The state of stress in the aftershock area of the March 11, 2011 Tohoku earthquake

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Abstract. This paper presents the results of the stress inversion in the Earth's crust in the Japanese seismic focal zone after the Tohoku earthquake of March 11, 2011. The stress tensor parameters are determined using the method of cataclastic analysis (MCA) of discontinuous displacements. The reconstruction of the stress state is based on earthquake focal mechanism data for magnitude range (Mw) 3.0–6.0. The calculations are performed at six depths. The 2011 Tohoku earthquake brought significant stress changes in the upper layers of the lithosphere of the continental slope (0-30 km). These changes have led to the emerging of extensive areas of horizontal extension here. The areas with changed geodynamic regime were not reduced over the past few years. The magnitude 9.0 Tohoku earthquake was a catastrophic mega earthquake and in this case the presence of an anomalous state of stress may take a long time.

1. Introduction

The 11 March 2011, great Tohoku earthquake (Mw = 9.0), occurred in the northwestern flank of the Pacific seismic focal zone. This earthquake is the last event in a chain of the largest earthquakes that occurred in the modern era of digital instrumental observations. These include the 2004 Sumatra-Andaman earthquake (Mw = 9.3), the 2010 Chile or Maule earthquake (Mw = 8.8) and the Great 2011 Tohoku earthquake (Mw = 9.0). The maximum slip of about 50 m associated with the 2011 Tohoku earthquake was determined near the trench at shallow depth [1, 2]. The significant co-seismic displacements of the seafloor benchmarks estimated by the Japan Coast Guard were 22 m eastward and 10 m southward [3]. A slow initial rupture speed was (1.5 km/s), with this speed the rupture expands to a distance of 100 km from the hypocenter, after which the rupture propagates outward with increased speed of 2.5 km/s [4].

The 2011 Tohoku earthquake stands apart from the list of significant earthquakes of the 21st century not only because of its disastrous consequences, but because of the area of its occurrences. The earthquake has occurred in the region with a high-density seismic and geophysical observation network system F-net (http://www.fnet.bosai.go.jp). The density of the seismic stations in Japan (the average distance between seismic stations is 100–200 km) is second only to the California Seismic Network. The 2011 Tohoku earthquake brought significant stress changes and consequent seismicity changes in and around the source region [5–9]. As a result, the numbers of normal fault earthquakes increased greatly in the lithosphere west of the thalweg of the trench.
Analysis of the earthquake focal mechanism data of the Japanese seismic focal zone has shown that the
earthquakes with normal-fault mechanisms occurred here from 1997 to 2011 [9, 11] and they were not
preceded by large earthquakes. The presence of a sufficient number of normal fault earthquakes defined
the result obtained in our previous study [12]. The stress field in the Earth’s crust of the oceanic slope
to the east of thalweg of the trench before the 2011 Tohoku earthquake already had a regime of
horizontal extension.

2. Initial seismological data
The earthquake focal mechanisms were the source of information about the state of stress of the Earth’s
crust. We used the CMT solutions of the F-net catalog (http://www.fnet.bosai.go.jp) in the area between
30° to 43°N and 135° to 146°E, for the period from 12 March 2011 to 31 December 2016. The catalog
for this area includes 12 900 events with magnitudes between 3.2 and 7.0, in the depth range from 0 to
60 km. This area is larger than the source area of the Tohoku earthquake, which allows us to see the
influence distances of the Tohoku earthquake.

Only earthquakes with magnitudes between 3.0 and 6.0 were used in the calculations. The minimum
radius of averaging was taken 10 km, the maximum radius was taken 50 km. The stresses were calculated
on a 0.2°×0.2° latitude/longitude grid. The calculations are performed at six depths: 1) 0–10 km, 2) 10–
20 km, 3) 20–30 km, 4) 30–40 km, 5) 40–50 km, 6) 50–60 km. The results of the stress reconstruction
process refer to the following depths: 1) 4 137, 2) 2 361, 3) 1 730, 4) 1 248, 5) 2 652, and 6) 768.

3. A tectonophysical method of reconstructing natural stresses
The reconstruction of the stress tensor parameters is based on the method of cataclastic analysis (MCA)
of discontinuous displacements [13–15]. The method determines the parameters of the stress ellipsoid,
which can also be done using other well-known methods [16–19, etc.]. It is also able to constrain the
absolute values of the stresses.

The MCA uses earthquake focal mechanism solutions, generalized results of rock failure
experiments, dynamic parameters of earthquakes (the radiated seismic energy and the decrease in stress)
and the vertical component of the equation of dynamic equilibrium. This method consists of four stages.
Each stage of the reconstruction uses data of one of these types. The stress components obtained at each
stage are used in the next stage. Six stress components, four incremental components of the stress tensor
for the seismotectonic deformation, the effective internal cohesion and the fluid pressure can be obtained
when all four stages of the MCA are completed correctly [20].

The stress tensor components are calculated in quasi-homogeneous crustal domains. The domains
are defined as quasi-homogeneous and depend on their deformation regime. Each of these domains
includes a group of earthquake focal mechanisms. This group of events is called homogeneous sample
set of earthquake focal mechanisms; it characterizes quasi-homogeneous deformations of certain crustal
domains in the vicinity of each grid node for stress calculations. The algorithm of the MCA has
procedures that allow one to control the homogeneous deformation of such domains.

In the present paper, we used the sign criterion of classical mechanics: the tensile is positive and the
compression is negative, according to the rule σ₁ ≥ σ₂ ≥ σ₃. Therefore, in these studies, σ₃ is the
maximum compression or compression, and σ₁ is the maximum extension or extension, because the
deviatoric part of the σ₁ is extension.

4. The results of stress reconstruction
The parameters of the stress ellipsoid are determined during the first stage of the MCA. The axes of
maximum compression, σ₃, (figure 1 a) oriented subvertically (70–85°) for the most part of the upper
layer (5 km) of the Earth’s crust of the continental slope along the Honshu Island, according to the
results of the stress inversion. It should be noted that such orientation of these axes did not exist here
before the Tohoku earthquake. There are two local areas in the southern and northern parts of the slope
near the thalweg of the trench, where the axes of these stresses generally dip slightly (5–20°) beneath
the oceanic plate i.e. the orientation of principal stress axes remains the same as it was here before the
Tohoku earthquake (10–20°) [12]. The principal stress axis, \( \sigma_1 \), is subhorizontal and suborthogonal to the oceanic trench for the rest parts of the continental crust (figure 2 a). The intermediate principal stress axis, \( \sigma_2 \), is oriented subhorizontally and parallel to the thalweg of the Japan Trench almost everywhere. This is the same orientation that this axis had before the Tohoku earthquake [12].

Thus, there is the geodynamic regime of horizontal extension almost everywhere in the upper layer of the Earth’s crust of the continental slope (figure 1 a). Only two above mentioned areas have the geodynamic regime of horizontal compression. This completely distinguishes the stress state of the aftershock stage from the stress state that existed here before the Tohoku earthquake.

The orientation of the principal stress axes in the Earth’s crust of the oceanic slope is the same as it was before the Tohoku earthquake [12]: the principal stress axis \( \sigma_3 \) is subvertical to the talweg of the oceanic trench and the principal stress axis \( \sigma_1 \) is subhorizontal and orthogonal to it. A large number of data on the earthquake focal mechanisms in the aftershock period made it possible to obtain good stress state data in the Earth’s crust of the oceanic slope. This partly refers to the Izu-Bonin zone, here there is an area of horizontal extension in the northern part of the Izu-Bonin zone to the east of the thalweg of the trench. The geodynamic regimes of horizontal compression in the oceanic slope along the southern part of the Izu-Bonin Trench may be associated with a low density of the earthquake epicenters and a large average stress window.

Thus, in the upper layer of 0–10 km, within the source area of the Tohoku earthquake, the plunge angles of the principal stress axes of maximum compression, \( \sigma_3 \), (figure 3 a) sharply increased in comparison with the angles of plunge which these axes had before the Tohoku earthquake [12]. These changes have led to the appearance of extensive areas of horizontal extension. The same changes in the angles of plunge of the maximum compressive axes are also observed in the areas of horizontal extension at greater depths. The plunge angles of these axes have not significantly changed outside the areas of horizontal compression (figure 2 b–f). It should be noted that there are some domains with subhorizontal orientation of these axes in the direction parallel to the thalweg of the trench (the transition zone to the Izu-Bonin Trench and several domains in the central part of the Tohoku earthquake source area). Almost always, such orientation of the axes corresponds to the geodynamic regime of horizontal shear. Such orientation was also observed for the intermediate principal stress axis, \( \sigma_2 \), before the Tohoku earthquake [12].

At depth of more than 10 km (figure 1 b–f), the stress data are mainly presented in the Earth’s crust of the continental slope and they tend to extend northward beyond the source area of the Tohoku earthquake. This tendency is especially evident at depths of more than 40 km. At a depth of 15 km (figure 1 b) and at depths greater than 15 km (figure 1 c–f), the areas of horizontal extension in the Earth’s crust of the continental slope start decreasing, as a result the areas of horizontal compression are growing. Especially it can be observed in the northeastern part of the continental slope. The much sharper changes occur at a depth of more than 40–45 km (figure 1 d–f): the axis of maximum compression, \( \sigma_3 \), dips slightly under the oceanic plate at an angle of 25–30° almost everywhere in the continental slope (figure 1 d–f), the axis of minimum compression, \( \sigma_3 \), (figure 2 d–f), dips more steeply beneath the subcontinental lithosphere and therefore, the stress is in the horizontal compression regime.

Some changes have also occurred with the form of the stress tensor, which is characterized by the values of the Lode-Nadai or ratio coefficient (figure 2). Before the Tohoku earthquake, its values were changed from a combination of pure shear and compression to a combination of pure shear and extension. After the Tohoku earthquake, there are many domains in which the values of the Lode-Nadai are close to the uniaxial compression or uniaxial tension.
Figure 1. A projection of the principal stress axes $\sigma_3$ onto a horizontal plane and the types of stress, i.e., the geodynamic regimes: 1 horizontal extension, 2 – horizontal extension with shear, 3 – horizontal shear, 4 – horizontal compression with shear, 5 – horizontal compression, and 6 – vertical shear. In the lower left corner, circle diagrams show various azimuths and dip angles of the principal stress axes $\sigma_3$. In the lower right corner, the diagram shows the numbers of crustal domains under different types of stress.
Figure 2. A projection of the principal stress axes $\sigma_1$ onto a horizontal plane and the Lode–Nadai coefficient, $\mu_0$. In the lower left corner, circle diagrams show various azimuths and dip angles of the principal stress axes $\sigma_1$. In the lower right corner, the diagram shows the prevailing value of the Lode–Nadai coefficient.
5. Conclusion
The continental crust moved eastward as a result of the Tohoku earthquake, but it does not cause an additional compression (sliding friction is always less than static friction) in the oceanic lithosphere in the latitudinal direction according to the stress inversion. However it forced the patterns in the orientation of the principal stress axes (the geodynamic regime of horizontal extension) which existed before the Tohoku earthquake. This can only be if the movement of the continental crust eastward increases the compression stress in a vertical direction.

The areas in the upper layers of the continental slope (0–20 km), where the geodynamic regime has changed after the Tohoku earthquake, did not reduce over the past few years according to the monitoring of the state of stress. One would expect that the forces that move the plates for an almost seven-year period have created here additional compression which should lead to the gradual disappearance of seismicity in these areas (transition to an elastic state).

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