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Changes in seismic activity following the 2011 Tohoku-oki earthquake: Effects of pore fluid pressure

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ABSTRACT

We examined the effects of pore fluid pressure on seismicity changes following the 2011 off the Pacific coast of Tohoku (Tohoku-oki) earthquake through the analysis of aftershocks based on the Coulomb failure criterion. Background tectonic stress fields in Northeast Japan are generally characterized by E–W compression. After the Tohoku-oki earthquake, as expected from decrease in the Coulomb failure function (= shear stress − 0.4 × normal compressive stress), seismicity in the upper crust of Northeast Japan decreased except some restricted regions, where we observed many aftershocks with unfavourable focal mechanisms to the background stress fields. By mapping the focal mechanisms of aftershocks on the 3-D Mohr diagram region by region, we confirmed that the aftershocks occurred on optimally oriented faults in some regions but on misoriented faults in other regions. The aftershocks on optimally oriented faults indicate the increase in regional ambient fluid pressure caused by the flow of over-pressurized fluid from a deep reservoir. On the other hand, the aftershocks on misoriented faults, which cannot be attributed to coseismic stress rotation, indicate the increase in fault-confined fluid pressure relative to the ambient fluid pressure.

1. Introduction

The Mw 9.0 off the Pacific coast of Tohoku (Tohoku-oki) earthquake occurred at the interface between the Pacific and North American Plates on 11th March of 2011. From the inversion analysis of GPS array data, Hashimoto et al. (2012) have obtained reliable coseismic slip distribution on the plate interface: the maximum slips are 32 m for the 300 km-long Miyagi-oki main-rupture zone and 7 m for the 100 km-long Fukushima-oki sub-rupture zone. The slip directions are almost parallel to the direction of plate convergence. This megathrust earthquake has triggered thousands and thousands of seismic events across much of East Japan (e.g., Hirose et al., 2011). Large earthquakes generally trigger aftershocks within a few fault lengths from the main shock (e.g., Utsu and Seki, 1955). So, such widespread seismicity activation in East Japan is nothing surprising, though its physical mechanism is not well understood.

The occurrence of earthquakes is generally governed by the Coulomb failure criterion:

$$\tau_s = \mu(\sigma_n - P_f), \qquad (1)$$

where τ_s and σ_n are the shear stress (positive in the direction of fault slip) and normal stress (positive in compression) on a specified fault, respectively, P_f is pore fluid pressure in the fault, and μ is the intrinsic friction coefficient of rocks. Aftershocks are not an exception of ordinary earthquakes in this sense. To explain the triggering of aftershocks, the change in Coulomb failure function, defined by

$$\Delta CFF = \Delta\tau_s - \mu(\Delta\sigma_n - \Delta P_f), \qquad (2)$$

has been widely used (e.g., King et al., 1994; Stein, 1999). On the assumption of undrained, homogeneous, and isotropic conditions for pore fluid pressure ($\Delta P_f = B\Delta\sigma_n$, denoting the Skempton's coefficient by B), Eq. (2) can be reduced to

$$\Delta CFF = \Delta\tau_s - \mu'\Delta\sigma_n, \qquad (3)$$

where $\mu' = (1-B)\mu$ is the effective friction coefficient. In either equation, the first and second terms on the right hand side represent the shear stress and shear strength changes of the specified fault, respectively. From these equations we can see that decrease in fault strength as well as increase in shear stress encourages shear failure on the specified fault (Hubbert and Rubey, 1959).

Since the fault strength decreases with the increase of pore fluid pressure (Eq. (1)), the existence of over-pressurized fluid in the Earth's crust must play an important role in earthquake generation (e.g., Nur and Booker, 1972; Sibson, 2007). However,

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in most studies, effects of shear and normal stress changes have been focused on, because of the difficulty of estimating realistic pore fluid pressure fields. According to poroelastic fluid diffusion models (e.g., Bosl and Nur, 2002; Cocco and Rice, 2002; Miller et al., 2004), the occurrence of large earthquakes can drastically change the surrounding pore fluid pressure fields. In such a case we cannot apply the effective ΔCFF in Eq. (3) to the assessment of aftershock triggering. In other words, aftershocks can be triggered even in a region where the effective ΔCFF is negative.

Focal mechanisms of seismic events reflect the pore fluid pressure as well as the shear and normal stresses (Eq. (1)). As suggested by Byerlee's law (Byerlee, 1978) and in situ stress measurements in deep boreholes (e.g., Zoback and Healy, 1992; Zoback and Townend, 2001), intrinsic friction coefficients of rocks are nearly constant (0.5–0.7) in seismogenic depths. Based on this fact, Terakawa et al. (2010) developed a new method to estimate pore fluid pressure fields by mapping focal mechanisms (fault strike, dip-angle, and slip-angle) of seismic events on the 3-D Mohr diagram for a given tectonic stress field. In this method, termed focal mechanism tomography (FMT) method, the spatial variation of focal mechanisms is attributed to fault strength heterogeneity due to the spatial variation of pore fluid pressures. Applying the FMT method to the focal mechanism solutions of the seismic events induced by fluid injection experiments in Basel Enhanced Geothermal System, Terakawa et al. (2012) demonstrated its validity and applicability. These studies show that we can estimate spatiotemporal change in pore fluid pressure from focal mechanism changes of seismic events if the tectonic stress pattern does not change with time.

In Section 2 of the present paper, first, we show the background tectonic stress field in East Japan, estimated from the inversion analysis of Centroid Moment Tensor (CMT) data of seismic events during 1997–2007 (Terakawa and Matsu'ura, 2010), and the stress changes due to the 2011 Tohoku-oki earthquake, computed from the coseismic slip distribution estimated from the inversion analysis of GPS array data (Hashimoto et al., 2012). Then, we evaluate the effective ΔCFF resolved in the direction of shear traction on the maximum shear plane of the background stress field. In Section 3, we analyse aftershocks in the regions where seismicity has increased after the main shock contrary to negative ΔCFF by mapping their focal mechanisms on the 3-D Mohr diagram. In Section 4, we discuss the effects of pore fluid pressure on aftershock triggering together with the physical mechanisms changing pore fluid pressure fields.

2. Stress change due to the 2011 Tohoku-oki earthquake

Tectonic stress fields in the Japan region have been inferred from geophysical and geological data for several decades (e.g., Huzita, 1980; Townend and Zoback, 2006; Terakawa and Matsu'ura, 2010). These studies commonly concluded that the background tectonic stress pattern in East Japan is generally characterized by the maximum compressive stress in E–W direction and the minimum compressive stress in vertical direction.

Fig. 1 shows the tectonic stress pattern in East Japan estimated by Terakawa and Matsu'ura (2010) from 12,500 seismic events during 1997–2007 with the CMT data inversion method (Terakawa and Matsu'ura, 2008). On the other hand, Fig. 2 shows the stress changes due to the 2011 Tohoku-oki earthquake, computed from the coseismic slip distribution estimated from the inversion analysis of GPS array data (Hashimoto et al., 2012). Comparing the background tectonic stress pattern with the coseismic stress change pattern, we can see that this megathrust event released the tectonic stress accumulated in Northeast Japan. The amount of stress release is about 8 MPa at the centre of the Miyagi-oki main-rupture zone, but only 2 MPa on the Pacific coast and 0.1 MPa on the Japan Sea coast of Northeast Japan.

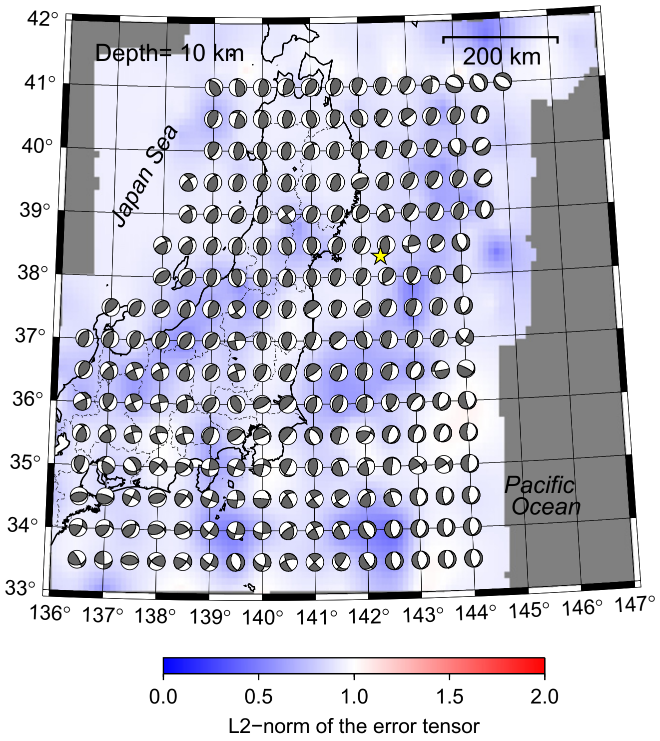

Fig. 1. Background tectonic stress pattern in East Japan. The tectonic stress pattern (at the depth of 10 km) estimated from CMT data of seismic events before the 2011 Tohoku-oki earthquake is represented with the lower hemisphere projection of focal mechanisms of potential seismic events at maximum shear planes. The star indicates the hypocentre of the main shock. The colour scale indicates the L_2 norm of error tensor defined by Eq. (17) in Terakawa and Matsu'ura (2010). We can read the values of the L_2 norm of error tensor, 0.5, 1.0 and 1.5, for example, as the standard errors in azimuth of principal stress axes, 15°, 30° and 45°, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The Earth's crust includes a number of small faults with various orientations. Among them, according to the Coulomb failure criterion, faults optimally oriented to tectonic stress fields will be most likely to slip in the direction of shear traction. We define ΔCFF as a perturbation to the Coulomb failure criterion, and so it should be evaluated for slip in the direction of shear traction on the optimally oriented fault. For simplicity, taking the maximum shear plane of the background tectonic stress field (Fig. 1) as the receiver fault, we evaluated the effective ΔCFF in Eq. (3) with $\mu'=0.4$ (e.g., King et al., 1994). In Northeast Japan, the strength of shallow pre-existing faults was generally weakened by the coseismic E–W tension of the upper crust, but the negative effect of shear stress decrease overwhelmed the positive effect of normal stress decrease, and so the values of ΔCFF were negative as shown in Fig. 3. In Central Japan, on the other hand, the values of ΔCFF were positive by the effects of shear stress increase and normal stress decrease. The assessment of seismicity changes by the effective ΔCFF is consistent with observations as a whole except some restricted regions (e.g., Toda et al., 2011).

3. Effects of pore fluid pressure on focal mechanisms of seismic events

It is interesting that the seismicity rates increased in some restricted regions (A–C in Fig. 3) although the values of ΔCFF are negative. In this section, we analyse aftershocks in these regions