Available online at www.sciencedirect.com
ScienceDirect
Tectonophysics 426 (2006) 95 – 105
TECTONOPHYSICS
www.elsevier.com/locate/tecto

New discoveries in dynamics of an M8 earthquake-phenomena and their implications from the 2003 Tokachi-oki earthquake using a long term monitoring cabled observatory

Hitoshi Mikada [a,]*, Kyohiko Mitsuzawa [b], Hiroyuki Matsumoto [c], Tomoki Watanabe [b], Shigehiko Morita [b], Riyo Otsuka [d], Hiroko Sugioka [c], Toshitaka Baba [c], Eiichiro Araki [c], Kiyoshi Suyehiro [e]

[a] *Department of Civil and Earth Resources Engineering, Kyoto University, Yoshida-hommachi, Sakyo-ku, Kyoto, Japan*
[b] *Marine Technology Center, Japan Agency for Marine–Earth Science and Technology, Japan*
[c] *Institute for Research on Earth Evolution, Japan Agency for Marine–Earth Science and Technology, Japan*
[d] *Seismic Monitoring Section, International Monitoring System Division, CTBTO, Austria*
[e] *Japan Agency for Marine–Earth Science and Technology, Japan*

Accepted 7 February 2006
Available online 7 July 2006

Abstract

At the 2003 Tokachi-oki earthquake of M8, seafloor phenomena such as a generation process of tsunami, seafloor uplifts, turbidity current, etc., were observed using a cabled observatory installed on the seafloor. The turbidity current was observed as a benthic storm caused presumably by the mainshock. The seafloor uplifts were observed at the mainshock and continuously after the mainshock. The uplifts were 0.35, 0.37, and 0.12 m for epicentral distances of 25.5, 31.4, and 81.7 km, respectively. After the mainshock, a continuous uplift of the seafloor is observed at all three pressure gauge locations indicating that there was a change in the state of friction on the plate boundary interface by the mainshock. In this paper, we first show what was observed using the cabled observatory installed right above the focal area of the earthquake, and then we discuss to summarize these phenomena associated with the earthquake, its possible causes, and future directions in long term monitoring of seismogenic processes.

Keywords: 2003 Tokachi-oki earthquake; Coseismic turbidity current; Seafloor geodesy; Pressure gauge; Earthquake precursory; Real-time cabled observatory

1. Introduction

The 2003 Tokachi-oki earthquake took place on September 25 2003, at 19:50 (UTC) at almost the same location as the 1952 Tokachi-oki earthquake (Watanabe et al., 2004). The focal area of the Tokachi-oki earthquakes is close to the southern end of the Kuril trench where an arc–arc junction from the Kuril to Japan trench began as a result of the southwestward migration of the Kuril forearc sliver (Kusunoki and Kimura, 1998). This earthquake is interpreted as a megathrust earthquake caused by a slip on a plate boundary interface. The focal area is in a seismogenic zone of the North American and Pacific plates where the oblique subduction of latter is in

---

* Corresponding author. Tel.: +81 75 7534935; fax: +81 75 7534776.
E-mail address: mikada@tansa.kumst.kyoto-u.ac.jp (H. Mikada).

0040-1951/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.tecto.2006.02.021

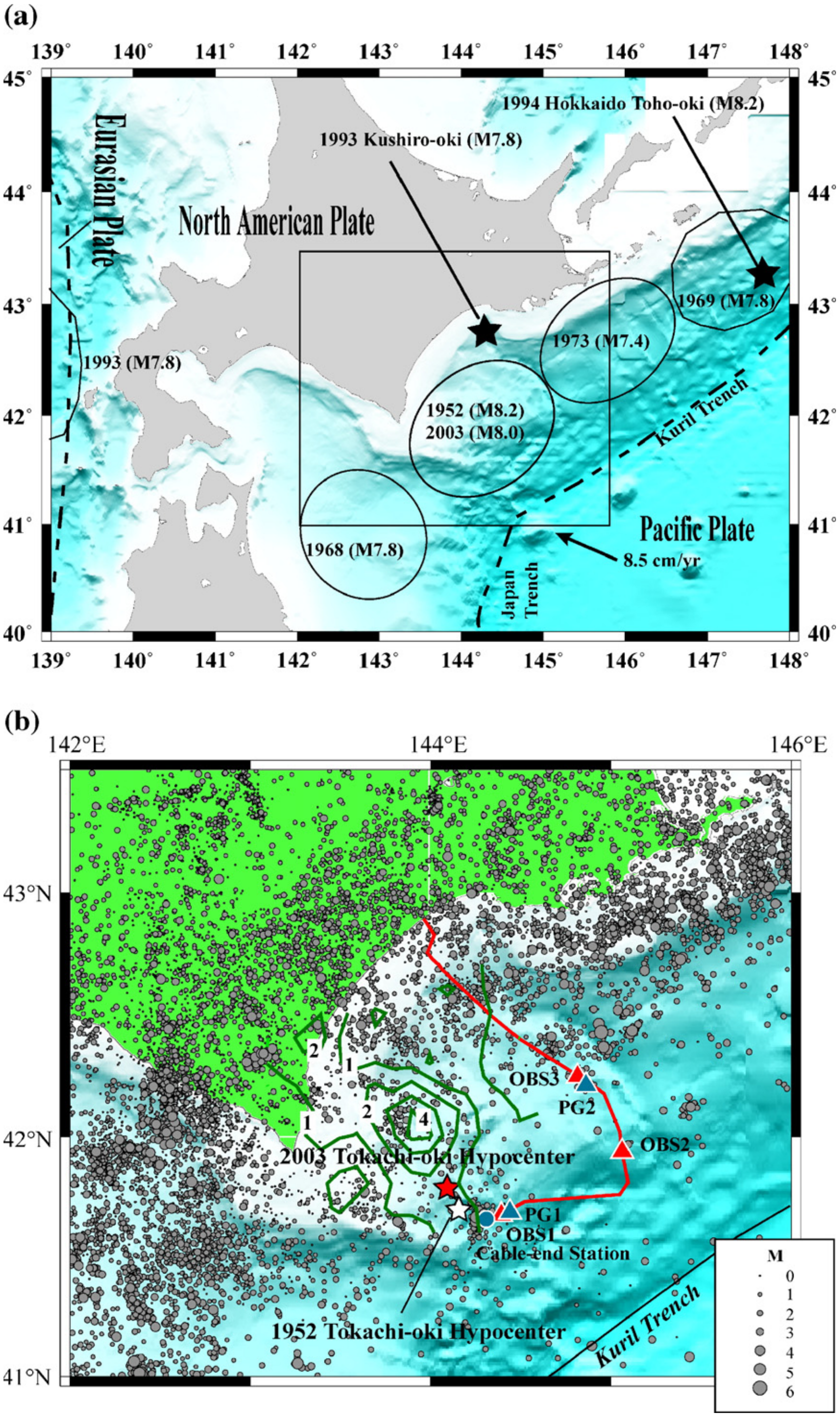

Fig. 1. (a) Locations of recent historical plate boundary earthquakes along the southern Kuril subduction zone and Eastern Japan Sea. Hypocenters of two major intraplate earthquakes mentioned in the text are also depicted. Pacific plate is subducting beneath the North American plate with the velocity of 8.5 cm/yr (DeMets et al., 1994). Open rectangle indicates a region shown in (b). (b) Locations of sensors in the region of the 2003 Tokachi-oki earthquake. A solid and an open star depict the hypocenter of the 2003 and 1952 Tokachi-oki earthquakes, respectively. Thick solid line and triangles represent a cable and either seismometer or tsunami gauge locations, respectively. A circle at the end of the cable represents the location of a cable-end station. Contour lines are drawn every meter for the displacements estimated by a joint inversion of teleseismic and strong ground motion data (Yagi, 2004) for the earthquake. Dark circles are for microseismic events since 2000 until August 2003 whose locations were determined by the Japan Meteorological Agency (JMA). Also the magnitudes of the events are indicated by the size of the circles.

Table 1
Location of the earthquake and sensors of the cabled observatory (datum: WGS-84)

	Latitude	Longitude	Depth bsl/ km	Delta/ km
2003Tokachi-oki earthquake	41°46.86′N	144°04.47′E	42	0
Cable-end station	41°40.05′N	144°20.45′E	2.540	25.5
PG1	41°42.24′N	144°26.25′E	2.237	31.4
PG2	42°14.19′N	144°50.72′E	2.219	81.7
OBS1	41°41.22′N	144°23.67′E	2.391	28.6
OBS2	41°56.45′N	145°03.37′E	3.435	83.6
OBS3	42°15.17′E	144°48.64′E	2.163	80.2

Depths are all in km below the sea level. Delta, rightmost column of the table, represents epicentral distances from the location of the 2003 Tokachi-oki earthquake. The locations of the sensors, sensor types, etc., are found in Hirata et al. (2002).

progress (DeMets, 1992) with a rate of 8.5 cm/year (DeMets et al., 1994). The amount of dislocation of the 2003 Tokachi-oki earthquake was estimated from 3 to 5 m on the slip interface from an inversion analysis of teleseismic signals (Yagi, 2004; Yamanaka and Kikuchi, 2004).

In the focal area of the earthquake, a cabled observatory was deployed in 1999 (Hirata et al., 2002), four years and two months before the mainshock. The observatory recorded a set of data at the time of the earthquake. The data acquired have provided us indispensable information on what took place at the earthquake. Pressure gauge data led researchers to studies on tsunami generation process (Mikada et al., 2004), and crustal deformation (this paper). Real-time seismic data are used for detailed discussions on seismicity (Watanabe et al., 2006-this issue). For further understanding on what to be obtained using cabled observatories at a seismogenic zone, it is necessary to summarize what were observed using our cabled observatory at the 2003 Tokachi-oki earthquake. It is also necessary to discuss if there was any detectable precursory before the earthquake or not. Post seismic phenomena need to be described for future monitoring of earthquakes taking place in seismogenic zones.

In this paper, we try to describe what were observed on the seafloor at the time of the M8 megathrust earthquake. The observations of the monitoring of benthic storms and seafloor uplift associated with the earthquake are described based on acquired data on the seafloor. Unfortunately, there is no remarkable short-

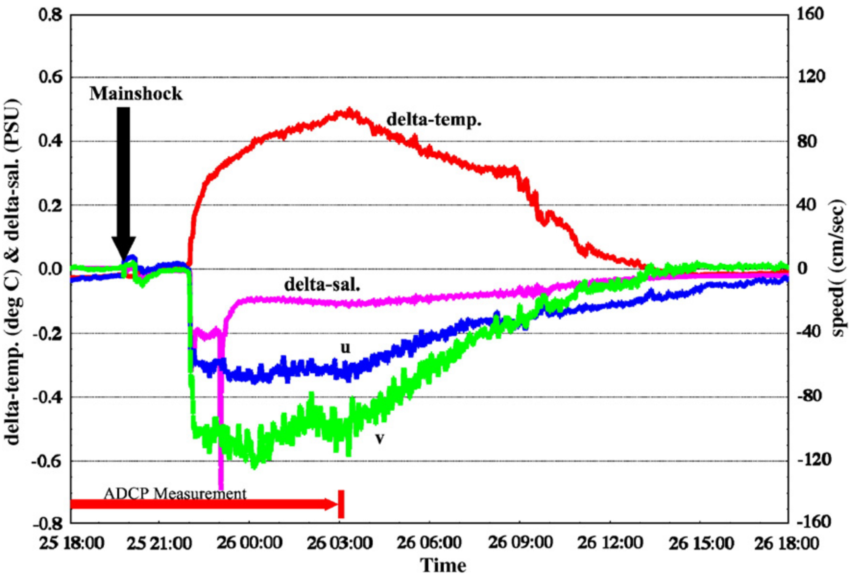

Fig. 2. Time series of current components, delta-temperature and delta-salinity obtained by electro-magnetic current meter and CTD in September 25–26, 2003 (UTC). Symbols: u: eastward component of current speed; v: northward component of current speed; delta-temp: temperature difference from average of September 24, 2003; delta-sal: salinity difference from average of September 24, 2003. Right after the mainshock, the direction and the velocity of seafloor current varied slightly. This might reflect seafloor uplift due to the mainshock, although detailed discussions are not possible. Then, 2 h after the mainshock, a benthic storm arrived and caused a major change in the direction and the velocity. Original data of the electro-magnetic current meter were included in some time differences and magnetic errors. Data of the electro-magnetic current meter are re-calculated using bottom current data of the ADCP.

term precursory resolved until now in any available data from the cabled observatory. As discussed in Watanabe et al. (2006-this issue), the cabled observatory has proven the effectiveness of such observation system in the monitoring of earthquakes at the south-western end of the Kuril seismogenic zone. Discussions

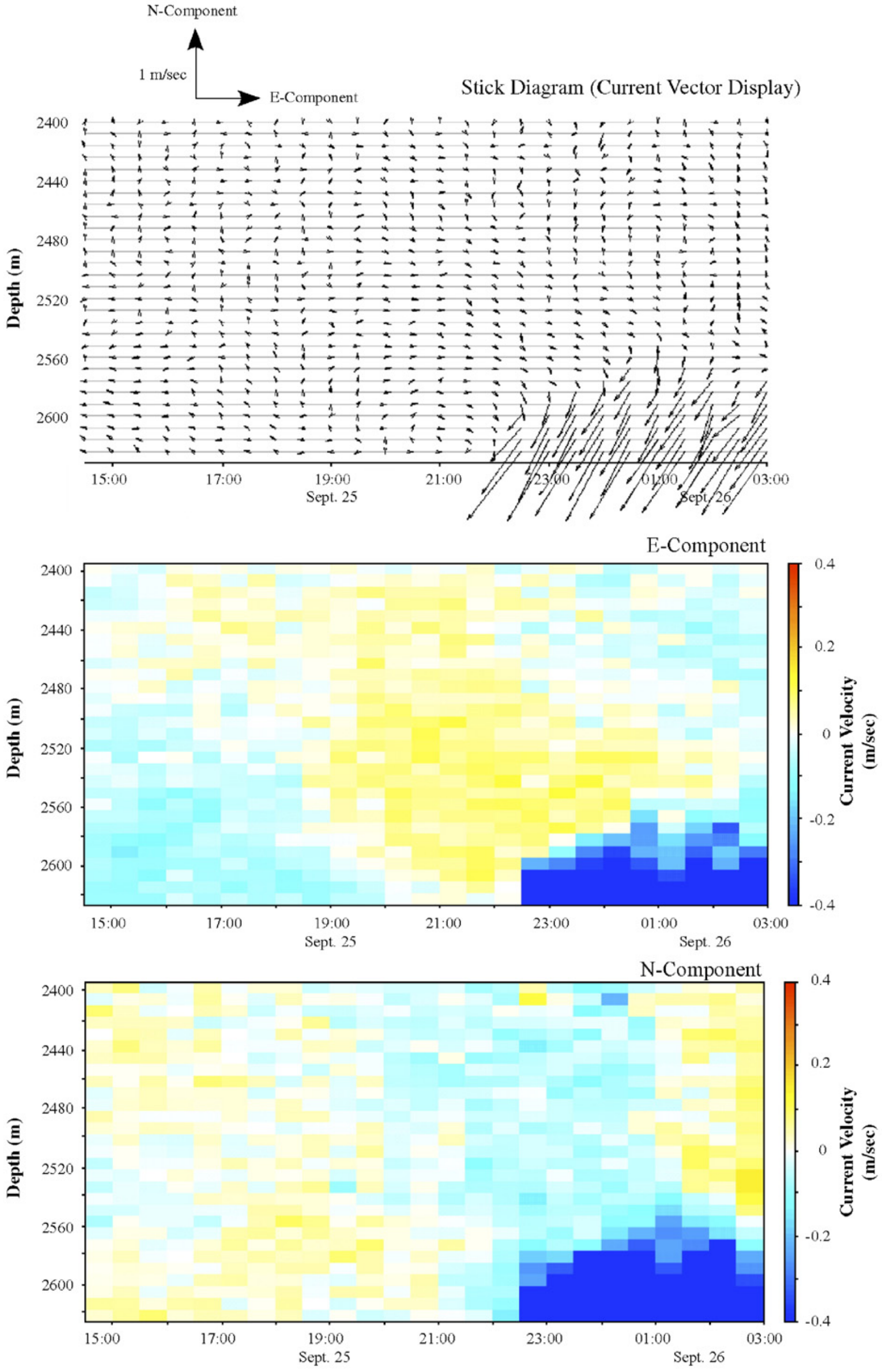

Fig. 3. Time series of the current profiles obtained by ADCP to 15 pm, September 25 to 03 am, September 26, 2003 (UTC). Upper figure: stick diagram; Middle figure: Eastward component; Bottom figure: Northward component. Current velocity profile dramatically changed at the arrival of the benthic storm while coseismic changes are not clearly visible.

finally make it clear that it is necessary to enhance the resolution or signal-to-noise ratio of observations on top of the existing technology of cabled observatories. Especially, much closer access should be tried to seismogenic zones to monitor deep processes or to detect any precursory of plate boundary megathrust earthquakes.

2. 2003 Tokachi-oki earthquake and cabled observatory

Crustal deformation is in progress around the Hokkaido Island caused by the plate motion of the three major plates, i.e., the Pacific, North American and Eurasian plates (Takahashi et al., 1999). The off-Tokachi

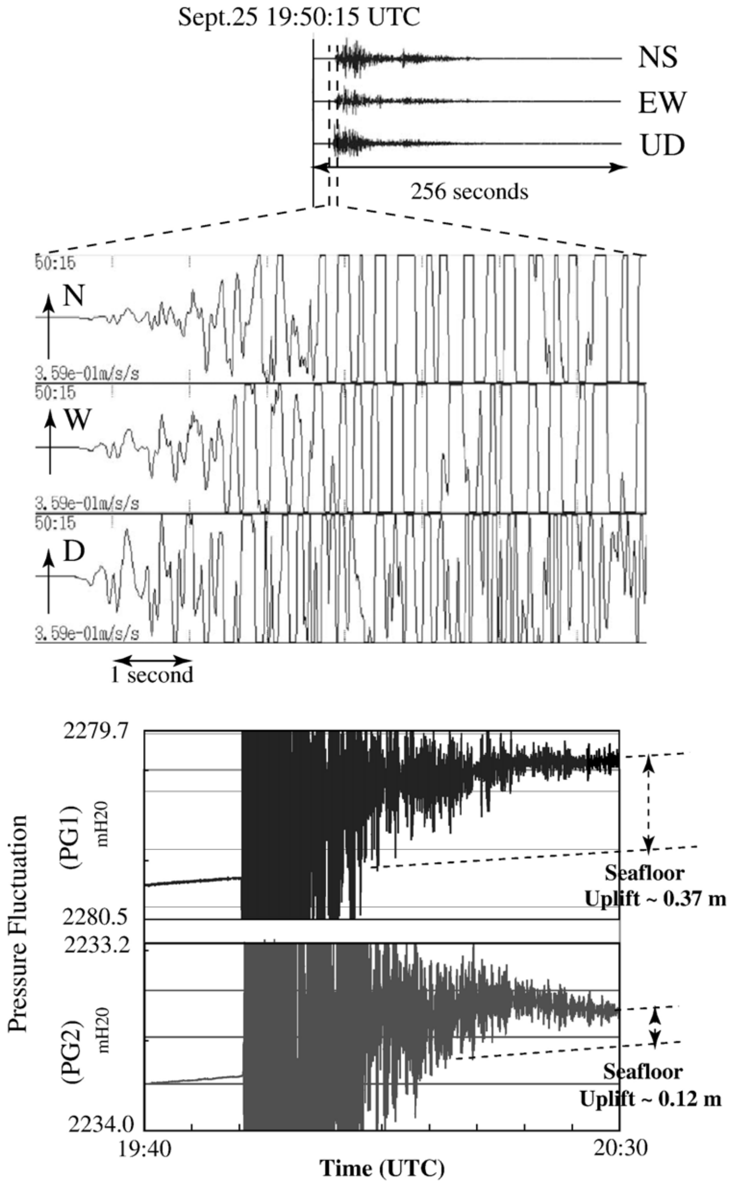

Fig. 4. Observed tidal record (bottom) and seismic waveforms (top) acquired by the cabled observatory at the time of the 2003 Tokachi-oki Earthquake. Fluctuations in water pressure at the onset of the mainshock were about 40 m in equivalent water depth at PG1, while about 30 m for PG2. The mainshock caused a step change in the water depths at all the sensor locations (Table 2). These water pressure fluctuations were caused by abrupt seafloor uplift (Mikada et al., 2004). Tsunami is also included in the tide record whose half amplitudes were about the same as the seafloor uplift values (Mikada et al., 2004).

subduction zone is located at the boundary between the Pacific and North American plates, has been less active seismically in the last decade compared to the other parts of the Kuril trench seismogenic zone (Takahashi and Kasahara, 2003). At the same time, two disaster intra-plate events, the 1993 Kushiro-oki earthquake (Takeo et al., 1993), and the 1994 Hokkaido Toho-oki earthquakes (Takahashi and Hirata, 2003), took place in the southern side of the Kuril subduction zone (Fig. 1(a)). A cabled observatory was deployed in the southwestern end of the Kuril subduction zone in 1999 and consists of three omni-directional tri-component seismometers, two high-precision pressure gauges, and benthic environment monitoring sensors at cable end (Hirata et al., 2002; Table 1). The two pressure gauges (PG1 and PG2) are located about 31.4 km southeast (2237 m below sea level: denoted as mbsl hereafter) and 81.7 km northwest (2219 mbsl) from the epicenter, respectively (Fig. 1(b)). The closest seismometer is located about 28.6 km from the epicenter. The cable end station is located about 25.5 km from the epicenter of the 2003 Tokachi-oki earthquake and consists of electromagnetic current meter, acoustic Doppler current profiler (ADCP), hydrophone, CTD (Conductivity–Temperature–Depth meter), video-camera, etc., for monitoring environmental changes on the seafloor at a depth of 2540 m. The locations of hypocenter (determined by the Japan Meteorological Agency, denoted as JMA here) of the 2003 Tokachi-oki earthquake and sensors of the cabled observatory are summarized in Table 1.

3. Observed phenomena

3.1. Benthic storm associated with the earthquake

Fig. 2 shows time series of current, temperature and salinity changes on September 25–26, 2003 (UTC). Bottom current direction changed from westward to southwestward right after the mainshock. A benthic storm, which was south–southwest strong bottom current of over 100 cm/s, started two hours after the mainshock at 22:01 (UTC) on September 25, 2003. The benthic storm continued for about five hours. The current speed reached 140 cm/s four hours later, and decreased gradually. The temperature increased in 0.5 °C at maximum and salinity decreased in 0.2 PSU simultaneously. The current, temperature and salinity were back to normal about twenty hours after the mainshock.

The vertical profile of the current speed was obtained by the ADCP as shown in Fig. 3. The thickness of the benthic storm is estimated to about 60 m. According to acoustic scattering signals, the suspended particles from sediments reached up to 100 m above the seafloor. ADCP was interrupted five hours later due to computer failure followed the ground motion of an aftershock near the land base of the cabled observatory. The direction of current was toward a deeper area, and vertical component of current inside the benthic storm was in a downward direction at about 10 cm/s. The benthic storm can be interpreted as a gravity-driven flow, hypothetically associated with a debris flow or turbidity current. These observations may be explained if the mainshock triggered submarine slope failures.

3.2. Geodetic phenomena

The cabled observatory has recorded unsaturated seismic waveforms and water pressure fluctuations at the time of the mainshock (Fig. 4). A continuous drift in water pressure informed us of post-seismic seafloor uplift was taking place. As briefly discussed in Satake and Shimazaki (1988), pressure gauges data can be used for detecting geodetic events of very long time scale, which may not be detected by seismograms. The two high-precision pressure gauges (maximum resolution of 0.3 mm after averaging over 10 s) records 0.1 Hz sampled pressure fluctuations in water depth. Also, the CTD at the cable-end station records a time series of water depth with a sampling frequency of a second. They all recorded abrupt changes in water pressure, i.e., the water depths, at the time of the earthquake at these three locations. The maximum amplitudes of water pressure fluctuations are ca. 40 m and 30 m for PG1 and PG2, respectively, due to standing acoustic waves caused by an abrupt seafloor uplift (Mikada et al., 2004). After a removal of short period component and a tide compensation using a method proposed by Matsumoto et al. (2000), it becomes clear that the pressure gauges have recorded vertical uplift of the seafloor. The pressure fluctuations caused by tsunami were observed after the mainshock at 19:50 (UTC). The vertical displacements caused by the mainshock at these sensor locations are estimated as 0.35, 0.37 and 0.12 m, respectively at the cable end station, PG1 and PG2 locations (Table 2). This is the first time to record such a crustal uplift in the offshore at the time of plate-boundary earthquakes. The synthetic tidal pressure fluctuations matches quite well those observed before the earthquake.

Table 2
Estimated seafloor uplifts at pressure gauge locations at the mainshock

Sensor locations	Uplift (m)	RMS error (m)
Cable-end station	0.35	0.06
PG1	0.37	0.05
PG2	0.12	0.06

Values are estimated for pressure fluctuation data for a time window of 150 min starting 20:00, Sept. 25 (UTC).

After the mainshock, tidal gauge data show a linear trend in the difference between the synthetic and observed water depth. Since the difference between the observed and estimated was almost constant before the mainshock, the fluctuations after the earthquake indicate the existence of seafloor uplifts continued in time.

4. Discussions

4.1. Benthic perturbations

The large landslide, debris flows and turbidity currents in deep sea area occur around the margins of the ocean basin and slopes of the oceanic islands. For example, one large landslide was observed following the Grand Banks earthquake in 1929. The current speed of the landslide exceeded 20 m/s and transport range reaches 800 km, as known from the time and place of cutting off of several submarine telegraph cables (Heezen and Ewing, 1952). The landslide and turbidity current off-Tokachi at the time of the 2003 Tokachi-oki earthquake was relatively small scale compared with that of Grand Banks, since there was no damage to the cabled observatory system including the cable to land. Iwase et al. (1999) reported that mudflow was frequently observed at a slope in the Sagami Bay near the Sagami trough, when East-off-Izu earthquake swarms took place, the maximum JMA magnitude of which ranges from 4.4 to 5.4. Changes in salinity and temperature were in dilution and in rise, respectively, in the Sagami Bay, which is similar to those observed at the time of the 2003 Tokachi-oki earthquake. The dependency of mudflow outsets on the magnitude of earthquakes indicates that this type of mudflows might be caused by seafloor shaking due to incident seismic waves. In off-Tokachi area near the cable-end station, we think that the benthic storm we observed was caused by slope destabilization due to earthquake motion of the seafloor during the 2003 Tokachi-oki earthquake.

The temperature ascent of 0.5 °C indicates that the water column of the benthic storm is entrained at an upper slope at depths of about 1700 m. If we constrain the water depth of the source using temperature conservation, i.e., no mixing with the surrounding sea water, and the origin time of the observed flow assuming a constant velocity of 140 cm per second, the source area of the landslides may be located at about 10 km at north-northeast from the observatory (Fig. 5). According to the calculation of progressive vector from current data, benthic storm could reach the trench about 40 km down the slope at 4:00 on September 27, UTC. Otherwise, the turbidity current would have been mixed with much amounts of entrained water at the upper slope. If this estimation is right, the

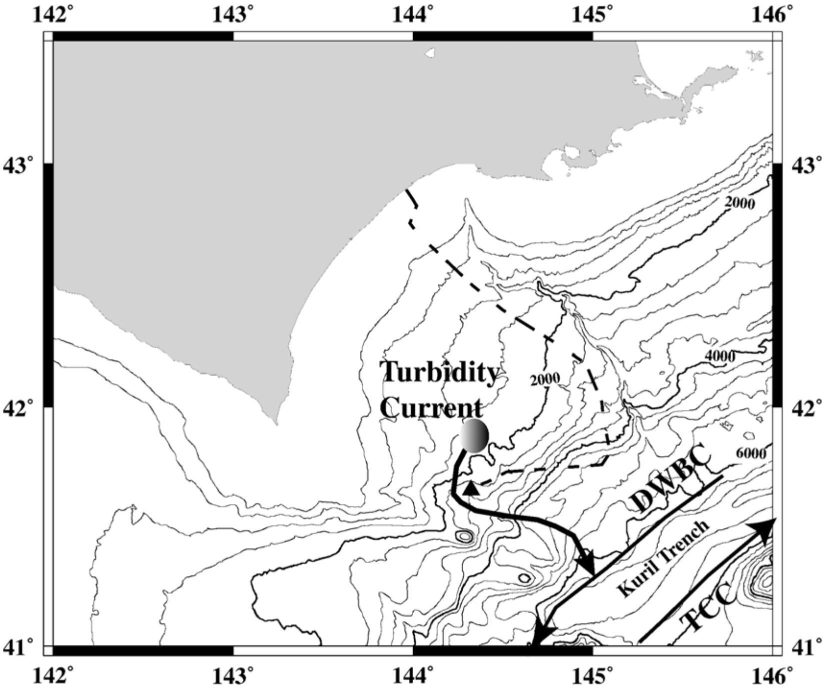

Fig. 5. Possible flow path of the turbidity current. Observed temperature and assumptions to origin time and velocity constrain the source area. Isodepth contours are drawn every 400 m. Dashed line and triangle indicate the cable route of the observatory and the location of observation station at the cable-end. DWBC and TCC denote deep water western boundary current and trench counter current, respectively.

storm direction is changed from south southwestward to south-southeast by the southwestern ridge at a depth of about 3000 mbsl, and then it flew down along a subsea canyon shown in the topography (Fig. 5) and could have reached at the bottom of the southern Kuril Trench. In addition, sediments, which are driven by turbidity current, would be carried southwestward toward the Japan Trench by deep western boundary current which exists along the landside slope of the trench system in the northwest Pacific (Mitsuzawa and Holloway, 1998). Although the mudflow we observed was a relatively small phenomenon, observatory data shows much sediment could be transported from shallow to abyssal area. This indicates that the origin of the trench fill materials is supplied from shallow area of the continental slope with some influence of deep water current. Also, it is obviously indicated that turbidity currents or mudflows associated with earthquakes could be of common phenomena in the marine environment.

4.2. Pressure fluctuations and crustal uplift

Mikada et al. (2004) briefly discussed that the pressure fluctuations during the 2003 Tokachi-oki earthquake are composed of the following phenomena: (1) incident seismic waves, (2) acoustic standing waves, (3) tsunami waves, and (4) coseismic and postseismic seafloor uplift. The uplifts have larger values near the epicenter and might be considered as a change in the water depths, i.e., seafloor uplifts, due to the slip on the fault plane of the 2003 Tokachi-oki earthquake. A modeling result using the Okada model (Okada, 1992) indicates that coseismic slip could account for permanent pressure changes (Table 2) on the seafloor as crustal uplift (Fig. 6). Before the earthquake, there was no clear precursory (see the next subsection) prior to the earthquake. Then, a continuous change in water pressure after the mainshock started at each pressure gauge stations. At the same time, there is a distribution of post-seismic slip complementary to the asperity in the focal area of the 2003 Tokachi-oki earthquakes (Miura et al., 2004; Miyazaki et al., 2004; Ozawa et al., 2004). Aftershock activity (Watanabe et al., 2006-this issue) and land-based GPS observations indicate there is difference in the locality of post-seismic activity, and post-seismic slip could explain the pressure variations during the aftershock activity (Fig. 7).

Watanabe et al. (2006-this issue), pointed out that an active area of the aftershocks are located in the eastern

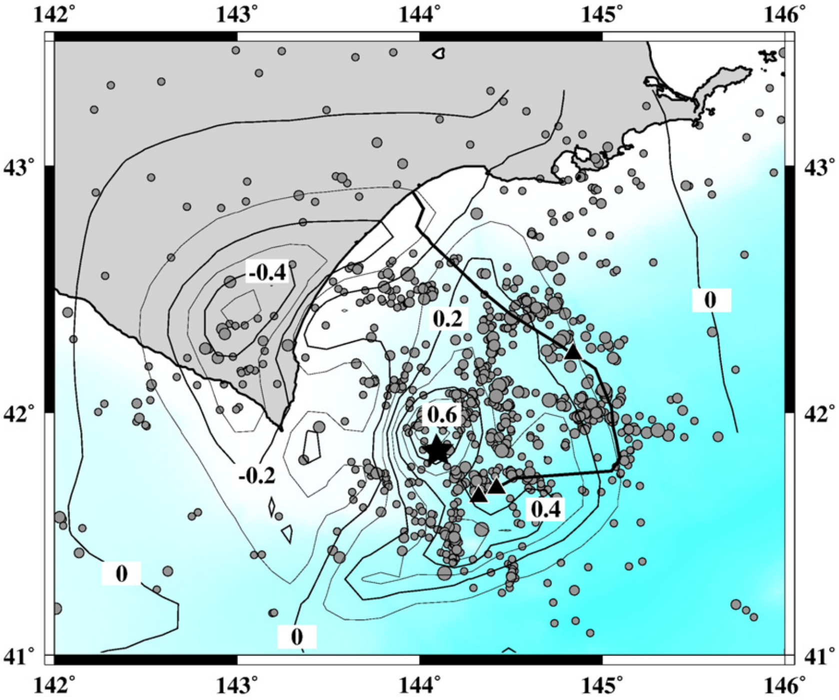

Fig. 6. Estimated coseismic uplift at the time of the 2003 Tokachi-oki earthquake using the slip model shown in Fig. 1 (b). Because of displacement distribution for the plate boundary, large area of vertical displacement is found in the offshore and relatively minor subsidence takes place along the coastline. The numbers on the contours are in meter and solid circles are for post-seismic events (Watanabe et al., 2006-this issue) whose estimated magnitudes are more than three. Observed seafloor uplifts are 0.35, 0.37, and 0.12 m at the three tidal gauge locations indicated by solid triangles from left to right in the figure. These values are all in good agreement with the estimated uplift.

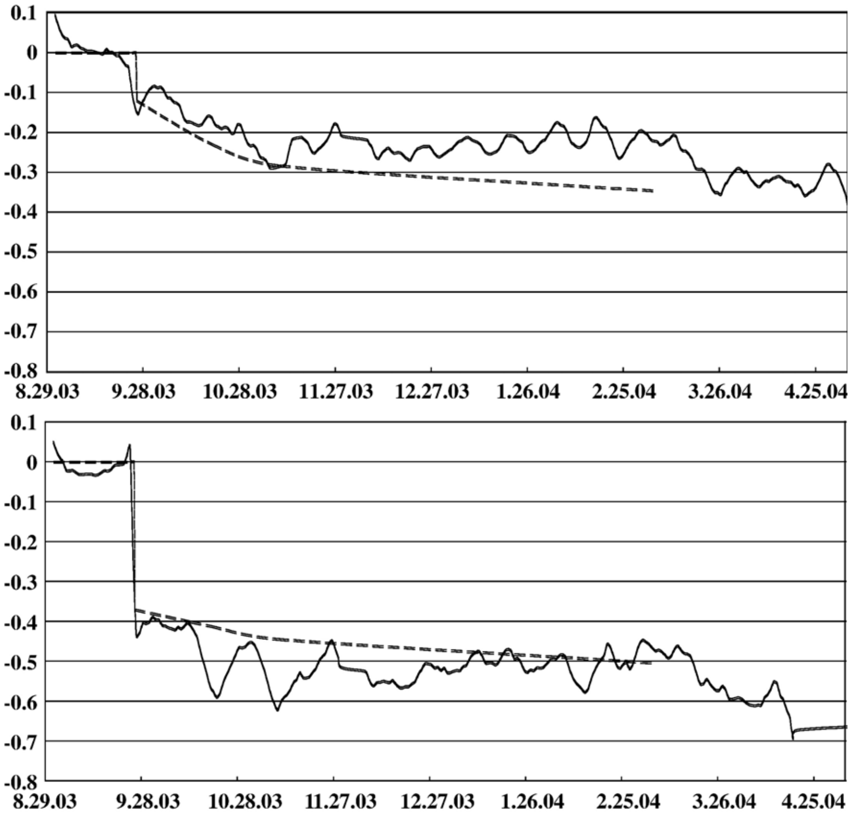

Fig. 7. Estimated and observed post-seismic pressure decay in time for the two tidal gauge locations due to post-slip of the 2003 Tokachi-oki earthquake. Post-slip distributions are taken from Ozawa et al. (2004) and uplift values are calculated using the Okada model (Okada, 1992). Tidal records are given in daily mean after the synthetic tide corrections (Matsumoto et al., 2000). Tidal baselines at the beginning of the figure are estimated by averaging all records for three months before the earthquake. Although there are high amplitude fluctuations remaining in the record, overall trend in the tidal signals show good agreements with estimated seafloor uplift.

side of the asperity but is bounded by the Kushiro Submarine Canyon. The inversion analyses of seismic waves indicated very small displacement distributions in the eastern side of the focal plane of the mainshock (Fig. 1; Yagi, 2004; Yamanaka and Kikuchi, 2004). Although these observational facts suggest that a slip may take place in the eastern side after the mainshock as intensive micro seismic activity, but a well-fitted trend shown in Fig. 7 rather supports the idea of continuous slip taking place after the mainshock. Watanabe et al. (2006-this issue) also found that the aftershocks spread out in the focal area and form a vertically thick zone rather than a plane even after the precise location determination of hypocenters. The aftershock locations may tell that the fracturing of both the subducting slab and the overhang Kuril forearc sliver started locally but widely.

Detailed discussions on the localization and thickening of aftershock zones should be done and might require much geophysical data including land GPS observations as Tsuji et al. (1995) showed for the 1994 Hokkaido Toho-oki earthquake or as Kikuchi et al. (1993) proposed for the 1988 Armenian earthquake. It is worth mentioning that it is important to improve the resolution and spatial coverage of monitoring capability for offshore crustal deformation.

4.3. Precursory

Rikitake (1979) classified, strain accumulation rate, tilt, seismicity change, etc., as parameters for the earthquake precursory of the first kind and specified a leading time prior to mainshocks as a function of magnitude. A long-term observation of 16 years would be necessary to detect any precursory of the first kind if we apply his theory to earthquakes of M8. Melbourne and Webb (2002) reported that there was precursory phenomena observed in an earthquake sequence at the Peru subduction related earthquake but could not find any precursory before the mainshock in their GPS measurements. The precursory they found belongs to one of short-precursories. Katsumata et al. (2002) reported that two tide gauges recorded several cm of subsidence during a five-year period prior to the 1994 Hokkaido Toho-oki earthquake as an intermediate-term precursory and claimed that it is necessary to investigate if subduction-related earthquakes are associated with such intermediate-term geodetic precursory or not. These phenomena may explain that there were, prior to earthquakes, geophysical processes on-going silently in the Kuril seismogenic zones.

Watanabe et al. (2006-this issue) found that a period of quiescence started about 10 days before the mainshock and that the region of the quiescence spread out over the focal area of the earthquake. However, our observations in the offshore detected no significant precursory prior to the earthquake. There might be three reasons: (1) precursory phenomena may have scales of fluctuations below any detectable signal level on the seafloor, (2) precursory phenomena involved some other parameters than those monitored by the cabled observatory, or (3) no precursor appeared on the seafloor. We do not have any means now to identify which is the right answer to this question but would like to state the following: (1) higher signal-to-noise ratio could be obtained if we install our sensors near or in seismogenic zones, (2) precursors could hypothetically be detected with sensors not included in the present day observatory. The former requires drilling or any other means to install sensors as close as possible to seismogenic zones, while the latter requires better understanding of seismogenic processes and of possible short-term precursory phenomena.

4.4. Future directions

Plate boundary megathrust earthquakes take place in the offshore. As in the modeling results shown in Fig. 6, major crustal deformation took place in the offshore in the case of the 2003 Tokachi-oki earthquake. Although high density seismological and geodetic observations are now possible on land, we would like to emphasize that long-term and high precision measurements or observations in the offshore would be one of the most important directions for detecting any changes related to generation of subduction related earthquakes, i.e., seismogenic and interseismic processes, at much closer locations to seismogenic zone. The current technology of cabled observatory or any offshore observational schemes should be enhanced to accommodate any future extension of observations in terms of precision and spatial coverage.

5. Summary

At the time of the 2003 Tokachi-oki earthquake, a megathrust earthquake at the Kuril subduction zone, a cabled observatory recorded invaluable data on both crustal uplift of the seafloor and a benthic storm caused by the earthquake. Our environmental sensors of the cabled observatory have recorded the effects of the benthic storm. The storm could originate upslope from a landslide at a depth of about 1700 m, assuming that there is no mixing nor velocity change in the flow. No clear precursory was observed before the earthquake, but co-seismic and post-seismic continuous crustal uplifts were detected using data from the cabled observatory. The crustal uplift due to the mainshock was estimated as 0.35 m at the cable-end station (25.5 km from the epicenter), 0.37 and 0.12 m at locations of the two tsunami gauges (31.4 and 81.7 km from the epicenter). The estimated rate of the continuous crustal uplifts satisfies a model driven by land-based GPS data. We think it is important to have an observatory close to seismogenic zones for further understanding of seismogenic processes and earthquake precursory.

Acknowledgement

Authors would like to express their sincere gratitude to anonymous reviews and Pierre Henry for comments and suggestions. Also special thanks to Hiroo Kanamori for his generous advice in the processing of the tidal records, to Makoto Murakami for discussions on crustal deformation, and to Yuji Yagi for providing his slip distribution estimates in a digital form. This work was supported by a project research program A02 of the Japan Marine Science and Technology Center (JAMSTEC: Now renamed as Japan Agency for Marine–Earth Science and Technology). We used high-resolution seafloor topography data from the Japan Oceanographic Data Center (JODC) for mapping. Some figures were generated using the Generic Mapping Tools (Wessel and Smith, 1991).

References

DeMets, C., 1992. Oblique convergence and deformation along the Kuril and Japan trenches. J. Geophys. Res. 97 (B12), 17,615–17,625.

DeMets, C., Godon, R., Argus, F., Stein, S., 1994. Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions. Geophys. Res. Lett. 21, 2191–2194.

Heezen, B.C., Ewing, M., 1952. Turbidity currents and submarine slumps, and the 1929 Grand Banks earthquake. Am. J. Sci. 250, 849–873.

Hirata, K., Aoyagi, M., Mikada, H., Kawaguchi, K., Kaiho, Y., Iwase, R., Morita, S., Fujisawa, I., Sugioka, H., Mitsuzawa, K., Suyehiro, K., Kinoshita, H., Fujisawa, N., 2002. Real-time geophysical measurements on the deep seafloor using submarine cable in the southeastern Kurile subduction Zone. IEEE J. Oceanic Eng. 27, 170–181.

Iwase, R., Mitsuzawa, K., Momma, H., 1999. Mudflow associated with the swarm earthquakes east off Izu Peninsula in April 1998, observed by the long-term deep sea floor observatory off Hatsushima

Island in Sagami Bay. JAMSTEC. Jpn. Deep-Sea Res. 14, 301–317 (in Japanese with English abstract).

Katsumata, K., Kasahara, M., Ozawa, S., Ivashchenko, A., 2002. A five years super-slow aseismic precursor model for the 1994 M8.3 Hokkaido-Toho-Oki lithospheric earthquake based on tide gauge data. Geophys. Res. Lett. 29 (13), 1654. doi:10.1029/2002GL014982.

Kikuchi, M., Kanamori, H., Satake, K., 1993. Source complexity of the 1988 Armenian earthquake: evidence for a slow after-slip event. J. Geophys. Res 98 (B9), 15,797–15,808.

Kusunoki, K., Kimura, G., 1998. Collision and extrusion at the Kuril-Japan arc junction. Tectonics 17 (6), 843–858.

Matsumoto, K., Takanezawa, T., Ooe, M., 2000. Ocean tide models developed by assimilating TOPEX/POSEIDON altimeter data into hydrodynamical model: a global model and a regional model around Japan. J. Oceanogr. 56, 567–581.

Melbourne, T.I., Webb, F.H., 2002. Precursory transient slip during the 2001 Mw = 8.4 Peru earthquake sequence from continuous GPS. Geophys. Res. Lett. 29 (21), 2032. doi:10.1029/2002GL015533.

Mikada, H., Matsumoto, H., Watanabe, T., 2004. Wanted long-term observations? Experience from a recent plate boundary earthquake. Proc. 1st International Workshop on Active Monitoring in the Solid Earth Geophysics. Task Group for Active Monitoring, International Union of Geodesy and Geophysics, Mizunami, Japan. Paper S02–4, 4 pp.

Mitsuzawa, K., Holloway, G., 1998. Characteristics of deep currents along trenches in the northwest Pacific. J. Geophys. Res. 103 (C6), 13085–13092.

Miura, S., Suwa, Y., Hasegawa, A., Nishimura, T., 2004. The 2003 M8.0 Tokachi-Oki earthquake — how much has the great event paid back slip debts? Geophys. Res. Lett. 31, L05613. doi:10.1029/2003GL019021.

Miyazaki, S., Segall, P., Fukuda, J., Kato, T., 2004. Space time distribution of afterslip following the 2003 Tokachi-oki Earthquake: implications for variations in fault zone frictional properties. Geophys. Res. Lett. 31, L06623. doi:10.1019/2003GL019410.

Okada, Y., 1992. Internal deformation due to shear and tensile faults in a half-space. Bull. Seismol. Soc. Am. 82, 1019–1040.

Ozawa, S., Kaidzu, M., Murakami, M., Imakiire, T., Hatanaka, Y., 2004. Coseismic and postseismic crustal deformation after the MW 8 Tokachi-oki earthquake in Japan. Earth Planets Space 56, 675–680.

Rikitake, T., 1979. Classification of earthquake precursors. Tectonophysics 54, 293–309.

Satake, K., Shimazaki, K., 1988. Detectability of very slow earthquake from tide gauge records. Geophys. Res. Lett. 15 (7), 665–668.

Takahashi, H., Hirata, K., 2003. The 2000 Nemuro-Hanto-Oki earthquake, off eastern Hokkaido, Japan, and the high intraslab seismic activity in the southwestern Kuril Trench. J. Geophys. Res. 108 (B4), 2178. doi:10.1029/2002JB001813.

Takahashi, H., Kasahara, M., 2003. Seismic activity off Tokachi region, Hokkaido, Japan, Zisin. J. Seismol. Soc. Jpn., Ser. II 56, 393–403 (in Japanese with English abstract).

Takahashi, H., Bahtiarov, V., Levin, V., Gordeev, E., Korchagin, F., Gerasimenko, M., Kasahara, M., Kimata, F., Miura, S., Heki, K., Seno, T., Kato, T., Vasilenko, N., Ivashchenko, A., 1999. Velocity field of around the Sea of Okhotsk and Sea of Japan regions determined from a new continuous GPS network data. Geophys. Res. Lett. 26 (16), 2533–2536.

Takeo, M., Ide, S., Yoshida, Y., 1993. The 1993 Kushiro-Oki, Japan, earthquake: a high stress-drop event in a subducting slab. Geophys. Res. Lett. 20 (23), 2607–2610.

Tsuji, H., Hatanaka, Y., Sagiya, T., Hashimoto, M., 1995. Coseismic crustal deformation from the 1994 Hokkaido-Toho-Oki earthquake monitored by a nationwide continuous GPS array in Japan. Geophys. Res. Lett. 22 (13), 1669–1672.

Watanabe, T., Matsumoto, H., Sugioka, H., Mikada, H., Suyehiro, K., Otsuka, R., 2004. Offshore cabled earthquake monitoring system successfully recorded the 2003 Tokachi-oki earthquake, Hokkaido, Japan, on 25 September 2003. EOS Trans. 85 (2), 14.

Watanabe, T., Takahashi, H., Ichiyanagi, H., Okayama, M., Takada, M., Otsuka, R., Hirata, K., Morita, S., Kasahara, M., Mikada, H., 2006. Seismological monitoring on the Tokachi-oki Earthquake in 2003, derived from Off-Kushiro permanent cabled OBSs and land-based observations. Tectonophysics 426, 107–118. doi:10.1016/j.tecto.2006.02.016 (this issue).

Wessel, P., Smith, W., 1991. Free software helps map and display data. EOS Trans. 72 (441), 445–446.

Yagi, Y., 2004. Source rupture process of the 2003 Tokachi-oki earthquake determined by joint inversion of teleseismic body wave and strong ground motion data. Earth Planets Space 56, 311–316.

Yamanaka, Y., Kikuchi, M., 2004. Source processes of the recurrent Tokachi-oki earthquake on September 26, 2003, inferred from teleseismic body waves. Earth Planets Space 55, e21–e24.