regime varies with depth from normal faulting at shallow depths (<15 km) to thrust faulting at greater depths. Seismic tomography and magnetotelluric soundings defined a geophysical anomaly with low seismic velocity and low resistivity clearly visible beneath the swarm activity, strongly supporting the existence of an interconnected network with fluid-filled porosity. The upper boundary of the conductor is in good agreement with an extensional–compressional stress transition zone. A plausible explanation for these drastic changes in the stress regime is upward flexure of the upper crust due to partly anelastic deformation in the weakened lower crust. Additionally, remarkable upwarping and localized extensional tectonics during the late Pleistocene reflect the long-term rheological heterogeneities in the crust beneath the seismic source region.

Keywords: Localized extensional tectonics, Earthquake swarms, 2011 Tohoku-Oki earthquake

Introduction

Convergent plate boundaries are classified into two groups according to whether their back-arc regions are or not actively spreading (Mariana type) or (Chilean type), respectively (Uyeda and Kanamori 1979). In Northeast Japan, the Pacific plate is subducting along the Japan Trench under the North American plate at a rate of nearly 8–9 cm/year (DeMets 1992). The NE Japan arc is recognized as Chilean type, characterized by compressional subduction tectonics, increased seismic coupling and the occurrence of megathrust earthquakes (Conrad et al. 2004). Indeed, the overriding plate contraction in a roughly E–W direction is widely observed in the NE Japan arc based on a national geodetic survey (e.g., Sagiya et al. 2000). Geological data on slip rates of active faults indicate that significant E–W contraction across the NE Japan arc occurs on different time scales (Wesnousky et al. 1982). Earthquake focal mechanisms also reveal that the maximum principal stress (σ_1) is oriented in a WNW–ESE direction and reverse faulting occurs in this compressional tectonic regime throughout NE Japan (e.g., Townend and Zoback 2006; Terakawa and Matsu'ura 2010). However, recent dense seismic observations reveal that the σ_1 axes are oblique to plate convergence directions on the fore-arc side (Yoshida et al. 2015a).

After the M_w 9.0 earthquake off the Pacific coast of Tohoku (hereafter, referred to as "Tohoku-Oki earthquake"), induced earthquakes occurred actively within the inland crust of NE Japan, in addition to ordinary aftershocks. Several induced $M \sim 6.0$ shallow inland earthquakes have struck as far as ~300 km from the source region of the mainshock. Amongst inland earthquakes induced by the Tohoku-Oki earthquake, a particularly notable event was the shallow, swarm sequence that occurred immediately after the Tohoku-Oki

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earthquake near the Pacific coast in the Southeast Tohoku district. In addition, on April 11, 1 month after the Tohoku-Oki mainshock, the largest event of M_w 6.7 Iwaki (Fukushima-Hamadori) earthquake occurred in the central part of the seismogenic zone (Fig. 1). It should be noted that the focal mechanisms of these events are indicative of normal faulting with roughly E–W or NW–SE extension direction (Yoshida et al. 2015a). Although the background seismicity in the studied region before the Tohoku-Oki earthquake was extremely low (~5 events/year) based on the Japan Meteorological Agency (JMA) dataset, the notable change in stress regime from compression to extension can be ascribed to *a* <1 MPa static stress change caused by the Tohoku-Oki earthquake (Yoshida et al. 2012). However, it remains ambiguous as to why the extensional tectonics, exceeding the regional compressive stress regime, were limited to near the Pacific coast in the Southeast Tohoku district (Imanishi et al. 2012; Hyndman 2013).

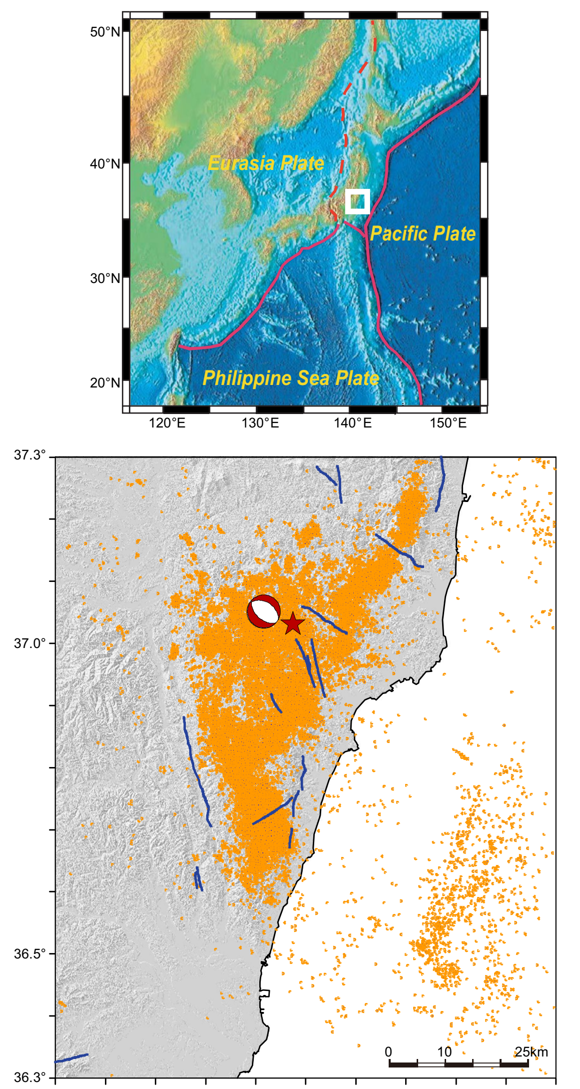

Fig. 1 **a** Location and shaded relief maps, and **b** generalized structure of the Southeast Tohoku district. *Yellow dots* the epicenters of earthquakes identified by the JMA that occurred from March, 2011 to August, 2012 at depths shallower than 20 km. *Red star* and *focal mechanism symbols* (F-net catalog from NIED) indicate the M_w 6.7 Iwaki earthquake, on April 11. Active faults are also shown (*dark blue lines*) (after Nakata and Imaizumi 2002)

The 2011 Tohoku-Oki earthquake was an unprecedented megathrust earthquake, monitored by the dense nationwide, high-sensitivity seismograph network (Hi-net) and global navigation satellite system (GNSS). A large number of studies have been reported since the earthquake, based on multiple lines of evidence identified in geological, geophysical and geochemical data (e.g., Somerville 2015; Hasegawa and Yoshida 2015). The amount and quality of various data can advance our understanding of earth and planetary sciences, including megathrust earthquakes in the subduction zone. Especially, geophysical findings of crustal heterogeneities and geological records of crustal deformation provide a clue to the mechanism for the generation of localized extensional tectonics in an overriding compressional island-arc crust. In this review, I focus on seismotectonics before and after the Tohoku-Oki earthquake, the details of seismic velocity structure and electrical resistivity structure in the seismogenic zone, and vertical crustal deformation for the late Pleistocene and the present time.

Review

Focal mechanisms

As mentioned previously, the stress pattern in NE Japan is WNW–ESE compression due to the Pacific plate subduction direction, with intermediate principal stress (σ_2) oriented in the N–S direction, resulting in an N–S reverse-faulting stress regime prevailing throughout the whole region. To clarify, it is known that stress orientations rotate due to the release of shear stress in a major earthquake, and the degree of rotation can place some constraints on the ambient level of stress in the crust surrounding the mainshock (e.g., Hardebeck and Hauksson 2001). Several researchers estimated the stress induced by the 2011 Tohoku-Oki earthquake using inverting focal mechanism data (e.g., Hasegawa et al. 2012; Yoshida et al. 2012). At depths shallower than 20 km, the stress field in the Northwest Tohoku district changed significantly; σ_1 rotated counterclockwise and has a NE–SW direction, whereas the minimum principal stress (σ_3) in the Southeast Tohoku district aligned with the plate convergence direction. However, in other areas of the Central Tohoku district, there seems to be no significant change in the stress regime (Yoshida et al. 2012).

To determine the focal mechanisms of crustal earthquakes not affected by the megathrust earthquake perturbations, Yoshida et al. (2015b) applied stress tensor inversions to data for the period between October 1997 and March 2011, prior to the Tohoku-Oki earthquake. The results indicate the following three features (Fig. 2): (1) the σ_1 axis tends to be oriented E–W or WNW–ESE, approximately parallel to the direction of the plate subduction, (2) the σ_1 orientation has an N–S direction in the Northeast Tohoku district, corresponding to the fore-arc side, and (3) in the Southeast Tohoku district, normal-faulting stress regime with the minimum principal horizontal stress oriented in the NW–SE or N–S directions is predominant, but reverse-faulting stress regime occupies in the deeper portion of the seismogenic zone (>15 km). Although the stress field in the source region of the earthquake swarms changed from reverse or strike-slip faulting to normal faulting due to static stress change associated with the Tohoku-Oki earthquake (e.g., Asano et al. 2011), the stress regime is characterized as normal-faulting type at depths shallower than 15 km in the Southeast Tohoku district, even before the 2011 Tohoku-Oki earthquake (Imanishi et al. 2012; Yoshida et al. 2015b).

Geophysical observations

Geophysical findings from surveys of the Earth's inner heterogeneities provide a clue to the mechanism for the generation of earthquakes and active tectonics. The primary geophysical methods applied are seismic methods. Recent high-resolution Vp and Vs tomographic images of the crust and the upper mantle have been defined beneath the fore-arc side of NE Japan, extending eastward to the megathrust zone off the Pacific coast, utilizing a large array of P- and S-wave arrival-time data from local shallow and intermediate-depth earthquakes (Zhao et al. 2011; Wang et al. 2011; Tong et al. 2012; Kato et al. 2013; Zhao 2015). Detailed tomographic images show that significant low-*V* and high Poisson's ratio (high-σ) anomalies in the crust and the uppermost mantle are detectable beneath the seismogenic zone in the Southeast Tohoku district. The seismic structural anomalies are interpreted to be aqueous fluid networks located beneath the source region of the swarm that affected the rupture nucleation (e.g., Zhao 2015). On the other hand, Tong et al. (2012) performed separate tomographic inversions using data from seismic events before and after the Tohoku-Oki earthquake (Fig. 3). These results indicate that the tomographic images are generally similar to each other, suggesting that the low velocity zone beneath the seismogenic zone existed before the megathrust earthquake.

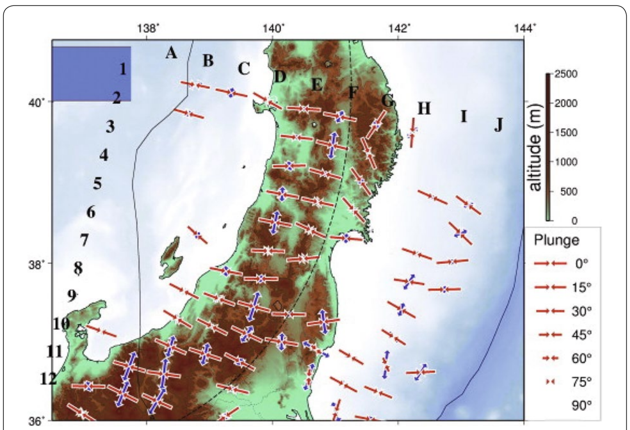

Fig. 2 Orientations of the best fit σ_1 and σ_3 axes projected onto a gridded horizontal plane are indicated by *red* and *blue arrows*, respectively. The length of *arrows* varies in proportion to the steepness of the plunge (after Yoshida et al. 2015b)

Additionally, magnetotelluric (MT) signals are an indication of the electrical resistivity of the Earth, a physical parameter that is highly sensitive not only to the temperature and bulk composition of rocks, but also to the presence and connectivity of melt, volatiles, and especially fluids (Hyndman and Shearer 1989; Becken and Ritter 2012). A great deal of effort has been made using MT soundings to obtain information on subsurface electrical conductivity anomalies around seismically active regions in subduction zones. Recently, MT data were acquired along a 90 km long profile oriented in a WNW–ESE direction crossing the seismic source region of the earthquake swarms, nearly perpendicular to the strike of the NE Japan arc (Fig. 4) (Umeda et al. 2015). The inversion of the MT data shows that the swarm-like earthquake source region coincides with the high electrical resistivity region adjacent to a conductor with a width of 20 km at depths of ~15 km depths, and extending down to the base of the crust (Fig. 4). Despite comparison of 2-D resistivity and 3-D seismic velocity images, there appears to be good correlation between spatial heterogeneity of resistivity structure and seismic velocity structure. Independent geophysical observations strongly support the indication that aqueous fluid networks existed beneath the source region of the earthquake swarms, prior to the Tohoku-Oki earthquake.

Vertical crustal deformation

Vertical deformation at the present time, before the Tohoku-Oki earthquake, is characterized by rapid subsidence in the fore-arc side and gentle uplift in the back-arc side, with a hinge line (zero vertical velocities) running along the middle of the NE Japan arc (Fig. 5a) (Suwa et al. 2006; Nishimura 2014). However, the vertical velocities

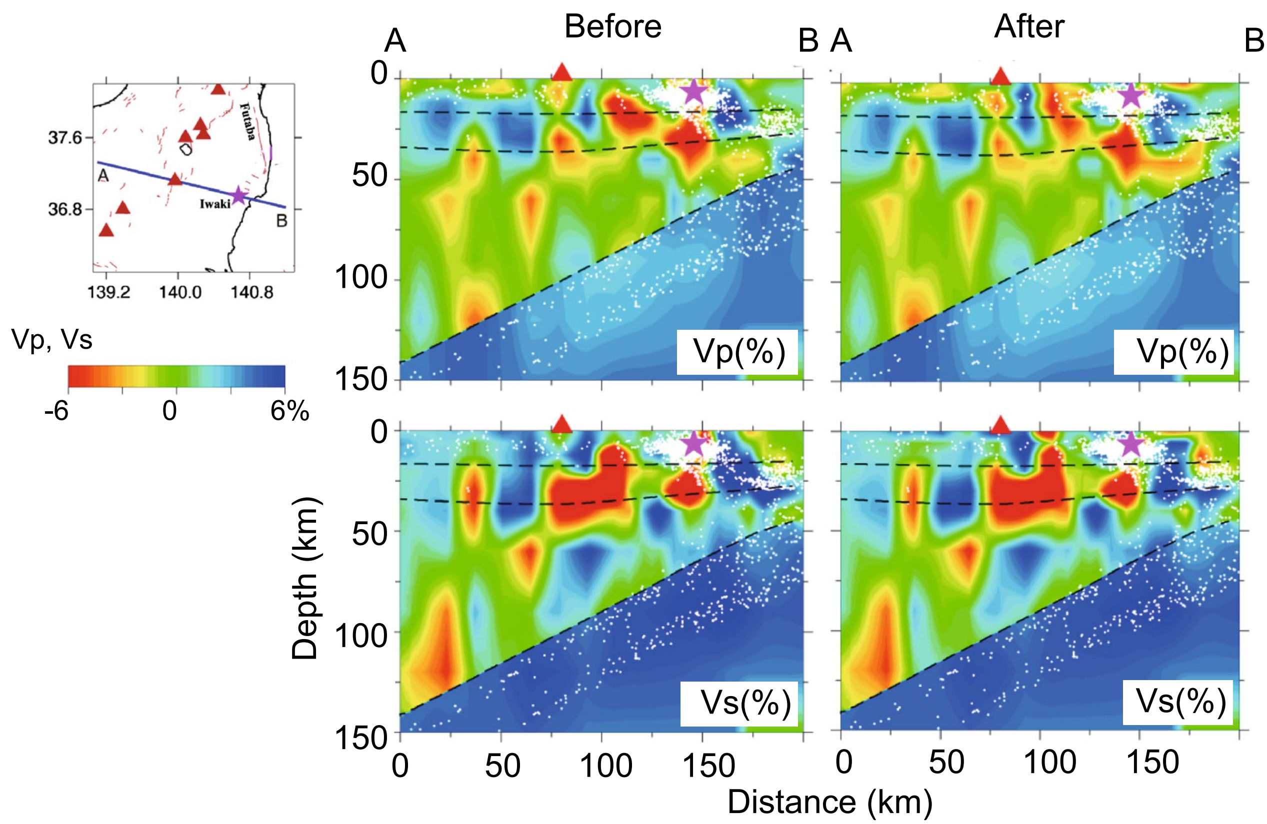

Fig. 3 Vertical cross-sections of P-wave and S-wave velocity images along the profile as shown in the *inset map* using the data sets from earthquakes that occurred before (*left*) and after (*right*) the 11 March 2011 Tohoku-Oki earthquake (after Zhao 2015)

around the source region of earthquake swarms facing the Pacific coast indicate localized, notable upheaval of several mm/year. By comparison of the results of the leveling survey shown in Fig. 5b, despite the different observation periods, overall, the features agree well with Fig. 5a.

Permanent coastal uplift often results from local reverse faulting and folding within the overriding island-arc crust (McCalpin and Carver 2009). Long-term deformation data along the Pacific coast, NE Japan, have been inferred from late Quaternary marine terraces (Suzuki 1989; Ota and Omura 1991). In the coastal region of the Southeast Tohoku district, to the east of the Abukuma Mountains, the ancient strandline elevations of the last interglacial terraces of late Pleistocene age range from 32 to 78 m above sea level (Fig. 6a), which inclines to the north and southwest of 37.0°N latitude. The crustal deformation pattern during the late Quaternary is characterized by local uplift around the seismic source region. The average vertical displacement rate is estimated to be >0.6 mm/year (Fig. 6 b).

Discussion and conclusions

Most of the earthquake swarms that occurred in the Southeast Tohoku district after the Tohoku-Oki earthquake are atypical of NE Japan, because the focal mechanism is indicative of normal faulting. Actually, the Iwaki earthquake occurred in the central part of the seismogenic zone, on April 11, accompanied by surface ruptures along about 30 km of normal faulting with offset of ~2.0 m (Tsutsumi and Toda 2012). In addition, an extensional stress regime prevailed even before the 2011 Tohoku-Oki earthquake. This area has previously been shown to contain active normal faults; for example, the Itozawa and Yunotake faults, are concordant with surface ruptures associated with the Iwaki earthquake. A paleoseismic trench dug across the Itozawa fault exposed evidence for a penultimate earthquake that occurred sometime between 12,620 and 17,410 cal year B.P. (Toda and Tsutsumi 2013).

Imanishi et al. (2012) insisted that the recurrence of displacement along a low-angle seaward-dipping weak alignment extending from the seismogenic zone to the plate boundary contributes to the development of a normal-faulting stress field in an overall reverse-faulting regime in NE Japan. On the other hand, regional bending deformation of the overriding plate is proposed as a possible mechanism for creating an extensional stress

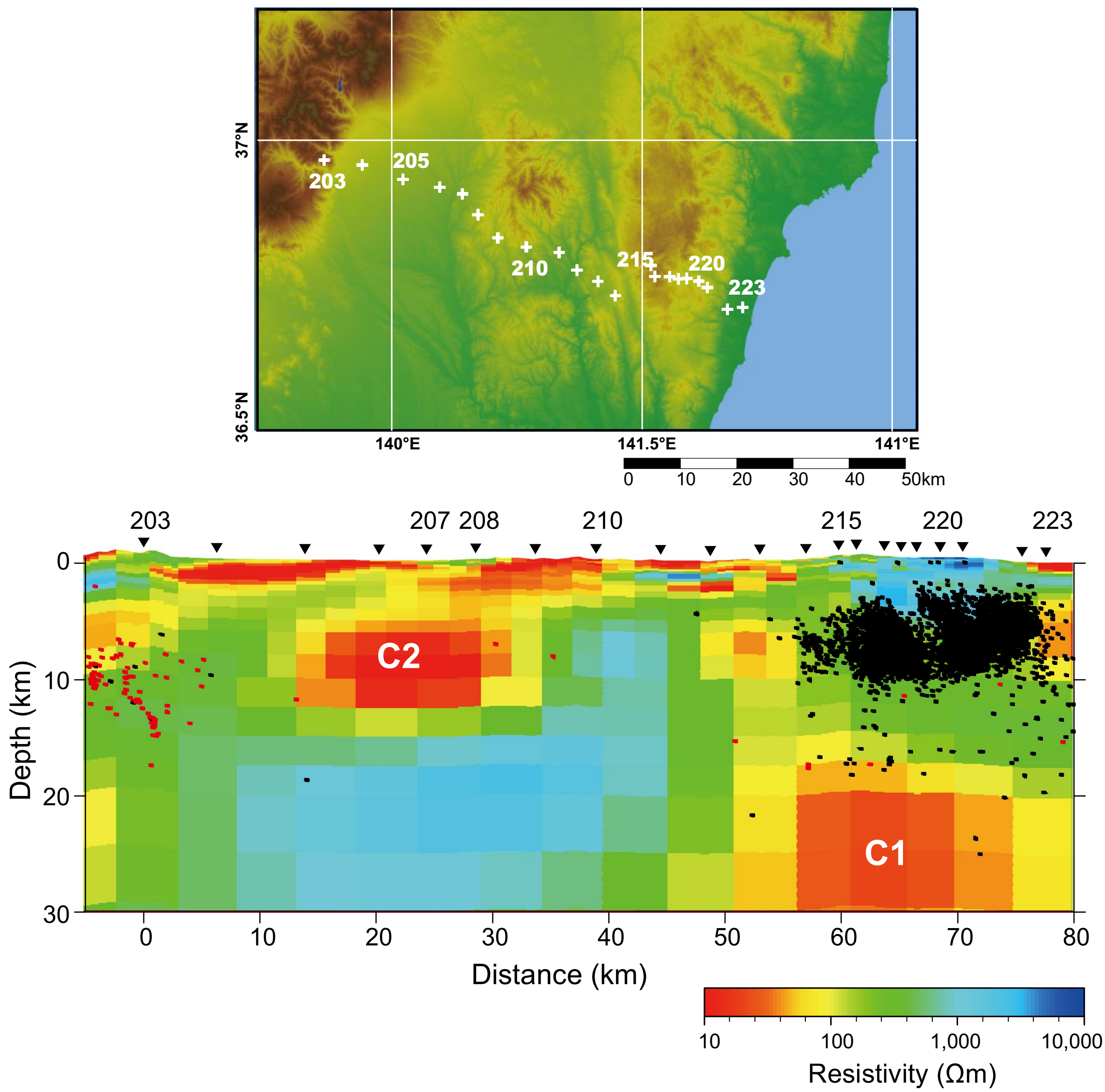

Fig. 4 2-D resistivity model. Hypocenters of earthquake swarms (*black dots*) within a 10 km width of the MT profile from March, 2011 to August, 2012, are shown on this figure. Also shown is the hypocenter distribution (*red dots*) before the Tohoku-Oki earthquake, from January 2008 to March 2011, identified by the JMA (after Umeda et al. 2015). *Inset map* the locations of MT stations (*filled crosses*)

regime in the fore-arc side of NE Japan (Hashimoto and Matsu'ura 2006; Yoshida et al. 2015b). Upper plate bending would facilitate large tensional stresses locally in the shallower part of the overriding plate that exceeds horizontal compression due to subduction (e.g., Turcotte and Schubert 2002). The effect of plate bending in the subduction zone is expected to affect areas over several 100 km. As mentioned above, long-term extension and uplift has been prevalent along the Pacific coast in the Southeast Tohoku district. However, remarkable uplift has observed on length scales of several tens of kilometers (Fig. 6).

The strength and mechanical behavior of the crust is critical to the tectonic evolution and crustal deformation in subduction zones. Especially, fluids residing in brittle crust have a significant weakening effect on the mechanics

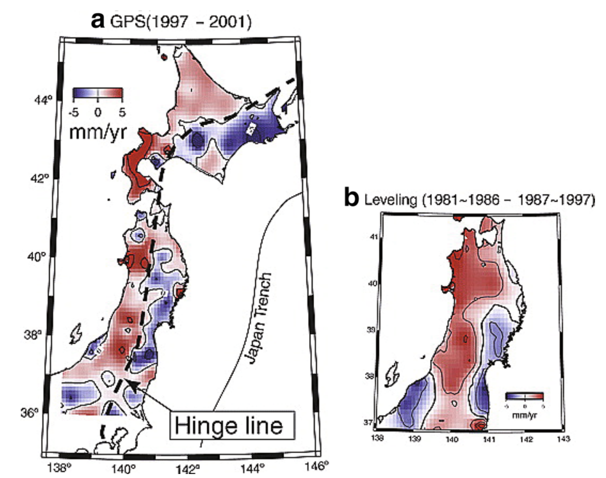

Fig. 5 Vertical velocities **a** observed by GPS and **b** observed by the recent GSI leveling survey. Contour interval is 5 mm/year. *Blue* and *red areas* denote subsidence and uplift, respectively (after Suwa et al. 2006)

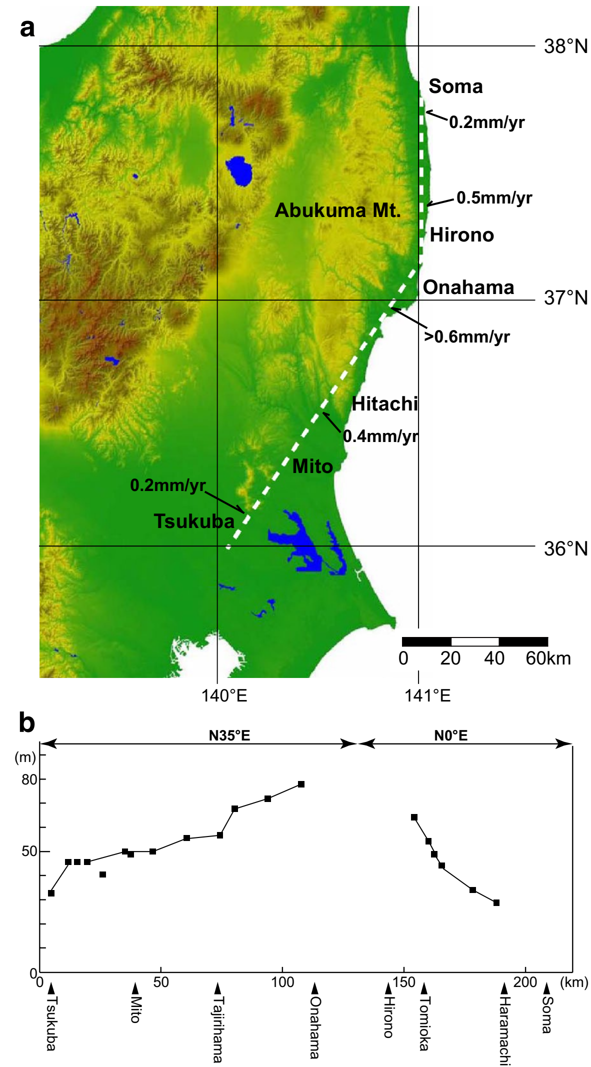

Fig. 6 **a** Late Quaternary uplift rate inferred from marine terraces in the Southeast Tohoku district. **b** Elevations of marine terraces formed during the late Pleistocene along the Pacific coast (*white broken line*), shown in **a** (after Suzuki 1989)

of rocks and affect the long-term structural and compositional evolution of the crust (e.g., Hickman et al. 1995). Beneath the seismogenic zone of the earthquake swarms, a prominent, low seismic velocity, low electrical resistivity anomaly with a width of 20 km is defined at depths of ~15 km, indicating the possibility that aqueous fluid networks exist in the lower crust. It is therefore likely that rheological heterogeneities in the crust beneath the seismic source region would control the localized crustal deformation due to anelastic deformation under E–W compressional regional stress (e.g., Hasegawa et al. 2005). Iio et al. (2004) anticipated that uplift with slight contraction occurs above the weakened lower crust based on models having different assumptions of the viscosity, which can explain the vertical crustal deformation within the range of several tens of kilometers on different time scales in the Southeast Tohoku district.

Additionally, in the source region of the earthquake swarms, the stress regime is estimated to vary with depth from normal fault type at shallow depths to thrust or strike-slip fault type at greater depths (Yoshida et al. 2015b). The depth variation in the relative magnitudes of the three principal stress axes (A_{ϕ}: Simpson 1997) drastically changes at a depth of around 15 km from an extensional stress regime to a compressional stress regime (Fig. 7a). It should be noted that depth variations in the stress regime correlate well with depth variations in electrical resistivity of the crust. The abrupt transition of the stress field with depth can be interpreted to be upward flexure of the upper crust associated with the vertical anelastic deformation in the lower crust. At the shallower parts, σ_1 corresponds to vertical stress (σ_V) because the transition of the stress regime can be expected by a decrease in magnitude of the horizontal stress ($\sigma_{Hmax} = \sigma_2$, $\sigma_{Hmin} = \sigma_3$) in compressional subduction tectonics due to convex upward flexure of the upper crust. In contrast, the strike-slip fault type ($\sigma_{Hmax} = \sigma_1$, $\sigma_v = \sigma_2$, $\sigma_{Hmin} = \sigma_3$) or thrust fault type ($\sigma_{Hmax} = \sigma_1$, $\sigma_{Hmin} = \sigma_2$, $\sigma_v = \sigma_3$) stress becomes dominant in the deeper part, owing to a sharp decrease in magnitude of localized extensional stress with depth (Fig. 7b).

Following the 2011 Tohoku megathrust earthquake, shallow, normal-faulting earthquake swarms occurred along the Pacific coast in the Southeast Tohoku district. I have reviewed geophysical information on the

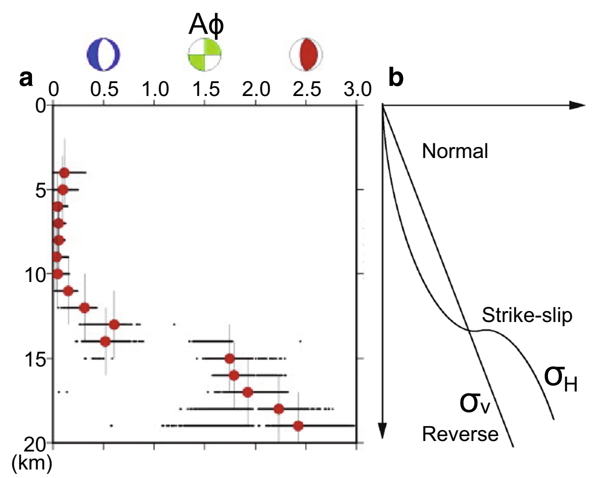

Fig. 7 **a** Relative magnitude of the three principal stress axes, A_ϕ plotted against depth in the south part of the forearc. A_ϕ was estimated from the focal mechanisms within 2 km of each depth. *Red circles* the best-fit solutions. *Black dots* the 95 % confidence limits (after Yoshida et al. 2015b). **b** Schematic image of the depth variations in the stress field

structural heterogeneities in the crust and the upper mantle, and crustal deformation at different timescales in and around the seismic source region. Independent geophysical observations indicate that aqueous fluid networks were present beneath the source region, prior to the Tohoku-Oki earthquake. Localized extensional tectonics in an overall reverse-faulting regime would be caused by upward flexure of the upper crust due to partly anelastic deformation in the weakened lower crust. However, other seismic source regions with low seismic velocity and low resistivity in the lower crust (e.g., Ichihara et al. 2011; Ogawa et al. 2014) have not been observed to develop localized extensional tectonics on the back-arc side of the NE Japan arc. Future research into the stress regime relationship with crustal heterogeneities due to aqueous fluids is needed to address these issues.

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Competing interests
The author declares that they have no competing interests.

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