GPS observation of the first month of postseismic crustal deformation associated with the 2003 Tokachi-oki earthquake (M_{JMA} 8.0), off southeastern Hokkaido, Japan

Hiroaki Takahashi[1], Shigeru Nakao[2], Noritoshi Okazaki[3], Junji Koyama[4], Takeshi Sagiya[5], Takeo Ito[5], Fumio Ohya[6], Kazutoshi Sato[6], Yasuyoshi Fujita[6], Manabu Hashimoto[6], Yoshinobu Hoso[6], Teruyuki Kato[2], Takeshi Iinuma[2], Jun'ichi Fukuda[2], Takeshi Matsushima[7], Yuhki Kohno[7], and Minoru Kasahara[1]

[1]*Institute of Seismology and Volcanology, Hokkaido University, Sapporo 060-0810, Japan*
[2]*Earthquake Research Institute, University of Tokyo, Tokyo 113-0032, Japan*
[3]*Geological Survey of Hokkaido, Sapporo 060-0819, Japan*
[4]*Division of Earth and Planetary Sciences, Hokkaido University, Sapporo 060-0810, Japan*
[5]*Research Center for Seismology, Volcanology and Disaster Mitigation, Nagoya University, Nagoya 464-8602, Japan*
[6]*Disaster Prevention Research Institute, Kyoto University, Uji 611-0011, Japan*
[7]*Institute of Seismology and Volcanology, Kyushu University, Shimabara 855-0843, Japan*

(Received December 1, 2003; Revised January 30, 2004; Accepted February 10, 2004)

To investigate the postseismic crustal deformation associated with the Tokachi-oki earthquake ($M_{JMA} = 8.0$) of 26 September 2003 in Japan Standard Time (JST), off southeastern Hokkaido, Japan, we newly established thirty GPS sites just after the mainshock in the eastern part of Hokkaido. Rapid data analysis for one month after the mainshock clearly indicated postseismic displacements only in the horizontal components. Observed maximum horizontal displacement was 6.6 cm from 28 September to 24 October, 2003. Absence of the vertical suggests that afterslip occurred in and around the coseismic fault rather than at downdip extension. Time series of coordinates are characterized by logarithmic decay functions with 4–11 days relaxation times. This suggests that postseismic deformation was due to afterslip on the fault following the large earthquake.

Key words: The 2003 Tokachi-oki earthquake, GPS, postseismic deformation, afterslip.

1. Introduction

In the southwestern Kuril trench, off eastern Hokkaido, large earthquakes have been recurring due to the subduction of the Pacific Plate at about 8.3 cm/yr (DeMets *et al.*, 1994). The Tokachi-oki earthquake ($M_{JMA} = 8.0$) on 26 September 2003 in JST (on 25 in UTC), ruptured almost the same focal region as the 1952 Tokachi-oki earthquake ($M_{JMA} = 8.2$) (Yamanaka and Kikuchi, 2003). Focal mechanism solutions of these earthquakes indicated typical shallow dipping thrust faulting between the subducting Pacific and overriding plates (e.g. Yamanaka and Kikuchi, 2003).

Interseismic subsidence had been observed in the southeastern part of Hokkaido from tide gauges (e.g. Katsumata *et al.*, 2002), leveling (e.g. Geographical Survey Institute of Japan (GSI), 2002), and recent continuous GPS observations (e.g. Aoki and Scholz, 2003). Coseismic subsidences associated with past interplate events (1952 Tokachi-Oki ($M_{JMA} = 8.2$), 1973 Nemuro-Hanto-Oki ($M_{JMA} = 7.4$)) have also been reported (Shimazaki, 1974; Kasahara, 1975; Kasahara and Kato, 1981). These observations indicate that only subsidence takes place in this region. Recently, Heki (2004) proposed an idea that the continuous subsidence observed in northeastern Japan is due to the deep basal subduction erosion.

On the other hand, sediment analysis including tsunami deposits from lagoons along the Pacific coast in eastern Hokkaido revealed the occurrence of rapid postseismic uplifts (Sawai, 2001; Sawai *et al.*, 2002; Sawai, 2002). These events are hypothesized to occur together with the "multi-segment" earthquakes which generated unusual mega-tsumami (Hirakawa, 2000; Nanayama *et al.*, 2003). These visible ground uplifts requested the sizable slips at the downdip extension of the seismogenic part, where we believe that plate interface is decoupled.

These studies showed that there are two characteristics postseismic deformation types in the subduction earthquakes series in eastern Hokkaido. It is therefore very important to investigate the mode of postseismic deformation associated with the 2003 Tokachi-oki earthquake.

Recent continuous GPS observations have revealed remarkable postseismic crustal deformations following large earthquakes with high precision in spatiotemporal domain (e.g. Nakano and Hirahara, 1997; Heki *et al.*, 1997; Melbourne *et al.*, 2002). Some of those showed that additional moment released by the afterslip is comparative to the main shock. This suggests that continuous GPS observations for postseismic crustal deformation are important to reveal the whole picture of an earthquake.

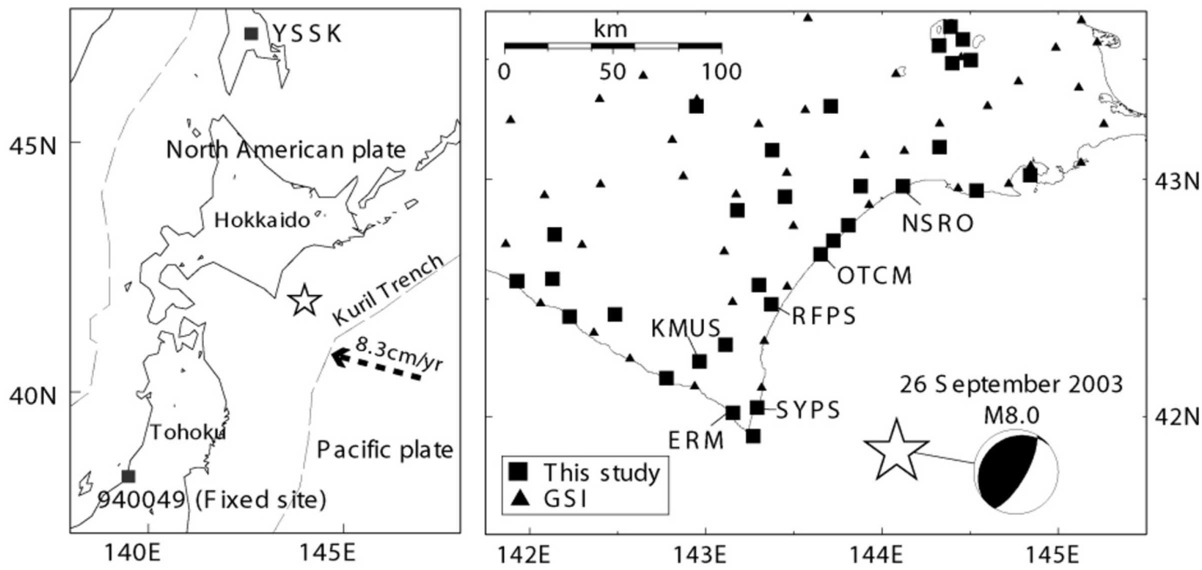

Fig. 1. Tectonic setting and the distribution of GPS sites newly established by JUNCO (Japan UNiversity GPS COnsortium) (black squares), and the nationwide continuous GPS network (GEONET) operated by the Geographical Survey Institute of Japan (black triangles). We also show the fixed site in this study (940049). Star indicates the epicenter of the 2003 Tokachi-oki earthquake and mechanism solution taken from Yamanaka and Kikuchi (2003). Broken lines indicate the plate boundary.

Here, we report the preliminary results of a new GPS network near the focal region of the 2003 Tokachi-oki earthquake, established by the Japanese UNiversity COnsortium of GPS research (JUNCO) to monitor and investigate the postseismic deformation of the 2003 Tokachi-oki earthquake, especially check whether there is postseismic slip at the downdip extension of the seismogenic part.

2. GPS Observation and Data Analysis

The new GPS sites were established immediately after the occurrence of the earthquake. Figure 1 shows the distribution of thirty GPS sites newly deployed by JUNCO together with the nationwide continuous GPS network (GEONET) operated by the GSI. The relatively large GPS network was designed to monitor the afterslips not only near the focal region of the mainshock but its along-trench and/or downdip extensions. The size of aftershock region, that is about 160 $\times$ 160 km (Takahashi *et al.*, 2004), implied that the average intersite distance of GEONET (25–35 km) was insufficient for afterslip investigation. Our GPS sites were distributed to fill the gap of GEONET sites especially near the focal area (Fig. 1). GPS antennas were fixed on the roof tops of school and local government reinforced-concrete buildings using buried stainless bolts and/or antenna attachments. We used dual frequency GPS receivers recording carrier phases at every 30 seconds. Observations continued at five sites, KMUS, SYPS, RFPS, OTCM and NSRO, until 29 October 2003.

In this preliminary report, we analyse GPS data obtained from these five sites. The data cover about a month after the mainshock. The GPS data were processed using the Bernese GPS Software Version 4.2 (Hugentobler *et al.*, 2001) with International GPS Service for Geodymamics (IGS) precise ephemeris and earth orientation parameters. The station coordinates and tropospheric parameters were estimated daily and every 3 hours, respectively. We selected the station 940049 (Murakami, Niigata Prefecture, Japan; Fig. 1) operated by GSI, sufficiently far from the focal region, as the reference station in the analysis. The coordinates of the station 940049 were collocated with the YSSK (Yuzhno-Sakhalinsk, Russia; Fig. 1), an IGS station, in the International Terrestrial Reference Frame 2000 (Altamimi *et al.*, 2002).

The estimated station coordinates of GPS sites could be affected by the instability of the reference site. To examine this problem, we analysed the data using a different reference station, GSI's 950196 (Asahi, Niigata Prefecture, Japan). The results of the two different analysis do not indicate any artificial noise caused by instability of the fixed sites in this analyzed period. We therefore adopt positions relative to the station 940049, hereafter.

3. Results and Discussion

Figure 2 shows the daily site coordinate series in horizontal and vertical components at KMUS, SYPS, RFPS, OTCM and NSRO operated by JUNCO. Clear postseismic displacements were observed at each GPS site in horizontal components. The maximum postseismic horizontal displacement of 6.6 cm to N120E direction was observed at SYPS, between 28 September and 24 October, 2003. It can be seen there was no significant subsidence or uplift signals in the vertical component.

We can recognize an irregular jump data on 11 and 12 October, 2003, at all the sites. This jump does not disappear by changing the reference station to 950196. It therefore indicates that this was not caused by the instability of the reference station. There were no geodetic signals on the fused-quartz extensometer records observed at ERM, 15 km east of the site SYPS (Fig. 1). Hence, this jump would not be due to real crustal deformation. On the other hand, a passage of an intense cold front over the Japanese Islands was observed in this period. Therefore, these apparent site movements would be due to the excess pass delay of GPS signals due to large atmospheric gradient (Miyazaki *et al.*,

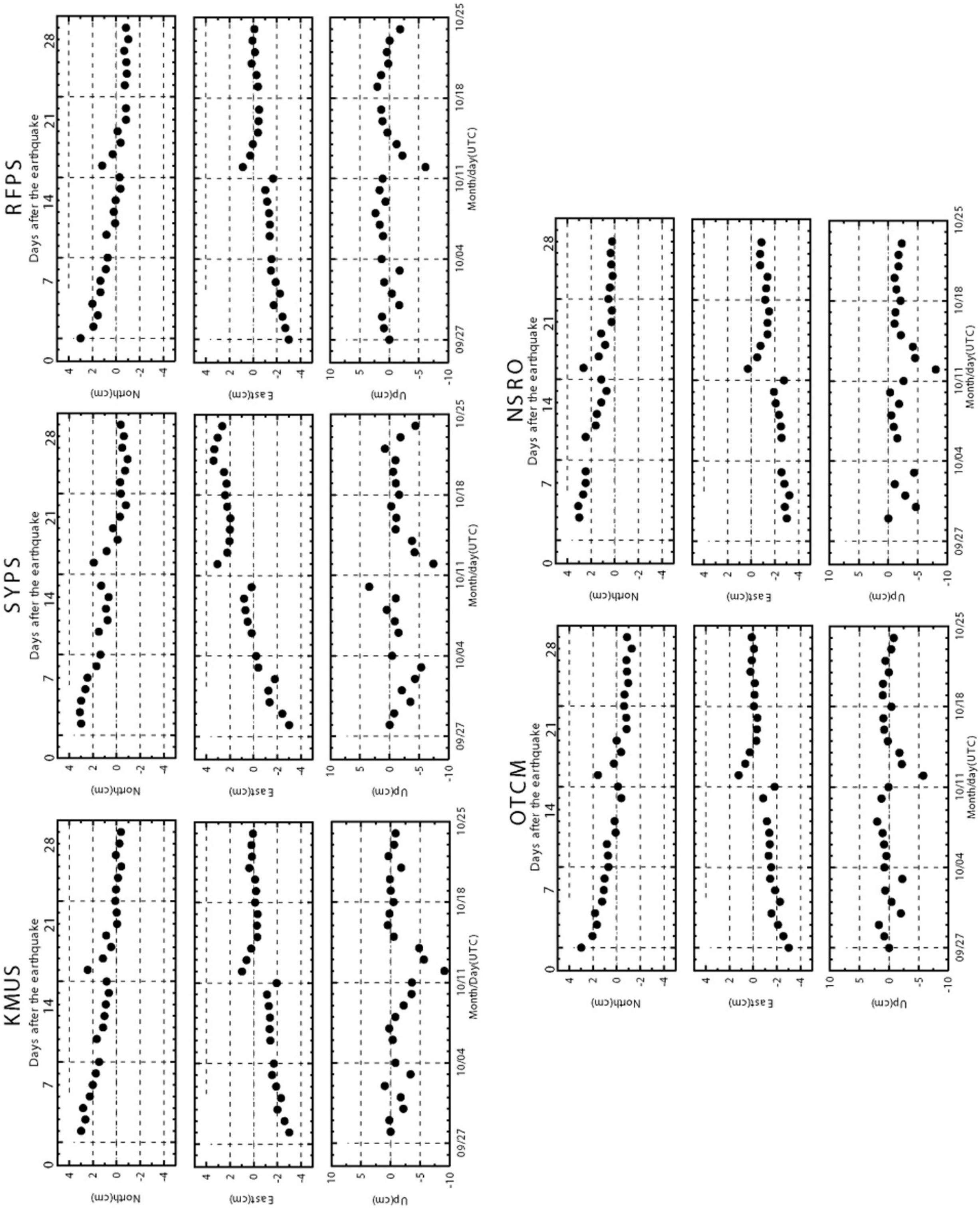

Fig. 2. Time series of coordinates for the one month period after the mainshock.

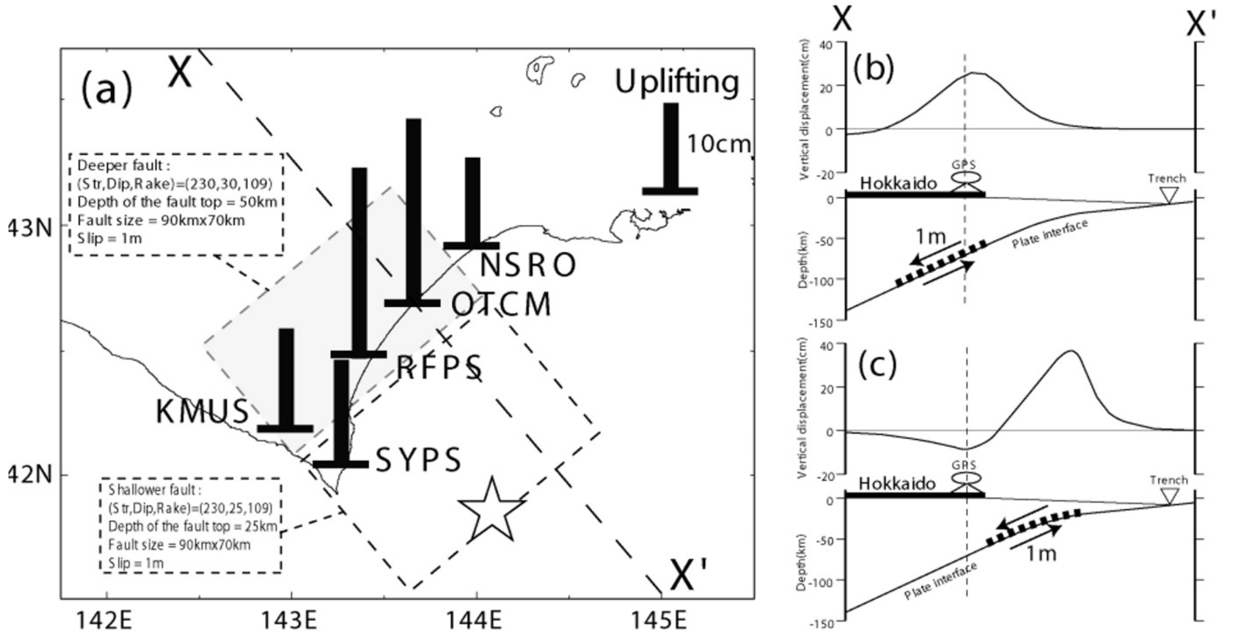

Fig. 3. (a) Theoretical uplift by a hypothetical deep afterslip. Solid and open rectangles illustrate parts of the faults of the assumed afterslip, and the coseismic rupture from Yamanaka and Kikuchi (2003), respectively. Star indicates the epicenter of the mainshock. (b) A vertical deformation profile along the line X-X′ in Fig. 3(a) computed from a deep afterslip (a solid rectangle in Fig. 3(a)). Thick dotted line indicates the assumed fault. (c) Same as Fig. 3(b) but from a shallow afterslip shown by an open rectangle in Fig. 3(a).

2003).

If we assume an aseismic slip on the downdip extension of the mainshock fault, ground uplift should be observed at all GPS sites. Figure 2 suggests that systematic vertical displacements exceeding 6 cm would be detectable from our GPS observation because standard deviations of vertical component were lass than 3 cm. We estimated the theoretical vertical deformation using a fault model shown in Fig. 3 with Okada's (1985) formula. The amount of the assumed aseismic slip on the deeper extension of the mainshock fault is 1.0 m, which corresponds to the 17% of the maximum mainshock slip (Yamanaka and Kikuchi, 2003). This afterslip predicts 10–20 cm uplift at our GPS sites (Fig. 3(a), 3(b)). This computed model implies that GPS sites in this region can detect more than 0.6 m aseismic slip on the deeper fault, because the amount of uplift is proportional to the slip amount on the fault (Okada, 1985). However, uplift of such an amount is not observed at any of our GPS sites. We therefore conclude that there was little afterslip on the deeper extension of the mainshock fault until end of October 2003. On the other hand, an assumption of afterslip on the coseismic fault predicts half to one-fifth subsidence of uplift caused by the deeper one (Fig. 3(b)). Absence of detectable systematic subsidence at all GPS sites implies that afterslip on the seismic fault is less than 0.6 m, which corresponds to the 10% of the maximum mainshock slip. Therefore, the large horizontal displacement without sizable vertical movements suggests that relatively small afterslip in comparison with the coseismic one occurred in the shallower part of the plate boundary.

The postseimic deformation rates seem to change with time. We tried to estimate the time-dependent relaxation function for each site. To extract the characteristics of the deformation, we examined a logarithmic decaying model, which is commonly used to model afterslips (Scholz, 1990; Marone *et al.*, 1991). An exponential model, which is often used to model viscoelastic processes (Scholz, 1990), was excluded because our observation period is much shorter than its time constants which often exceed 50 days (Nakano and Hirahara, 1997; Ergintav *et al.*, 2002). 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.

Figure 4 shows the best-fit logarithmic functions with their time constants and the observed data. They show better fits for all sites. The time constants for these sites were estimated to be 4.5 to 11.4 days except for the NSRO ($\tau = 22.5$ days). We suppose this rapid decay is one of typical characteristics of afterslips of large earthquakes (Scholz, 1990).

If the postseismic crustal deformation is the manifestation of the same afterslip at depth, the time constant should be the same for all sites. Amplitudes of logarithmic function estimated by fixing the time constant to 7.7 days, which corresponds to the SYPS's value, were (site, amplitude in cm)=(KMUS, 4.17), (SYPS, 5.56), (RFPS, 2.62), (OTCM, 2.8), (NSRO, 5.8). This implies relatively large amount of afterslip near the SYPS and NSRO.

4. Conclusion

We successfully established a new network of thirty GPS sites immediately after the 2003 Tokachi-oki earthquake.

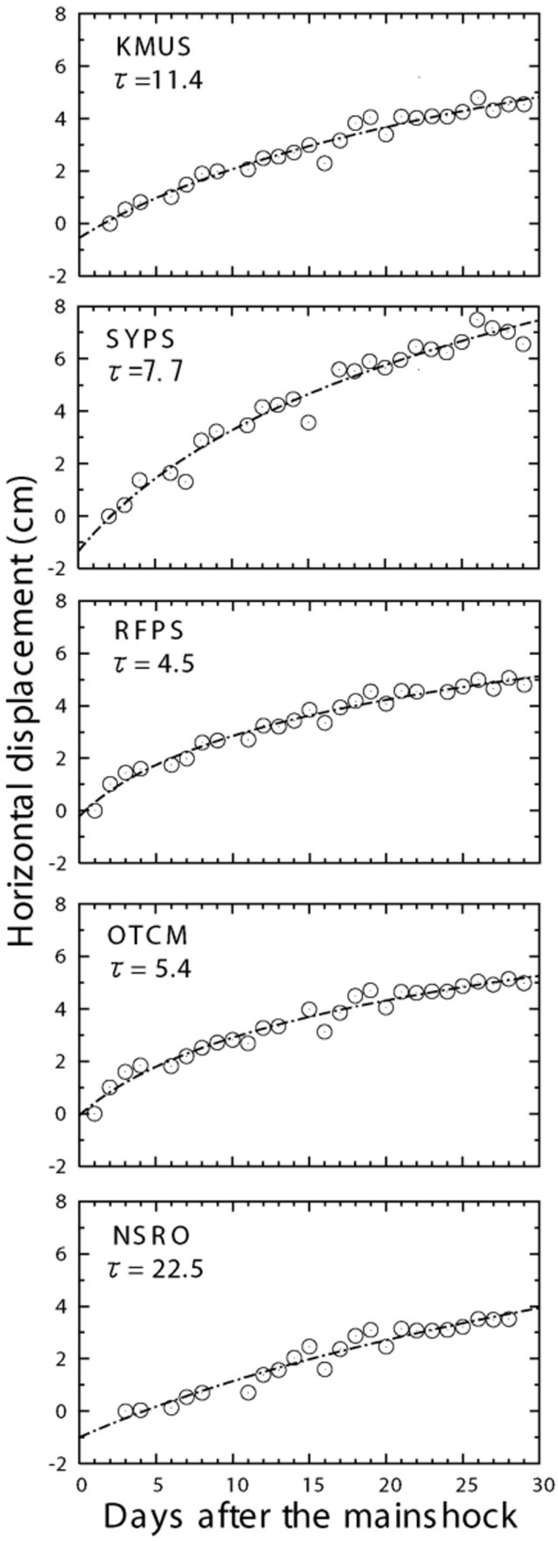

Fig. 4. Time series of length of the daily horizontal displacement projected onto the direction along which the horizontal signals are the largest for each GPS site. Time-constant (τ) for logarithmic functions are also indicated.

Analysis of the data obtained for a period of one month after the mainshock clearly indicates large horizontal postseismic crustal deformation in southeastern Hokkaido. Maximum horizontal displacement one month after the mainshock reached 6.6 cm at SYPS. Absence of the vertical displacements suggest there was little significant postseismic slip on the deeper extension of the mainshock fault, and relatively small afterslip ($<$10% of the mainshock) on the seismic fault. The coordinate time series are modeled with a logarithmic function, which agrees with the characteristics of afterslip of a large earthquake.

Acknowledgments. We are grateful to the staff of primary, secondary schools and local governments, who permitted us to install GPS receivers and antennas. Messers. T. Yamaguchi and M. Ichiyanagi help us in constructing the GPS sites, and Y. Ohta gave us valuable information of GPS sites. We also thank Drs. K. Heki and R. Bürgmann for their constructive and helpful comments which greatly improved the manuscript, and H. Waithaka for proofreadings. We obtained GPS RINEX data from Geographical Survey Institute of Japan, which is appreciated. This research is supported by the New Programm for Earthquake Prediction Research and Observation, and Special Coordination Funds for Promoting Science and Technology by Japanese Government. Figures were partially drawn using GMT software (Wessel and Smith, 1995).

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H. Takahashi (e-mail: hiroaki@eos.hokudai.ac.jp), S. Nakao, N. Okazaki, J. Koyama, T. Sagiya, T. Ito, F. Ohya, K. Sato, Y. Fujita, M. Hashimoto, Y. Hoso, T. Kato, T. Iinuma, J. Fukuda, T. Matsushima, Y. Kohno, and M. Kasahara