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Spatial variation of stress orientations in NE Japan revealed by dense seismic observations

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ABSTRACT

In order to investigate the spatial distribution of the crustal stress state across NE Japan, we determined 1370 focal mechanisms by picking P-wave polarities from seismograms observed by temporary and permanent seismic networks densely deployed in this area. We applied stress tensor inversions to these data, plus to those routinely determined. The results show that the stress state in NE Japan is heterogeneous in space, which is different from previous results that showed that the NE Japan arc is characterized by margin normal compression. The orientations of the maximum compressional stress (σ1.) axes are significantly different with 95% confidence limits between the arc–backarc region and the forearc region. The arc–backarc region is characterized by spatially uniform margin normal compression. However, the north and south parts of the forearc region have the σ1 axis oriented nearly N–S and vertical, respectively. The region in between has a similar stress orientation to the arc–backarc region. Moreover, the stress regime in the arc–backarc region varies spatially in response to change in the surface altitude. Beneath regions of relatively low altitudes, a reverse faulting stress regime is dominant. However, regions of higher altitudes are characterized by a strike–slip faulting stress regime. Numerical model calculations, in which gravitational and buoyancy forces caused by topography are incorporated, show that differential stresses of about 15–25 MPa are needed to explain the lateral variation of the stress regime observed in the arc–backarc region. This suggests that the background deviatoric stress magnitude in NE Japan is very low.

1. Introduction

The occurrence of an earthquake can be regarded as a stress-release process in the earth. Thus, information about the stress state is very important to understand the physical process of earthquake generation. Early studies, using stress measurements and focal mechanisms, showed that the first-order stress field is controlled by plate boundary forces with large intraplate forces such as gravitational forces near mountain ranges (Zoback, 1992).

Stress orientations at seismogenic depths in NE Japan have been estimated from earthquake focal mechanisms (e.g., Hasegawa et al., 1994, 2012; Terakawa and Matsu'ura, 2010; Townend and Zoback, 2006; Yoshida et al., 2012). These previous studies have indicated the following two features in NE Japan: (1) The maximum compressive stress (σ1) axes are oriented to the plate subduction direction, and this margin normal σ1 axis in the upper plate has been attributed to the plate coupling force (e.g., Wang and Suyehiro, 1999). (2) A reverse faulting stress regime prevails throughout the whole region.

If we look at things in more detail, however, the margin normal σ1 axis is observed primarily in the arc–backarc region and not in the forearc region of the NE Japan arc. This is because seismic activity is very low in the forearc region, although it is active in the arc–backarc region. Thus, the stress state in the forearc region in NE Japan remains unknown. Furthermore, the results of recent studies (Terakawa and Matsu'ura, 2010; Yoshida et al., 2012) have shown that strike–slip stress regimes also exist in some regions in NE Japan, although their detailed spatial distribution is not fully known.

The Japanese Islands are densely covered by a nationwide seismic network with short-period and broadband seismographs, called the Kiban Network. Based on data from the F-net broadband seismic network, the National Research Institute for Earth Science and Disaster Prevention (NIED) routinely determines moment tensor solutions for events with magnitudes of >~3.5 (Fukuyama et al., 1998). Based on P-wave polarity data, the Japan Meteorological Agency (JMA) routinely determines focal mechanisms for events with magnitudes of >~3.0 in the inland area (JMA, http://www.jma.go.jp/jma/indexe.html).

In NE Japan, in addition to this nationwide network, some temporary seismic networks have been deployed in the central and southern areas. For example, since 2006, a temporary seismic network of 52 stations has been operated in the central part of NE Japan by Tohoku University and the Japan Nuclear Energy Safety Organization (JNES). Furthermore, another very dense temporary seismic network of 50 stations has

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been operated in the northern part of Miyagi Prefecture by Tohoku University since 2010, as part of the "Geofluids: Nature and dynamics of fluids in subduction zones" project. Fig. 1 shows the station distribution of the temporary and routine seismic networks. The compilation of data from these networks enables the determination of the focal mechanisms of smaller events and the estimation of the stress field across NE Japan with a higher spatial resolution.

In this paper, we determined the focal mechanisms of small earthquakes in inland NE Japan using data from the temporary networks combined with data from the routine network. We then examine the spatial variation of stress orientations across NE Japan, including the forearc region, and present updated information on the stress field.

2. Regional tectonic setting

In NE Japan, the Pacific plate is subducting west-northwestward beneath the North American plate at a rate of 8–9 cm/yr along the Japan Trench (e.g., DeMets et al., 1994). In addition, the North American plate is colliding with the Eurasia plate along the eastern margin of the Japan Sea (Heki et al., 1999; Wei and Seno, 1998) west of NE Japan, with a broad convergence boundary composed of rifts that were formed during the period of the backarc opening of the Japan Sea (Okamura et al., 1995).

As the result of the plate convergences, margin normal contraction is widely observed in NE Japan by geodetic measurements (e.g., Kato et al, 1998; Miura et al., 2002; Ohzono, 2011; Sagiya et al., 2000). Spatial distribution of the strain rates derived from GEONET (GPS Earth Observation Network) data for the period 1997–2010 is shown in Fig. 2. Here we calculated the strain rates following Sagiya et al. (2000) and Ohzono (2011) who estimated the strain rates in NE Japan for the periods 1997–1999 and 2006–2008, respectively. The following function was fitted beforehand to a time series of station positions of the i-th component of the n-th station using the least square method:

$$u_n^i(t) = a_n^i + b_n^i t + c_n^i \sin(2\pi t) + d_n^i \cos(2\pi t) + e \sin(4\pi t) + f_n^i \cos(4\pi t) + \sum_{k=1}^{m} g_{n,k}^i H\left(t - t_n^k\right) \qquad (1)$$

where t is time in years. The coseismic steps that occurred at t_n^k are described as a sum of Heaviside functions $g_n^i H(t - t_n^k)$. Then, strain rates were calculated using the method by Shen et al. (1996). Fig. 2 clearly shows that the maximum contraction rate axes are oriented homogeneously WNW–ESE, parallel to the orientations of the plate convergences. The focal mechanisms of large shallow earthquakes with moment magnitude greater than 6 are also shown in the figure. Their P-axis orientations are WNW–ESE, similarly to those of the maximum contraction rate axes.

The stress orientations in NE Japan were investigated through analysis of earthquake focal mechanisms (e.g., Hasegawa et al., 1994, 2012; Terakawa and Matsu'ura, 2010; Townend and Zoback, 2006; Yoshida et al., 2012). The maximum compressive stress axes estimated in the previous studies are oriented WNW–ESE, which is parallel to the orientations of the plate convergences and the maximum contraction rate axes.

However, it should be noted that most of the focal mechanism data used for the previous stress analyses are distributed in the arc–backarc regions. The stress states in the forearc region have been poorly understood because of the low seismic activity there. In the south portion of the forearc region near Iwaki City, however, many shallow earthquakes, including the 2011 M 7.0 Fukushima–Hamadori earthquake (denoted

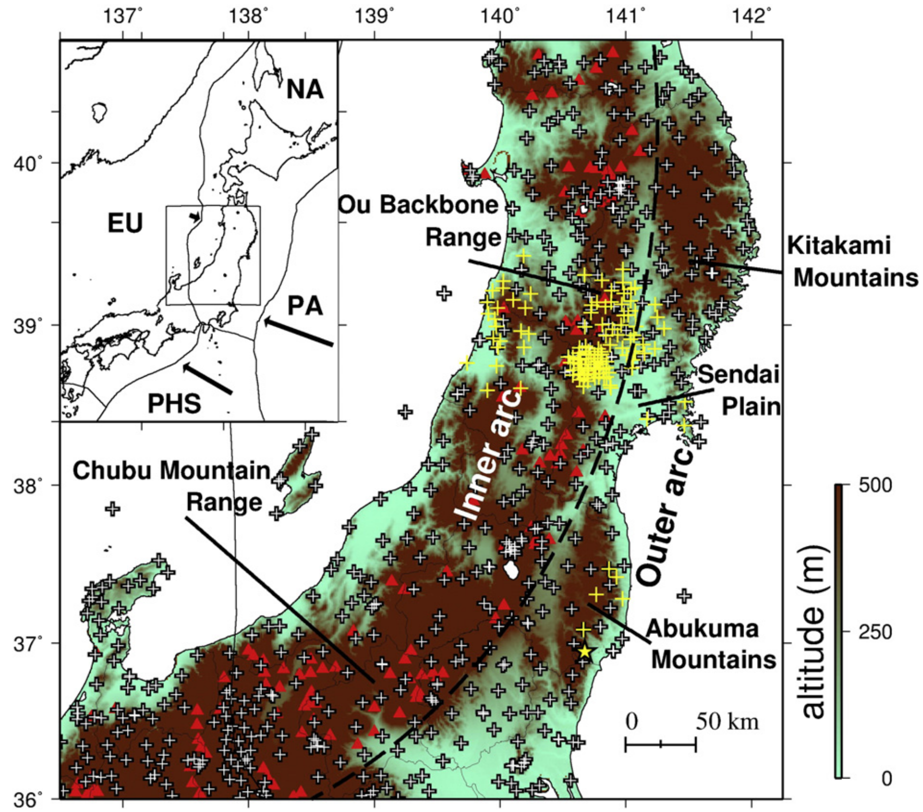

Fig. 1. Locations of seismic stations in the study area of NE Japan. Crosses represent stations: gray crosses show permanent stations of the NIED, the JMA and Tohoku University; yellow crosses show temporary stations. Red triangles show active volcanoes. The map is color shaded by the color scale on the right from green to brown with the increase in altitude. The inset map shows the study area enclosed in a rectangle, and the arrows in it indicate the plate convergence direction. NA: North American plate, PA: Pacific plate, PHS: Philippine Sea plate, EU: Eurasian plate. The broken line represents the border of the arc–backarc region and the forearc region.