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A dense GPS observation immediately after the 2004 mid-Niigata prefecture earthquake

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To investigate the postseismic crustal deformation associated with the 2004 mid-Niigata prefecture earthquake (M6.8), we newly started GPS observation to fill a gap of the nationwide continuous GPS network. Our GPS sites were mainly distributed in the focal region without permanent GPS site, and succeeded in obtaining the postseismic deformation. Coseismic displacements of two aftershocks were clearly detected because of immediate observation. Estimated fault parameters of the aftershock (M5.9) on November 8 occurring just beneath our GPS network indicated that geodetic data could be explained by either east- or west-dipping fault model inferred from detailed aftershock data. Moreover, clear postseismic deformation, which could be characterized by a logarithmic decay function, was observed. This signal probably suggests possible aseismic slip. Our results indicated that dense GPS observation could give important and interesting data to clarify the properties of shallow inland middle-size earthquakes.

Key words: The 2004 mid-Niigata prefecture earthquake, GPS, postseismic deformation, fault model, aseismic slip.

1. Introduction

The mid-Niigata prefecture earthquake (M6.8) occurred at shallow depth (13 km) on 23 October 2004 in Mid Niigata prefecture, central Japan. Focal mechanism estimated by the Japan Meteorological Agency (JMA) indicated pure reverse faulting with WNW-ESE compression axis (Fig. 1). Before occurrence of this earthquake, several researchers pointed out a seismic gap between the 1847 Zenkoji earthquake (M7.4) and the 1964 Niigata earthquake (M7.6) as shown in Fig. 1 (Ishikawa, 1995; Tsukuda, 1995; Ohtake, 2002). The 2004 earthquake partially filled this gap but not full.

It has been proposed that plate boundary between the Amurian and Okhotsk plates land at the southern edge of the 1964 earthquake fault (Nakamura, 1983; Kobayashi, 1983; Seno *et al*., 1996; Heki and Miyazaki, 2001). This hypothesis is consistent with geological and geophysical data in this region, e.g. active structure (Nakata and Imaizumi, 2002), active landslides, strain concentration revealed by nationwide GPS observation (Sagiya *et al*., 2000), and, of course, high seismicity. The epicenter of the 2004 earthquake was located in this active region.

In this report we introduce preliminary results of our new GPS observation and discuss several characteristics of postseismic crustal deformation.

2. GPS Observation and Data Analysis

The new GPS sites were established immediately after the occurrence of the mainshock by Hokkaido University, Kyushu University, the University of Tokyo and Toyama University. We first started the observation in October 24, the next day of the mainshock, at TODO site. Figure 1 shows the final distribution of our new GPS sites with the nationwide continuous GPS network (GEONET) sites operated by the Geographical Survey Institute. The GEONET sites were located only outside the aftershock area. In other words, average intersite distance of the GEONET (15–30 km) is insufficient for M$<$7 inland earthquakes because of an equivalent or smaller fault size. Therefore, our new sites distributed in the aftershock region would play a very important role for investigation of postseismic deformations. Antennas of the new GPS sites were fixed on the roof top of reinforced-concrete structures using buried stainless bolts, pillars, tripods and/or antenna attachments. We used dual frequency GPS receivers recording carrier phase at every 30 s.

In this report we tried to analyze the data covering about one and half months after the mainshock occurrence. There was no snow covering on GPS antenna during this period. Our GPS data were processed with the GEONET data using the Bernese GPS Software Version 4.2 (Hugentobler *et al*., 2001) with International GPS Service for Geodynamics (IGS) precise ephemeris and International Earth Rotation Service parameters. The station coordinates and tropospheric parameters were estimated daily and every 3

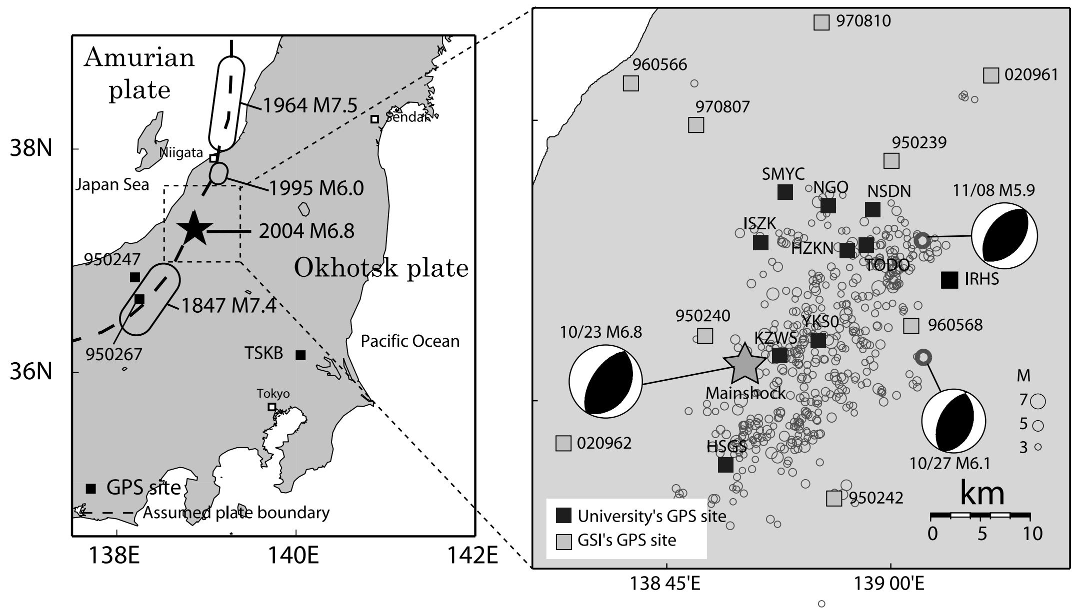

Fig. 1. Map showing the GPS sites. Focal regions of neighboring shallow large earthquakes along the plate boundary between the Amurian and Okhotsk plates (left) and M≥3 Aftershocks during a period from October 23 to December 15, 2004 (right), were also indicated. Mechanism solutions and epicenter distribution data were from the Japan Meteorological Agency.

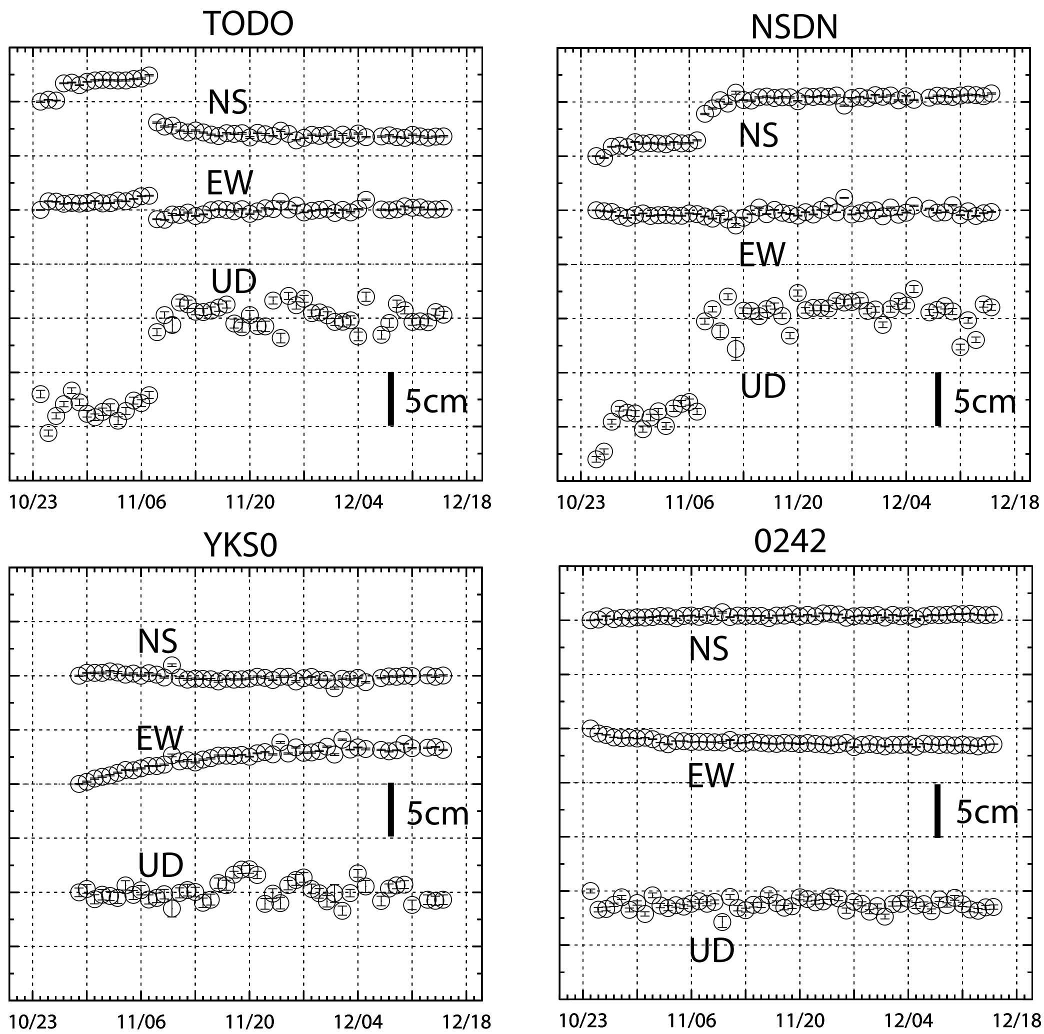

Fig. 2. Time series of coordinates and 2σ formal errors at selected sites for the one and half months after the mainshock.

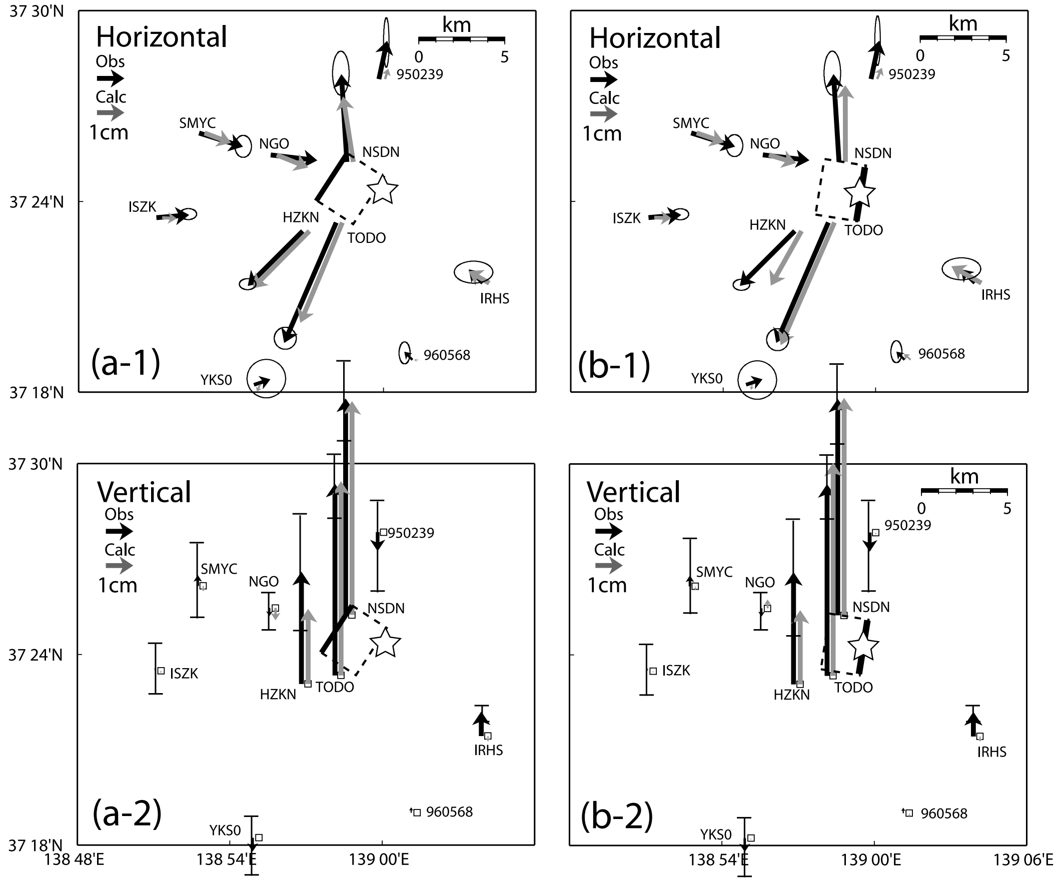

Fig. 3. Observed and calculated coseismic displacement field of an aftershock of November 8 (M5.9). Observed vectors and standard deviations were calculated from the average of three days coordinates before and after this earthquake. (a) East-dipping fault model and (b) west-dipping fault model were shown. Stars in (a) showed relocated epicenter of this earthquake by Kato *et al.* (2005), and in (b) by Shibutani *et al.* (2005).

Table 1. Estimated fault parameters of a November 8 aftershock (M5.9).

	Latitude	Longitude	Depth (km)	Strike (deg)	Dip (deg)	Rake (deg)	L (km)	W (km)	U (cm)	Mw	rms
East-dipping fault	37.40	138.96	2	33	45	108	3.5	5.0	44	5.7	0.0130
West-dipping fault	37.42	139.00	1	189	50	80	3.5	5.0	44	5.7	0.0133

hours, respectively. Two sites of the GEONET, 950267 (Nagano City) and 950247 (Myoko-Kogen Town, southwestern Niigata Prefecture) were sufficient far from the focal region and were selected as reference sites. We confirmed high stability of both sites from seven year's daily site coordinates since 1996 published by the GSI ftp site (ftp://terras.gsi.go.jp). The initial coordinates of reference sites were collocated with the TSKB IGS station in the International Terrestrial Reference Frame 2000 (Altamimi *et al.*, 2002).

3. Result and Discussion

3.1 Fault model estimation of an aftershock (M5.9) of November 8, 2004

Figure 2 shows daily site coordinate series at selected four sites. Clear offsets were recognized on October 27 and November 8 at TODO and NSDN. These step-like changes were induced by aftershocks of a M6.1 and a M5.9, respectively (Fig. 1). Particularly, many GPS sites recorded coseismic displacements of an aftershock on November 8 because this event occurred in the region where our GPS sites were densely distributed (Fig. 2).

We obtained the cosesicmic displacement data by comparing three days average coordinates of before and after this earthquake. The maximum coseismic signal of 4.9 cm in horizontal and 7.9 cm in vertical were observed at TODO and NSDN, respectively. However, little signals were detected at the GEONET sites. These results indicate dense GPS observation in advantageous for middle-size earthquakes.

Detailed aftershock distribution by Kato *et al.* (2005) indicated east-dipping alignment, but Shibutani *et al.* (2005)'s aftershock data showed west-dipping tendency. Therefore, we tried to look for best-fitting fault parameters for either east- or west-dipping fault plane by grid search procedure. Theoretical crustal deformation was calculated using horizontal and vertical components data with same weighting by using a simple, rectangular fault model in an elastic half space (Okada, 1985). Estimated fault parameters for both models were shown in Fig. 3 and Table 1. RMS residuals estimated by both fault models showed approximately the same values (Table 1). This indicated that geodetic

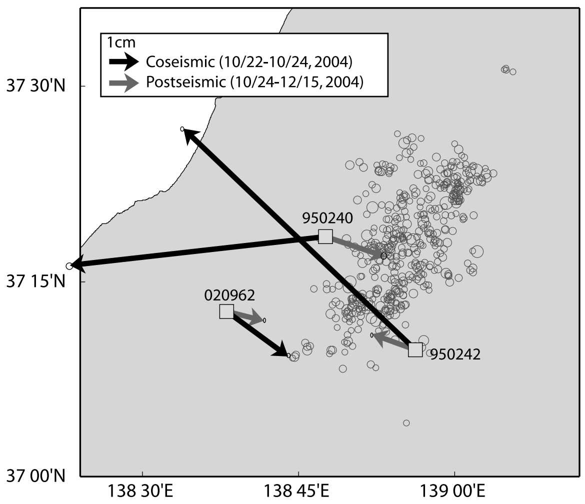

Fig. 4. Comparison of coseismic and postseismic horizontal displacement vectors from daily coordinate difference with 2σ formal errors. Postseismic vector at 950240 indicates opposite direction of coseismic one.

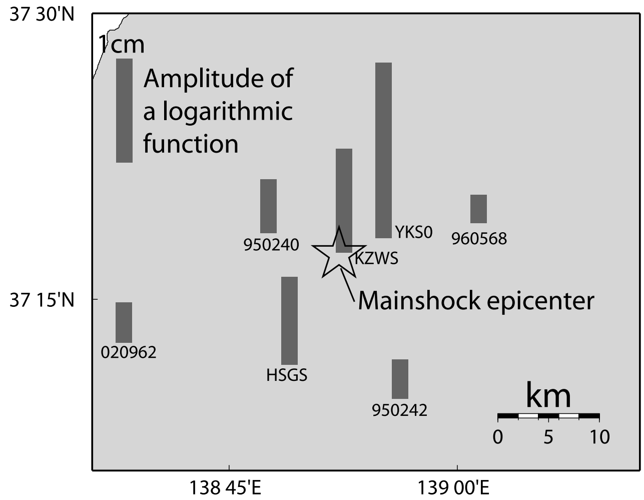

Fig. 6. Amplitude distribution of a logarithmic decay functions under a fixed time constant (0.21 days). Only sites with little coseismic deformation of October 27 and November 8 earthquakes were shown.

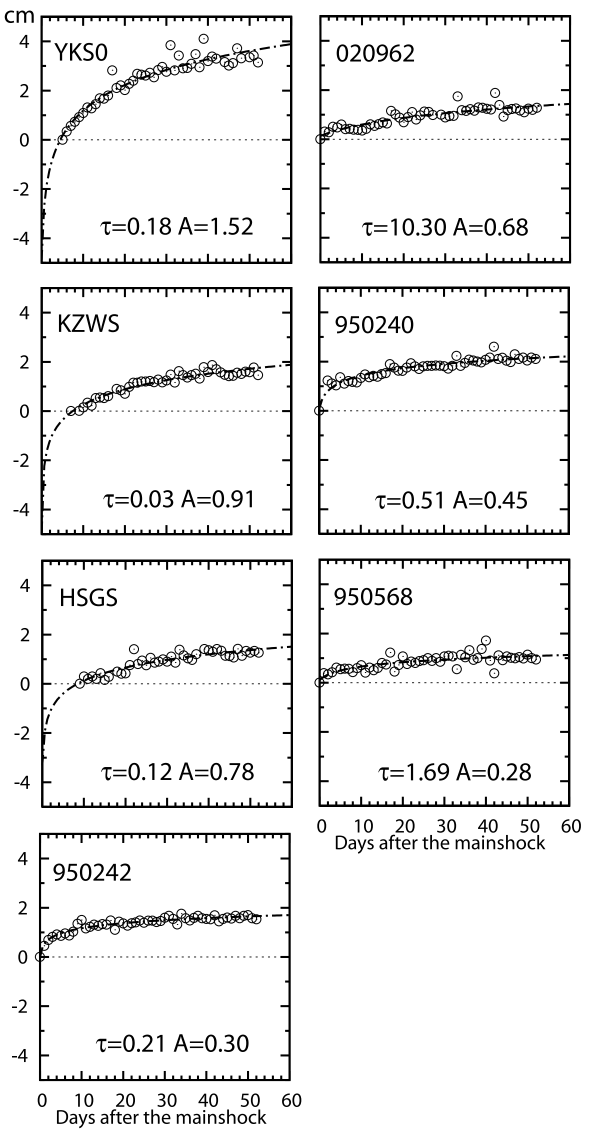

Fig. 5. Time series of length of the daily horizontal displacement projected onto the direction along which the horizontal signals are the largest. Time constant in days (τ) and amplitude in cm (A) were also shown.

data could be explained by either east- or west-dipping fault plane model.

3.2 Postseismic signals

Small but detectable postseismic deformations were observed at YKS0, KZWS, HSGS, 950242, 020962, 950240 and 950568 in horizontal component. We observed the maximum postseimic signal of 3.2 cm in horizontal component at YKS0, which was approximately twice as large as observed at the GEONET sites. Although it was difficult to extract the postseismic signal from the daily coordinates at sites where coseismic displacements of aftershocks were observed, for example, NSDN, TODO, HZKN, it was possible that postseimic components of these sites were smaller than a centimeter. Sites with relative large amplitude, that are YKS0 and KZWS (Fig. 2), were situated near the mainshock epicenter where the maximum coseismic slip was estimated (Yamanaka, 2004; Yagi, 2004; Honda *et al.*, 2005). A postseismic displacement of 2.1 cm at 950240 corresponds to the 25% of coseismic one (Fig. 4). Though coseismic displacement at this site was to the westward, postseismic had eastward direction (Fig. 4). This fact may reflect complex faulting in mainshock and aftershock sequence as indicated by seismological data (e.g. Shibutani *et al.*, 2005; Kato *et al.*, 2005).

The postseismic deformation rate seems to change with time. We tried to estimate a time-dependent relaxation function. To extract the characteristics of this deformation, we examined the logarithmic decaying model, which is commonly used to model afterslip (e.g. Scholz, 1990). The logarithmic decay model is expressed as

$$R(A, \tau) = A \ln(1 + t/\tau)$$

where t is the time elapsed after the mainshock, A is the amplitude of the function, and τ is the time constant. Unknown parameters, A and τ, were estimated from the length of the daily horizontal displacement projected onto the direction along which the horizontal signals are the largest for each GPS site. Calculated τ values ranged from 0.03 to 1.69 days except for those at 020962 (Fig. 5). We suppose this rapid decay is one of typical characteristics of afterslip of large earthquake (Scholz, 1990).

If the postseismic crustal deformation is the manifestation of the same afterslip at depth, the time constant should be same for all sites. Therefore, we estimated amplitudes of this decay function by fixing τ as that at 950242. Sites with little coseismic deformation due to the October 27 and November 8 aftershocks were selected for analysis, and the results were shown in Fig. 6. Relative large postseismic amplitudes were estimated at the sites in the southern part of the focal region. Ozawa *et al*. (2005) suggested a possible aseismic slip in the shallower part of the Western Muikamachi Basin fault by InSAR data. Observed postseismic signals by the present study may also indicate possible aseismic slips.

4. Conclusion

We successfully established new GPS sites in the focal region of the 2004 mid-Niigata prefecture earthquake (M6.8) immediately after the mainshock. Analysis of data obtained for a period of one and half months after the mainshock clearly recorded the coseismic displacements by the M5.9 aftershock and horizontal postseismic deformation. Fault model estimation of the M5.9 event suggested that geodetic data could be explained by either east- or west-dipping fault model inferred from detailed aftershock studies (Kato *et al*., 2005; Shibutani *et al*., 2005). Coordinate time series were modeled with a logarithmic function, which agree with the characteristics of afterslip of a large earthquake. Postseismic signals were relatively larger at sites in the southern part of the focal region, which implied possible aseismic slip. Dense GPS observation could give important and interesting data to clarify the properties of shallow inland middle-size earthquakes.

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