CRUSTAL DEFORMATION OF THE MID NIIGATA REGION DERIVED FROM GPS MEASUREMENTS ASSOCIATED WITH THE 2004 CHUETSU, THE 2007 CHUETSU-OKI, AND THE 2011 M_W 9.0 TOHOKU-OKI EARTHQUAKES

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ABSTRACT

The published F3 final daily coordinate solutions from GEONET (GPS Earth Observation Network) were analyzed to investigate the crustal deformation of the Mid Niigata (Chuetsu) region associated with the 2004 M6.8 Chuetsu, the 2007 M6.8 Chuetsu-oki, and the 2011 M_w 9.0 Tohoku-oki earthquakes. This kind of study is important to understand the effect of large earthquakes on surrounding faults, to have information about how the conditions of fault failure have been changed and eventually to progress the long-term forecast of crustal processes. High strain rates were estimated after the 2011 Tohoku-oki earthquake in the Mid Niigata region as well as in eastern Japan. We inferred that the deformation field of the Mid Niigata region is generally controlled by the west-east contraction due to the interactions between the Amurian and the Pacific plates. We found the strain redistribution in the period between the 2004 and the 2007 events. Since between the 2004 and the 2007 earthquakes significant seismic event was not observed in the Mid Niigata region, we interpreted this strain redistribution as a slow slip event with representation of a single, rectangular fault.

Keywords: Coseismic step, Displacement rate, Dilatation, Shear strain

1. INTRODUCTION

Previous crustal deformation studies in Japan based on GPS measurements have been done by several researchers (Sagiya et al., 2000; Iinuma et al., 2005; Ohta et al., 2008). In the research which has been done by Sagiya et al. (2000), it was pointed that a strain concentration zone with considerable width extends from Niigata to Kobe. This deformation belt is named Niigata-Kobe Tectonic Zone (NKTZ). Here the crust is contracting in the NW-SE direction and a similar contraction is likely to occur in the Chuetsu region which is located in the northern part of the NKTZ (Iinuma et al., 2005). Normal faults which were formed at the stage of extensional stress regime have been subsequently activated as reverse faults during shortening in the eastern margin of the Japan Sea in the past 3.5 Ma (Okamura et al., 1995; Ikeda et al., 2002; Sato et al., 2004). The 1964 M 7.5 Niigata earthquake, the 2004 M 6.8 Mid-Niigata Prefecture (Chuetsu) and the 2007 M 6.8 Niigata-ken Chuetsu-oki earthquakes ruptured such reverse faults. The dense GPS network in Japan enables us to calculate co-seismic strain and stress changes from observed data.

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2. THEORY AND METHODOLOGY

2.1 Displacement Rate Analysis

We estimated the displacement rate of GPS stations based on daily coordinate solutions (F3). In order to do this we fitted the following function to daily time series data of the *i*-th coordinate component of the *n*-th station.

$$x_n^i(t) = a_n^i + b_n^i t + c_n^i \, sin(2\pi t) + d_n^i \, cos(2\pi t) + \sum_{k=1}^{m} e_{n,k}^i H\big(t - t_n^k\big) \quad (1)$$

Here, the first two terms on the right side correspond to a linear trend, the next two terms to a sinusoidal annual variation, and the last term to coseismic steps. Coseismic steps are described as a sum of Heaviside functions, $\sum_{k=1}^{m} e_{n,k}^i H\big(t - t_n^k\big)$ where $e_{n,k}^i$ is a magnitude of the *k*-th step which occurred at t_n^k. The coefficient b_n^i is an estimate of displacement rate. We applied this expression to all three components separately, and estimated displacement rate components for all stations by solving least-squares problems (Sagiya et al., 2000).

2.2 Strain Rate Analysis

Using the method by Shen et al. (1996) we have calculated strain rates as a continuous function within the entire network. It is assumed that the strain rate field is uniform at each location. We applied the least squares inversion method to velocity solutions of all stations and their covariances to solve for six parameters: horizontal velocity components, rotation rate, and strain rate components. Then maximum shear strain rate and the dilatation rate were derived from the three strain rate components. The strain rate modeling algorithm can be written in the following form:

$$\begin{pmatrix} U \\ V \end{pmatrix} = \begin{bmatrix} 1 & 0 & \Delta x_i & \Delta y_i & 0 & \Delta y_i \\ 0 & 1 & 0 & \Delta x_i & \Delta y_i & -\Delta x_i \end{bmatrix} \begin{bmatrix} u \\ v \\ \dot{e}_{xx} \\ \dot{e}_{xy} \\ \dot{e}_{yy} \\ \omega \end{bmatrix} + \begin{pmatrix} \varepsilon_x^i \\ \varepsilon_y^i \end{pmatrix} \quad (2)$$

where (U, V) – displacement rate observed at a station which is located at point **X**=(X, Y). (u, v) – horizontal displacement rate components, $\dot{e}_{xx}, \dot{e}_{xy}, \dot{e}_{yy}$ – strain rate components and ω - rotation rate are to be calculated at a particular point $\boldsymbol{x}_i = (x_i, y_i)$. $\Delta x_i = X - x_i$, and $\Delta y_i = Y - y_i$ and $\dot{e}_{xy} = \frac{1}{2}(\partial u/\partial y) + (\partial v/\partial x)$. $(\varepsilon_x^i,\ \varepsilon_y^i)$ are the observational errors and they are weighted depending on the distance between the observation point *X* and the calculation point x_i in the following formula.

$$\varepsilon_{x,y}^i = \sigma_{x,y}^i \exp(\Delta R_i^2/2D^2) \quad (3)$$

Here, $\sigma_{x,(y)}^i$ is an original observational error of the *x* (or *y*) component of the displacement rate, $\Delta R_i = |X - x_i|$, and D is a parameter which controls weight among the observations and is called the Distance Decaying Constant (DDC). It depends on tectonic deformation features and density of observational points. Then we used the following formulas to calculate dilatation rate Δ and shear strain rate Σ at each point.

$$\Delta = \dot{e}_{xx} + \dot{e}_{yy}$$

$$\Sigma = \sqrt{\dot{e}_{xy}^2 + (\dot{e}_{xx} - \dot{e}_{yy})^2/4} \qquad (4)$$

3. RESULTS AND DISCUSSION

3.1 Displacement rate results

We calculated displacement rate distributions using daily coordinates from 2002 to 2006, namely two years before and after the 2004 M 6.8 Chuetsu and from 2005 to 2009 for the 2007 M 6.8 Chuetsu-oki earthquakes which occurred in our study area. In addition, in order to see the impact of the big seismic event such as the 2011 M_W 9.0 Tohoku-oki earthquake on a deformation pattern of our target area we also have calculated displacement rates from 2009 to 2012, two years before and one year after this earthquake.

3.2 Strain rate results

To make our results independent from reference frame and to be able to discuss deformation field related to local crustal processes we performed strain rate analyses. In our calculations we applied 20 km as a value of Distance Decaying Constant.

From comparison of all dilatational and maximum shear strain results for all time-periods except after the great 2011 Tohoku-oki earthquake we can conclude that they represent almost the same pattern. Previously, found by Sagiya et al. (2000) continuously high (over 0.1 micro-strain/year) strain rate zone which starts from around the Japan Sea coast near Niigata and continues to Kobe (Niigata-Kobe Tectonic Zone) can be clearly seen from our results. In addition, low strain rates found at the Kanto area which is consistent with results of previous studies (Sagiya et al., 2000). Another high positive dilatational rate (over 0.2 micro-strain/year) is estimated at Izu Peninsula. This can be interpreted as a result of volcanic activity due to the plate interaction near the northern end of the Philippine Sea plate. After the great 2011 Tohoku-oki earthquake the deformation pattern of Japan significantly changed (Figure 1b). Compressional deformation pattern changed to extensional almost all over the Japanese islands (Figure 1). Although principal strain axes before this event show the west-east contraction, whereas they changed to the west-east extension after the event.

The calculated dilatation and strain rate distributions for the 2011 Tohoku-oki earthquake are slightly different from each other (Figure 1b and Figure 2b). However, both plots show high strain rates over 0.7 micro-strain/year from Mid Niigata to northernmost Aomori. As we mentioned above before the 2011 Tohoku-oki earthquake high strain rates over 0.1 micro-strain/year can be seen at Niigata-Kobe Tectonic Zone except at the Izu Peninsula (Figure 2a).

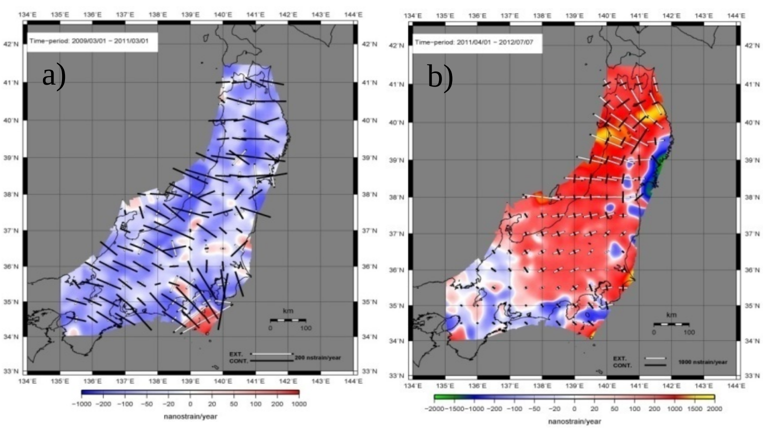

Figure 1. Dilatation rate distributions and corresponding principal strain axes two years before (a) and after (b) the 2011 M_W 9.0 Tohoku-oki earthquake.

However, after this event strain rates 2-4 micro-strain/year still high in eastern Japan (Figure 2b). Before the 2011 Tohoku-oki earthquake the strain rates at the Chuetsu region were between 0.1-0.2 micro-strain/year (Figure 2a). After the 2011 event the strain rate at the Chuetsu region increased to 0.7-0.9 micro-strain/year

(Figure 2b). This big difference of strain rates shows that it will require a long time to go back to the previous deformation pattern of Japan.

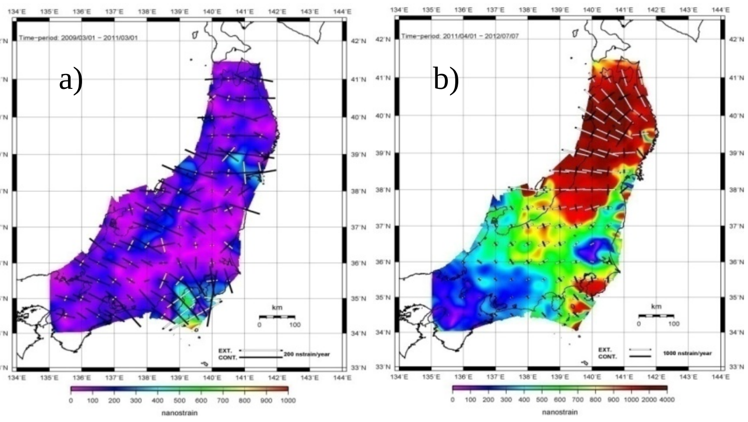

Figure 2. Strain rate distributions and corresponding principal strain axes two years before (a) and after (b) the 2011 M_W 9.0 Tohoku-oki earthquake.

From the above discussions we infer that the deformation field of our target area – Mid Niigata region is generally controlled by the west-east contraction due to the interactions between the Amurian and the Pacific plates. However, this kind of discussions could not represent local crustal processes occurring in such a small area as Chuetsu region. Thus, in order to understand crustal processes which have been the cause of the two notable earthquakes in this area we performed strain analyses with high resolution.

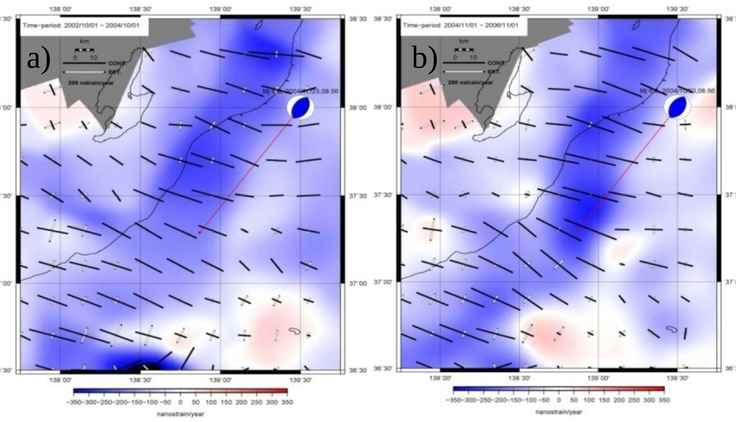

Figure 3. Dilatation rate distributions and corresponding principal strain axes two years before (a) and after (b) the 2004 M 6.8 Chuetsu earthquake.

Before the 2004 event we observed over 0.2 micro-strain/year contraction near the source region both in dilatational and maximum shear strain rate plots (Figure 3a; Figure 5a). However, during two years after this event high strain again has been accumulated at the source region of the 2004 event (Figure 3b; Figure 5b). Two years before the 2007 M 6.8 Chuetsu-oki earthquake, there was high contraction over 0.3 micro-strain/year at the source region of this event which is also reasonable (Figure 4a; Figure 6a).

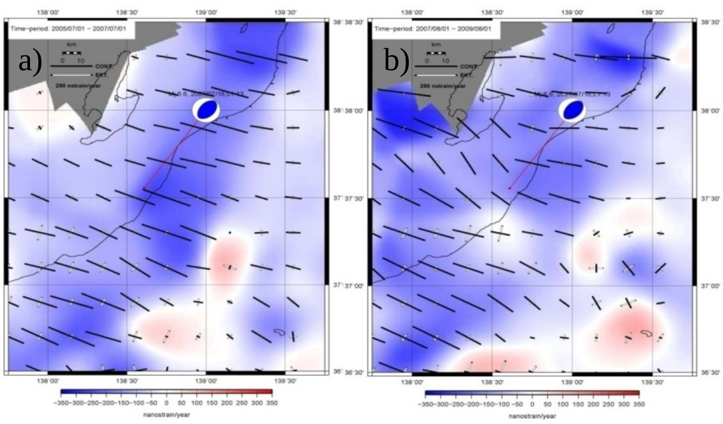

Figure 4. Dilatation rate distributions and corresponding principal strain axes two years before (a) and after (b) the 2007 M 6.8 Chuetsu-oki earthquake.

During two years after the 2007 event there was no significant strain accumulation near the source region and thus, we found the field has totally changed compared with the previous time-periods (Figure 4b; Figure 6b). The important point to note here is the period between the 2004 and the 2007 events. After the 2004 event we observed high strain rates at the source region of this event (Figure 5b). However, for the time-period of 2005-2007 we found that this pattern changed and a high strain zone shifted to the source region of 2007 event.

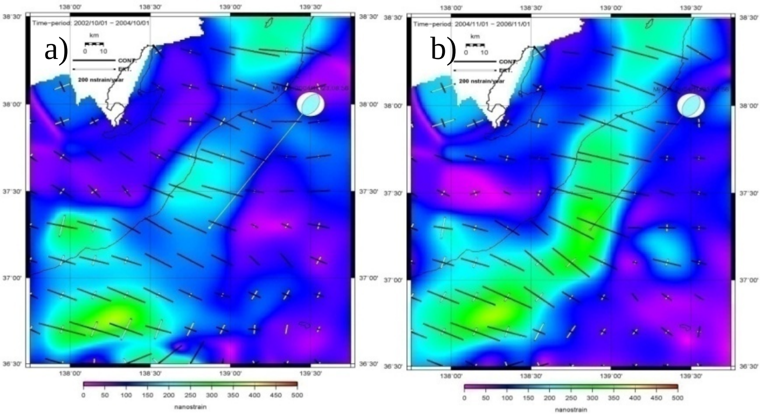

Figure 5. Strain rate distributions and corresponding principal strain axes two years before (a) and after (b) the 2004 M 6.8 Chuetsu earthquake.

The question is what happened during this period between the source regions of these two events. Since we did not observe a significant seismic activity between these two events, in order to answer to this important question we have calculated displacement rate distribution for this time-period and tried to interpret this as a slow slip event with representation of a fault (Figure 7).

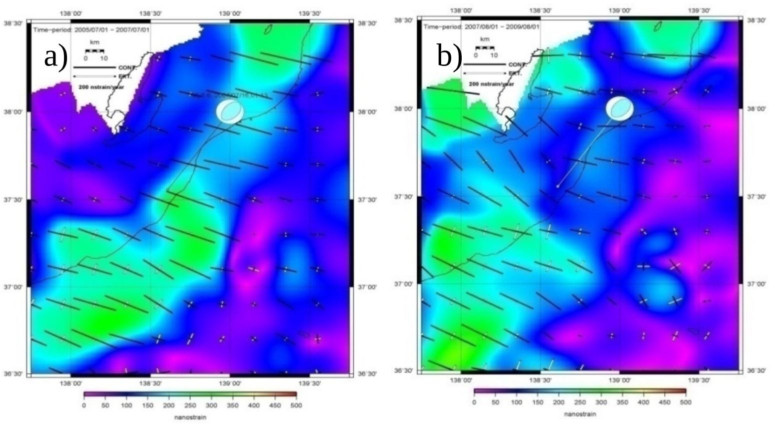

Figure 6. Strain rate distributions and corresponding principal strain axes two years before (a) and after (b) the 2007 M=6.8 Chuetsu-oki earthquake.

Theoretical crustal deformation was calculated based on horizontal component data by using a simple, rectangular fault model in an elastic half space (Okada, 1985). We used 0.25 as a value of Passion's ratio in our calculation. Our fault has a west dipping plane and lies about 8 km south-west from the source region of the 2004 Chuetsu earthquake. Assuming a rigidity of 30 GPa, we obtained moment magnitude M_w = 6.1 and the total amount of the slow slip for the period between events is estimated at 0.35 m. The estimated fault parameters are shown in Table 1.

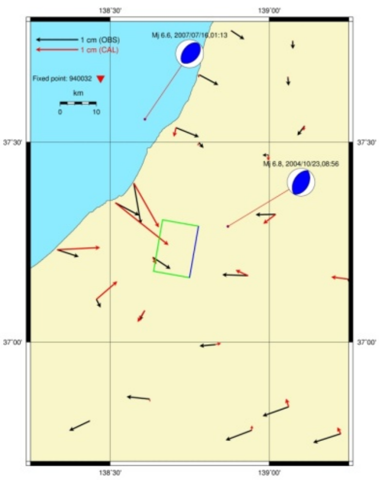

Figure 7. Observed (black arrows) and calculated (red arrows) displacement rate distribution for the interseismic period between the 2004 M 6.8 Chuetsu and the 2007 M 6.8 Chuetsu-oki earthquakes. Blue line shows the surface trace of the simplified fault model and the green line represents the 9-km depth position of the fault for a 32 degree dip angle.

Table 1. Estimated fault parameters of proposed slow-slip event for the interseismic period between the 2004 M 6.8 Chuetsu and the 2007 M 6.8 Chuetsu-oki earthquakes.

Latitude (deg)	Longitude (deg)	Depth (km)	Strike (deg)	Dip (deg)	Rake (deg)	L (km)	W (km)	Slip (m/year)	M_w
37.29	138.778	9.0	190	32	79	14.50	12.0	0.13	6.1

4. CONCLUSIONS

We found significant strain rate changes in eastern Japan due to the 2011 Tohoku-oki earthquake. Strain rates in the Chuetsu region before and after the 2011 Tohoku-oki earthquake were also calculated. We inferred that the deformation field of our target area – Mid Niigata region is generally controlled by the west-east contraction due to the interactions between the Amurian and the Pacific plates. We found strain redistribution in the period between the 2004 and the 2007 events. We tried to interpret this strain pattern change by a slow slip event with representation of a fault. We estimated the fault area to be 14.5 $\times$ 12 km^2. The strike, the dip and the rake of the source were estimated at 190°, 32°, 79° respectively. The depth of the upper edge of the fault was found as 9 km. Assuming a rigidity of 30 GPa, we obtained moment magnitude $M_w = 6.1$ and the total amount of the slow slip for the period between events is estimated at 0.35 m.

5. RECOMMENDATION

Since 1998 Geology Institute of Azerbaijan National Academy of Sciences has started the monitoring of crustal processes and currently Azerbaijan GPS network consists of 3 continuous GPS stations and 35 campaign survey points, which are not enough for the discussions of the deformation field. Therefore, it is needed to increase number of continuous GPS stations in order to be able to monitor time-dependent deformation all over the region and to get better resolution of deformation field.

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