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SURFACE DEFORMATION PRIOR TO THE IMMINENT 2011 Mw 9.0 TOHOKU-OKI EARTHQUAKE AND ITS GEODYNAMIC IMPLICATIONS

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Abstract: The 11 March 2011 Tohoku-Oki earthquake was the first Mw 9 event to be recorded by a dense network of continuous Global Positioning System (GPS) stations. In this paper, we at first presented the distribution of daily GPS velocities in Tohoku district, Japan, prior to the Tohoku-Oki earthquake in 30 days. Then, we proposed an approach that can verify how well the method to calculate strain rates on GPS data. It is found that Zhu’s method (2005) is stable and accurate in computation of strain rate. Particularly, we found that GPS velocities uncover some surface deformation anomaly before the coming 2011 Tohoku-Oki earthquake, which is helpful to illuminate preparatory processes for earthquake generation, and the strain rates before the Tohoku mainshock are much different from those in the period of interseismic phase. It could be expected that the results in the paper have some implications for earthquake prediction and risk assessment.

Key wards: GPS measurements; Strain rate; Surface deformation anomaly; 2011 Tohoku-Oki earthquake.

1. INTRODUCTION

The 2011 March 11 off the Pacific coast of Tohoku Earthquake with moment magnitude Mw 9.0 took place off the coast of northeastern Japan at 14:46:18.1, Japan Standard Time (JST). This megathrust earthquake, hereafter referred to as the 2011 Tohoku-Oki earthquake, is one of the largest seismic events recorded by modern instruments, and is comparable to the 1960 Chile (Mw 9.5), the 1964 Alaska (Mw 9.2) and the 2004 Sumatra–Andaman (Mw=9.0–9.3) earthquakes (Tajima et al., 2013). The Tohoku-Oki earthquake is the most devastating disaster recorded in Japan since the 1923 Great Kanto earthquake. Due to a devastating tsunami triggered by the mainshock, the Tohoku-Oki event caused extensive life loss, leaving 15,874 dead and 2,744 missing (November 28, 2012, National Police Agency) (Yun and Hamada, 2015). However, we do not make any prediction for this catastrophic event although earthquake science has made a tremendous progress.

Thanks to a network of continuously recording Global Positioning System (GPS) stations known as GPS Earth Observation Network (GeoNet) has been deployed in Japan, which is one of the most advanced and the highest density of stations in the world, deformations prior to the main earthquake event have been recorded. Therefore, in the research, we try to capture some characteristic features of the abnormal crustal deformation before the coming of the 2011 Tohoku-Oki earthquake in order to do something in the long term research of earthquake prediction.

2. METHODOLOGY

(1) Method for calculation of strain rates

In order to obtain stable surface deformation, we should calculate strain rates from velocity vectors measured by GPS observation. It seems easy and simple to calculate strain rates based on GPS measurement because of forward modelling. In fact, this process has been found to be much complex since the GPS stations is not evenly distributed in space. For example, quite a few Chinese researchers calculated the strain rate field in the Chinese Continent utilizing different methods, but they obtained different results even though they made use of the same GPS data in computations (Zhu et al., 2005, 2006). For this purpose, Zhu et al., (2005, 2006) developed the method to calculate the strain rate from GPS data, and provided the distribution of strain rates in the whole Chinese Continent (Zhu and Shi, 2011). The calculated results are consistent with the corresponding observation data. The idea is simple, and easy to perform in computation. In calculation, we at first apply the kriging method to interpolate the spatially irregular scattered GPS velocity data to uniform grid values, and then calculate the strain rate for each volume element, using the approach similar to the derivation of shape functions in the finite element algorithm. In this way, we could obtain the strain rates on the whole study area.

Therefore, in the research, we will calculate the strain rate in Tohoku, Japan, by means of the above mentioned method.

(2) Verification of the Method

Since we do not know the exact value of the strain/strain rate at the specified point on the Earth's surface although we can get strain value by means of borehole surveying theoretically, in fact we cannot directly verify the strain rates calculated from GPS data. Thus, we do not have knowledge of which method is better and which result is correct. To this end, in the study, we will put forward a method to verify the result of strain rate calculated from GPS data. The method is described in the following.

First of all, we construct a mathematical function randomly. Then the velocity vectors (or displacements) can be obtained at the sites of the GPS stations according to the mathematical function which has been constructed. At last, we can calculate the strain rate at each site in space, according to the components of partial derivatives to the constructed function. In this way, the strain rate at each site in space is a correct value with the error of zero because the value is derived by means of purely mathematical operation. The stain rate is called a theoretical strain, or real strain rate, in the following context.

On the other hand, we could calculate the strain rates by the method of Zhu or some other authors' with the data of velocity vectors from mathematical operation above. In this manner, one can tell how well the method by comparing the strain rates calculated by the method with the corresponding theoretical strain rates.

Here, suppose displacements in θ- and φ-direction (east- and north-direction) are varied according to the following function.

$$\begin{cases} u_\theta = \mathrm{f}_u(\theta,\varphi) \\ u_\varphi = \mathrm{f}_v(\theta,\varphi) \end{cases} \tag{1}$$

Then, the components of strain on the spherical earth surface can be written as,

$$\begin{cases} \varepsilon_\theta = \frac{1}{R}\cdot\frac{\partial u_\theta}{\partial\theta} \\ \varepsilon_\phi = \frac{1}{R\sin\theta}\cdot\frac{\partial u_\phi}{\partial\phi} + \frac{u_\theta}{R}ctg\theta \\ \varepsilon_{\theta\phi} = \frac{1}{2}[\frac{1}{R}(\frac{\partial u_\phi}{\partial\theta} - u_\phi ctg\theta) + \frac{1}{R\sin\theta}\cdot\frac{\partial u_\theta}{\partial\phi}] \end{cases} \tag{2}$$

Where R denotes the radius of the Earth.

Therefore, principle strain, maximum shear strain and dilatation strain could be obtained based upon equation group (2).

$$\dot{\varepsilon}_{1,2} = \frac{\dot{\varepsilon}_\theta + \dot{\varepsilon}_\varphi}{2} \pm \sqrt{\frac{(\dot{\varepsilon}_\theta - \dot{\varepsilon}_\varphi)^2}{4} + \dot{\varepsilon}_{\theta\varphi}{}^2} \tag{3}$$

Where $\dot{\varepsilon}_{1,2}$ represent two principle strain rates, one is maximum, the other is minimum.

Likewise, the maximum shear strain rate and surface dilation strain rate can be expressed as (4) and

(5), respectively.

$$\dot{\chi} = (\dot{\varepsilon}_1 - \dot{\varepsilon}_2) / 2 \tag{4}$$

$$\dot{\Delta} = \dot{\varepsilon}_\theta + \dot{\varepsilon}_\varphi \tag{5}$$

In real simulation, formula (1) can be taken many forms. In general, formula (1) is taken as a periodic function in space. For example, in the study, we specify the functions as

$$\begin{cases} u_\theta = \text{-}4\sin(2(\theta + 20.0^0)) + 2\cos(3\varphi) \\ u_\varphi = \text{-}2\sin(3(\theta + 10.0^0)) + 4\cos(2\varphi) \end{cases} \tag{6}$$

According to Eq. (6), we could generate velocity vector at the point where the GPS station was deployed in the Chinese Continent as in the paper of Zhu and Shi (2011). Thus, 1202 points of data were produced, mainly located inside Chinese territory. When calculation, we should pay special attention to equation (6), in which 20.0° and 10.0° represent 20.0 degree and 10.0 degree, respectively, and thus the units of θ, φ are also degree, but they are radian when in derivative calculations. With the 1202 points of surface velocity data, we calculate the strain rates in and around the Chinese Continent by means of method proposed by Zhu et al.(2005, 2006), the principle strain rates are plotted in Figure 1.

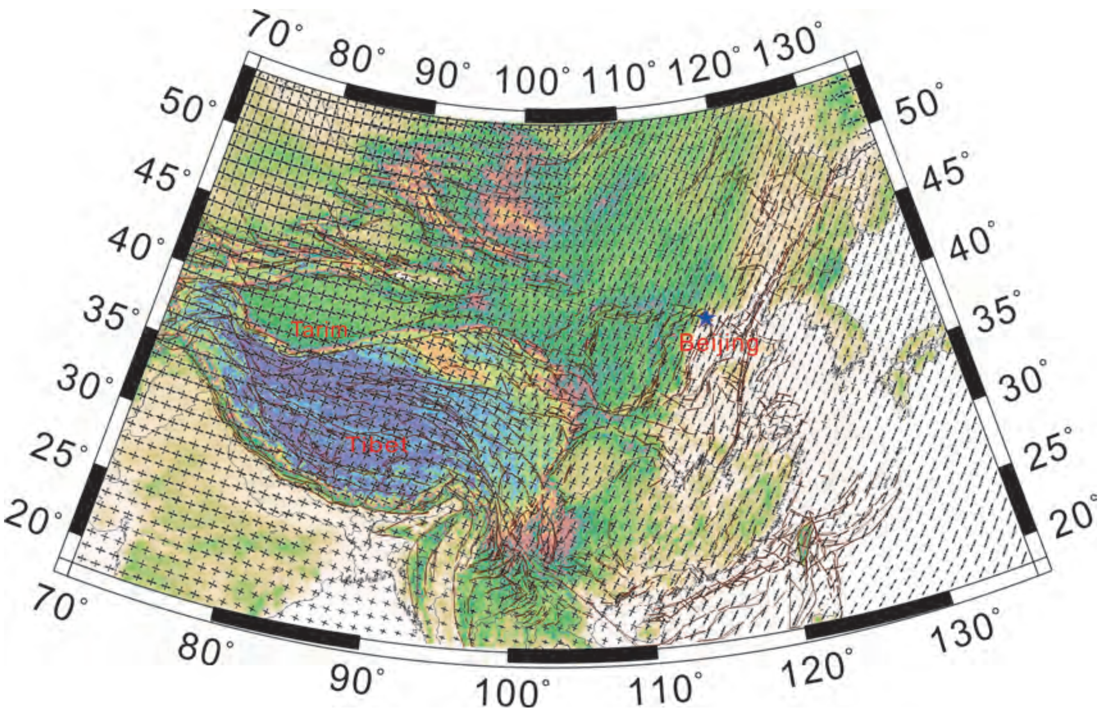


Figure 1. Map of principal strain rates calculated by means of the methods of Zhu et al.(2005, 2006) in the Chinese continent and adjacent areas. Principal strain rates are shown in the regular grid of 1.0°×1.0° (the arrow outward denotes tensile, and the inward one compressive). We should note that the scale is not given for the strain rate in the figure with the purpose of comparing with

Figure 2 in the following.

At the same time, we calculated the strain rates by means of mathematical operations according to equations (2)-(6) in the Chinese continent. Then, the theoretical principal strain rates, namely real strain rates, are plotted in Figure 2. Comparing the strain rates in Figure 2 with that of in Figure 1, obviously we could see the two results are almost the same except outside of the Chinese territory where no data of GPS stations are available.

As a matter of fact, we constructed many types of functions like equation (3) with different wavelengths in the research, Figures 1 and 2 are just some typical results. Through extensive digital experiments, we found that Zhu's method to calculate strain rates based upon GPS data is stable and accurate, particularly in the circumstance where GPS stations are not uniformly distributed in space.

In the following section, we will calculate the strain rates in the area of Tohoku, Japan, prior to the coming 2011 Tohoku-Oki earthquake.

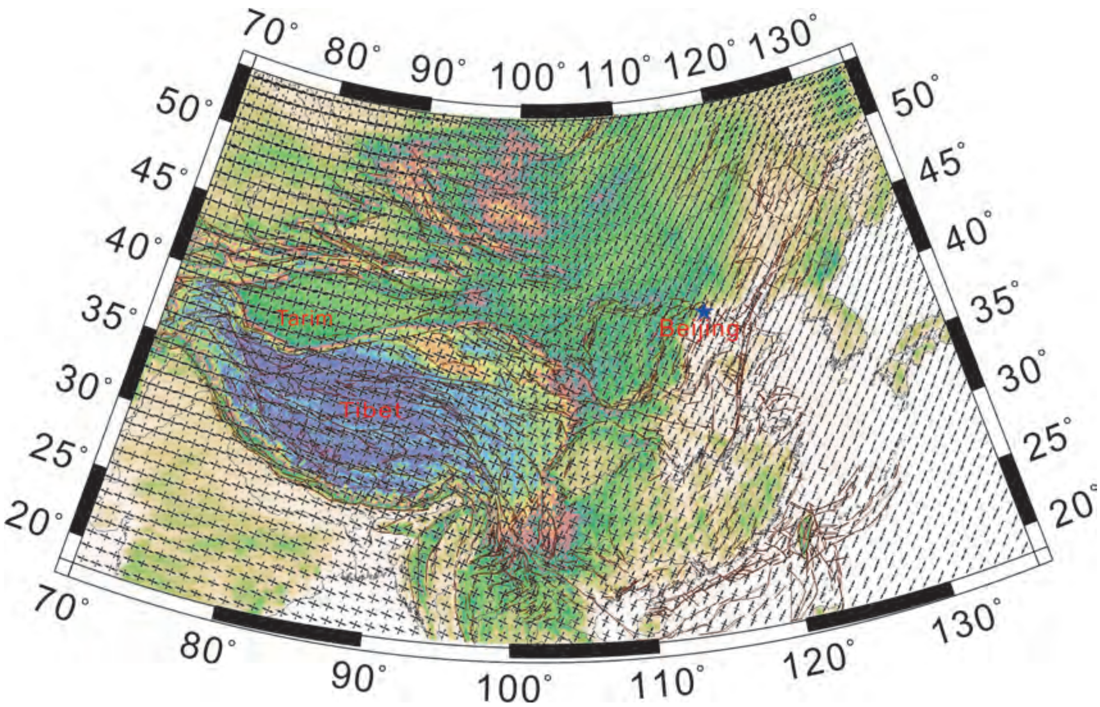


Figure 2. Map of theoretical (or real) principal strain rates in the Chinese continent and adjacent areas. Principal strain rates are shown with the grid density of 1.0°×1.0° (the arrow outward denotes tensile, and the inward one compressive).

However, from the viewpoint of mathematics, the above verification is not complete, which needs further research. Nevertheless, through digital verification we could understand the overall behaviors of the approach in calculating strain rate. It is expected that a better method will be developed in the near future.

3. GPS DATA

To monitor the crustal movements of the Japanese islands, a nation-wide dense GPS network has been operated by the Geographical Survey Institute of Japan since 1996. According to the continuous recordings of GPS stations day by day, we derived GPS data in each day, and present the spatial distribution of displacements at each GPS site. In Figure 3 is shown the distribution of GPS displacements at 163 stations in Tohoku area varying day after day in 30 days before the 2011 Tohoku Oki earthquake. From these 30 sub-figures, we could see clearly the GPS displacements are almost the same from 30 days to 1 day before the mainshock. We could see from Figure 3 that the area of Tohoku, Japan, is in the compressive regime because of the subduction of Pacific Plate to the Japanese Island. In addition, the figures show the magnitude of GPS displacement is very large, to be tens of centimeters. However, hardly could we see any changes of the displacements at each GPS stations in 30 days although, in this period of time, the Mw7.3 event occurred 2 days before the 11 Mar., 2011 Tohoku earthquake. Therefore, no further useful information can be obtained from these displacement figures.

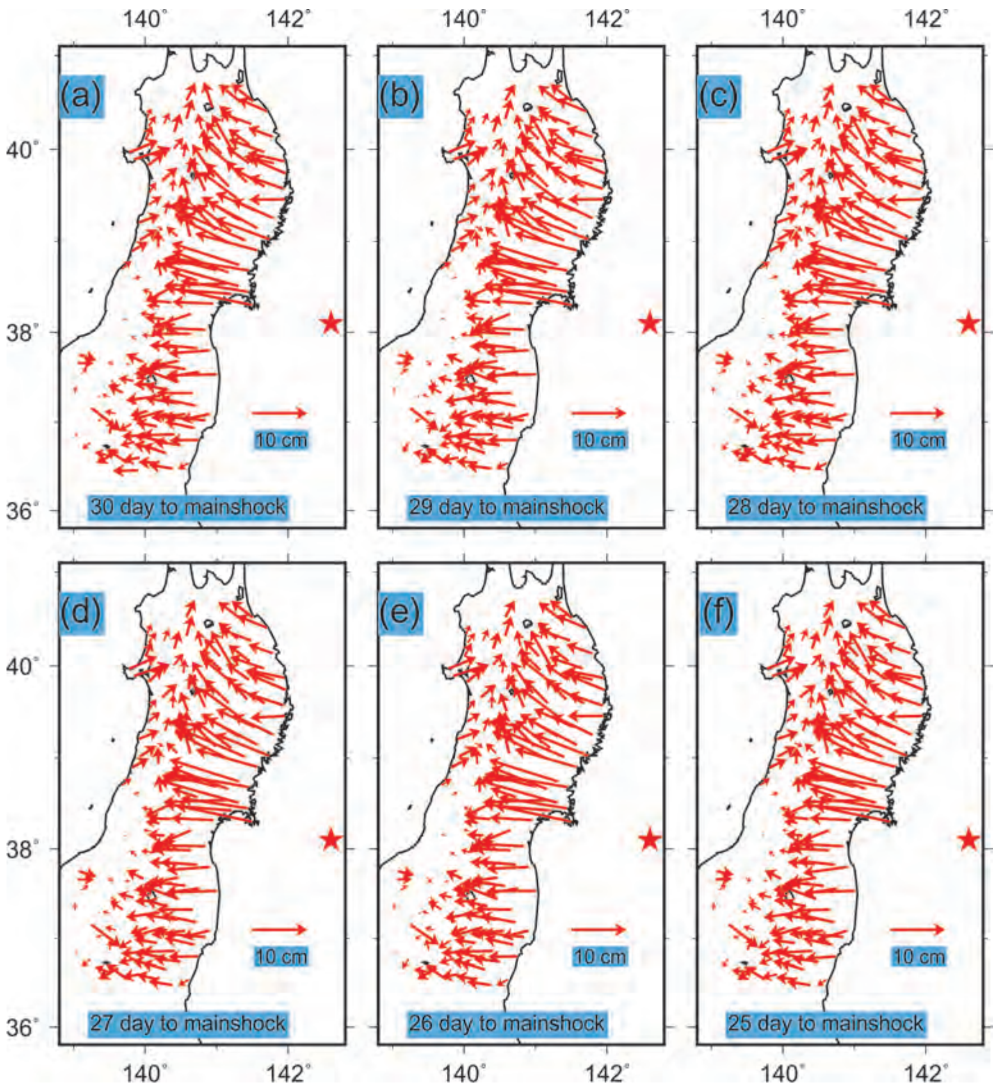
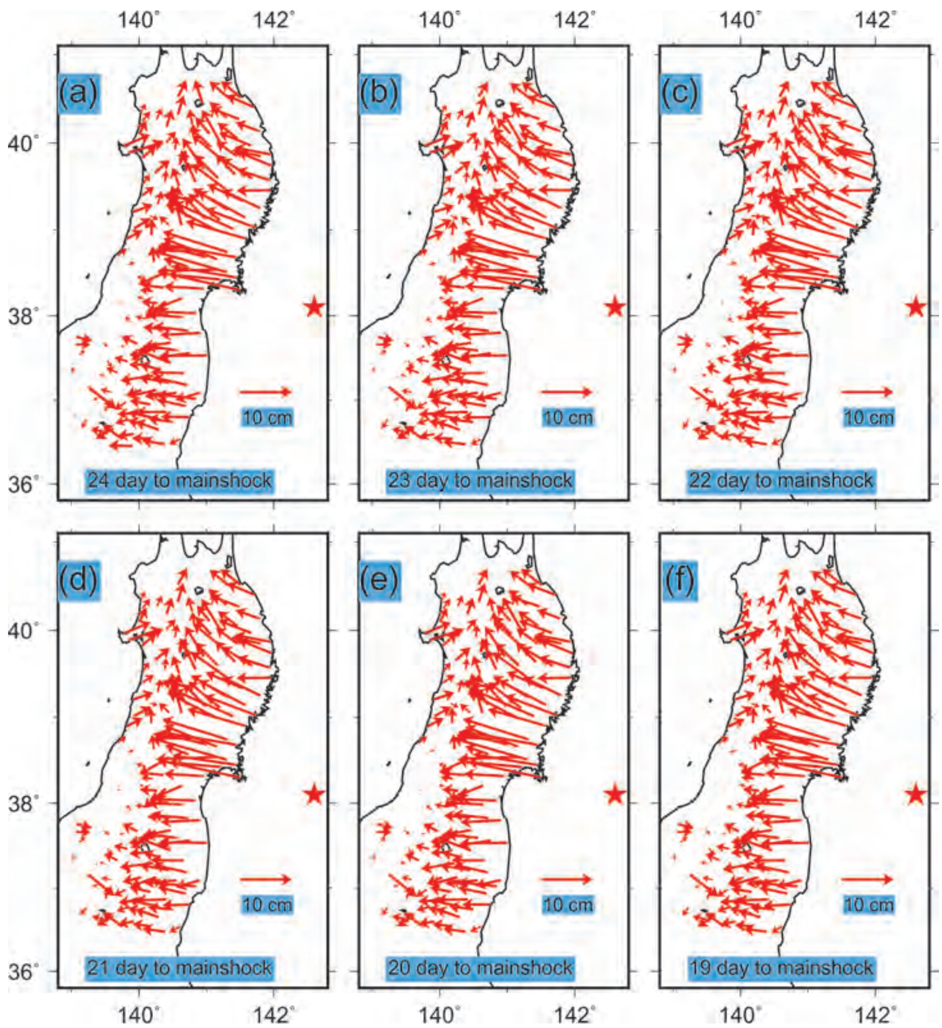


Fig. 3-1



(a)
(b)
(c)
(d)
(e)
(f)
140°
142°
40°
38°
36°
10 cm
24 day to mainshock
23 day to mainshock
22 day to mainshock
21 day to mainshock
20 day to mainshock
19 day to mainshock

Fig. 3-2.

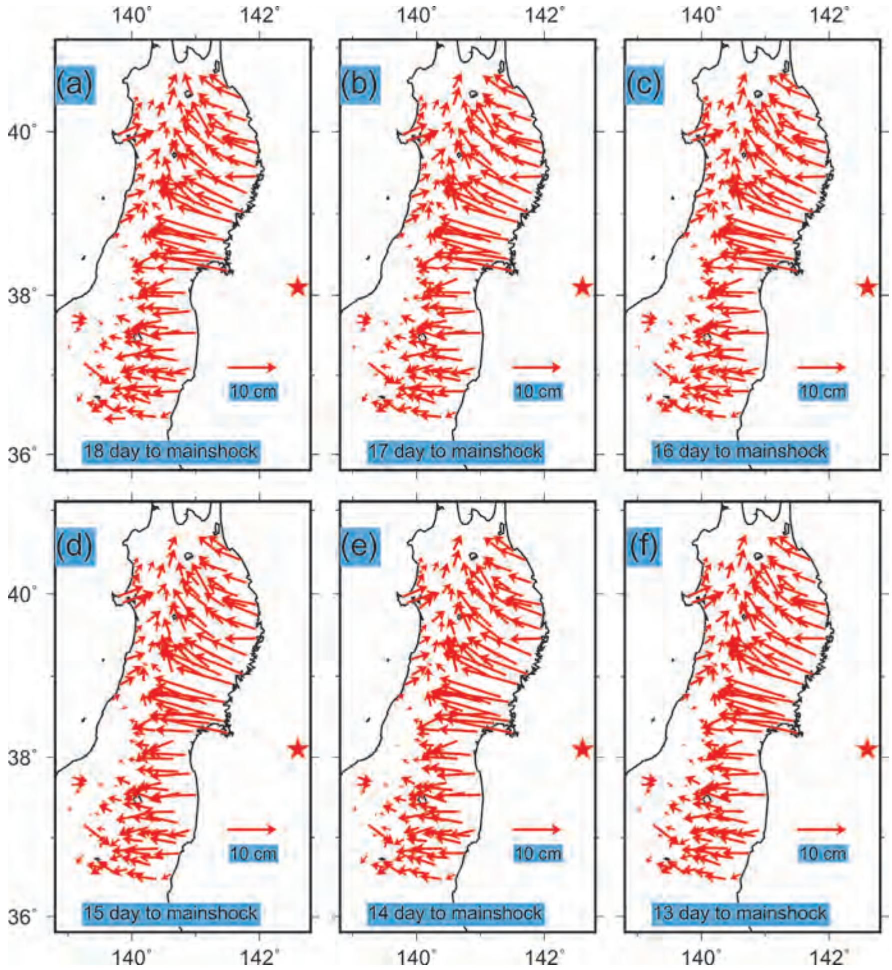
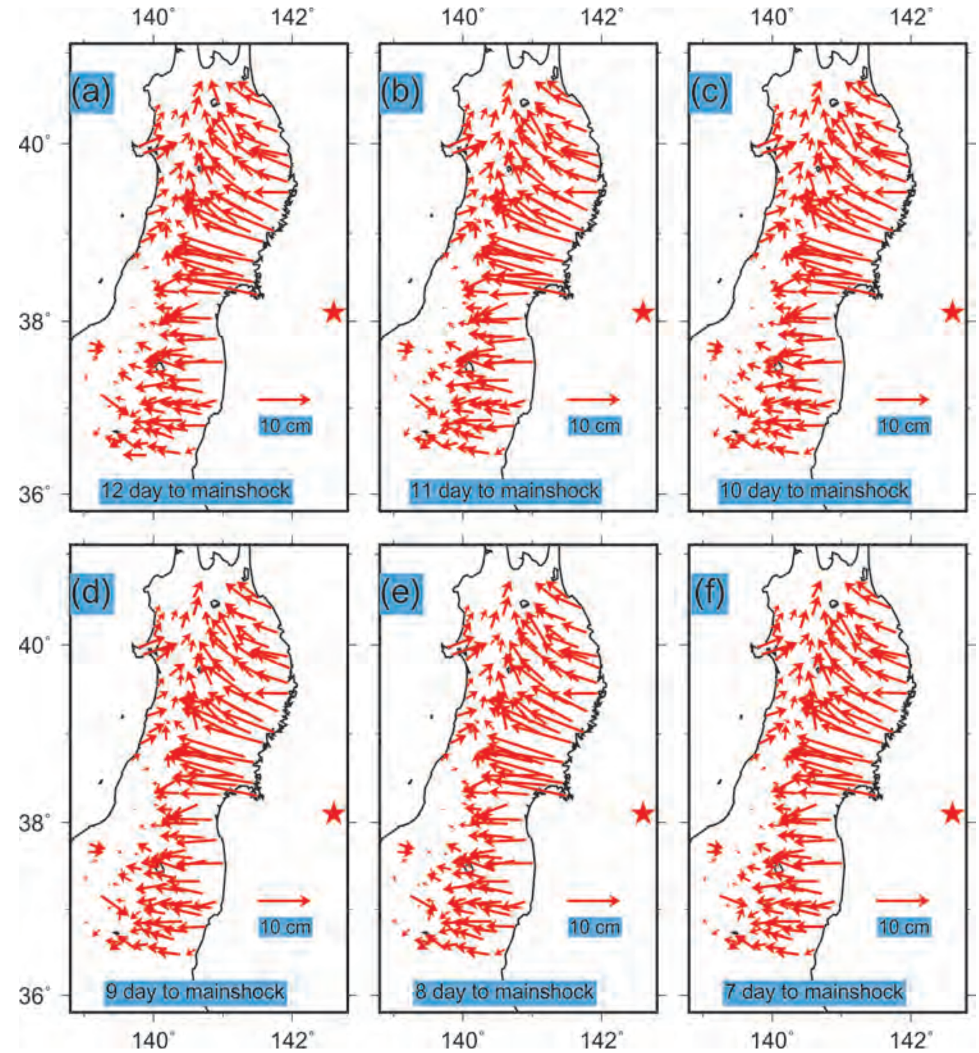

140°
142°
40°
38°
36°
(a)
10 cm
18 day to mainshock
(b)
10 cm
17 day to mainshock
(c)
10 cm
16 day to mainshock
(d)
10 cm
15 day to mainshock
(e)
10 cm
14 day to mainshock
(f)
10 cm
13 day to mainshock

Fig. 3-3



(a)
(b)
(c)
(d)
(e)
(f)
140°
142°
40°
38°
36°
10 cm
12 day to mainshock
11 day to mainshock
10 day to mainshock
9 day to mainshock
8 day to mainshock
7 day to mainshock

Fig. 3-4

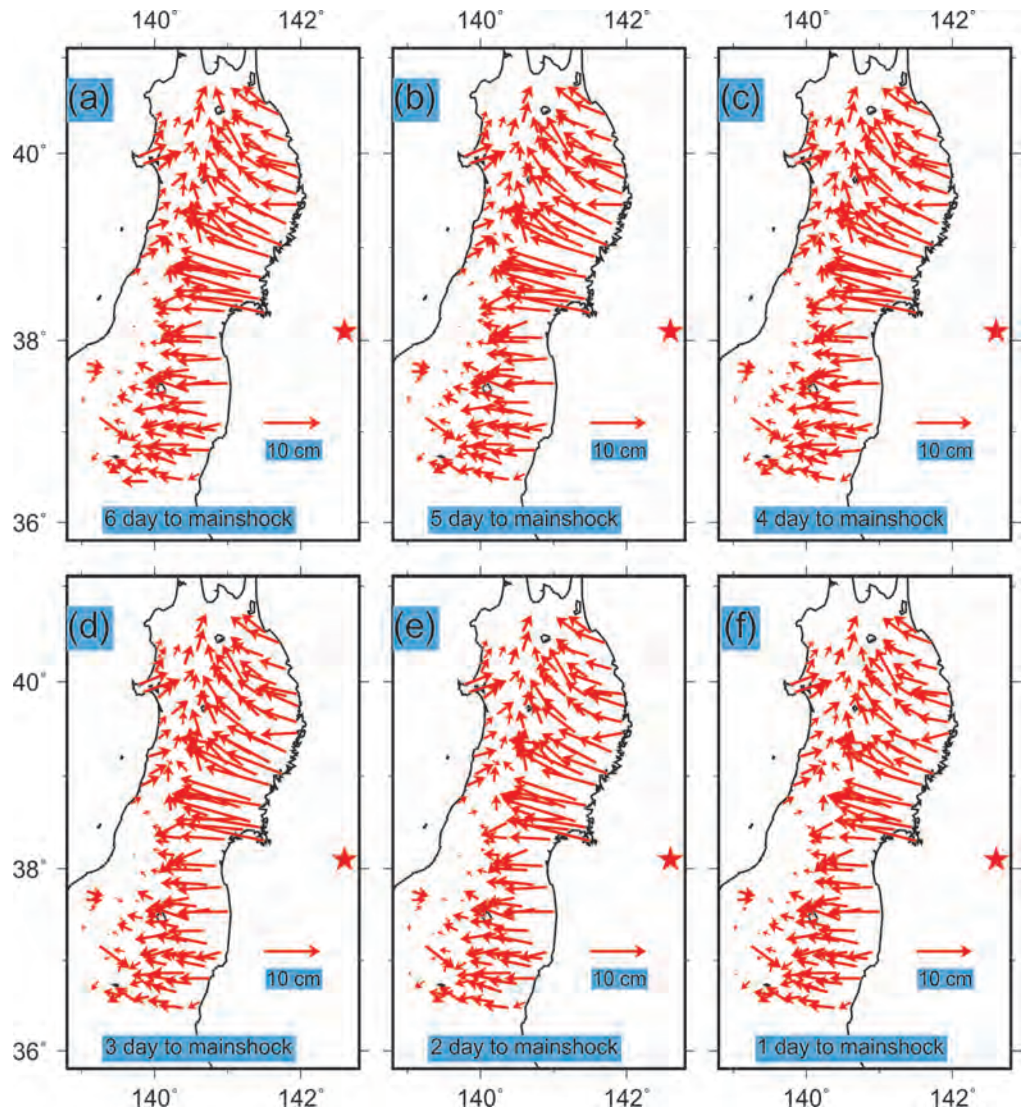


Fig. 3-5

Figure 3. Distribution of GPS displacements at 163 stations in Tohoku area. Red star denotes the epicenter of the 2011 Tohoku-Oki earthquake.

4. RESULTS

(1) Spatial distribution of strain rates

Fig. 4-1

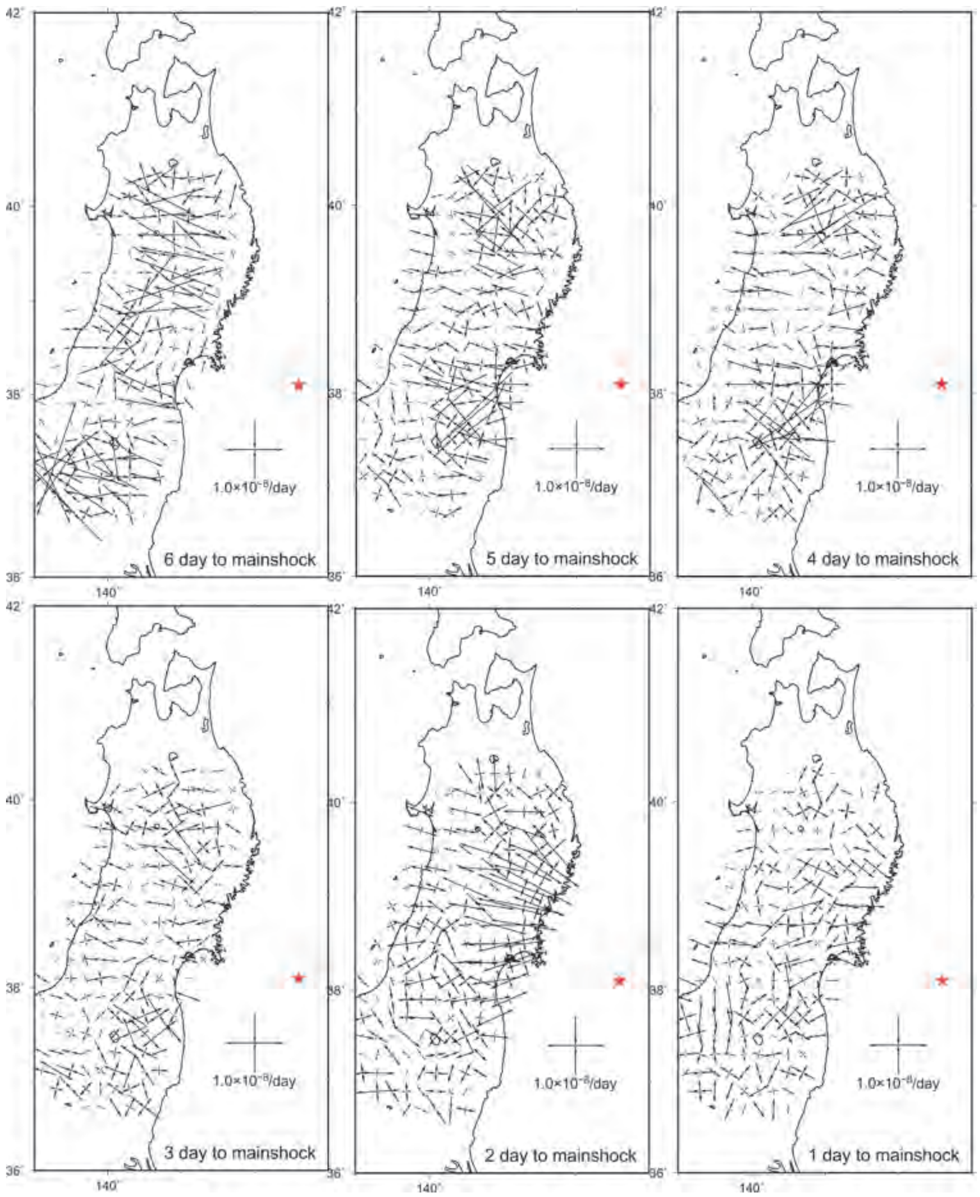


Fig. 4-2

Figure 4. Distribution of principal strain rates before the 2011 Tohoku Main shock. The arrow inward denotes compressive, outward denotes tensile strain rate.

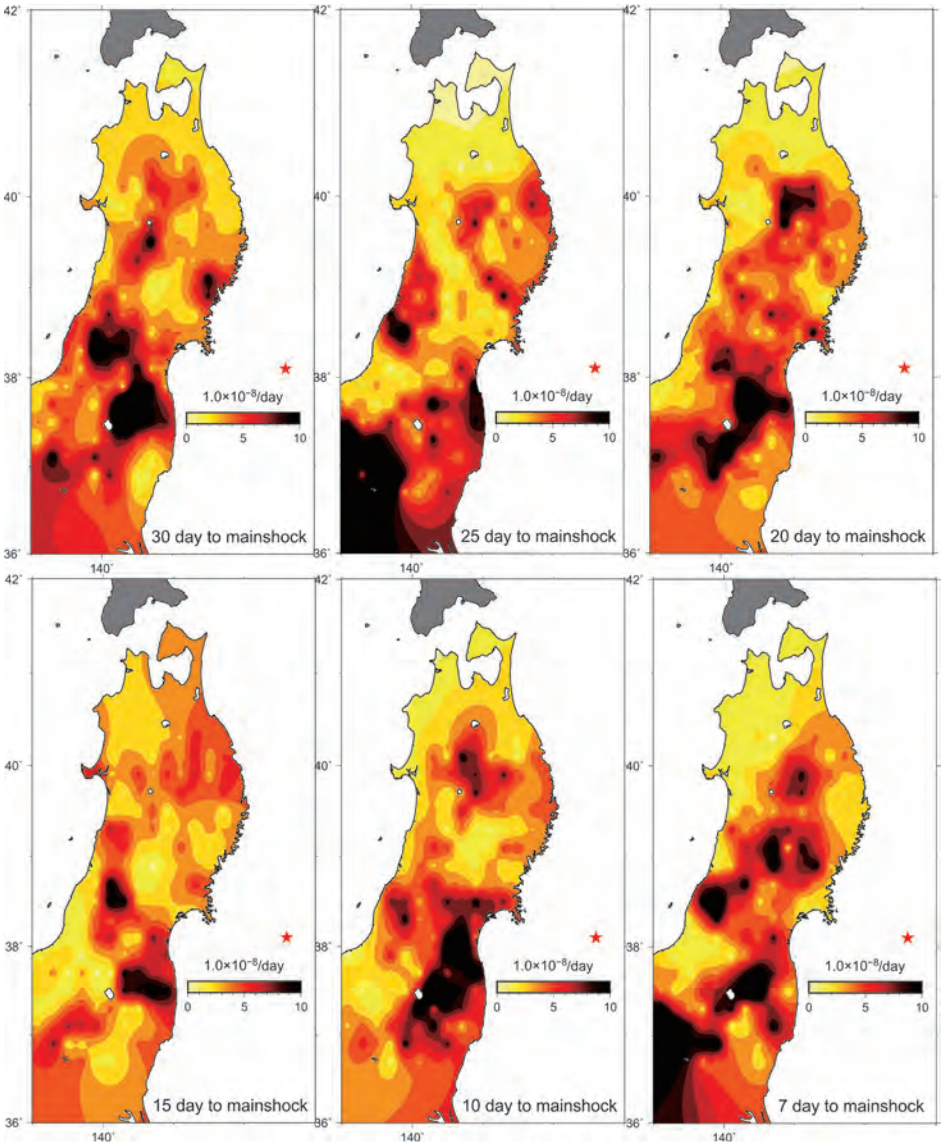

42°
40°
38°
36°
140°
1.0×10⁻⁸/day
0
5
10
30 day to mainshock
25 day to mainshock
20 day to mainshock
15 day to mainshock
10 day to mainshock
7 day to mainshock

Fig. 5-1

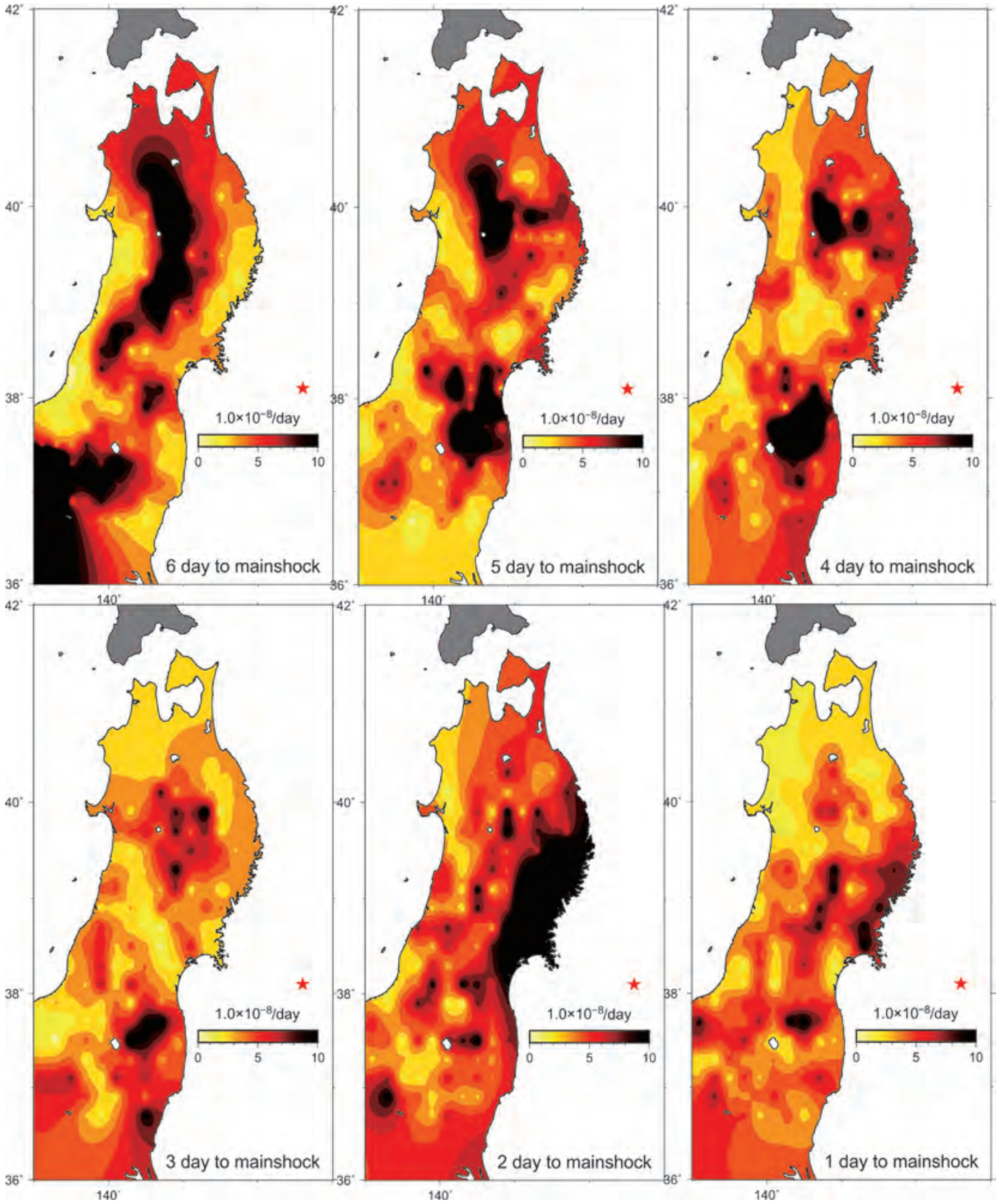


Fig. 5-2

Figure 5. The distribution of maximum shear strain rates before the 2011 Tohoku Main shock.

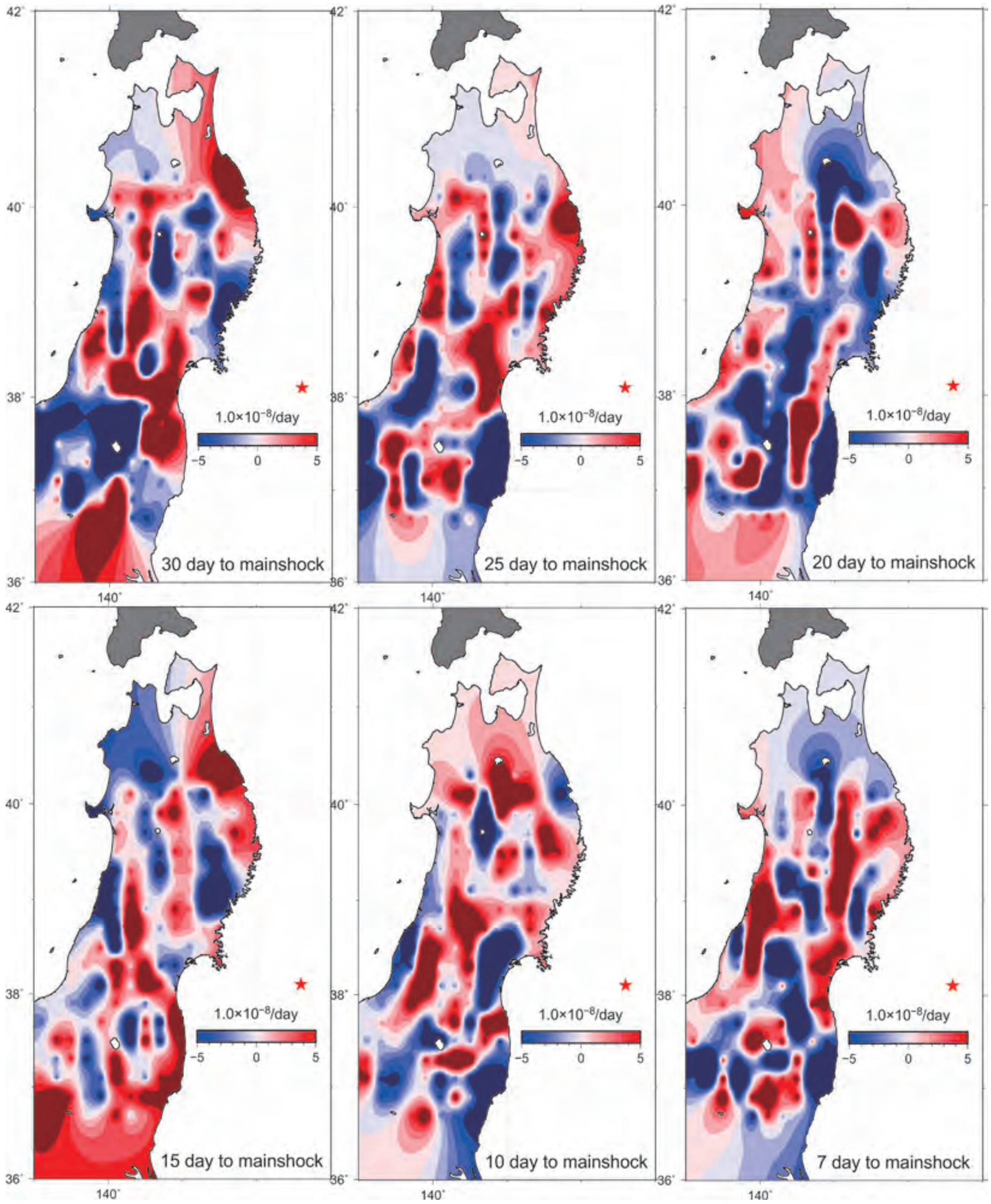

30 day to mainshock
25 day to mainshock
20 day to mainshock
15 day to mainshock
10 day to mainshock
7 day to mainshock
1.0×10⁻⁸/day
−5
0
5
42°
40°
38°
36°
140°

Fig. 6-1

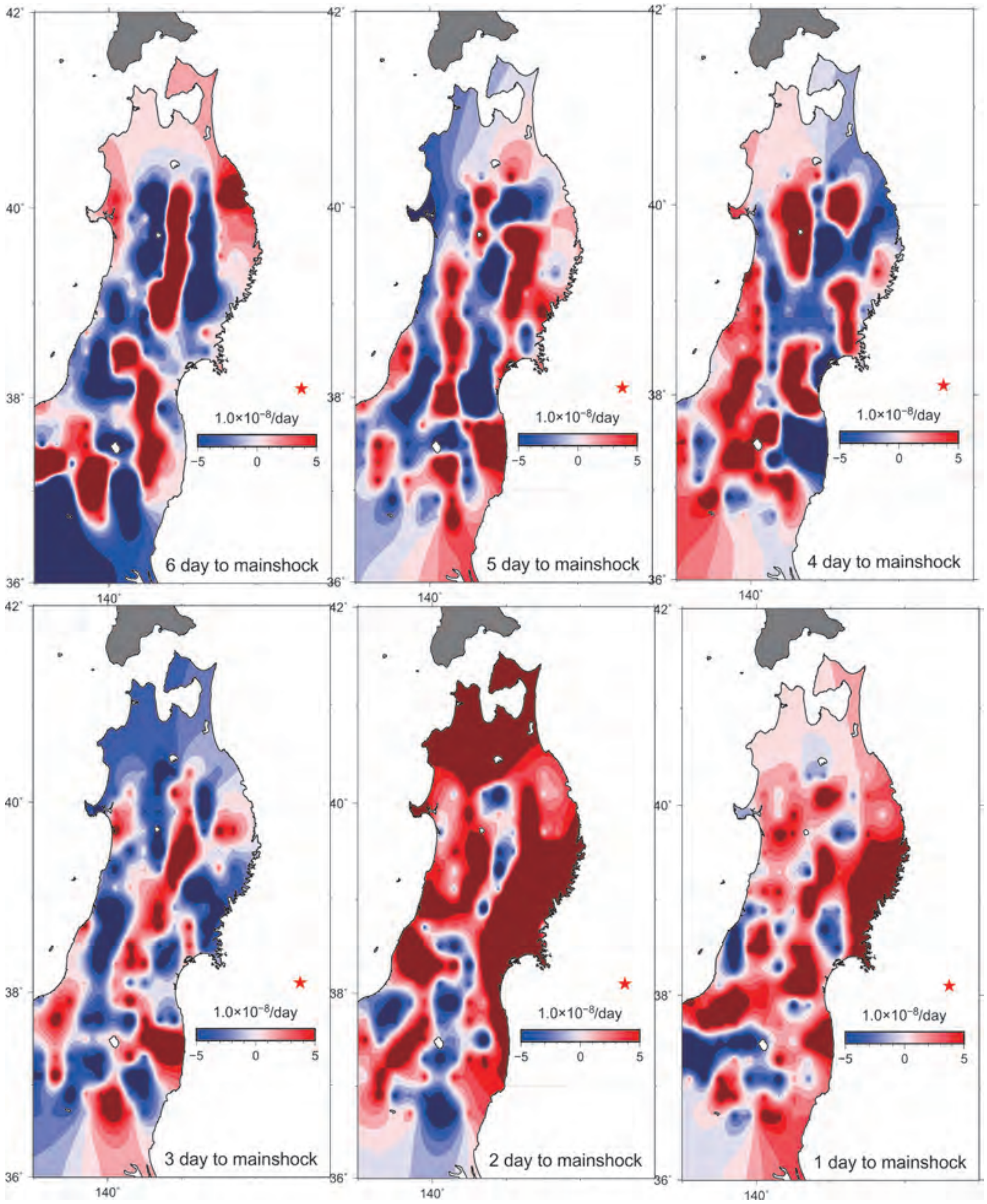


Fig. 6-2

Figure 6. The distribution of the surface dilation rates before the 2011 Tohoku Main shock.

To uncover more deformation anomalies before the mainshock, we calculate the strain rates based on the GPS velocities shown in Figure 4 by means of the method proposed by Zhu et al.(2005,2006). Figure 5 depicts the distribution of principal strain rates in Tohoku area, Japan. In general, the principal strain rates are much different from those in interseismic period in which principal strain is dominated by east-west compression (Kato et al., 1998; Sagiya et al., 2000; Miura et al., 2004). The principal strain rate before the 2011 mainshock turns to be tensional. It is suggested that strain regime would change before large earthquakes. Therefore, it is important to monitor surface deformation in capturing seismic anomaly which is helpful in earthquake prediction.

Figure 6 presents the distribution of maximum shear strain rates before the 2011 Tohoku Main shock. The high value of the maximum shear strain rates changes with time and space, possibly as a result of foreshocks and the preparatory process of the mainshock.

Figure 7 shows the surface dilation rates before the 2011 Tohoku Main shock. Basically, dilatation rate can be considered as representative of horizontal deformation related to dip-slip faulting (Sagiya et al., 2000). What kind of association between dilatation rates and earthquakes need further research.

5. CONCLUSIONS

An approach is proposed in this paper which can verify the method to calculate strain rate based on GPS measurement. It is found that the Zhu's method in computation of strain rates is stable and accurate.

The GPS velocities with 30 days before the coming 2011 Tohoku-Oki earthquake, derived from continuous GPS displacement, uncover some surface deformation anomalies before mainshock, which is helpful to illuminate preparatory processes for earthquake generation.

The strain rates calculated with GPS vectors in 30 days before the mainshock are much different from those in the period of interseismic phase, possibly due to foreshocks and the preparatory process of the mainshock.

GPS measurements densely distributed in space and in time will be useful in the research of earthquake prediction.

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