Co- and post-seismic slip associated with the 2005 Miyagi-oki earthquake (M7.2) as inferred from GPS data

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Abstract:

A large earthquake with M7.2 occurred on August 16, 2005 along the plate boundary off Miyagi Prefecture. Co- and post-sesimic deformations associated with this event were investigated to reveal the causal interplate slips using continuous GPS data and geodetic inversion. The coseismic slip distribution shows good agreement with that estimated by seismic waveform inversions. The major slip area is limited to the southeastern part of the rupture area of the previous 1978 event. The postseismic slip extended uni-laterally to the south of the coseismic slip area. These distinctive features of both the co- and post-seismic slips might be caused by the existence of the locked plate interface, where seismogenic stress has not released yet, in the northern and southwestern parts of the 1978 rupture area.

Key words: GPS, asperity; subduction zone; interplate earthquake; slip distribution

1. Introduction

Northeastern Japan, where the Pacific plate is subducting at a rate of about 80 mm/yr beneath the overriding continental plate, is one of the most active areas in seismicity in the world. Various studies on major interplate earthquakes around this area have revealed that some of those events can be regarded as recurrent ruptures of asperities, which are defined by distributed patches showing large coseisimc slips (Nagai et al., 2001; Matsuzawa et al., 2002; Okada et al., 2003; Yamanaka and Kikuchi, 2003, 2004; Hasegawa et al., 2005).

Earthquakes with magnitudes of about 7.5 or larger have repeatedly occurred on the plate boundary east off Miyagi Prefecture (Miyagi-Oki) with an interval of about 37 years. The most recent one took place in 1978, i.e., the M7.4 Miyagi-oki earthquake (e.g., Seno et al., 1980). Based on historical records of these recurrent earthquakes, the Headquarters of Earthquake Research Promotion of Japan (HERP) stated that the next Miyagi-Oki earthquake will occur with a probability of about 50 % in the next 10 years (HERP, 2003). In response to this seismic hazard assessment, Tohoku University established 13 new continuous GPS stations around the source area of the 1978 event to complement the nationwide GPS network operated by the Geographical Survey Institute of Japan (GSI), GEONET (e.g.,. Miyazaki et al., 1997).

On August 16, 2005, there occurred an interplate earthquake with magnitude 7.2, hereafter referred to as the 2005 Miyagi-Oki earthquake. Okada et al. (2005) carried out the relocation of aftershocks of the 1978 and 2005 events to reveal that the aftershock area of the 2005 event is overlapped only with the southeastern part of that of the 1978 event. In addition, they performed the seismic waveform inversion for the 2005 event to estimate the coseismic slip distribution and found that it also overlapped with the southeastern part of the 1978 rupture area.

The surface displacement data derived by the dense GPS network demonstrate clear coseismic deformation together with minor postseismic one. In the present study, we use GPS data to estimate both co- and post-seismic slip distributions on the plate boundary by means of a geodetic inversion technique (Yabuki and Matsu'ura, 1992).

2. Data

A nation-wide GPS network, GEONET (GPS Earth Observation Network System), operated by the Geographical Survey Institute (GSI) of Japan, includes more than 1200 stations distributed all over Japan (Miyazaki et al., 1997) for the purpose of monitoring regional crustal deformation. GEONET data are routinely analyzed by using BERNESE software (Hugentobler et al., 2001), which is capable of estimating site coordinates by taking double differences of carrier phase between satellites and receivers to cancel out clock errors of both receivers and satellites. Recently, taking into account improved models and methods, a new strategy for data analysis has been applied to demonstrate that the root mean square coordinates are reduced by about 50 % comparing with the past analysis (Hatanaka et al., 2003). Daily coordinates obtained from this new analysis strategy are called F2 solutions and made public.

Tohoku University has also been conducting continuous GPS observations in the Tohoku district, the northeastern part of Honshu island of Japan, since 1987 (Miura et al., 1993). The data analysis for the GPS data from sites of Tohoku University has been carried out using a PPP (Precise Point Positioning) strategy of GIPSY/OASIS-II (GOA-II) developed by the Jet Propulsion Laboratory (JPL), NASA (Zumberge et al., 1997). The principle of this method is that through the use of global parameters such as precise ephemerides, clock errors of GPS satellites, and earth rotation parameters, which JPL estimates precisely based on a global GPS observation network, site coordinates can be obtained with high accuracy using data from only one station. We used data from both of these networks in this study.

3. Coseismic slip distribution

Black arrows in Figure 1 denote observed coseisimic displacements associated with the 2005 Miyagi-Oki earthquake at the continuous GPS stations. Coseismic displacements are defined as differences between averaged site coordinates for 5 days from August 11 and those from August 17. Horizontal displacements amounting about 50 mm were observed near the main shock epicenter. Directions of the coseismic displacements toward the epicenter suggest that the event was a typical interplate earthquake. We estimate coseismic slip distribution on the plate interface by applying the geodetic inversion technique devised by Yabuki and Matsu'ura (1992) to these observed displacements. The shape of the plate boundary here was proposed by Hasegawa et al. (1994) and we adopt it in our model for the plate interface. We assumed a curved fault surface with a dimension of 135 km in strike direction by 120 km in dip direction, and coseismic slip distribution is evaluated as amplitudes of B-spline basis functions located at 9 (strike-direction) by 8 (dip-direction) grid points. Coseismic slip is constrained to the direction of the relative plate motion (N65W-N115E) plus/minus 15 degrees.

Estimated slip vectors on the hanging wall of the plate interface are shown by blue arrows and contours with an interval of 0.1 m in Figure 1. Coseisimc displacements calculated from the estimated slip distribution are demonstrated by white arrows. The coseisimc slip is centered around the epicenter of the earthquake denoted by a yellow star. Looking at the area of major slip shown by the contour of 0.3 m, it covers a southeastern part of the coseisimc slip area of the 1978 event, which was estimated by Yamanaka and Kikuchi (2004). This distinctive feature in the coseismic slip distribution is also demonstrated by seismic waveform inversion performed by Okada et al. (2005) and Yaginuma et al. (this issue). The total seismic moment obtained by integrating the distributed slips shown in Figure 1 amounts to 6.4 x 10^19 Nm, which is equivalent to the moment magnitude of 7.1 and almost identical with the result obtained by Yaginuma et al. (this issue).

4. Postseismic slip distribution

In the last decade, there have been many reports of postseismic deformations after large earthquakes that occurred not only at plate boundaries (e.g.,. Heki et al., 1997; Nishimura et al., 2000; Hirose et al., 1999; Miura et al., 2004) but also inland areas (e.g. Nakano and Hirahara, 1997) , owing to the innovation of GPS into geodesy as a powerful tool to measure site coordinates with exceptionally high accuracy and temporal resolution. Intimate investigation on small repeating earthquake data by Uchida et al. (2004) also clarified spatio-temporal variation of quasi-static, or slow slip on the plate boundary before and after three major earthquakes with magnitudes around 7 that occurred off Sanriku.

Minor postseismic deformation was also detected after the 2005 Miyagi-Oki earthquake by discreet processing for the observed time series of site coordinates: a polynomial consisting of linear trend, annual and semi-annual terms, and coseismic step is fit to the time series for the period from January 1, 2004 to August 17, 2005 by least square method, and then extracted from raw data. An example of this processing for a GEONET site, 0550 (Ayukawa) near to the epicenter is shown in Figure 2. Examining residuals between raw data and polynomial, eastward and slightly southward movement is dominant after the main shock. Postseismic displacements after major inter-plate earthquakes are often modeled by afterslips on plate boundaries and characterized by decaying feature with time. Marone et al. (1991) proposed a model for afterslip based on rate and state variable friction laws suggesting that temporal characteristics of afterslip can be approximated by a logarithmic function. In Figure 2, we can see decaying feature in the site velocity after the main shock ; however, its quantity seems to be too small to discuss in detail. We then fit regression lines to the time series for the period from August 17 to October 22 to obtain postseismic velocities of each displacement component.

Black arrows in Figure 3 indicate postseismic displacements derived from the site velocity multiplied by the length of the period (67 days). Because of the weakness of the postseismic signanature, irregular distribution of displacements is noticeable comparing with the coseismic displacements (Figure 1). However, there exists a systematic pattern in the distribution showing larger displacements near the source area along the Pacific coast, while smaller ones in the northern, the southern, and the western areas. This suggests that the postseismic displacements arise from a physical process occurring around the source area of the main shock. We therefore assume that the postseismic deformation is caused by afterslip on the plate interface and apply the same inversion technique as the coseismic case using the postseismic displacements shown by black arrows in Figure 3. We adopted the same parameters for the inversion except for a larger dimension of a model fault, 250 km by 250 km in the first trial, because we do not know where the afterslip occurred. We found that the afterslip has a spatial extent of about 100 km by 100 km after some trials and finally deployed a fault dimension of 145 km by 145 km to cover the afterslip area.

Slip vectors on the hanging wall of the plate interface estimated by the inversion are demonstrated by blue arrows and contours with an interval of 0.02 m in Figure 3. Postseisimc displacements calculated from the estimated afterslip distribution are indicated by white arrows. The postseisimc slip is located in the southern neighborhood of the coseisimc slip area shown by pink contours. It should be noted that the areas of major co- and post-seismic slips defined by the contours of 0.3 m and 0.02 m, respectively, are completely separated, though small amount of slips from the co- and post-seismic analyses overlap each other. Similar characteristics of complementary distribution of coseismic slip and afterslip have been pointed out in some literatures (e.g.,. Yagi and Kikuchi, 2003; Yagi et al. 2003; Miura et al., 2004; Miyazaki et al., 2004; Ozawa et al., 2004; Yui et al., 2005). The integrated moment of the afterslip amounts to 2.0 x 10^19 Nm, about 30 % of the coseisimc moment obtained in this study. This moment is equivalent to Mw6.8.

4. Discussion

Okada et al. (2005) carried out precise relocations of main shocks and aftershocks of the 1978 and 2005 Miaygi-Oki earthquakes to reveal that the 2005 main shock was closely located to that of the 1978 main shock and that the 2005 aftershock area is overlapped with the southern/south-eastern part of the 1978 case. Okada et al. (2005) and Yaginuma et al. (this issue) performed seismic waveform inversions for the 2005 event to demonstrate that the coseismic slip area of the 2005 event corresponds to the southeastern part of that of the 1978 event and to conclude that the 2005 event can be regarded as re-activation in the part of the coseismic slip area of the 1978 event. Coseismic slip distributions both from the waveform inversion by Yaginuma et al. (this issue) and the geodetic inversion by this study are compared in Figure 4. The slip area larger than 0.3 m which was estimated in this study, shown by a green contour, indicates broader distribution than the result by Yaginuma et al. (this issue). However, they agree well concerning less spatial resolution in geodetic inversion than waveform inversion. The coseismic slip distribution inferred from independent GPS data also suggests that the coseismic slip area due to the 1978 event consists of some sub-faults or asperities and the 2005 earthquake ruptured just the southeastern asperity (Okada et al., 2005; Yaginuma et al., this issue). Conversely, there still remains an area not displaced by the 2005 event.

Umino et al. (this issue) relocated the main shocks and aftershocks of the 1933 (M7.1), 1936 (M7.4), 1937 (M7.1), and 1978 (M7.4) Miyagi-oki earthquakes to conclude that three earthquakes in 1930's ruptured different parts of the source area of the 1978 event, i.e., its eastern, central and western portions, respectively. This result leads us to an idea that the next major earthquakes with magnitudes about 7 will occur in the near future.

Distinctive feature of the afteslip distributed in the southern neighborhood of the coseismic slip area is obtained in this study (Figure 3). Uchida et al (2004) found many repeating earthquakes occurring during the earthquake swarms of the 1989 and 1992 events and during the aftershock activity of the 1994 Sanriku-Oki earthquake (M7.6); however, the 2005 earthquake did not activate repeating earthquakes around its source area (Uchida et al., 2005). This is probably caused by the fact that the amount of afterslip is too small (about 5 cm at its maximum) to promote repeating earthquakes.

Looking at seismicity around the 2005 focal area, we can see some indication suggesting the occurrence of the afterslip. Figure 5 represents M-T diagrams around the aftershock area from an earthquake catalog by the Japan Meteorological Agency. There is no difference in seismicity before and after the 2005 earthquake in the northern neighborhood, while the number of earthquakes with magnitude 3 to 4 was slightly increased after the earthquake in the southern adjoining area. Cumulative numbers of earthquakes in the same areas are shown in Figure 6. The number of earthquakes in the northern neighborhood of the 2005 aftershock area shows no temporal change even after the earthquake, however, deviation from linear trend can be seen in the southern neighborhood. Seismic activity raised after the 2005 Miyagi-Oki earthquake in the southern neighborhood of the focal area may support the occurrence of the afterslip in the same area.

The 2003 Tokachi-Oki earthquake was followed by dominant afterslip lasting for more than one year as reported by Yui et al. (2005). The afterslip area of the 2003 event extended bi-laterally along the trench axis. This feature contrasts strikingly with the present study: the afterslip occurred only down to the south. This might be caused by the existence of the locked plate interface at the north of the 2005 source area.

5. Conclusions

Co- and post-sesimic deformations associated with the 2005 Miyagi-Oki earthquake were investigated to resolve the causal interplate slips, using continuous GPS data and the geodetic inversion. The coseismic slip distribution estimated by the present study shows good agreement with that estimated by waveform inversions. The major slip area corresponds to the southeastern part of the rupture area of the 1978 event. This suggests that there still remains the locked plate interface, which may cause major interplate earthquakes in the near future.

The afterslip seems to have extended uni-laterally to the south of the coseismic slippage. This distinctive feature also might be caused by the presence of asperities, where seismogenic stress has not released yet, in the northern neighborhood. Monitoring of space-time evolution in aseisimic slip occurring on the plate interface is a clue to predict occurrences of interplate earthquakes and to understand the process of plate subduction.

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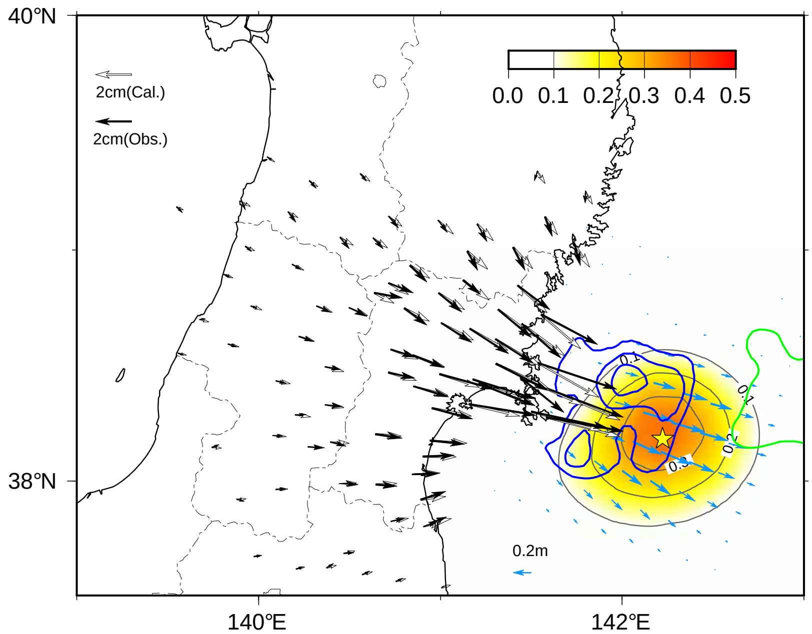

Fig. 1 Coseismic displacements and slip distribution estimated on the plate boundary. Black, blue and white arrows denote observed displacements, slip vectors on the hanging wall of the plate interface, and calculated displacements from the slip distribution, respectively. Contours of the inter-plate slip are also shown with a color scale. Yellow star indicates the epicenter of the 2005 Miyagi-oki earthquake (M7.2). Blue and green contours denote slip distributions of the 1978 (M7.4) and 1981 (M7.0) earthquakes, respectively, estimated by Yamanaka and Kikuchi (2004).

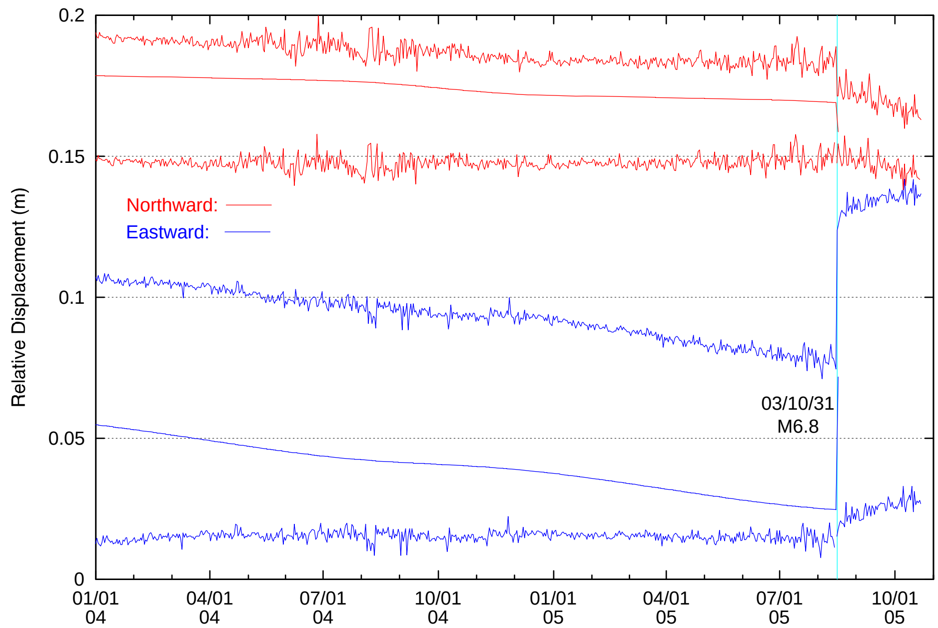

Fig.2 Example showing how to evaluate postseismic displacements at a GEONET station, 0550 (Ayukawa). Red and blue traces denote northward and eastward displacements, respectively. Top, middle, and bottom of each component represent raw data, linear trends with annual and semi-annual variations and coseismic step estimated by least square fitting, and residuals, respectively.

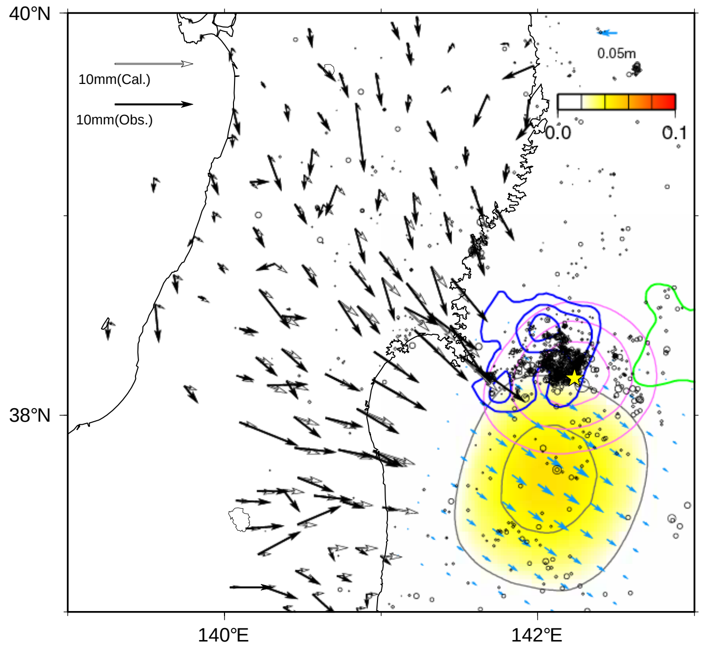

Fig.3 Postseismic displacements and slip distribution estimated on the plate boundary. Black, blue and white arrows denote observed displacements, slip vectors on the hanging wall of the plate interface, and calculated displacements from the slip distribution, respectively. Contours of the postseisimc slip are also shown with a color scale. Yellow star and open circles indicate epicenters of the main shock (M7.2) and aftershocks. Blue and green contours denote slip distributions of the 1978 (M7.4) and 1981 (M7.0) earthquakes, respectively, estimated by Yamanaka and Kikuchi (2004). Pink contours indicate the coseismic slip of the 2005 event derived in this study (see Figure 1).

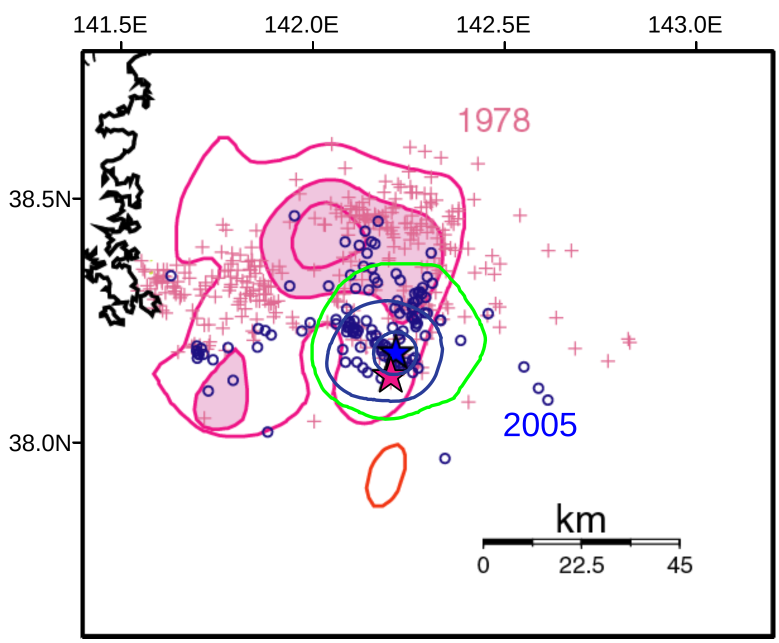

Fig. 4 Comparison of the coseismic slip distributions of the 2005 Miyagi-Oki earthquake estimated by seismic waveform inversion (blue contours) performed by Yaginuma et al. (this issue) and the geodetic inversion using GPS data in this study (green contours) with an interval of 0.3 m. Blue circles and red crosses indicate epicenters of aftershocks for 2 days of the 2005 and 1978 events, respectively, relocated by Okada et al. (2005).

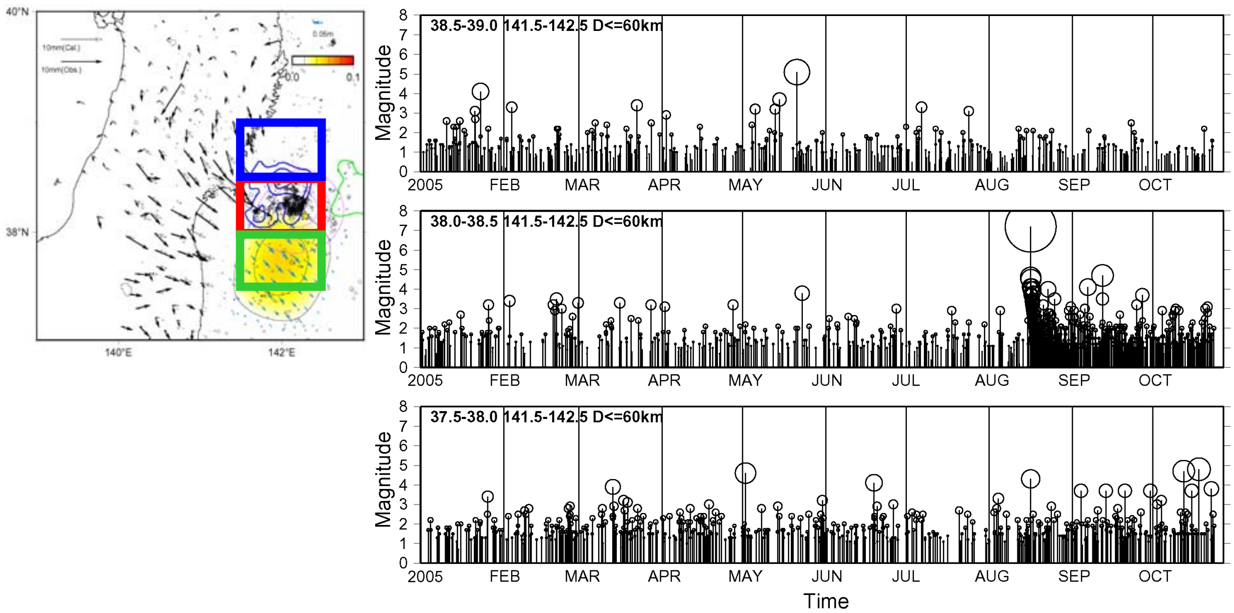

Fig. 5 Magnitude-Time diagrams in the three areas in and around the aftershock area of the 2005 earthquake. Top, middle, and bottom panel represent the northern neighborhood of the aftershock area, the aftershock area, and its southern neighborhood, respectively. They are shown by blue, red, and green rectangles in the insert map.

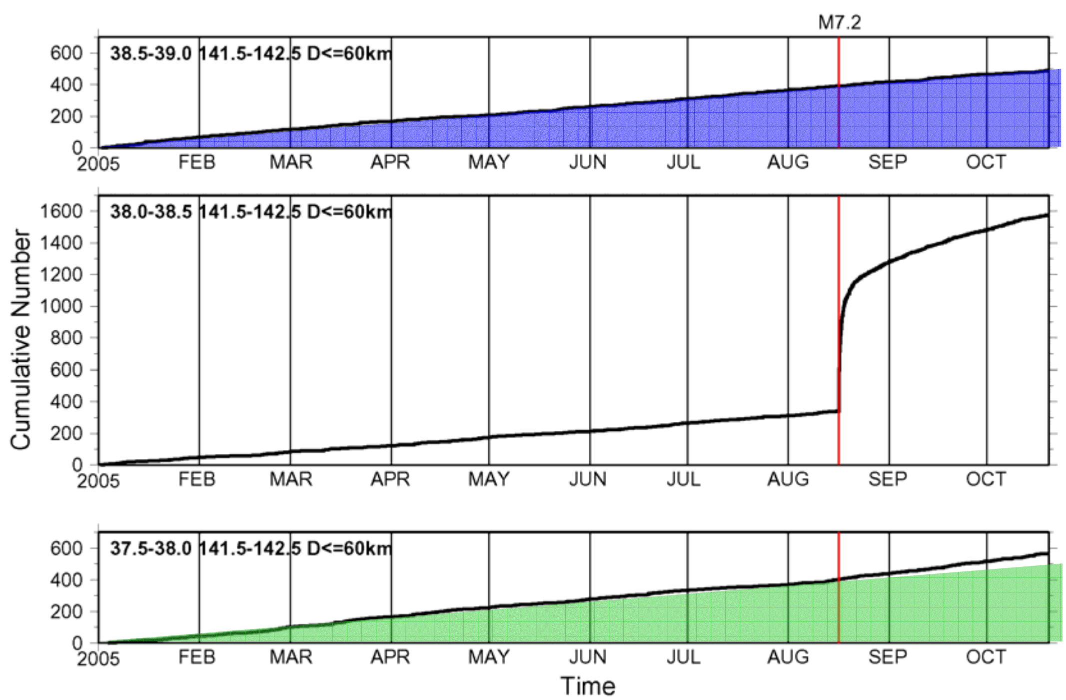

Fig. 6 Cumulative number of earthquake in the three areas in and around the aftershock area of the 2005 earthquake. Top, middle, and bottom panel represent the northern neighborhood of the aftershock area, the aftershock area, and its southern neighborhood, respectively, shown by blue, red, and green rectangles in the insert map of Figure 5.