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Quasi-static slip on the plate boundary associated with the 2003 M8.0 Tokachi-oki and 2004 M7.1 off-Kushiro earthquakes, Japan

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ABSTRACT

We analyzed small repeating earthquakes recorded over a 13-year period and GPS data recorded over an 8-month period to estimate interplate quasi-static slip associated with the 2003 Tokachi-oki earthquake (M8.0) and the 2004 off-Kushiro earthquake (M7.1). The repeating-earthquake analysis revealed that the slip rate near the source region of the Tokachi-oki earthquake was relatively low (<5 cm/year) prior to the earthquake; however, in the last 3 years leading up to the event, a minor acceleration in slip occurred upon the deeper extension of the coseismic slip area of the earthquake. Repeating-earthquake and GPS data indicate that large amounts of afterslip occurred around the rupture area following the earthquake; the afterslip mainly propagated to the east of the coseismic slip area. We also infer that the occurrence of the 2004 off-Kushiro earthquake, located about 100 km northeast of the epicenter of the Tokachi-oki earthquake, was advanced by the afterslip associated with the Tokachi-oki earthquake.

1. Introduction

The Japanese islands occur in an active subduction setting and many seismological studies in this area contributed to the understanding of the nature of the subduction zone (e.g., Hasegawa et al., 1978; Matsuzawa et al., 1990; Umino et al., 1995; Miura et al., 2004a; Maruyama and Okamoto, 2007; Yamamoto et al., 2009; Zhao and Ohtani, 2009-this issue; Ariyoshi et al., 2009–this issue; Igarashi, 2009–this issue; Nakajima et al., 2009–this issue; Hasegawa et al., 2009–this issue). In the northeastern area, the Pacific plate is currently subducting along the Kuril and Japan trenches off the southeast coast of Hokkaido, Japan, at a rate of about 8 cm/year (DeMets, 1992) (Fig. 1). Recent studies have revealed the distribution of source regions for large interplate earthquakes in this area. The contours in Fig. 1 show the main slip areas (asperities) of the three most recent large earthquakes on the plate boundary, as determined from waveform inversion (Yamanaka and Kikuchi, 2003, 2004). The 2003 Tokachi-oki earthquake (M8.0) occurred on September 26, 2003 and ruptured offshore of Cape Erimo (Fig. 1) (e.g. Yamanaka and Kikuchi, 2003; Ito et al., 2004; Miura et al., 2004b; Tanioka et al., 2004; Yagi, 2004; Miyazaki et al., 2006; Rubinstein et al., 2007). The slip area of the 2003 event was overlapped with that of the 1952 Tokachi-oki earthquake (M8.2) (Yamanaka and Kikuchi, 2003) and estimated maximum coseismic slip of the 2003 event is approximately equal to the slip-deficit that accumulated at the site since the occurrence of the 1952 earthquake (Miura et al., 2004b). The 1973 Nemuro-oki earthquake (M7.4) (Fig. 1; northeast of the 2003 Tokachi-oki earthquake) ruptured almost the same area as the 1894 Nemuro-oki earthquake (M7.9), while the 1968 Tokachi-oki earthquake (M7.9) ruptured an area to the southwest of the 2003 Tokachi-oki earthquake (Yamanaka and Kikuchi, 2004) (Fig. 1).

The above observations indicate that large earthquakes repeatedly rupture within similar or even overlapping areas. The slip histories of areas other than these coseismic slip areas have been investigated using GPS data and the records of small repeating earthquakes. The back-slip (slip deficit) rate distribution estimated from GPS data for the period 1997–2001 shows that the plate interface is coupled to depths of 80–100 km in this region (Suwa et al., 2006). Using GPS data for the period 1998–2003, Baba and Hori (2006) obtained a clear image of the slip deficit distribution for the period leading up to the 2003 event. Their results show a correlation between the estimated slip deficits and coseismic slip areas for large earthquakes (the 2003 Tokachi-oki earthquake and the 1973 Nemuro-oki earthquake). Baba and Hori (2006) also suggested that the deeper half of the plate interface, within the rupture area of the 2003 Tokachi-oki earthquake, became uncoupled several years prior to the event. Post-seismic deformation associated with the 2003 Tokachi-oki earthquake was observed by GPS and indicates that afterslip was distributed mainly in the region outside of the area of coseismic slip (Ozawa et al., 2004;

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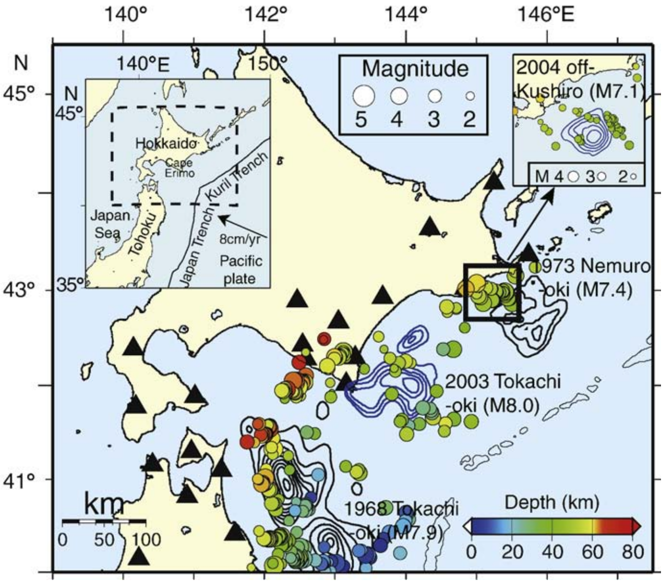

Fig. 1. Distribution of groups of repeating earthquakes. Each circle is located at the centroid of the hypocenters of the earthquakes from each group; the depth of the centroid is indicated by the circle color. Solid triangles indicate stations used for the analysis of repeating-earthquake data. Contours show the slip distributions of large earthquakes (Yamanaka and Kikuchi, 2003).

Miyazaki et al., 2004; Baba et al., 2006). Matsubara et al. (2005) and National Research Institute for Earth Science and Disaster Prevention (2006) analyzed small repeating earthquakes and found that repeating earthquakes in afterslip areas showed large amounts of slip following the 2003 event. Based on an analysis of GPS data, Murakami et al. (2006) proposed that slow slip related to the 2003 event triggered the 2004 off-Kushiro earthquake (M7.1).

Aseismic slip probably plays an important role in the earthquake generation process at plate boundaries, as investigated in other areas (e.g., Matsuzawa et al., 2004; Uchida et al., 2004, 2005). To clarify the role of aseismic slip in earthquake generation, it is necessary to precisely estimate the spatio-temporal evolution of aseismic slip before and after large earthquakes. In the present study, we conducted analyses of small repeating earthquakes to reveal the long-term (13-year) quasi-static slip distribution on the plate boundary southeast of Hokkaido, Japan. We also analyzed GPS data to compare with the results of our analysis of repeating earthquakes.

2. Analysis of repeating-earthquake data

Sequences of small repeating earthquakes are thought to represent recurring slip on small asperities (seismic patches) upon a fault plane (Ellsworth, 1995; Nadeau and McEvilly, 1999; Igarashi et al., 2003; Uchida et al., 2003). This interpretation implies that an isolated asperity repeatedly slips as a repeating earthquake sequence to keep pace with aseismic (quasi-static) slip in the surrounding region. Thus, we are able to estimate the slip rate in the area around small asperities by assuming that the cumulative slip of the repeating earthquakes corresponds to the cumulative aseismic slip in the surrounding region (Nadeau and McEvilly, 1999; Igarashi et al., 2003; Uchida et al., 2003). The analysis of repeating earthquakes in the present study has the advantages of relatively high spatial resolution, especially near the trench, and the availability of long-term data compared to the availability of GPS data.

We analyzed more than 20,000 earthquakes of M≥2.5 using waveform data observed at 30 seismic stations operated by Hokkaido, Hirosaki, and Tohoku Universities (solid triangles in Fig. 1) over the period July 1993 to February 2005. Those earthquakes with a high degree of similarity in their waveforms were selected as repeating earthquakes, as detailed below.

Earthquake pairs with epicenter separations of less than 40 km were selected for analysis, and coherences were calculated for a 40 s window that includes P and S phases. Consequently, pairs have almost identical S–P times if the coherence is high. We treated an earthquake pair as a pair of repeating earthquakes if the averaged coherences for 1–8 Hz were larger than 0.95 at two or more stations. A pair of repeaters was linked with another pair if both pairs shared the same earthquake. This grouping procedure was iterated until no repeaters are shared by two or more groups. As a result, we obtained 1369 repeating earthquakes that were grouped into 349 sequences.

The cumulative slip for each group of repeating earthquake was then calculated using the following procedure, as described by Uchida et al. (2004). We calculated the seismic moment of each repeating earthquake from the magnitude determined by the Japan Meteorological Agency (JMA) using the following relationship between magnitude (M) and seismic moment (Mo; dyne-cm) (Hanks and Kanamori, 1979):

$$log(M_0) = 1.5M + 16.1. \tag{1}$$

The slip amounts were then determined using the following relationship between seismic moment and slip (d; cm), as proposed by Nadeau and Johnson (1998):

$$log(d) = -2.36 + 0.17log(M_0). \tag{2}$$

Igarashi et al. (2003) confirmed that the slip calculated from this relation is consistent with the slip estimated from the relative plate motion and repeating intervals using the data of several events in NE Japan.

The identified repeating earthquakes are distributed in the area between the trench and the coast of Hokkaido and northern Honshu (Fig. 1). Low-angle thrust-type focal mechanisms (National Research Institute for Earth Science and Disaster Prevention, 2005) (Fig. 2) and depth ranges (color scale in Fig. 1) indicate that the earthquakes are

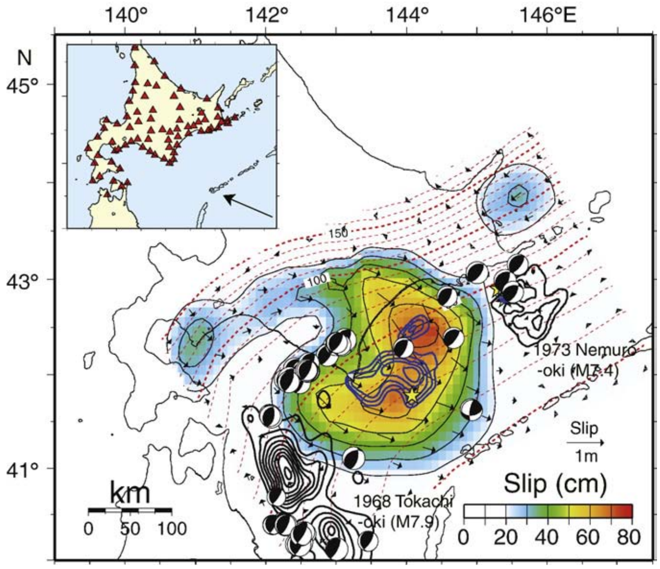

Fig. 2. Afterslip distribution for the 2003 Tokachi-oki earthquake. Interplate slip estimated from GPS data for the period September 26, 2003 (immediately after the 2003 Tokachi-oki earthquake) to November 29, 2004 (just prior to the 2004 off-Kushiro earthquake) is also shown. The color scale and contours indicate the slip amount, and arrows show the slip vectors of the upper plate. Dashed red contours show the plate model used in the inversion. In the insert map, GPS stations used in the analysis are represented by red triangles, and the direction of relative plate motion is indicated by the black arrow. Also shown are the best double-couple moment tensors for the repeating earthquakes determined by the National Research Institute for Earth Science and Disaster Prevention, Japan (National Research Institute for Earth Science and Disaster Prevention, 2005).

interplate events. Some outliers in terms of focal mechanism and depth for events located far from land probably reflect poor station coverage. We note that the repeating earthquakes are distributed largely outside the coseismic slip areas (asperities) of the 1968 Tokachi-oki, 1973 Nemuro-oki, and 2003 Tokachi-oki earthquakes (Fig. 1). The depths of repeating earthquakes (i.e., earthquakes on the plate boundary) extend to about 60–70 km. This depth is shallower than the extent of interplate coupling in eastern Hokkaido estimated from GPS data (80–100 km (Suwa et al., 2006)).

3. Analyses of GPS data

Previous GPS-based studies have investigated afterslip associated with the 2003 Tokachi-oki earthquake (Miura et al., 2004b; Miyazaki et al., 2004; Ozawa et al., 2004; Baba and Hori, 2006). We performed geodetic inversion analyses using GPS data to obtain the spatio-temporal evolution of interplate aseismic slip in order to directly compare the results with those derived from repeating earthquakes. Analyzed GPS data were sourced from stations located in and around Hokkaido (red triangles in Fig. 2) as part of the GPS Earth Observation Network (GEONET) operated by the Geographical Survey Institute of Japan (GSJ). Analysis of the GPS data has the advantages of obtaining estimated slip at high temporal resolution and the ability to estimate slip over a wide area compared with the analysis of repeating earthquakes. This is because we use continuous GPS data and the displacement at a GPS station reflects crustal deformation in a wide area.

We used the geodetic inversion method developed by Yagi and Kikuchi (2003), in which aseismic slip (slip rate function) in each grid point allocated on the plate interface is expressed by the superposition of triangular slip functions. We inverted the displacements at GPS stations to estimate the amplitudes of each slip function with some constraints: we assumed that the slip distribution should be smooth in space. This can be obtained if the Laplacian of the slip vectors tends to zero. Temporal variations in slip at each grid point should also be smooth. This can be realized if the acceleration of slip at each grid point and at each time step is approximately zero. In addition, the slip angle at each grid point should be in the range of −90+/−45° (normal slip) or 90+/−45° (reverse slip). These three constraint equations can be written in a vector form as $\mathbf{P_n x}+\mathbf{e_n}=0$ (n = 1, 2, 3), where $\mathbf{P_n}$ is the constraint on slip, $\mathbf{x}$ is the parameter vector, and $\mathbf{e_n}$ is the Gaussian error with a variance of σ_n^2 (Yagi et al., 2003). For given values of σ_n^2, we can estimate the model parameters

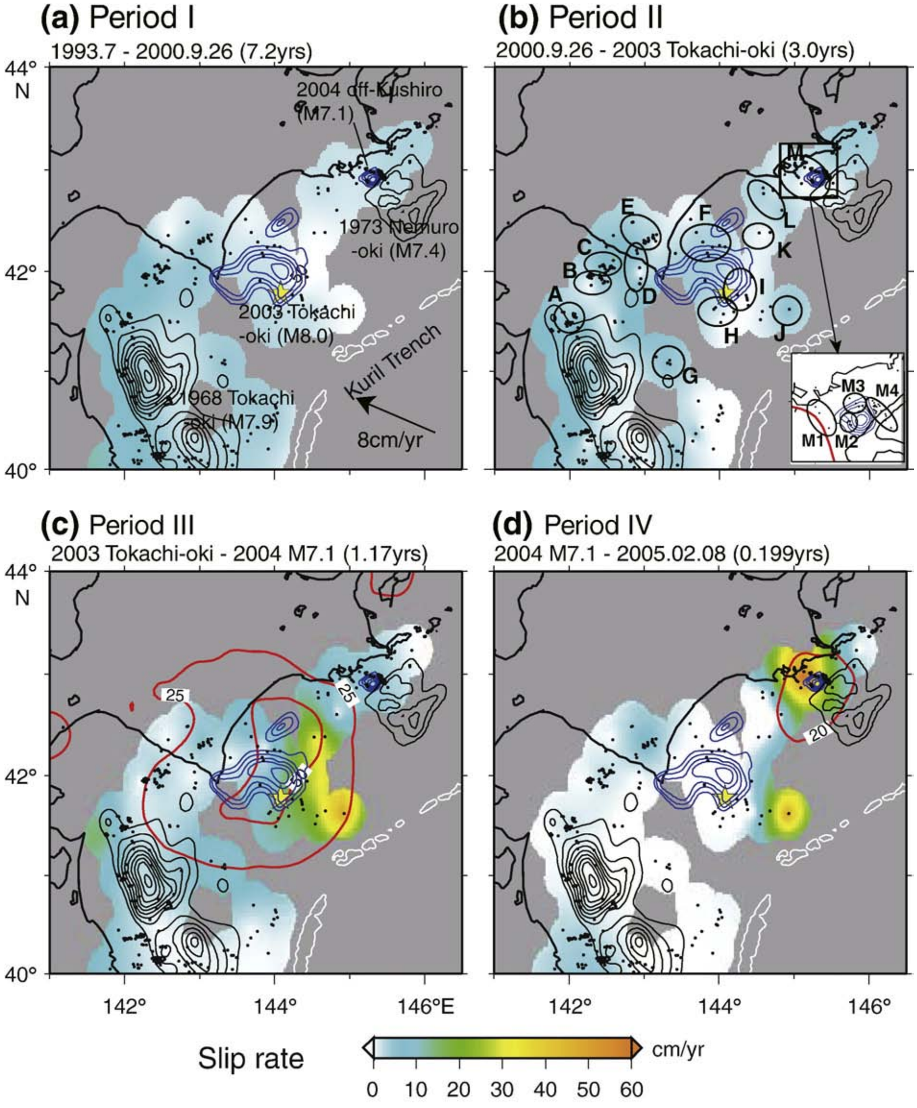

Fig. 3. Spatio-temporal distribution of interplate slip. Slip rates estimated from groups of repeating earthquakes (black dots) are shown by the color scale for the periods of (a) July 1993 to September 26, 2000; (b) September 26, 2000 to September 26, 2003; (c) September 26, 2003 to November 29, 2004; and (d) November 29, 2004 to February 8, 2005. The slip rates are averaged for every 0.5×0.5 degree square and interpolated using a spline function. Red contours in figures b and c denote slip rates estimated from the analysis of GPS data. Coseismic steps were removed in the analysis of GPS data. The gray areas are unresolved areas due to the absence of small repeating earthquakes.

using the least-squares method. To determine the optimum values of σ_n^2 objectively, we minimized the Akaike's Bayesian information criterion (ABIC) (Akaike, 1980).

The geometry of the plate boundary was assumed from iso-depth contours derived from the hypocenters of repeating earthquakes (this study) located shallower than 70 km and from the model of Katsumata et al. (2003) for areas deeper than 70 km (Red contours in Fig. 2). We assigned a model fault to the plate boundary and divided it into a grid of 13 × 10 sub-faults. The precise daily solutions of the coordinates of GEONET sites obtained by GSI (Hatanaka et al., 2003) were used to obtain the three-dimensional displacements at 74 GEONET stations. The preseismic linear trend and annual and semi-annual constituents were estimated for the period January 1, 1999 to September 25, 2003, and then extracted from the raw data for use in the inversion.

Fig. 2 shows the afterslip distribution on the plate boundary estimated from GPS data for the period September 26, 2003 (immediately after the 2003 Tokachi-oki earthquake) to November 29, 2004 (immediately before the 2004 off-Kushiro earthquake). Large amounts of afterslip were estimated for the areas near the asperities of the 2003 Tokachi-oki earthquake (blue contours). Two peaks in the afterslip of up to about 70 cm were estimated outside the asperity. The arrows in Fig. 2 indicate the slip directions of the overriding plate. These directions are subparallel to the relative plate motion (arrow in the insert map in Fig. 2), indicating that the slip deficit around the asperity during the interseismic period was released as afterslip following the large earthquake. The areas of slip appear to be distributed in the region between the areas of coseismic slip related to the 2003 Tokachi-oki and 1968 Tokachi-oki earthquakes, the region between the coseismic slip areas of the 2003 Tokachi-oki and 1973 Nemuro-oki earthquakes, and the region north of the 2003 Tokachi-oki earthquake (Fig. 2).

4. Spatio-temporal variations in quasi-static slip

In Fig. 3, slip rates estimated from repeating earthquakes and GPS data are shown for four different time periods by the color scale and red contours, respectively. For area to the west (deeper levels) of the slip area of the 1968 Tokachi-oki earthquake, the analysis of repeating earthquakes indicates that the slip rate for the period from 10.2 to 3 years prior to the 2003 event (July 1, 1993 to September 26, 2000; Period I) ranges from 6 to 10 cm/year (Fig. 3a). These values are comparable to the plate convergence rate in the region (8 cm/year) (DeMets, 1992). The slip rate in areas to the east (shallower levels) of the asperity of the 1968 Tokachi-oki earthquake and to the northwest (deeper levels) of the 1973 Nemuro-oki earthquake are around 5 cm/year. In contrast, the slip rate during this period for the area around the 2003 event is very low (<5 cm/year) (Fig. 3a). For the 3-year period prior to the 2003 Tokachi-oki earthquake (September 26, 2000 to September 26, 2003; Period II), the overall slip rate distribution (Fig. 3b) is similar to that for Period I (Fig. 3a); however, there is a small decrease in slip rate in the area to the east (shallower levels) of the slip area of the 1968 Tokachi-oki earthquake (40°–41°N, 143°–144°E), and slip rate increase in the area to the northeast of the slip area of the 2003 Tokachi-oki earthquake (around Region F in Fig. 3b).

Following the 2003 event, high slip rates were observed around the asperity of the event (Fig. 3c; Period III). The slip rate to the south and east of the asperity is especially high, as deduced from the analysis of repeating earthquakes. Although the peak of slip is a little shifted, our analysis of GPS data also shows a high slip rate in these regions (red contours in Fig. 3c). The discrepancy in the peak of slip rate is probably due to the errors in both repeating earthquake and GPS data analyses such as error in the slip and seismic moment relationship used for small repeating earthquake data and relatively poor resolution for GPS data for the region far from land stations. Following the 2003 event, the off-Kushiro earthquake (M7.1) occurred on November 29, 2004 along the deeper extension of the 1973 Nemuro-oki earthquake (Fig. 3d). After the M7.1 event, a high slip rate was again observed around the source area, both from analysis of the repeating earthquakes and GPS data (Fig. 3d; Period IV). Note that the accuracy of the slip-rate estimates derived from repeating earthquakes for Periods III and IV are relatively low because of the short duration of the analysis period relative to the recurrence intervals of the small repeating earthquakes.

Our analysis of long-term repeating earthquakes shows that the averaged cumulative slip of small repeating earthquakes increased at

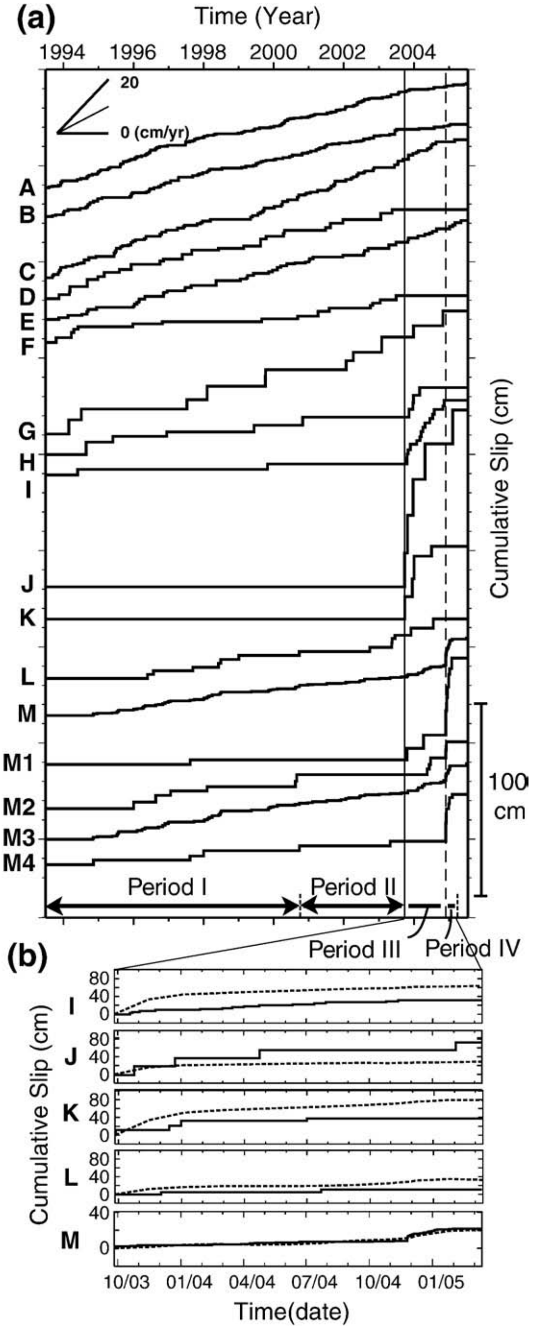

Fig. 4. Time histories of quasi-static slip on the plate boundary. (a) Averaged cumulative slip in the small regions (A–M) shown in Fig. 3 b for an 11-year period. Solid and dashed vertical lines represent the dates of the 2003 Tokachi-oki earthquake (September 26, 2003) and 2004 off-Kushiro earthquake (November 29, 2004), respectively. (b) Time histories of quasi-static slip following the 2003 Tokachi-oki earthquake. Solid and dashed lines denote slip estimated from repeating earthquakes and GPS data, respectively.

an approximately constant rate in the area to the west of the 2003 Tokachi-oki earthquake (Regions A–E in Figs. 3b and 4a) for the entire study period. In contrast, for regions to the east of the coseismic slip area of the 2003 Tokachi-oki earthquake (Regions I–M), significant accelerations in slip rate occurred following the 2003 Tokachi-oki earthquake (solid vertical line in Fig. 4a). Our analysis of GPS data also shows a high slip-rate for the period following the 2003 Tokachi-oki earthquake (Fig. 4b). The temporal changes in slip rate for these areas deduced from GPS data are almost the same as those for Regions J, L, and M, although the slips estimated from repeating earthquakes are smaller in Regions I and K. Changes in the rate of cumulative slip in Regions L, M1, M2 and M3 (Fig. 4) indicate that slip accelerated following the 2003 Tokachi-oki earthquake (Period III), even in regions close to the asperity of the 2004 M7.1 event. Here, the timing of acceleration in region M3 that is more distant from M2 seems to start earlier than that in M2. This probably shows the afterslip propagated non-uniformly, according to heterogeneous coupling on the plate interface.

5. Discussion

We observed accelerations in slip during Period II around the north part of the coseismic slip area of the 2003 Tokachi-oki earthquake (Fig. 3b; in and around Region F). Most of the repeating earthquakes (black dots) in the area are located near the northern (deeper level) edge of the coseismic slip area of the 2003 event (Fig. 3b). This suggests that quasi-static slip in the deeper area neighboring the coseismic slip area accelerated approximately 3 years before the 2003 Tokachi-oki earthquake. This decoupling of the plate boundary prior to the 2003 event was also documented by Baba and Hori (2006) on the basis of GPS data. Fig. 4a shows that the slip rate in Region F only accelerated in 1994 and during Period II. The behavior in Region F is probably peculiar to the transition zone between strongly locked (coseismic slip area) and stably slipping areas. Such episodic slip prior to large seismic slip has been predicted in some cases from numerical simulations based on laboratory-derived friction laws (Kato et al., 1997; Kato, 2003; Yoshida and Kato, 2003).

In contrast, quasi-static slip during Period II decelerated in the area to the east (shallower extension) of the source region of the 1968 Tokachi-oki earthquake (Fig. 3b). This phenomenon is probably explained by the deceleration in afterslip related to the 1994 Far-off-Sanriku earthquake (December 28, 1994, M7.6) that occurred during Period I (July 1, 1993 to September 26, 2000). The 1994 earthquake ruptured the southern half of the coseismic slip area of the 1968 Tokachi-oki earthquake (Nagai et al., 2001), and large amounts of afterslip even occurred in the shallower extension of the coseismic slip area (Uchida et al., 2004).

We estimated the afterslip distribution of the 2003 Tokachi-oki earthquake from both repeating earthquakes and GPS data. The afterslip appears to be large around the source region of the 2003 Tokachi-oki earthquake where the slip rate was low prior to the earthquake. The temporal changes in afterslip estimated from repeating earthquakes and GPS data show similar patterns, although the slip amounts differ by a factor of around two in some regions (Fig. 4b). These discrepancies probably stem from errors in estimates of the slip amount derived from both the repeating earthquakes and the GPS data. The simultaneous analysis of both datasets will provide a more reliable distribution of quasi-static slip, but such an approach is beyond the scope of the present study.

The 2004 off-Kushiro earthquake (M7.1) occurred on November 29, 2004 near the edge of the afterslip area of the 2003 Tokachi-oki earthquake (Fig. 3c). To explain the continuous GPS data in western Hokkaido, Murakami et al. (2006) modeled the afterslip distribution of the 2003 Tokachi-oki earthquake using three rectangular faults. They also detected slow slip near the 2004 M7.1 event and considered that the slow slip (afterslip) of the 2003 event triggered the 2004 M7.1 event. This result is consistent with the results of the present study. We also analyzed GPS data, but used an inversion technique with objective constraints for GPS data. The repeating-earthquake analysis also shows that slip rates increased prior to the M7.1 event in the immediate vicinity of the event (Fig. 3, regions M1–M3 in Fig. 4a). These observations support the hypothesis that afterslip associated with the 2003 Tokachi-oki earthquake and located near the asperity of the M7.1 event advanced the occurrence of the M7.1 event.

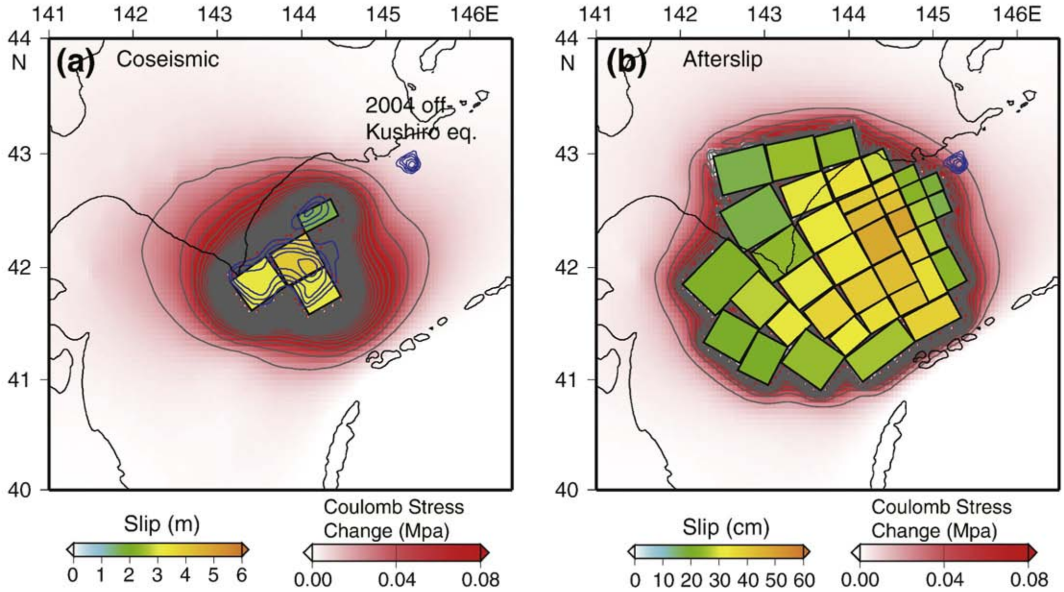

Fig. 5. Changes in Coulomb failure stress on the plate boundary (red color-scale and contours) caused by (a) coseismic slip and (b) afterslip of the 2003 Tokachi-oki earthquake. Rectangles show the assumed fault segments on the plate boundary, whose colors indicate slip amounts. The geometry of the plate boundary is shown in Fig. 2. The slip amount and slip vector for coseismic slip were determined based on the work of Yamanaka and Kikuchi (2003). In determining the amount of afterslip for each segment, we used the average of the results derived from repeating earthquakes and GPS data. The slip direction was assumed to be parallel to the movement of the Pacific Plate relative to the North American Plate (N63 W) (DeMets, 1992). For calculation of the coulomb failure stress change, the slip direction of the target earthquake is also assumed to be parallel to the relative plate motion. Calculation was made in an elastic half-space following Okada (1992), assuming a shear modulus of 3.0×10^{10} N/m^2, Poisson's ratio of 0.25, and apparent coefficient of friction of 0.3.

As discussed above, we consider the accumulation of stress on the asperity for the M7.1 earthquake was progressed due to afterslip of the 2003 Tokachi-oki earthquake and the asperity for the M7.1 earthquake, whose stress level was close to its strength, ruptured due to this small stress increase. Although we do not know the actual stress level and strength of the asperity for the M7.1 earthquake, we try to estimate the effect of the afterslip in a quantitative manner. We used the formulation of Okada (1992) to calculate changes in Coulomb failure stress (ΔCFS) on the plate boundary that were related to coseismic slip (Fig. 5a) and afterslip (Fig. 5b) of the 2003 Tokachi-oki earthquake. In these calculations, the area of coseismic slip comprised three segments, and the slip amount of each segment was calculated from the slip distribution estimated by Yamanaka and Kikuchi (2003) (blue contours in Fig. 5a). For the period prior to the M7.1 earthquake, the afterslip area of the 2003 Tokachi-oki earthquake was divided into 40 rectangular segments, and the slip amount at the center of each segment was determined by averaging estimates derived from repeating earthquakes and GPS data. In calculating the Coulomb failure stress, we assumed that the slip vectors for each segment and for the M7.1 event were parallel to the movement direction of the Pacific Plate relative to the North American Plate (N63 W) (DeMets, 1992). The difference in slip direction between that assumed in the present study and that estimated from body waves for the M7.1 event (Yamanaka, 2004) is less than 4°.

Okada's method can treat only rectangular segments, and the stress gradient close to the edge of each segment is very large. It is difficult to correctly estimate the stress for the region close to the edge of the afterslip area because a very small change in the location of the edge causes a large change in the estimated stress. Thus, we did not place model segments close to the M7.1 event, even though afterslip was observed in areas neighboring the source region of the event (Figs. 3c and 4a). We note that the true effect of the afterslip was probably greater than the value estimated here.

The resultant stress increases for coseismic slip and afterslip at the location of the M7.1 event were 0.0058 Mpa and 0.025 Mpa, respectively. This indicates that the afterslip promoted rupture at the location of the M7.1 event and that the effect was four-times larger than that of the coseismic slip. The increase in coulomb stress was greater than the minimum change in stress (~0.01 Mpa) indicated by estimates of the changes in seismicity reported in other studies (Stein et al., 1992; Harris et al., 1995; Toda et al., 1998). Accordingly, the occurrence of the 2004 M7.1 event was probably fostered by the afterslip related to the 2003 Tokachi-oki earthquake. This observation that the quasi-static slip (afterslip) of large earthquake can remotely trigger other large earthquake is important for the earthquake probability assessment.

6. Conclusions

We estimated the spatio-temporal distribution of quasi-static slip on the plate boundary southeast off Hokkaido from detailed analyses of repeating earthquakes and GPS data over a 13-year period that encompasses the 2003 Tokachi-oki (M8.0) and 2004 off-Kushiro (M7.1) earthquakes. The main results of our study are summarized as follows.

(1) The quasi-static slip are distributed largely outside the coseismic slip areas (asperities) of large earthquakes including the 2003 Tokachi-oki earthquake. The areas immediately surrounding and to the east of the coseismic slip area of the 2003 Tokachi-oki earthquake showed small amounts of quasi-static slip prior to the 2003 Tokachi-oki earthquake, but slip accelerated significantly following the event.

(2) We found small fluctuations in slip rate along the deeper extension of the coseismic slip area of the 2003 Tokachi-oki earthquake: the slip rate for the 3 years immediately preceding the earthquake was faster than that of the previous 7 years. This behavior is probably peculiar to the transition zone between strongly locked (area of coseismic slip) and stably sliding areas.

(3) The 2004 off-Kushiro earthquake occurred near the edge of the afterslip area of the 2003 Tokachi-oki earthquake. On the basis of a comparison of the stress changes associated with coseismic slip and afterslip, we conclude that the afterslip loaded the asperity of the M7.1 event and probably advanced the occurrence of the earthquake.

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