GEOPHYSICAL RESEARCH LETTERS, VOL. 29, NO. 13, 10.1029/2002GL014982, 2002

A five years super-slow aseismic precursor model for the 1994 M8.3 Hokkaido-Toho-Oki lithospheric earthquake based on tide gauge data

Kei Katsumata and Minoru Kasahara
Institute of Seismology and Volcanology, Hokkaido University, Sapporo, Japan

Shinzaburo Ozawa
Geographical Survey Institute, Tsukuba, Japan

Alexei Ivashchenko
Institute of Marine Geology and Geophysics, Yuzhno-Sakhalinsk, Russia

Received 24 February 2002; revised 21 May 2002; accepted 29 May 2002; published 13 July 2002.

[1] Here we present a super-slow aseismic event model prior to the magnitude 8.3 Kurile Island (Hokkaido-Toho-Oki) earthquake on 4 October 1994 based on data recorded by two tide gauges, located 50–150 km from the earthquake epicenter. Both instruments recorded several cm of subsidence during a five-year period prior to the earthquake. The observed signals are consistent with a precursory quasi-stable slip on the western half of the Hokkaido-Toho-Oki fault plane. When recognized, such aseismic events can considerably improve our intermediate-term (several years) prediction capability. *INDEX TERMS:* 1206 Geodesy and Gravity: Crustal movements—interplate (8155); 7209 Seismology: Earthquake dynamics and mechanics; 7223 Seismology: Seismic hazard assessment and prediction; 8124 Tectonophysics: Earth's interior—composition and state (8105)

1. Introduction

[2] Strong ground motions are made up of seismic waves from ruptured fault planes within the Earth's crust. The speed of propagation is usually as fast as that of shear waves (~3 km/s). However, slow or silent slip events devoid of strong ground motions also occur. Recently afterslips had been reported by many authors [*Kawasaki et al.*, 1995; *Heki et al.*, 1997; *Donnellan and Lyzenga*, 1998; *Hirose et al.*, 1999; *Burgmann et al.*, 2001; *Ueda et al.*, 2001; *Hutton et al.*, 2001]. However much less is known on a precursory slip [*Sacks et al.*, 1978; *Linde et al.*, 1988]. Especially preslip event with very long time period lasting several years has never been detected geodetically.

[3] Hokkaido-Toho-Oki earthquake of magnitude 8.3 occurred on 4 October 1994, 150 km east of Hokkaido. Aftershock locations by the International Seismological Center (Figure 1) indicate fault rupture within the Pacific plate, along a steep southeastward dipping fault [*Katsumata et al.*, 1995; *Kikuchi and Kanamori*, 1995; *Ozawa*, 1996]. Tide gauge records are a valuable data source for detecting very slow earthquakes [*Satake and Shimazaki*, 1988] and crustal deformation [e.g. *Savage and Thatcher*, 1992; *Mitchell et al.*, 1994]. In order to investigate possible surface movements prior to this event we analyzed data from four tidal stations in Japan and Russia.

2. Data and Analysis

[4] Four tidal stations, HNS, KSR, MLK and YNK (Figure 1) currently operated by the Japan Meteorological Agency and the Institute of Marine Geology and Geophysics, Russian Academy of Science. Continuous records are available from the Japanese stations HNS and KSR since their installment in 1958 but the Russian stations ceased recording just after the 1994 earthquake and have not been in operation since then.

[5] Time series of tide gauge data are influenced by many factors, including seasonal change (thermal steric components as well as wind-driven real sea surface height changes), atmospheric pressure effect, and longer-term oceanographic phenomena (e.g., switch between the two modes in the Kuroshio routes). We have reduced these effects by using Tsumura's method [*Tsumura*, 1963]. Monthly tidal data are made up of three components as follows.

$$H = H_s + H_t + H_f, \tag{1}$$

H on the left hand side represents tidal records corrected for the atmospheric pressure. H_s, H_t and H_f on the right hand side are annual, geodetic secular trend and residual components, respectively. One often assumes both annual and biannual frequencies for the seasonal changes. In this paper H_s does not include the biannual but only the annual components. H_t would also include eustatic global sea level rise, which is estimated to be around 1–2 mm/year [*Mitrovica et al.*, 2001]. H_f shows similar patterns among the stations in an empirically grouped sea area, suggesting that this component is mainly due to the sea level change in each sea area. In Tsumura's method, the sea level change in each sea area is assumed to be the average of H_f in the equation (1) among the stations in the same sea area. By using the average, H_f for each station is expressed as follows.

$$H_f = H_{f0} + dH_f, \tag{2}$$

where H_{f0} is the average and assumed to represent the sea level change in each sea area. The deviation term dH_f is

0094-8276/02/2002GL014982$05.00

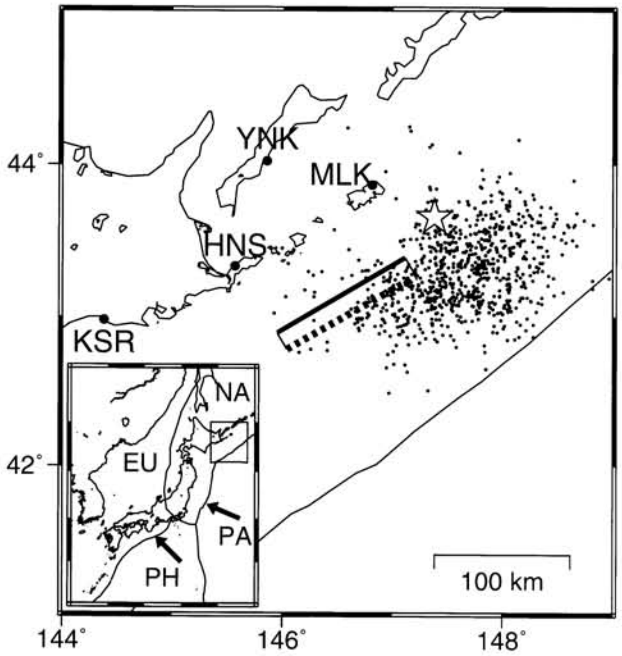

Figure 1. A map showing the location of the four tide gauge stations HNS, KSR, MLK and YNK used in this study relative to the main shock (open star) and aftershocks (dots) of the M8.3 Hokkaido-Toho-Oki earthquake in 1994. A 110 km long, near-vertical fault plane provided the best fit to the super-slow precursory slip observed on the tide gauges. The top (bold line) and bottom (broken line) of the fault dipping 75 degrees toward the southeast are located 3 and 56 km beneath the ocean bottom. An inset shows plate boundaries around Japan, the Eurasian (EU), the Pacific (PA), the North American (NA) and the Philippine Sea (PH) plates.

regarded as the local crustal movements at each station. Tsumura's method takes,

$$H_{crust} = H_t + dH_f \tag{3}$$

as the vertical crustal movement at each station. A moving window with a length of 12 months have been applied to H_{crust} in the equation (3). We assumed that the four tidal stations in Figure 1 were in the sama sea area to calculate H_{f0}.

3. Vertical Ground Movements

[6] Whereas no significant ground movement was detected at MLK between 1980 and 1989, an average surface subsidence rate amounting to 0.3 cm/year was observed at HNS between 1975 and 1989 (Figure 2). From 1990, a marked increase in surface subsidence rates is observed at both these stations, amounting to 0.9–1.1 cm/year. During 1990–1994, a fairly constant but unusually rapid subsidence amounting to 5 ± 2 cm and 4 ± 1 cm was recorded at HNS and MLK, respectively. No comparable signal was observed at stations YNK and KSR during this period indicating a signal source closer to the other two tide meters.

[7] Another outstanding fact is that rapid subsidence was also recorded at HNS prior to the M7.4 Nemuro-Hanto-Oki earthquake in 1973 (E3 on Figure 2), 51 km from HNS. The rate of subsidence increased from 0.3 to 1.5 cm/year four years before the earthquake.

[8] Both the M7.9 Tokachi-Oki earthquake in 1968 (E1 on Figure 2) and the M7.8 Kurile Islands earthquake in 1969 (E2 on Figure 2) did not generate any signal prior to the main shocks because they were too far away from the tide meters; HNS was 333 and 182 km from E1 and E2, respectively. Actually no clear movement was recorded at HNS and KSR even when the main shocks occurred. Clear subsidence was recorded at KSR when the M7.5 Kushiro-Oki earthquake occurred in 1993 (E4 on Figure 2) though no precursory signal was detected. This earthquake was located at a depth of 100 km within the Pacific plate [*Ide and Takeo*, 1996; *Suzuki and Kasahara*, 1996; *Ozel and Moriya*, 1999], which was much deeper than the other shallow earthquakes on Figure 2.

4. Super-slow Aseismic Slip Model

[9] Whereas the continuous deformation we observe may be explained by various crustal sources, our preferred explanation is that it is caused by slow propagation of slip along a fault rather than i.e. a deflating point source. Our choice is also supported by recent simulations based on a laboratory-derived friction law [*Kato and Hirasawa*, 1999] showing that a future fault plane can generate a quasi-stable slip starting several years prior to a main shock. Their model predicts not only the precursory slip but also afterslips. Although afterslip is not observed on the tide gauge records, movements recorded on a nearby GPS network indicated the presence of afterslip following the 1994 Hokkaido-Toho-Oki earthquake [*Heki and Miyazaki*, 1997]. Therefore a sequence: quasi-stable sliding, main shock and afterslip is

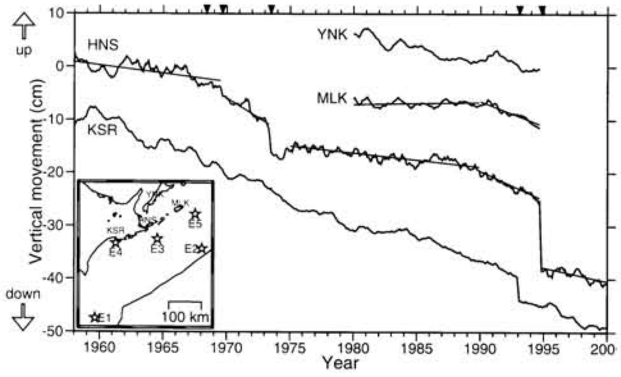

Figure 2. Vertical movements deduced from ocean tide gauge data. Monthly means, that is, one sample per month, were corrected for variations in atmospheric pressure and ocean currents, filtered by running averages with a time window of 12 months. Then linear trends were calculated for each period by a least squares method and are shown as straight lines on the HNS's and MLK's traces. Coseismic subsidences were recorded at HNS for the M7.4 Nemuro-Hanto-Oki earthquake in 1973 (E3), the M8.3 Hokkaido-Toho-Oki earthquake in 1994 (E5) and at KSR for the M7.5 Kushiro-Oki earthquake in 1993 (E4). E1 and E2 denote the M7.9 Tokachi-Oki earthquake in 1968 and the M7.8 Kurile Islands earthquake in 1969, respectively.

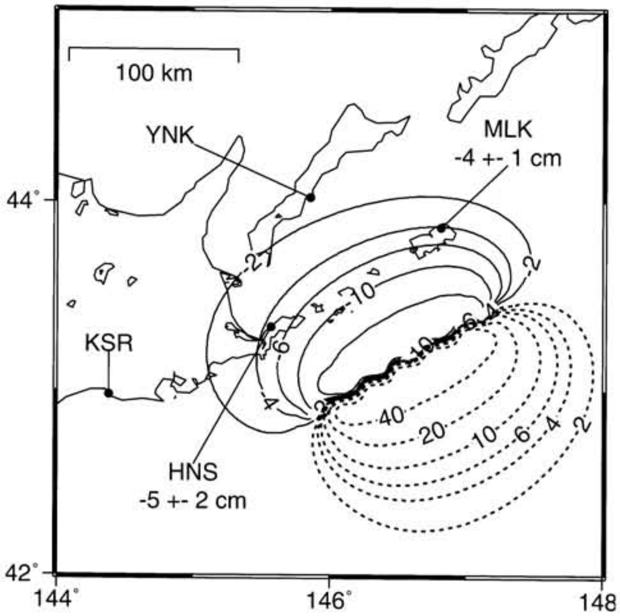

Figure 3. Calculated vertical movements on the assumption that a five-years super-slow aseismic faulting occurs along the fault plane shown in Figure 1. Bold contours indicate subsidence and broken contours uplift in centimeters. Observed subsidences were 5 cm at HNS and 4 cm at MLK. No significant change was detected both at YNK and at KSR.

a scenario the best fitted for our analysis. However, note that the amounts of preslip and afterslip relative to the main slip would still be fairly different from *Kato and Hirasawa* [1999] predicts.

[10] There are two candidates for the fault plane ruptured by the 1994 main shock: a steep-dip fault parallel to the trench and a shallow-dip fault perpendicular to the trench. Relocated aftershocks [*Katsumata et al.*, 1995; *Hurukawa*, 1995], a seismic waveform inversion [*Kikuchi and Kanamori*, 1995; *Cho et al.*, 1995] prefer the steep-dip fault. *Ozawa* [1995] applied a geodetic inversion method to all available coseismic movement data from GPS measurements both in Hokkaido and in Shikotan island, showing that the steep-dip fault was better. On the other hand *Tanioka et al.* [1995] reported that crustal deformation and tsunami wave can be explained by either model. *Tsuji et al.* [1995] also reported that crustal deformation can be explained by either model. Neither *Tanioka* nor *Tsuji* took the data observed in Shikotan into account. Therefore in this study the steep-dip fault was assumed to be ruptured by the 1994 main shock.

[11] Using the formulation by *Okada* [1985] our model fault has a length of 110 km, a down-dip width of 55 km and movement identical to the main event: (strike, dip, slip) = (60°, 75°, 145°), i.e. reverse thrust (0.95 m) and right lateral strike-slip (1.37 m). The slip velocity is held constant at 0.34 meters per year and the slip continues for five years. A map projection of this fault is shown on Figure 1. Calculated vertical surface movements according to this model fit the observed tidal changes (Figure 3) at all stations. Since we estimated a detection threshold of the four tide gauges as $\sim$1 cm/five-years, YNK and KSR are located too far away from the fault. The fact that the observed surface deformation rates are similar at HNS and MLK indicates that they are situated at about equal distance from the source. A fault plane further to the northeast or southwest would unbalance the observed signal at these stations. Its depth was also well controlled because a deeper fault plane will generate signals not observed at YNK and KSR.

[12] The anomaly before the Nemuro-Hanto-Oki earthquake in 1973 was also most likely caused by super-slow aseismic slip along the eventual seismic fault, however, no further data is available to confirm this theory.

5. Discussions

[13] We applied the Tsumura's method to tide gauge data for reducing oceanographic effects. However, curves in Figure 2 still have a lot of signatures in addition to what we claim to be the preseismic signals of the 1973 and 1994 events. For example KSR data seem to have a break point at around 1985 with a size comparable to the HNS data breaks a few years prior to the 1973 and the 1994 events. We concluded that this apparent anomaly was caused by stagnation of sea level rising rate between 1980 and 1984. Besides this period the rate was rather constant at $\sim$1 cm/y. However the origin of the stagnation was unknown.

[14] The following two points suggest that the Tsumura's method worked well. One, the KSR and the YNK tide gauge data do not show preseismic signals similar to those at HNS and MLK. Two, Minobe (personal communication) calculated sea surface height changes using a global ocean data assimilation method [*Carton et al.*, 2000a; *Carton et al.*, 2000b], suggesting that the changes due to oceanographic phenomena were so similar at the four tidal stations between 1985 and 1995 that they were assumed to be in the same sea area.

[15] Further constraints to our model are provided by seismic and strain meter observations. A marked decrease in seismicity within the area surrounding the 1994 earthquake fault (Figure 4, *Katsumata and Kasahara* [1999]) coincided

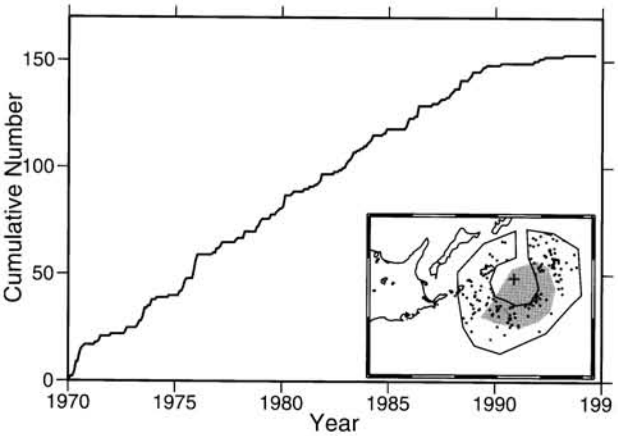

Figure 4. Cumulative number of earthquakes with a magnitude of 5 and larger as determined by the International Seismological Center. An inset shows the area of earthquakes sampled, the main shock of the 1994 Hokkaido-Toho-Oki earthquake (+) and the aftershock area (shadowed polygon).

chronologically with the increase in crustal deformation, in 1990. Super-slow aseismic slip along the eventual fault plane provides the most likely explanation of this seismic quiescence. In August 1994, 2 months prior to the M8.3 earthquake, the Institute of Seismology and Volcanology, Hokkaido University reported to the Coordinating Committee for Earthquake Prediction that a vault strain meter at Nemuro, 14 km east of HNS, had been showing unusual dilatational changes in strain changes from 1990 [*Hokkaido University*, 1994]. The calculated strain magnitude agrees within an order of one with the observed extensional strain of a few tens of microstrains. The direction of calculated extensional axis also agrees within 20 degrees with the observed one. Based on the limited surface measurements available and thus control on the model parameters all the above observations are in agreement.

6. Concluding Remarks

[16] The tide gauge data have a good signal-to-noise ratio, are chronologically related to both the decrease in seismic activity and the Nemuro strainmeter anomaly, and exhibit a strong temporal association with the 1994 Hokkaido-Toho-Oki earthquake. We thus interpret them as clear evidence for a super-slow precursory slip on the eventual earthquake fault. Although currently data on slow aseismic events is very limited we are of the opinion that they are commonly associated with subduction zone earthquakes. Improved monitoring of such aseismic slip is therefore of utmost importance for future intermediate-term earthquake prediction.

[17] **Acknowledgments.** We would like to thank Bryndis Brandsdottir at University of Iceland for revising our manuscript and useful comments, Shoshiro Minobe at Hokkaido University for providing us with valuable information on changes in sea surface height and two anonymous reviewers for constructive comments. GMT-SYSTEM [*Wessel and Smith*, 1991] was used to map data.

References

Burgmann, R., M. G. Kogan, V. E. Levin, C. H. Scholz, R. W. King, and G. M. Steblov, Rapid aseismic moment release following the 5 December, 1997 Kronotsky, Kamchatka, earthquake, *Geophys. Res. Lett.*, *28*, 1331–1334, 2001.

Carton, J. A., G. Chepurin, X. Cao, and B. Giese, A simple ocean data assimilation analysis of the global upper ocean 1950–95 Part I: Methodology, *J. Phys. Oceanography*, *30*, 294–309, 2000a.

Carton, J. A., G. Chepurin, and X. Cao, A simple ocean data assimilation analysis of the global upper ocean 1950–95 Part II: Results, *J. Phys. Oceanography*, *30*, 311–326, 2000b.

Cho, I., I. Nakanishi, K. Imanishi, and T. Sato, The CMT Solution of the 1994 October 4 Shikotan island earthquake (M_{jma} = 8.1) recorded by broad-band strong-motion seismographs (in Japanese), *J. Seismol. Soc. Jpn.*, *48*, 353–364, 1995.

Donnellan, A., and G. A. Lyzenga, GPS observations of fault afterslip and upper crustal deformation following the Northridge earthquake, *J. Geophys. Res.*, *103*, 21,285–21,297, 1998.

Heki, K., S. Miyazaki, and H. Tsuji, Silent fault slip following an interplate thrust earthquake at the Japan Trench, *Nature*, *386*, 595–598, 1997.

Heki, K., and S. Miyazaki, Postseismic crustal deformation of the 1994 Hokkaido-Toho-Oki earthquake, *Programme and Abstracts the Seismological Society of Japan, No. 2*, No. 2, P76, 1997.

Hirose, H., K. Hirahara, F. Kimata, N. Fujii, and S. Miyazaki, A slow thrust slip event following the two 1996 Hyuganada earthquakes beneath the Bungo Channel, southwest Japan, *Geophys. Res. Lett.*, *26*, 3237–3240, 1999.

Hokkaido University, Continuous observation of crustal deformation in Hokkaido region -Strain accumulation of 9 stations for the period from May 1987 to November 1992, *Report of the Coordinating Committee for Earthquake Prediction*, *52*, 45–55, 1994.

Hurukawa, N., Quick aftershock relocation of the 1994 Shikotan earthquake and its fault planes, *Geophys. Res. Lett.*, *22*, 3159–3162, 1995.

Hutton, W., C. DeMets, O. Sanchez, G. Suarez, and J. Stock, Slip kinematics and dynamics during and after the 1995 October 9 M_w = 8.0 Colima-Jalisco earthquake, Mexico, from GPS geodetic constraints, *Geophys. J. Int.*, *146*, 637–658, 2001.

Ide, S., and M. Takeo, The dynamic rupture process of the 1993 Kushiro-oki earthquake, *J. Geophys. Res.*, *101*, 5661–5675, 1996.

Kato, N., and T. Hirasawa, Nonuniform and unsteady sliding of a plate boundary in a great earthquake cycle: A numerical simulation using a laboratory-derived friction law, *Pure Appl. Geophys.*, *155*, 93–118, 1999.

Katsumata, K., M. Ichiyanagi, M. Miwa, M. Kasahara, and H. Miyamachi, Aftershock distribution of the October 4, 1994 Mw8.3 Kurile islands earthquake determined by a local seismic network in Hokkaido, Japan, *Geophy. Res. Lett.*, *22*, 1321–1324, 1995.

Katsumata, K., and M. Kasahara, Precursory seismic quiescence before the 1994 Kurile Earthquake (M_w = 8.3) revealed by three independent seismic catalogs, *Pure Appl. Geophys.*, *155*, 443–470, 1999.

Kawasaki, I., Y. Asai, Y. Tamura, T. Sagiya, N. Mikami, Y. Okada, M. Sakata, and M. Kasahara, The 1992 Sanriku-oki, Japan, ultra-slow earthquake, *J. Phys. Earth*, *43*, 105–116, 1995.

Kikuchi, M., and H. Kanamori, The Shikotan earthquake of October 4, 1994: lithospheric earthquake, *Geophys. Res. Lett.*, *22*, 1025–1028, 1995.

Linde, A. T., K. Suyehiro, S. Miura, I. S. Sacks, and A. Takagi, Episodic aseismic earthquake precursors, *Nature*, *334*, 513–515, 1988.

Mitchell, C. E., P. Vincent, R. J. Weldon II, and M. A. Richards, Present-day vertical deformation of the Cascadia margin, Pacific Northwest, United States, *J. Geophys. Res.*, *99*, 12,257–12,277, 1994.

Mitrovica, J. X., M. E. Tamisiea, J. L. Davis, and G. A. Milne, Recent mass balance of polar ice sheets inferred from patterns of global sea-level change, *Nature*, *409*, 1026–1029, 2001.

Okada, Y., Surface deformation due to shear and tensile faults in a half-space, *Bull. Seismol. Soc. Am.*, *75*, 1135–1154, 1985.

Ozawa, S., Geodetic inversion for the fault model of the 1994 Shikotan earthquake, *Geophys. Res. Lett.*, *23*, 2009–2012, 1996.

Ozel, N., and T. Moriya, Different stress directions in the aftershock focal mechanisms of the Kushiro-Oki earthquake of Jan. 15, 1993, SE Hokkaido, Japan, and horizontal rupture in the double seismic zone, *Tectonophysics*, *313*, 307–327, 1999.

Sacks, I. S., S. Suyehiro, A. T. Linde, and J. A. Snoke, Slow earthquakes and stress redistribution, *Nature*, *275*, 599–602, 1978.

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

Savage, J. C., and W. Thatcher, Interseismic deformation at the Nankai Trough, Japan, Subduction zone, *J. Geophys. Res.*, *97*, 11,117–11,135, 1992.

Suzuki, S., and M. Kasahara, Unbending and horizontal fracture of the subducting Pacific plate, as evidenced by the 1993 Kushiro-oki and the 1981 and 1987 intermediate-depth earthquakes in Hokkaido, *Phys. Earth Planet. Interiors*, *93*, 91–104, 1996.

Tanioka, Y., L. Ruff, and K. Satake, The great Kurile earthquake of October 4, 1994 tore the slab, *Geophys. Res. Lett.*, *22*, 1661–1664, 1995.

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

Tsumura, K., Investigation of the mean sea level and its variation along the coast of Japan (Part I) - Regional distribution of sea level variation-, *J. Geodetic Soc. Japan*, *9*(no.2), 49–90, 1963.

Ueda, H., M. Ohtake, and H. Sato, Afterslip of the plate interface following the 1978 Miyagi-Oki Japan, earthquake, as revealed from geodetic measurement data, *Tectonophysics*, *338*, 45–57, 2001.

Wessel, P., and W. H. F. Smith, Free software helps map and display data, *Eos Trans. AGU*, *72*, 445–446, 1991.

K. Katsumata and M. Kasahara, Institute of Seismology and Volcanology, Hokkaido University, Sapporo 060-0810, Japan. (katsu@eos.hokudai.ac.jp)

S. Ozawa, Geographical Survey Institute, Tsukuba 305-0811, Japan.

A. Ivashchenko, Institute of Marine Geology and Geophysics, Yuzhno-Sakhalinsk, Russia.