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Pre- and postseismic slow slip surrounding the 2011 Tohoku-oki earthquake rupture

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ABSTRACT

Slow (aseismic) slip that accommodates part of the long-term plate motion on subduction megathrusts is thought to be strongly related to the occurrence of large earthquakes on the same fault zone. However, the temporal evolution and spatial distribution of the aseismic slip before major earthquakes and of accelerated postseismic afterslip are largely unconstrained. We estimate cumulative offsets of small repeating earthquakes that are interpreted to reflect the in situ aseismic slip history on the subduction zone offshore northeastern Japan. These data reveal contrasting aseismic slip patterns between the coseismic rupture area of the Mw 9.0 Tohoku-oki earthquake and surrounding portions of the subduction thrust. The rupture area is characterised by low and variable slip rates before 2008, and the slip stopped almost completely after the earthquake. The region surrounding the rupture area exhibited higher aseismic fault slip rates before the earthquake and clear postseismic slip of up to 1.6 m within 9 months following the main shock. The frictional fault properties and complete relief of ambient stress in the central rupture zone of the main shock probably control the observed distribution. The postseismic slip shows a more abrupt increase in the region closer to the source, suggesting outwards propagation of afterslip. Small but distinct increases in the slip rate in the $\sim$3 yr before the earthquake near the area of large coseismic slip suggests preseismic unfastening of the locked area in the last stage of the earthquake cycle.

1. Introduction

Monitoring of aseismic slip at plate boundaries is important for understanding the processes that occur before and after major earthquakes. Rock mechanics experiments and numerical simulations of earthquakes using friction laws suggest the occurrence of premonitory and postseismic slip transients. Some studies indicate a nucleation process that initially involves stable, slow rupture growth within a confined zone on a fault, just before unstable, high-speed rupture (Dieterich, 1979; Lapusta et al., 2000; Ohnaka, 1992; Shibazaki and Matsu'ura, 1992). Other studies predict longer precursory slip accelerations that may extend for a considerable fraction of the earthquake cycle (Hori and Miyazaki, 2010; Yoshida and Kato, 2003). However, precursory slip before a large earthquake is not commonly observed (Roeloffs, 2006). Whether this is due to the small amount of slip and difficulty in observation or because the phenomena are not generally active on natural faults is under discussion. Postseismic slip is observed for many earthquakes (Heki et al., 1997; Ozawa et al., 2011) and may reflect the response of creeping areas adjacent to the coseismic slip area. However, well-resolved slip distributions that enable the evaluation of the relationship between coseismic slip and postseismic slip are not always available.

Repeating earthquakes are thought to occur at small asperities on the fault zone that catch up with aseismic fault slip on the surrounding surface (Nadeau and McEvilly, 1999). They represent direct evidence of aseismic fault slip at depth and have good spatial resolution of 20–30 km in the Tohoku area. The source location of repeaters can be precisely determined using ordinary hypocenter location techniques (Uchida et al., 2004).

Uchida and Matsuzawa (2011) document the existence of small repeating earthquakes in the coseismic slip area of the 2011 Tohoku-oki earthquake. This indicates that the aseismic slip pattern in the source region of a future large earthquake can be monitored by repeating earthquake data with high spatial resolution. Understanding of the temporal evolution of such slip in the future slip zone and surrounding area is of great importance. Does the Tohoku-oki earthquake coseismic slip area reveal different fault slip properties compared to other regions?

In this paper, we estimate the long-term (27 yr) spatio-temporal distribution of aseismic slip using small repeating earthquakes to demonstrate how the plate boundary slip evolved in and around the source region of the 2011 Tohoku-oki earthquake.

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2. Repeating earthquake analysis

2.1. Selection of repeating earthquakes

We analysed waveform data for the period from 1984 to 2011 to find repeating earthquakes based on waveform similarity. The waveform data used here are from the microearthquake observation network of the Hokkaido University, Hirosaki University, Tohoku University and University of Tokyo (triangles in Fig. 1). Most of the seismometers are of 1 Hz velocity type and sampling frequency is 100 Hz. We used earthquakes larger than M2.5 before the Tohoku-oki earthquake and larger than M4.0 after the earthquake. This difference is because the earthquake catalogue is not complete for events smaller than M4.0 after the Tohoku-oki earthquake.

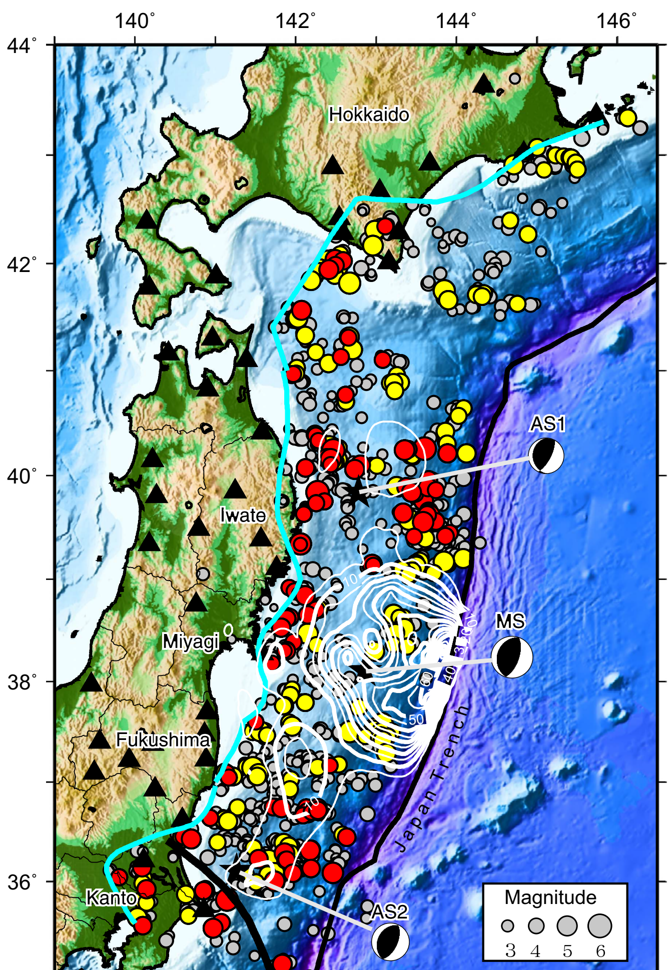

Fig. 1. (a) Distribution of small repeating earthquake groups (sequences) for the period from 1984 to 31 December 2011 (circles). Location of each group is estimated by averaging the locations of earthquakes in the group. Red circles show repeating earthquake groups larger than M4.0 that contain earthquakes occurring before and after the Tohoku-oki earthquake. Yellow circles mark repeating earthquake groups larger than M4.0 that only contain earthquakes before the Tohoku-oki earthquake. Grey circles indicate repeating earthquakes smaller than M4.0, which have only been determined for before the Tohoku-oki earthquake. Blue bold lines show the downdip limit of interplate earthquakes (Igarashi et al., 2001; Kita et al., 2010; Uchida et al., 2009). Black bold line shows northeastern limit of the Philippine Sea plate (Uchida et al., 2009) and triangles show seismic stations used in the analysis. White contours illustrate the slip distribution of the Tohoku-oki earthquake in 5 m intervals (Iinuma et al., 2012). Black stars and beach balls show the epicentres and focal mechanisms of the M9.0 Tohoku-oki earthquake (MS) and M7.4 and M7.7 aftershocks that occurred at 15:08 (AS1) and 15:15 (AS2) on 11 March 2011 (JST). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

It should be noted that waveform data is not complete for the period prior to 1993 due to the insufficient dynamic range of observations and unstable recording system (Uchida et al., 2006). It also should be noted that the waveform data is unavailable for the period within 3 days after the Tohoku-oki earthquake because the data acquisition system failed due to electric power and telemetry link failure by the earthquake damage.

Waveform similarity is a good indication of repeated slip at the same location because if the same patch on the fault slips repeatedly in the same way, the waveforms observed at a particular station should be the same (Ellsworth, 1995). We calculated the coherence of waveforms for events whose epicentral separations are less than 30 km. The epicentre location errors in the catalogue are estimated to be about 5–15 km (relative location errors ≤30 km). The time windows for the seismogram cross-spectral analysis were set at 0–40 s from P wave arrivals. Since the distance between every event to the nearest land station is less than 300 km, the windows always contain the S phases at most of stations. Accordingly, if waveforms from two events observed at a station show high coherence, the two events are considered to have the same S–P times. If multiple stations show high coherences, it is assured that the two events occurred at the same location.

We consider an earthquake pair to represent repeating earthquakes based on a coherence threshold at two or more stations. For earthquakes from M2.5 to M4.0, the threshold is 0.95 for averaged coherences at 1–8 Hz (Uchida et al., 2009). For earthquakes larger than M4.0, we choose the frequency band around the corner frequency of the smaller event (f_0) in the pair. This is because the waveform similarity at higher frequencies than the corner frequency sometimes decreases due to differences in rupture process even if the two events ruptured the same area. We used a frequency band extending from $(1/2)f_0$ to $2f_0$ and the coherence threshold for these larger events is 0.8. The thresholds were determined based on frequency distribution of coherence and hypocenter location of earthquakes determined precisely by waveform-based differential time data for off-Kamaishi repeaters (Uchida et al., 2010). The coherences for overlapping pairs and non-overlapping pairs differ dramatically and the coherence for any non-overlapping pair does not exceed 0.7. A pair (group) of repeaters thus obtained was linked with another pair (group) if the two pairs (groups) contained a common earthquake. The effect of the choice of coherence threshold and the grouping procedure is examined in the Supplementary material.

The corner frequency of the smaller event (f_0) for each pair is calculated from the following equation based on a circular crack model (Sato and Hirasawa, 1973):

$$r = Cv/2\pi f_0, \quad (1)$$

where v is the phase velocity (4.2 km/s), C is a constant (1.9) and r is the source radius. We used the shear wave velocity for v since the S wave is always dominant in every 40 s window. The source radius was estimated from the formula (Eshelby, 1957):

$$\Delta\sigma = (7/16)(M_0/r^3), \quad (2)$$

where M_0 is the seismic moment and the stress drop $\Delta\sigma$ was assumed to be 10 MPa for all the events. Thus if M_0 is given, r can be estimated from Eq. (2) and then f_0 from Eq. (1). If the waveforms show high coherences in the frequency band around f_0, we can infer that the source regions of the two events are overlapped.

As we are interested in slip taking place on the upper surface of the Pacific plate where the 2011 Tohoku-oki earthquake occurred, we had to distinguish repeating earthquakes on the Pacific plate from those on the Philippine Sea plate in the Kanto region (to the south of the bold black line in Fig. 1). This classification method is the same as that used in a previous study (Uchida et al., 2009), which selects the nearest plate boundary based on the earthquake hypocenter and plate model depths. Only the earthquakes occurring on the upper surface of the Pacific plate are used in this study.

We also checked the focal mechanisms of the selected earthquakes using F-net focal mechanism data from 1997 to 2011 to confirm that they occurred on the subduction thrust (plate boundary). Most of the selected earthquakes have low-angle thrust type focal mechanisms that are similar to that of the 2011 Tohoku-oki earthquake (Fig. 2) suggesting they occurred on the Pacific plate subduction thrust. The final repeating earthquake catalogue was constructed by removing earthquakes whose focal mechanisms were very different from that of the Tohoku-oki earthquake. Here, we used the minimum 3-D rotation angle—Kagan angle (Kagan, 1991) to measure the similarity of focal mechanisms. We calculated the rotation angle between the focal mechanisms of the target earthquake and the Tohoku-oki earthquake. We removed the repeating earthquake groups that include events with a rotation angle larger than 50° because such events are inferred to be on a different fault than the plate boundary. The angle threshold was determined by taking into account the plate boundary strike and dip changes in the study area.

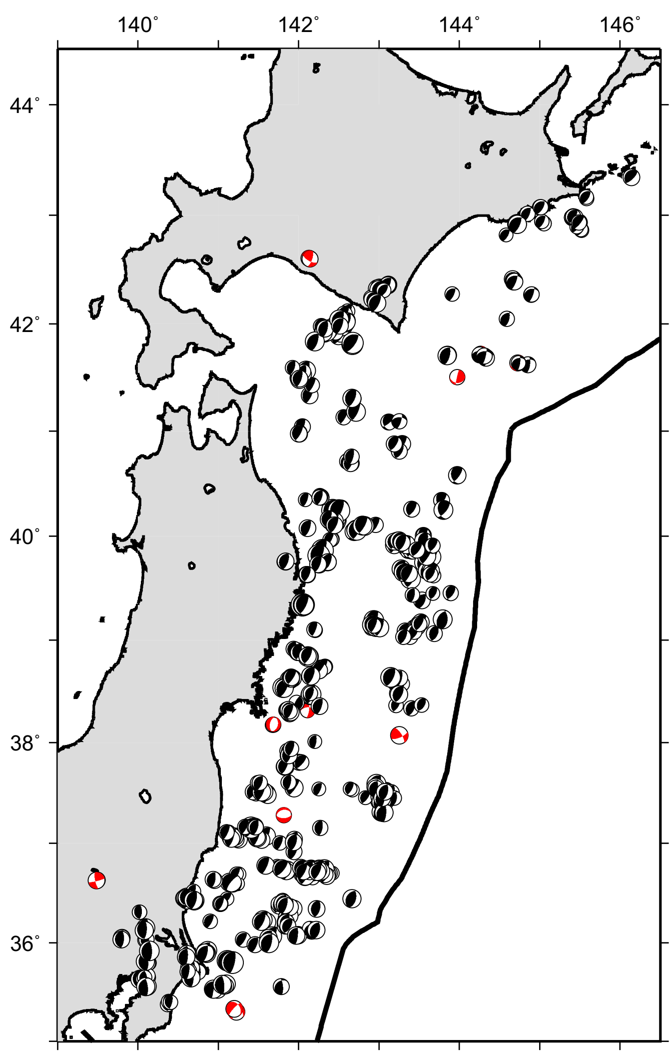

Fig. 2. Focal mechanisms of repeating earthquakes determined by F-net moment tensor analysis of broadband seismic waveforms. To use reliable focal mechanisms, we selected focal mechanisms with variance reduction of larger than 80% and determined using three or more stations. Black and red focal mechanisms show earthquakes whose minimum 3-D rotation angle (Kagan angle) (Kagan, 1991) with respect to the Tohoku-oki earthquake's focal mechanism (strike, dip, rake)=(22°, 63°, 91°) is smaller than or larger than 50°, respectively. Note that the focal mechanisms of small repeating earthquakes (ca. M2.5–M3.5) are not usually determined by F-net due to low signal-to-noise ratios but 97.7% of the earthquakes whose focal mechanisms have been determined show minimum rotation angles of less than 50°s from the Tohoku-oki earthquake. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. Estimation of cumulative slip

As we have selected repeating earthquakes that occurred at the same position on the plate boundary, cumulative slip can then be estimated from the repeating earthquake catalogue using the same procedure as in previous studies (Uchida et al., 2004). The repeated fault–patch–slips are driven by aseismic slip in the areas surrounding the patch. The cumulative slip is interpreted to represent the aseismic slip on the plate boundary, because the small repeating earthquakes are thought to slip to catch up with aseismic slip in the surrounding region (e.g., Nadeau and McEvilly, 1999). This is because the long-term slip amount on the same fault plane should be the same for close locations regardless the slip mode (seismic or aseismic) and aseismic slip loads the rupture patches that are responsible for repeating earthquakes, during the recurrence interval preceding each event. Although stress triggering by other nearby earthquakes (Chen et al., 2013) or other perturbations may cause some slip deficit or slip excess for each repeating earthquake compared to the aseismic slip in the surrounding area, we assume that the slip in one cycle of an repeating earthquake is equal to the aseismic slip in the same period. Therefore we consider repeating earthquake as a creep metre that is embedded in the plate boundary. The slip in each small repeating earthquake was estimated based on the following relationship between the seismic moment (M_0; dyn cm) and fault slip (d; cm) (Nadeau and Johnson, 1998; Uchida et al., 2003).

$$\log(d) = -2.36 + 0.17\log(M_0) \tag{3}$$

This empirical relationship was obtained from shallow repeating earthquake data in California. Igarashi et al. (2003) and we confirmed that this slip estimate is consistent with the slip estimated from the relative plate motion and the time intervals between repeating earthquakes close to the coast of northeastern Japan. The seismic moment was estimated from the following relationship between the moment and magnitude (M) (Hanks and Kanamori, 1979):

$$\log(M_0) = 1.5M + 16.1. \tag{4}$$

The magnitude used here is determined by the Japan Meteorological Agency. Cumulative slip was then estimated by summing all the slip increments of small repeating earthquakes in each group.

3. Results

3.1. Repeating earthquake activity

Most of the repeating earthquakes selected in this study are considered to be interplate events and located between the Japan trench and the downdip limit of interplate events (Fig. 1). They mainly occurred outside the area that underwent large coseismic slip (> 40 m) during the Tohoku-oki earthquake as inferred from on- and offshore GPS data (Iinuma et al., 2012) (Fig. 1). Given the large coseismic slip during the earthquake, the near-trench repeating earthquake gap around latitude 38° probably represents an almost fully locked region before the Tohoku-oki earthquake.

A number of repeating earthquakes had occurred prior to the Tohoku-oki earthquake in the areas with moderate to large

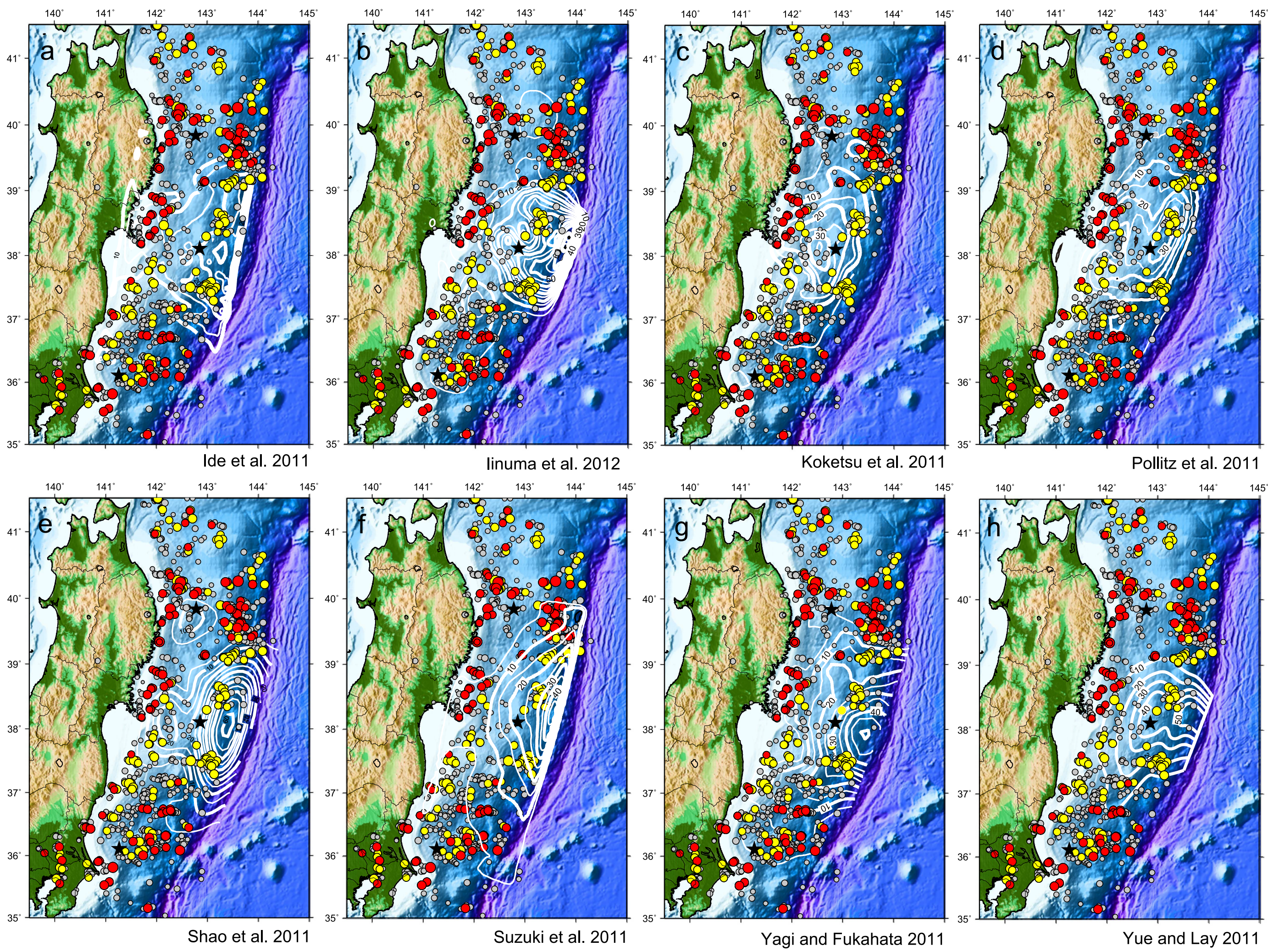

Fig. 3. Comparison of slip distributions of the 2011 Tohoku-oki earthquake and repeating earthquake activity after the Tohoku-oki earthquake. Red circles show repeating earthquake groups of magnitudes larger than 4.0 that contain earthquakes both before and after the Tohoku-oki earthquake. Yellow circles show repeating earthquake groups of magnitudes larger than 4.0 that have earthquakes only before the Tohoku-oki earthquake. Grey circles indicate repeating earthquakes smaller than M4.0. The slip distributions are from (a) Ide et al. (2011), (b) Iinuma et al. (2012), (c) Koketsu et al. (2011), (d) Pollitz et al. (2011), (e) Shao et al. (2011), (f) Suzuki et al. (2011), (g) Yagi and Fukahata (2011), and (h) Yue and Lay (2011). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(5–40 m) coseismic slip (Fig. 1). After the earthquake, however, the occurrence of these repeater sequences effectively ceased as indicated by yellow circles in Fig. 1, which contrasts sharply with frequent recurrences of repeating earthquakes (red circles) surrounding the earthquake source region. This feature can also be seen when considering other coseismic slip models (Fig. 3). Most of the slip models show large slip between the hypocenter (black star) and the Japan trench where the repeating-earthquake gap appears after the mainshock. The lack of repeating earthquakes in the coseismic slip area after the Tohoku-oki earthquake persists when we examine a larger, but possibly incomplete dataset of smaller repeaters ($M \geq 2.5$, Fig. 4a). Focal mechanism analysis of the aftershocks (Asano et al., 2011) also shows a lack of interplate earthquakes in the area of large coseismic slip. Kato and Igarashi (2012) estimated the outer edge of this large-slip zone based on the change in occurrence rates of the interplate, repeating, and down-dip compressional earthquakes. The lack of interplate earthquakes is probably due to nearly complete stress release in the coseismic slip area of the Tohoku-oki earthquake (Ide et al., 2011; Yagi and Fukahata, 2011). The nearly complete stress release is also estimated from stress rotation after the earthquake based on stress tensor analyses of focal mechanisms (Hasegawa et al., 2011). An alternative possibility for shutting off the repeaters is that the event waveforms changed because of the changes in the fault properties due to the large slip of the main shock and could not be registered as proper sequence members anymore. However, even the search for repeating (or similar) earthquakes using a lower coherence threshold (0.6) than the original one (0.8) also showed a lack of repeating earthquakes in the earthquake source region (Fig. 4b).

The accelerated recurrence of repeaters adjacent to the rupture indicates rapid and aseismic afterslip, as a fast loading process is required to explain their short earthquake recurrence intervals. At larger distances from the rupture (east off Hokkaido), few events have recurred in 9 months since the Tohoku-oki earthquake (Fig. 1). Considering the long average intervals of these sequences (5.3 ± 3.4 yr), this suggests the postseismic slip did not extend to this region, in the first 9 months following the event.

3.2. Spatiotemporal evolution of aseismic slip in the coseismic slip area of the Tohoku-oki earthquake

In this section, we examine the slip characteristics in the coseismic slip area of the Tohoku-oki earthquake based on the

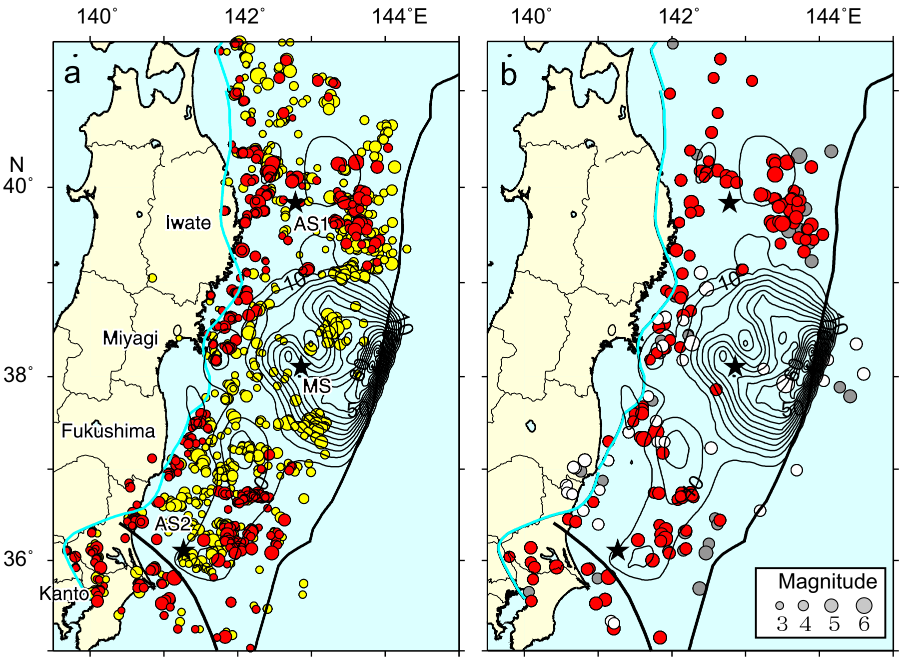

Fig. 4. (a) Distribution of repeating earthquakes before and after the Tohoku-oki earthquake for M2.5 or larger earthquakes from 1984 to 31 December 2011. Red circles show repeating earthquake groups that contain earthquakes occurring before and after the Tohoku-oki earthquake. Yellow circles mark repeating earthquake groups that only contain earthquakes before the Tohoku-oki earthquake. Note that some of the repeating earthquakes smaller than M4.0 and after the Tohoku-oki earthquake are missing due to incompleteness of the earthquake catalogue. Stars, blue lines, and black line are the same as those in Fig. 1. (b) Distribution of similar earthquakes groups (waveform coherence ≥0.6, magnitude ≥4.0) after the Tohoku-oki earthquake that have lower coherence than repeating earthquakes (coherence ≥0.8). Red and white circles show earthquake groups whose minimum 3-D rotation angle—Kagan angle (Kagan, 1991) with respect to the Tohoku-oki earthquake's focal mechanism is smaller than or larger than 50°, respectively. Grey circles denote earthquake groups without focal mechanism information. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

repeating earthquake data described in the previous section. Here, the cumulative slip of repeating earthquakes is estimated following the procedure shown in Section 2.2 and this cumulative slip history is considered to represent the evolution of aseismic slip on the plate boundary.

Fig. 5 shows the slip rate distribution for every 3-yr period before the Tohoku-oki earthquake. During the 27-yr period before 2008 (Fig. 5a–h), the slip rates in the large-coseismic-slip areas of the Tohoku-oki earthquake (grey contours) were relatively low (indicated by blue colour) or no slip rates were estimated (indicated by white colour) because 2 or less repeating earthquake groups existed in a grid window ($0.3^\circ \times 0.3^\circ$ areas). The depth distribution of slip rate from 1997 to just before the 2011 Tohoku-oki earthquake shows low slip rate in all depth ranges for the area that includes the main slip area (middle area indicated by diamonds in Fig. 6). Here, the depths to the plate boundary are estimated from the plate model of Zhao et al. (1997). The cumulative slip time series (slip history) calculated for different areas of the plate boundary before the occurrence of the Tohoku-oki earthquake also show unique aseismic slip behaviour for the coseismic slip area (Fig. 7a). In addition to the relatively low slip rate before 2008, the cumulative slip curves in the future coseismic slip area for the Tohoku-oki earthquake show strong rate fluctuations (episodic slips) except for region 10 as shown in Fig. 7a. These slip characteristics may reflect different frictional properties in the rupture area. In the period from 2008 to just before the 2011 Tohoku-oki earthquake, the slip rate increased near the trench and the Tohoku-oki earthquake's slip area off Miyagi to Kanto (regions 8 and 11 in Figs. 7a, 8a and b). Modest preseismic slip rate increases are also seen in regions 6, 9 and 12 although the slip rate seems decreased in region 9 just before the Tohoku-oki earthquake (Fig. 7a). Such high near-trench slip rates were not observed from 1984 to 2008 off south Iwate to Kanto (Figs. 5 and 8a). After the Tohoku-oki earthquake, the repeating earthquake activity in the large coseismic slip area stopped completely suggesting the aseismic slip stopped in the area as already discussed in Section 3.1 (Figs. 7d and 8c).

3.3. Spatiotemporal evolution of aseismic slip outside of the coseismic slip area of the Tohoku-oki earthquake

The slip evolution in the areas outside of the coseismic rupture zone is shown in Figs. 5, 7b and c. In these areas relatively high slip rates are estimated along the deeper portions of the plate boundary (along the seashore of Honshu) before the Tohoku-oki earthquake (Fig. 5; regions 1, 3, 4, 7 and 14 in Fig. 7b and c). The variation of slip rate with depth can be seen in plots of averaged slip rate vs. depth as shown in Fig. 6. In the area outside of the main coseismic slip for the Tohoku-oki earthquake (north and south regions), the slip rate at depths greater than ∼35 km increases with depth. The high deep slip rate is probably related to relatively constant speed aseismic slip on the deeper plate boundary (Igarashi, 2010; Uchida et al., 2009). The depth below which slip rates increase (depth > 35 km) corresponds to the region where the subducting plate is in contact with the uppermost mantle of Japan (Ito et al., 2004, 2005; Fujie et al., 2006).

There were only modest fluctuations in slip rate outside of the Tohoku-oki earthquake coseismic rupture area (Fig. 7b and c) and the slip rates before the Tohoku-oki earthquake were generally higher than within the region showing large coseismic slip. The rate fluctuations in region 5 are related to postseismic slip of a M7.2 interplate earthquake in 1989 and the fluctuations in regions 2 and 3 are related to postseismic slip following the 1994 Far-off-Sanriku earthquake (M7.6) as discussed in a previous study (Uchida et al., 2004). These slip rate changes tend to last several years. Possible preseismic slip rate increases are also seen in regions 13 and 15 along the trench.

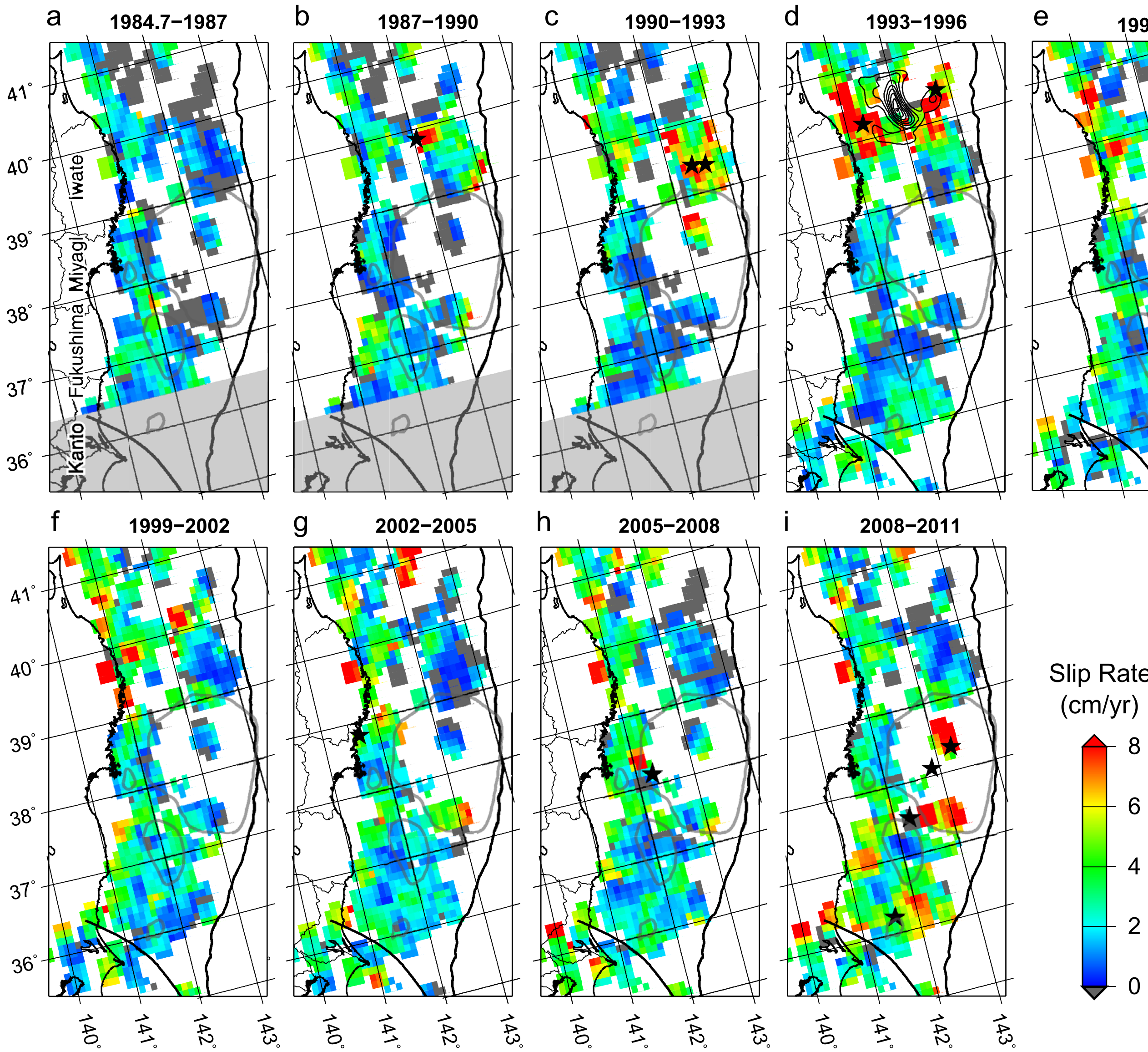

Fig. 5. Interplate slip rate distribution in each 3-yr interval (colour). The slip amounts estimated from repeaters are averaged in $0.3^\circ \times 0.3^\circ$ windows shifted in 0.1° increments. The windows (regions) with two or less repeating earthquake groups are shown in white. Grey windows indicate zero aseismic slip (no repeater activity) during the period. Black stars show earthquakes of M6.9 or larger and shallower than 70 km depth. Grey lines show 10 m coseismic contour of the Tohoku-oki earthquake (Iinuma et al., 2012). The black line marks the northeastern limit of the Philippine Sea plate. Note that relatively high slip rates were observed in the coseismic slip area of the Tohoku-oki earthquake for the period just before the Tohoku-oki earthquake. Light grey areas before 1993 show no estimation because of data limitation in that period. Relatively high and stable slip rates are seen in the deeper (western) portion of the plate boundary. The high slip rate in the northern part in 1993–1996 (d) is related to the Sanriku-haruka-oki earthquake in 1994 (M7.6) whose slip distribution is shown by contours (Uchida et al., 2004; Yamanaka and Kikuchi, 2004). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

After the Tohoku-oki earthquake, postseismic slip is clearly seen in the areas outside of the coseismic slip zone. The postseismic slip was most rapid near shore of northern Miyagi and southern Iwate, where the inferred slip amounted to as much as 160 cm in the period before the end of 2011 (Fig. 8c). The location of the maximum slip is close to that deduced from slip inversions of postseismic GPS displacement data (Ozawa et al., 2012) (Fig. 9b), but the spatial distribution of slip inferred from the two types of data differs substantially. The spatial resolution of smoothed inversions of GPS data is severely limited due to the distance between the GPS network and the slip zone. The afterslip inferred from repeating earthquakes provides unique information especially in the offshore areas. The postseismic slip off Iwate delineates the northern part of the coseismic slip and extends to near the trench whereas off southern Fukushima, the postseismic slip is not large along the coast but is prominent further offshore (Figs. 8c and 9). Moderate (20–60 cm) postseismic slip is estimated below land and in the offshore area of Kanto. In regions further away from the coseismic slip area of the Tohoku-oki earthquake (Fig. 7f) the increase in cumulative slip after the M9 earthquake was modest (e.g., areas 1, 3 and 14) or is seen only after a delay of 2–3 months (e.g., areas 2 and 15). The slow or delayed rise of slip acceleration at larger distances probably reflects the propagation of postseismic slip from near the coseismic slip area to the surrounding regions.

4. Discussion

4.1. Preseismic slip for the Tohoku-oki earthquake

We observed small but distinct increases in the slip rate in the ~3 yr before the earthquake near the area of large coseismic slip and the trench. This activity of repeating earthquakes in the coseismic slip area of the Tohoku-oki earthquake suggests the plate boundary cannot be simply divided into aseismic and seismic

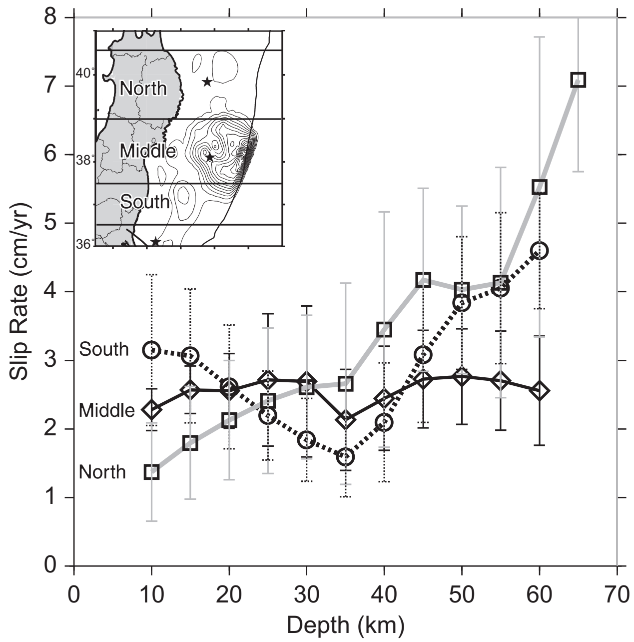

Fig. 6. Depth variation of slip rate for the period from 1997 to 11 March 2011. Averaged slip rates for the north region (39–40.5°N), middle region (37.5–39.0°N) and south region (36.5–37.5°N) are shown by squares, diamonds and circles, respectively. Error bars represent standard deviations of slip rates for grid points within 5 km of the respective depths.

areas as discussed in Uchida and Matsuzawa (2011). The occurrence of repeating earthquakes suggests an aseismic loading process but these areas can also slip coseismically during a large earthquake. The existence of repeating earthquakes near and within several historical $M \geq 7$ slip zones can also be seen in Fig. 9a.

The near-trench high slip-rate regions in Fig. 8b (off northern Kanto to Miyagi) roughly correspond to the slip extent of the Tohoku-oki earthquake. During the ~3 yr period, earthquakes of M7.0 on May 8, 2008 (08-1 in Fig. 8b), M6.9 on July 19, 2008 (08-2 in Fig. 8b) and M7.2 on March 9, 2012 (FS in Fig. 8b) occurred, which were followed by slip rate increases in their surrounding areas (Fig. 10). The earthquakes occurred sequentially from south to north and the main slip accelerations occurred on the trench side of each earthquake hypocenter. Continuous GPS time series also suggest decreased coupling rate for the period but the resolution of the slip area offshore is poor due to a low signal-to-noise ratio (Ozawa et al., 2012; Suito et al., 2011).

The recurrence interval of ~M9 earthquakes such as the 2011 event off Tohoku is estimated to be 400–800 yr from tsunami deposits and recent studies of interplate coupling (Minoura and Nakaya, 1991; Sawai et al., 2012; Uchida and Matsuzawa, 2011). Thus, our analysis captures the slip history for the final small fraction of the recurrence interval of the large earthquakes and during their immediate aftermath. Many earthquake cycle simulations show preseismic slip or unfastening of coupling before an earthquake (Ariyoshi et al., 2007; Chen and Lapusta, 2009; Kato, 2004; Yoshida and Kato, 2003). In the simulations the aseismic slip usually migrates from outside to inside the coseismic slip area for the future mainshock. The temporal evolution of slip observed in this study near the future coseismic slip area may indicate such unfastening of coupling in the last stage of the earthquake cycle. The high slip rate in region 8 was prominent 2 days before the 2011 earthquake, due to the postseismic slip of the M7.3 foreshock on March 9 (Fig. 10c) that appears to be associated with the short-term nucleation process of the Tohoku-oki earthquake (Kato et al., 2012). We suggest that the 3–4 yr slip-rate increases that occurred in several portions of the coseismic slip area of the future M9.0 earthquake are related to a more enduring pre-seismic process that preceded the slip near region 8 during the final 2 days leading up to the Tohoku-oki earthquake. Variable slip rates (episodic slips) before the earthquake are also seen in several earthquake cycle simulations (Kato, 2004; Yoshida and Kato, 2003). They occur in and around the coseismic slip area, suggesting the possibility that temporal changes of slip rate can be a diagnostic feature of an impending large seismic rupture.

4.2. *Postseismic slip of the Tohoku-oki earthquake*

The postseismic behaviour of the repeating earthquake sequences in the coseismic source region shows cessation of occurrence and suggests the arrest of aseismic slip in the region. This is probably related to the complete relief of ambient stress in the central rupture zone. The disappearance of interplate seismic activity in the coseismic slip area after a mainshock is also observed in the multiple earthquake cycles of an off-Kamaishi repeating earthquake sequence in the same subduction zone (Uchida et al., 2012). In that sequence, reduced seismic activity in the rupture area of the $M{\sim}5$ repeating earthquake lasts for about one-third of the earthquake cycle (~5 yr) after the mainshocks. Relatively active occurrence of interplate earthquakes within the future rupture area is observed in the final two-thirds of the cycle (Uchida et al., 2012). Although the earthquake size is different, the interplate earthquake activity on the main slip area before and after the mainshocks is similar for the Tohoku-oki earthquake (M9) and the Kamaishi-oki earthquake (M5), suggesting a common mechanism for the seismicity changes that is most likely the stress concentration on the asperity during the earthquake cycle and its release at the time of the mainshock.

The repeating-earthquake analysis is limited by the 3 days data gap following the Tohoku-oki earthquake, possible waveform contamination by other earthquakes, the uncertainty in the scaling relationship between the repeating earthquake magnitude and slip, and the uneven/sparse distribution of repeating earthquake groups. Some of the discrepancy between the maximum slip estimated from repeating earthquakes (~1.6 m) and the GPS data (~3 m, Fig. 9b) probably comes from these limitations. Although the simultaneous use of repeating earthquake and GPS data will provide improved results, the repeating earthquake data in the present study are not contaminated by contributions from viscous postseismic relaxation processes; they also have strength in spatial resolution of slip and can reveal temporal changes at respective locations on the plate boundary. The temporal change in postseismic slip shows a more abrupt increase in the region closer to the source, suggesting outwards propagation of afterslip. This migration probably results in stress concentrations in the other coupled regions around the Tohoku-oki earthquake. To the north of the slip accelerated area (off Aomori), the slip areas for the 1994 Sanriku-oki earthquake (M7.6) and 1968 Tokachi-oki earthquake (M7.9) are located (Fig. 9a). Although the density of repeating earthquake groups are low in the centre of these slip areas as indicated by white colour, repeating earthquakes close to these slip areas also show some afterslip within 7 and 9 months (Fig. 9b and c). To the south of the slip accelerated area (off Kanto) the interplate coupling was estimated to be relatively low from GPS data (Nishimura et al., 2007) and repeating-earthquake slip rates (Uchida et al., 2009); however, a $M{\sim}8.0$ tsunamigenic earthquake is believed to have occurred in 1677 near the trench (e.g., Hatori, 1975). It is important to monitor aseismic slip in these regions in future years because the afterslip will increase stress in these areas.

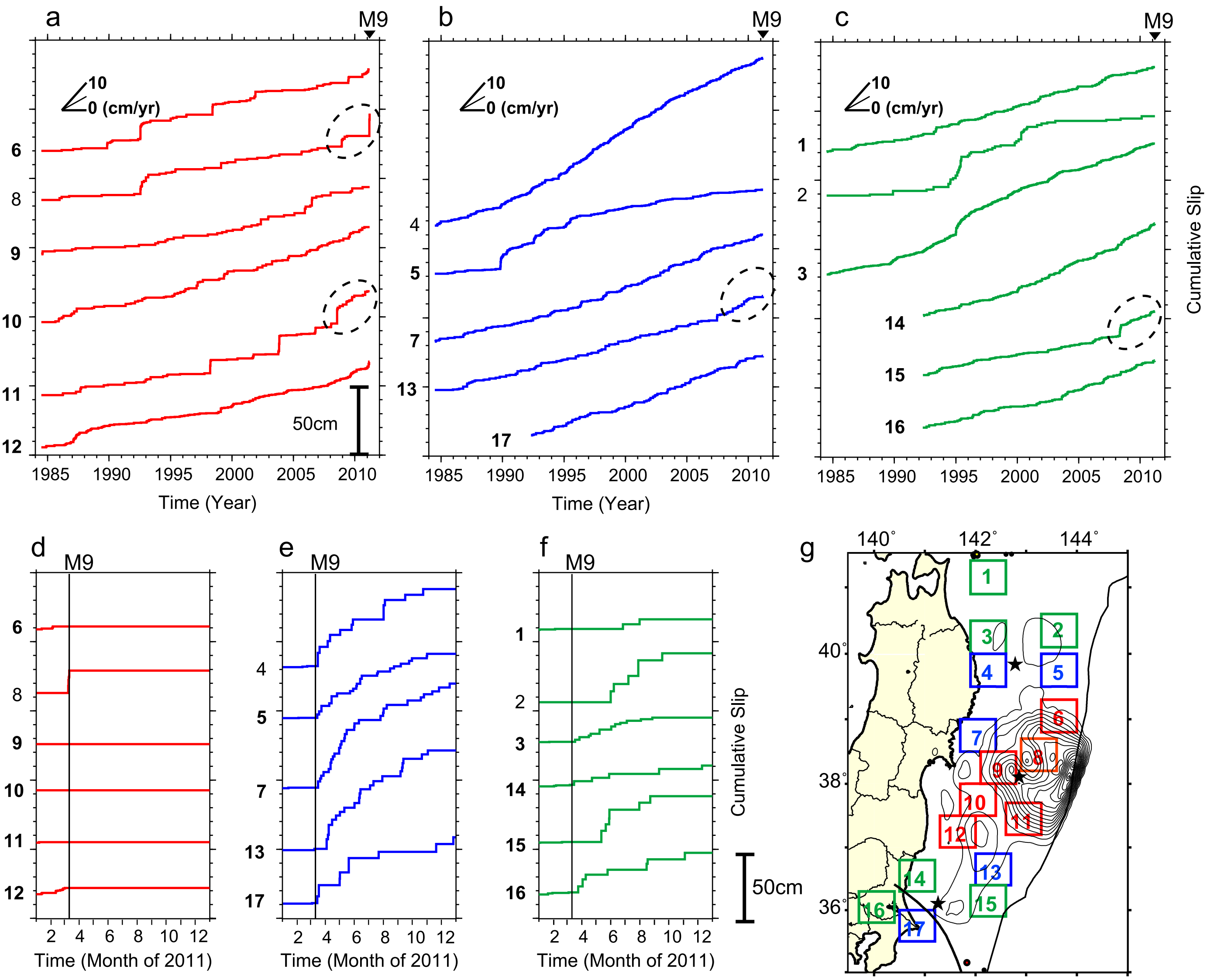

Fig. 7. Time history of aseismic slip at each portion of the plate boundary. (a–c) Averaged cumulative slip time series estimated from repeating earthquake groups in regions 1–17 shown in (g) before the Tohoku-oki earthquake. The cumulative slip curves are grouped into three (a–c) panels based on their postseismic slip pattern (d–f). The curves are categorised into the regions showing (d) no postseismic slip, (e) almost immediate and large slip after the Tohoku-oki earthquake and (f) small or delayed slip after the earthquake. (g) Map showing the locations of regions for calculating the averaged cumulative slip. The circles and contours are the same as in Fig. 1.

The afterslip distribution is also important in efforts to establish whether the slip mode (seismic vs. aseismic) of plate boundary faults is persistent or not. The estimated slip zones (asperities) of large historical earthquakes indicate seismic behaviour in those areas (Fig. 9a). Johnson et al. (2012) suggest the possibility that aseismic afterslip of the Tohoku-oki earthquake occurred on these historical asperities. The repeating earthquakes show some afterslip overlapping with the inferred slip areas of the 1960, 1968, 1978, and 1938 earthquakes (Fig. 9a), although the density of repeating earthquake groups is low in the centre of most slip areas as indicated by white colour. The distribution of repeating earthquakes suggests that relatively large amounts of interseismic aseismic-slip and post-Tohoku afterslip occurred preferentially near the margins and outside of the rupture areas of past large earthquakes.

5. Conclusions

We estimated the 27-yr aseismic slip history in and around the coseismic slip area of the 2011 Mw 9.0 Tohoku-oki earthquake on the subduction megathrust from the spatiotemporal distribution of small repeating earthquakes. The pre-M9 data shows ∼3 yr of slip-rate increases preceding the earthquake, near the future earthquake source. The increases in the slip rate suggest unfastening of coupling in the last stage of the earthquake cycle. The slip before the Tohoku-oki earthquake inferred from repeating earthquakes in the coseismic slip area shows particularly strong rate fluctuations. The postseismic quiescence of the repeaters suggests the arrest of slip in the coseismic source region related to the complete relief of accumulated stress in the central rupture zone. The postseismic repeating earthquake history shows sudden acceleration of slip near the rupture and a slower rise of slip rates at greater distances from the source, suggesting transient acceleration of aseismic slip on surrounding, uncoupled portions of the megathrust.

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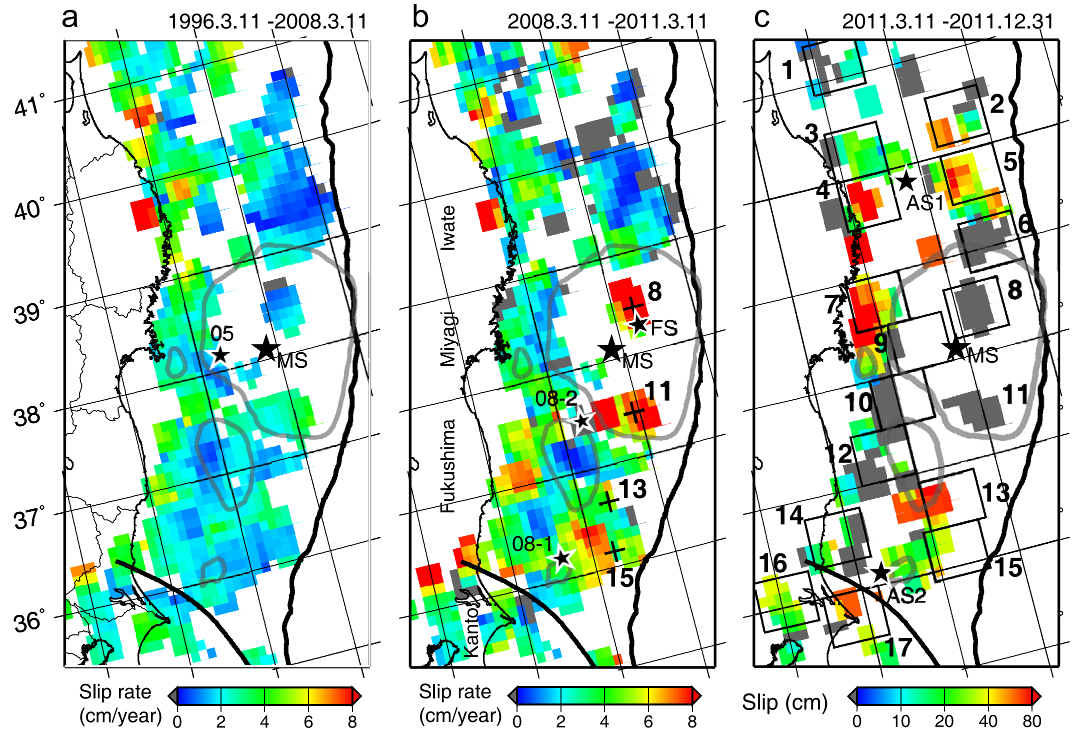

Fig. 8. Interplate slip distributions for the periods from (a) 11 March 1996 to 11 March 2008, (b) 11 March 2008 to 11 March 2011 (before the Tohoku-oki earthquake) and (c) 11 March 2011 to 31 December 2011 (after the Tohoku-oki earthquake). The slip amounts estimated from repeaters are averaged in 0.3° × 0.3° windows shifted in 0.1° increments. Note that the colours in figures (a) and (b) denote slip rates from repeating earthquakes larger than M2.5 while those in figure (c) indicate cumulative slip during the first 9 months following the earthquake from repeating earthquakes larger than M4.0. The windows (regions) with two or less repeating earthquake groups are shown in white. Grey windows indicate zero aseismic slip (no repeater activity) during the period. Grey contours show 10 m contour of the coseismic slip of the Tohoku-oki earthquake (Iinuma et al., 2012) for reference. Black stars show the hypocenters of major interplate earthquakes (05: M7.2 event on August 2005; 08-1: M7.0 event on May 2008; 08-2: M6.9 event on July 2008; FS: M7.3 foreshock on 9 March 2011). Crosses in figure (b) and rectangles in figure (c) represent location of window used in Fig. 7. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

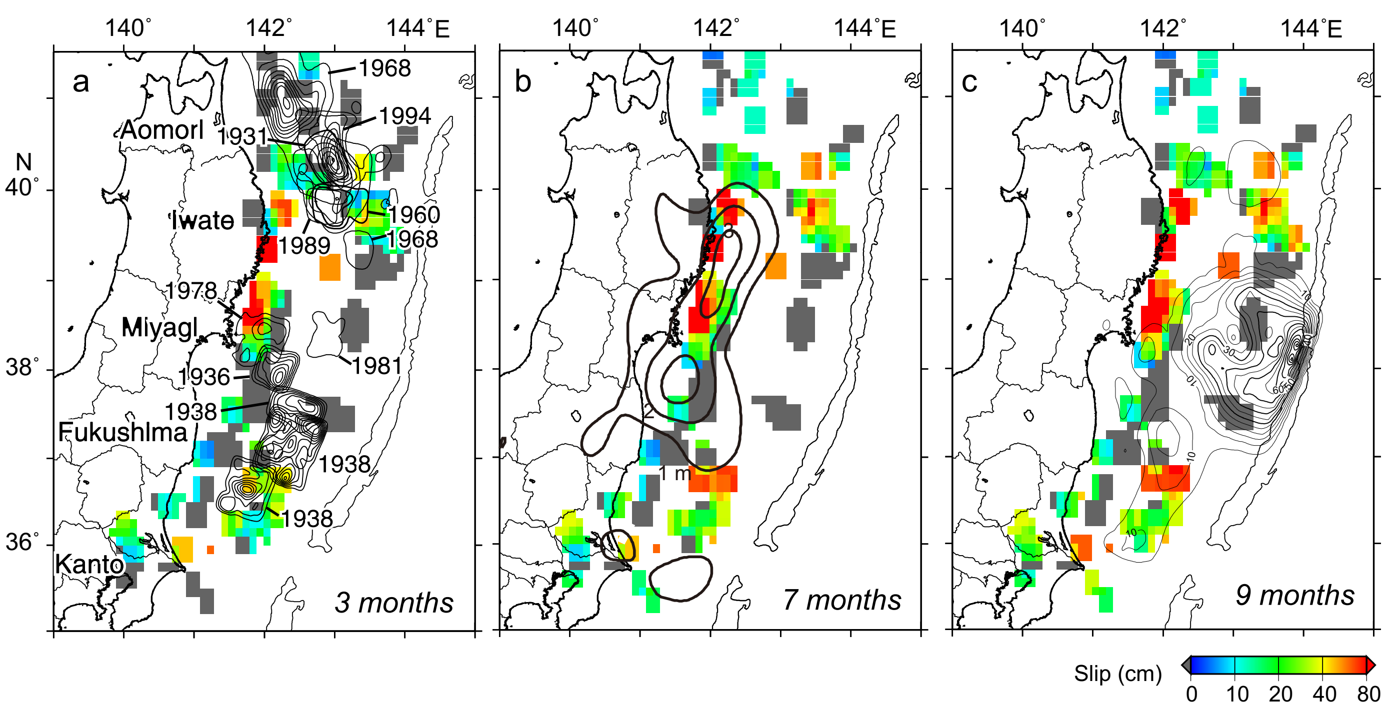

Fig. 9. Averaged cumulative slip in each 0.3° × 0.3° window for the periods (a) 3 months (to 11 June 2011) (b), 7 months (to 11 October 2011) and (c) ~9 months (to December 31) after the occurrence of Tohoku-oki earthquake on March 11, 2011. Only the cumulative slip at regions estimated from three or more repeating earthquake groups are coloured. Grey windows indicate zero aseismic slip (no repeater activity) during the period. Note that available repeating earthquakes become fewer after the 2011 earthquake because of the limitation of magnitude range ($M \geq 4.0$). Contours in figures (a), (b), and (c) respectively show slip distributions of $M \geq 7$ earthquakes since 1930 (Yamanaka and Kikuchi, 2004) and 1938 Shioyazaki-oki earthquakes (Murotani et al., 2003), afterslip distribution from on-land GPS data spanning 7 months (Ozawa et al., 2012) and coseismic slip distribution of the Tohoku-oki earthquake (Iinuma et al., 2012). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

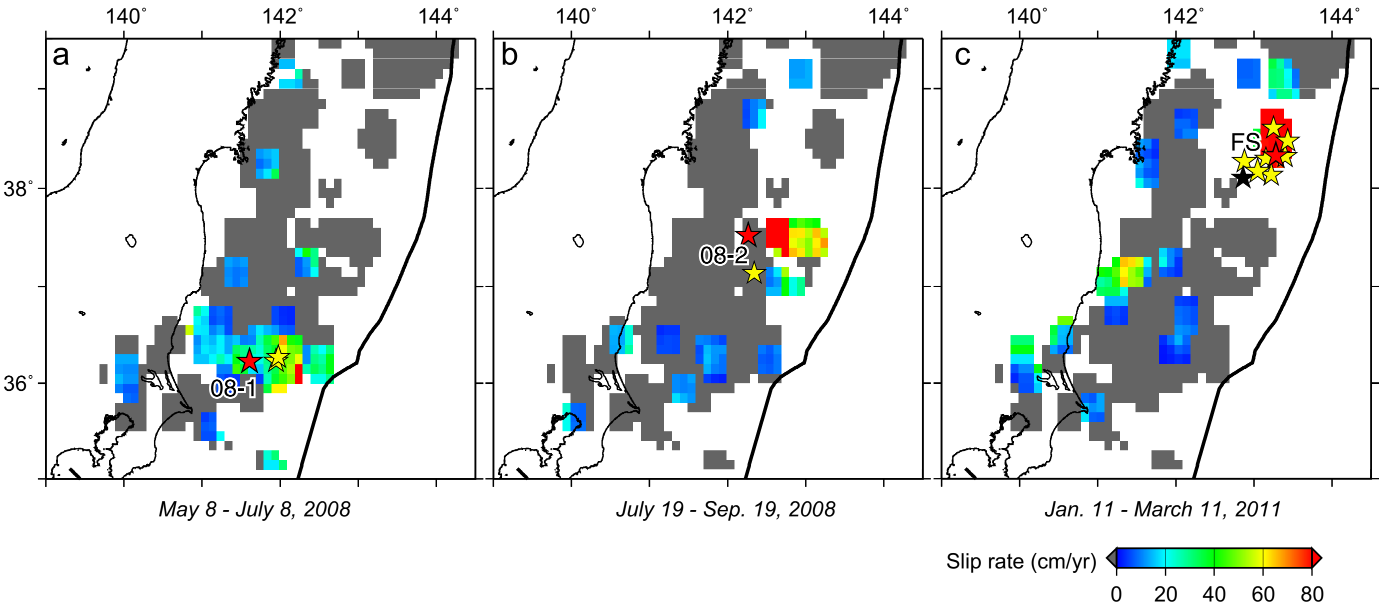

Fig. 10. Interplate slip rate distribution for 2 month periods during (a) May 8–July 8, 2008 (after a M7.0 event on May 8, 2008 [08-1]), (b) July 19–September 19, 2008 (after a M6.9 event on July 19, 2008 [08-2]) and (c) January 11–March 11, 2011 (before the Tohoku-oki earthquake and the time period that includes M7.3 foreshock [FS]). The windows (regions) with two or less repeating earthquake groups are shown in white. Grey windows indicate zero aseismic slip (no repeater activity) during the period. Red and yellow stars denote epicentres of earthquakes with magnitude 6.9 or larger and magnitude 6.0–6.8 for each period, respectively. Black star shows the epicentre of the Tohoku-oki earthquake. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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Appendix A. Supporting Material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.epsl.2013.05.021.

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