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Recurrence intervals of characteristic M4.8±0.1 earthquakes off-Kamaishi, NE Japan—Comparison with creep rate estimated from small repeating earthquake data

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Abstract

We examined the cause of the fluctuation in recurrence intervals of an M4.8±0.1 'characteristic earthquake' sequence off-Kamaishi, NE Japan by comparing the recurrence intervals with creep (quasi-static slip) rates around the asperity estimated from small repeating earthquake data. The eight recurrence intervals (5.52 yrs on average) of the sequence are almost constant but have small fluctuations (standard deviation of 0.68 yrs) characterized by a longer recurrence interval following a shorter one. From the analysis of small repeating earthquakes from 1990 to 2003, we found a significant acceleration of creep on the plate boundary during and after an earthquake swarm in 1992 to the east of the M4.8±0.1 event. The acceleration seems to have migrated from east (shallower part of the plate boundary) to west (deeper part) over about 80 km in 2 yrs to reach the asperity of the M4.8±0.1 events. The 1995 event that occurred with the shortest recurrence interval was probably advanced by this acceleration of creep in around 1994. We also found similar earthquake swarms prior to the 1962 and 1973 'characteristic' events that occurred after the second and third shortest recurrence intervals respectively. Therefore it is possible that the 1962 and 1973 events were also advanced by creep accelerations. The three pairs of longer and shorter recurrence intervals we observed suggest the existence of creep deceleration following the acceleration. We conclude that the recurrence interval fluctuations of the M4.8±0.1 events are mainly controlled by temporal changes of creep around its asperity.

Keywords: repeating earthquake; characteristic earthquake; subduction zone; asperity; creep; quasi-static slip; northeast Japan

1. Introduction

Recurrence of earthquakes provides important information on the nature of earthquakes. Quasi-

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periodic earthquake sequences have been widely investigated for statistical forecasting of earthquakes in many regions assuming the probability distribution of failure time (e.g. Utsu [1], Sykes and Nishenko [2], Working Group on California Earthquake Probabilities [3], Ohtake and Ueda [4]). However, the cause of fluctuation has received relatively little attention. Understanding the fluctuation mechanism will enhance not only the reliability of earthquake forecasting but also help elucidate the physics of earthquakes.

The characteristic earthquake model assumes that individual faults and fault segments tend to generate essentially the same-sized earthquakes over a relatively narrow range of magnitudes. This model predicts periodic occurrence of similar-sized events if the tectonic loading and the rupture strength for the fault plane are constant. Therefore, the fluctuations seen in many quasi-periodic sequences may imply temporal changes of tectonic loading or rupture strength of the fault plane (asperity).

Here, we analyze 'characteristic earthquake' sequence that consisted of eight quasi-periodic earthquakes with magnitude (M; magnitude determined by Japan Meteorological Agency) 4.8±0.1 that were identified between the years from 1957 to 2001 [5] (Figs. 1 and 2a) in off-Kamaishi region, NE Japan. Fig. 3 schematically shows probable distribution of asperities on the plate boundary. The asperities are thought to be surrounded by aseismic slip area. The ruptures of these asperities are probably responsible for the occurrences of interplate earthquakes. The 4.8±0.1 earthquakes, which have the same focal mechanisms: low-angle thrust fault type and have almost the same waveforms, are located near the Pacific coast at the deepest positions of the interplate main thrust zone [6,7]. From the past seismicity, it is thought that there are no large asperities near the M4.8±0.1 earthquakes [5] as schematically shown in Fig. 3 (inside the dashed line). The causes of the M4.8±0.1 events were considered to be the repeating slips of an asperity with a dimension of 1 km surrounded by aseismic area [5]. Okada et al. [8] confirmed that the asperity of the last two events in 1995 and 2001 are identical, by the comparison of the rupture areas estimated from waveform inversions. Therefore, we can treat these M4.8±0.1 earthquakes as 'characteristic events' on the plate boundary.

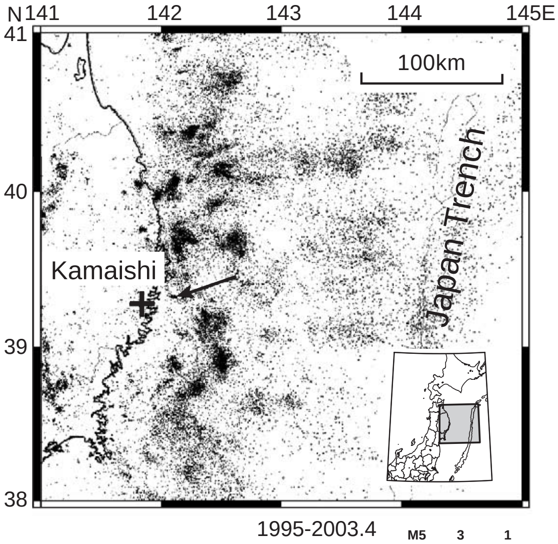

Fig. 1. Epicenter distribution for shallow (<60 km) earthquakes off Sanriku, northeastern Japan. Microearthquakes (M>1) for the period from January 1995 to April 2003 located by RCPEV are plotted. Arrow and cross indicate the locations of off-Kamaishi M4.8±0.1 earthquake sequence and Kamaishi City, respectively.

The occurrence of the M4.8±0.1 events (Fig. 2b) is quite periodic; the average recurrence interval is 5.52 yrs and the standard deviation of the recurrence interval is only 0.68 yrs. By using seven recurrence intervals from 1957 to 1995, it was expected that the 2001 event would occur by the end of November 2001 with 99% probability assuming that the recurrence interval follows a normal distribution [9]. An M4.7 event did indeed occur on November 13, 2001 as expected, and the next 'characteristic earthquake' is expected in May 2007±21 months with 99% probability [5].

The periodicity of the earthquake occurrence is probably caused by an almost constant rupture strength of the fault patch (asperity), stress drop, and a steady aseismic slip around it. Strictly speaking, however, the recurrence intervals are not completely the same. Among all, the intervals before and after the 1995 event were the shortest (4.65 yrs following the 1990 event) and the longest (6.68 yrs prior to the 2001 event), respectively. In addition to this, there is a curious feature that the recurrence interval becomes longer after a shorter recurrence interval as seen for the intervals before and after the 1995, 1973, and 1962 events (Fig. 2b).

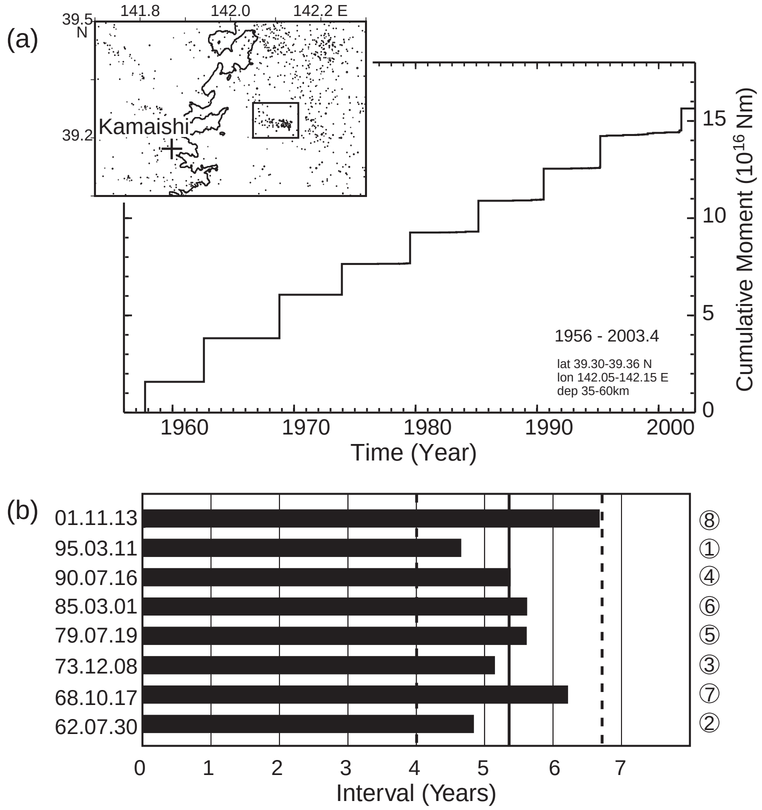

Fig. 2. (a) Cumulative seismic moment for a region including the off-Kamaishi earthquake sequence from 1956 to 2003. The region taken here is shown in the upper left corner of the figure (plotted earthquakes are the same as the earthquakes which plotted in Fig. 1). Hypocenter parameters determined by Matsuzawa et al. [5] are used for the events before 1975. The large steps about every 5 yr are due to the off-Kamaishi M4.8±0.1 events. (b) Recurrence intervals of the off-Kamaishi M4.8±0.1 events. The interval from each previous event is shown by a black bar. Solid and broken lines denote average and standard deviation for the intervals before the 1995 event, respectively.

One possibility for the fluctuation of the recurrence interval is due to small changes in the creep (quasi-static slip) rate around the M4.8±0.1 asperity. The M4.8±0.1 events provide an excellent opportunity to test this possibility because we have as many as eight recurrences of M4.8±0.1 earthquakes where modern observation data are available.

2. Small repeating earthquake analysis and recent creep rate

Small repeating earthquakes are thought to represent a series of earthquakes that occur regularly at the same asperity (or patch) on a fault plane [10,11]. Existence of isolated small asperities in the aseismic slipping area is probably responsible for the occurrence of such events. Taking advantage of this feature, we can infer the amount of aseismic slip around the small asperity by estimating the cumulative slip of the asperity (cumulative slip of repeating earthquakes). This assumes, of course, that the repeating earthquakes are occurring to 'keep up' with the aseismic slip around the asperity. Since the M4.8±0.1 events off-Kamaishi are thought to be occurring by the same mechanism as mentioned above, in this section, it is expected that smaller repeating earthquake activities around the M4.8±0.1 events also show the fluctuations if there are temporal variations in the aseismic slip [12,13]. Thus, we estimate temporal changes of creep around the asperity of the M4.8±0.1 events

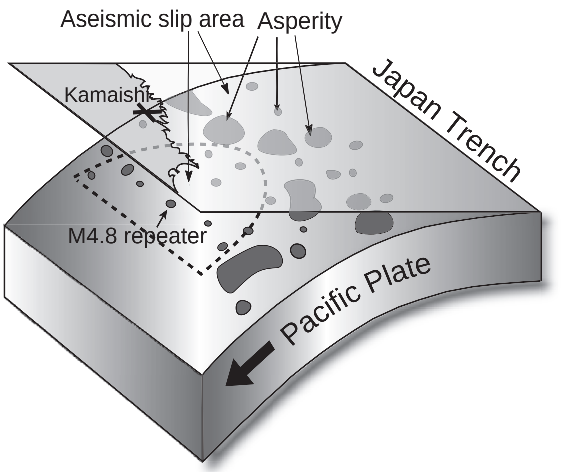

Fig. 3. Schematic diagram showing the distribution of asperities on the plate boundary off-Kamaishi, northeastern Japan.

by the activities of small repeating earthquakes on the plate boundary.

The criteria used for choosing the repeating earthquakes with a magnitude range of 2.5–4.0 was based on the similarities of the waveforms produced by a rupture of the same asperity, which is the same procedure used in Igarashi et al. [12] and Uchida et al. [13]. We selected earthquake pairs whose cross correlation coefficient for the same station was greater than 0.95 taken from the band-pass filtered (1–4 Hz) seismogram of 40 s containing both P and S wave arrivals. Pairs of earthquakes that satisfied the above conditions for two or more stations were then linked with another if the two pairs shared the same earthquake. To choose repeating earthquakes on the plate boundary where continuous creep is dominant, we select repeating earthquake sequences whose activity duration is longer than one month. We calculated the cumulative slip of each repeating earthquake sequence by using the relation between slip and seismic moment proposed by Nadeau and Johnson [14]. Although this relation was originally derived from measurements of moment release rate of repeating earthquakes in Parkfield and Stone Canyon, California, Igarashi et al. [12] confirmed for several repeating earthquakes in the NE Japan subduction zone that the slip calculated from this relation was consistent with the slip estimated from relative plate motion and repeating intervals. Note that the relation probably represents the maximum slip on the fault while usual constant stress-drop model predicts the slip averaged over the fault surface [15]. Igarashi et al. [12] and Uchida et al. [16] compared the creep distributions estimated from GPS data and from repeating earthquakes using Nadeau and Johnson's relation and found that both distributions were consistent. In this analysis, we used the waveform data of the Research Center for Prediction of Earthquakes and Volcanic Eruptions (RCPEV), Tohoku University from July 1984 to April 2003. Shallow (depth <60 km) earthquakes with magnitude 2.5 or larger were analyzed.

Fig. 4a shows the distribution of repeating earthquake groups (orange circles) around the M4.8±0.1 events (red star). Most of the repeating earthquakes are distributed to the east of the M4.8±0.1 events. The relatively large number of repeating earthquake groups in this area suggests the creeping area is widely distributed in this region compared to the north side of this region [13]. In this region, Okada et al. [17] estimated that earthquake activity on the plate boundary is not homogeneous but rather restricted in sparsely distributed clusters, most of which contains repeating earthquakes. This supports the idea that most of the areas on the plate boundary between the sparsely distributed asperities of repeating earthquakes are aseismic.

The estimated cumulative slips by the repeating earthquake groups in the five windows in Fig. 4a are shown in Fig. 4b. Each trace is obtained by averaging (stacking) the cumulative slips for the groups in each window and probably represents the creep history for each window. To evaluate the temporal change in reliability of the creep, we calculated the ratio of properly recorded earthquakes to all the analyzed events (Fig. 4c). 'Properly recorded earthquake' means that the waveforms of good quality were recorded for the earthquakes at two or more stations. The criteria for the quality of the waveforms were (1) the S/N ratio of waveforms defined as the ratio of the absolute amplitude for 4 s windows starting 6 s before and just after the P wave arrival is greater than 3 and (2) the waveforms were not saturated. The data before 1990 is not plotted in Fig. 4 because of the relatively poor ratio for properly recorded earthquakes.

In window A, the creep seems to be accelerated in 1992 and the high slip rate continued up to 1993 (Fig.

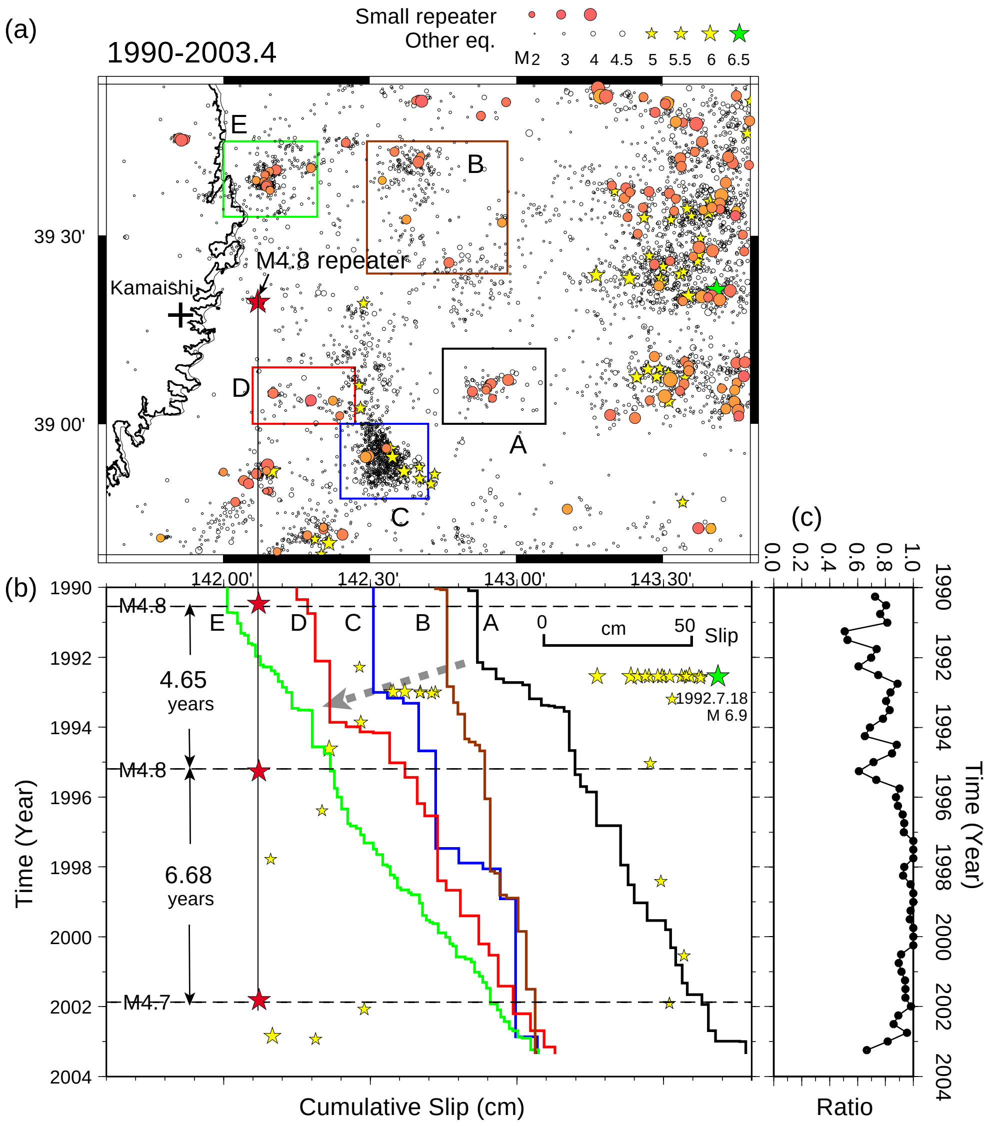

Fig. 4. (a) Distribution of repeating earthquake groups (orange stars) around the off-Kamaishi M4.8±0.1 earthquake sequence (red star). Open circles (M<5) and stars (M≥5) denote other earthquakes. Rectangles A–E denotes areas (windows) that are used in panel b. (b) Averaged cumulative slips for the repeating earthquake groups in the rectangles shown in panel a. The horizontal locations of the cumulative slips are located at the same longitude as the rectangles. Stars are the same as in panel a. Horizontal dashed lines indicate the occurrence times of the off-Kamaishi M4.8±0.1 events. (c) Ratios of earthquakes whose waveforms were properly recorded (i.e., saturated and bad S/N records were few) to all the analyzed earthquakes in the region 39.0–40.0N, 142.0–143.0E (see text for further details). The ratios were calculated for the moving window of 0.5 years for every 0.25 years and plotted at the end of the windows.

4b). Most of the slip occurred during and after the earthquake swarm in 1992 as already examined [16]. In window B, a high slip rate of creep is seen from the end of 1992 to 1994. In windows C and D, almost the same accelerations of creep are seen from 1992 to 1993. Small slip rate changes from 1993 to 1994 may also exist in window E considering the relatively low ratio of good waveforms from 1990 to 1995 (Fig. 4c). The start of the high slip rate (acceleration) of creep seems to have migrated from east to west in about 2 yrs. On the other hand, there are no prominent slip rate changes after the 1995 event except for window C. Although there is a little slip before the 1992 earthquake swarm in window A, the main part of the creep acceleration seems to have started after the 1992 earthquake swarm. The high creep rate is expected to lie around 1994 near the asperity of the M4.8±0.1 events and it is possible that this slip rate acceleration advanced the 1995 M4.8 event forward in time.

3. Creep accelerations and repeating intervals

The short recurrence interval before the 1995 event was estimated to be a result of the high slip rate that migrated westward from the location of the 1992 earthquake swarm near the Japan Trench. Fig. 5a shows the creep distribution during the 1992 earthquake swarm that was estimated from the repeating earthquake analysis. In this figure, averaged creep for the 0.3 by 0.3 degree windows are indicated by the 0.1 by 0.1 degree color patch for the period of 110 days including the 1992 earthquake swarm. The moving increment of the spatial window is 0.1 degrees. The estimated creeps were distributed in a wide area containing window A (black rectangle of Figs. 4a and 5a). With the creep, many moderate to large earthquakes occurred which are shown by the yellow ($6>M\geq5$) and green ($M\geq6$) stars in Fig. 5a. The largest one was a M6.9 event. Considering the focal mechanisms, most of the large ($M\geq6$) earthquakes that occurred during this period were interplate events [18], indicating the acceleration of creeps probably responsible for the successive occurrence of these earthquakes.

The inhomogeneous distribution of the $M\geq5$ earthquakes in the dashed rectangle (Fig. 5a) may be due to the spatial inhomogeneity of the asperity distribution that generates seismic slip in the aseismic area. The middle part of the rectangle where few $M\geq5$ earthquakes existed was considered an almost completely aseismic area [16,19]. Considering the above, the $M\geq5$ seismicity does not express the creep distribution directly. However, it gives some rough information on creep because the slip characteristics (the distribution of asperity) on the plate boundary will not change dramatically during the observational period and consequently, similar earthquake activity can be expected when a large creep event occurs like that in 1992. Therefore, we examined the seismicity to the east of the M4.8±0.1 events to find other large creep accelerations before the 1992 earthquake swarm.

The number of $M\geq5$ earthquakes located in the window (dashed rectangle in Fig. 5a) in each year is shown in Fig. 5c. The window was set to encompass most of the area where large creep was observed in the 1992 earthquake swarm, but was slightly shifted south to avoid the influence of the earthquake swarm in 1989 which occurred in the north neighboring the 1992 activity. The large number of earthquakes in 1960 and 1968 suggests the existence of widely distributed creep accelerations in these periods.

Fig. 5b shows M–T diagrams of the M4.8±0.1 events together with numbers indicating the recurrence interval in ascending order. The solid circle represents approximately time of creep acceleration near the asperity of the M4.8±0.1 events that estimated in the Section 2. If we assume the same creep migration and lag time (2 yrs) that observed after the 1992 earthquake swarm, the time of creep acceleration near the asperity of the M4.8±0.1 events after the 1960 and 1968 activity come to the location of open circles in Fig. 5b. The two open circles in 1962 and 1970 are located in the second and third shortest recurrence intervals (Fig. 5b). This suggests the possibility that the 1962 and 1973 events were also advanced by the migration of creep accelerations from the trench side.

To examine the patterns of seismicity in 1960 and 1968 that had many earthquakes as described above, we plotted epicenter distributions of the earthquakes with a magnitude 5 or larger in this region for eight periods as shown in Fig. 6. The epicenter distributions for the periods of 1956–1960 (Fig. 6a) and of 1967–1971 (Fig. 6c) are similar to that for the period of 1989–1993 (Fig. 6g) which involves the 1992 earthquake swarm. In the period of 1956–1960, distinctive activities are recognized in the southern area of the rectangle in 1958 and in the northern area of the rectangle in 1960. Considering the aseismic nature suggested for the middle part of the rectangle, we consider that the whole area in the rectangle had slipped quasi-statically during the 1958 to 1960 period. In the period of 1967–1971, a large number of $M\geq5$ earthquakes appear in the northern and southern areas of the rectangle in 1968. Therefore,

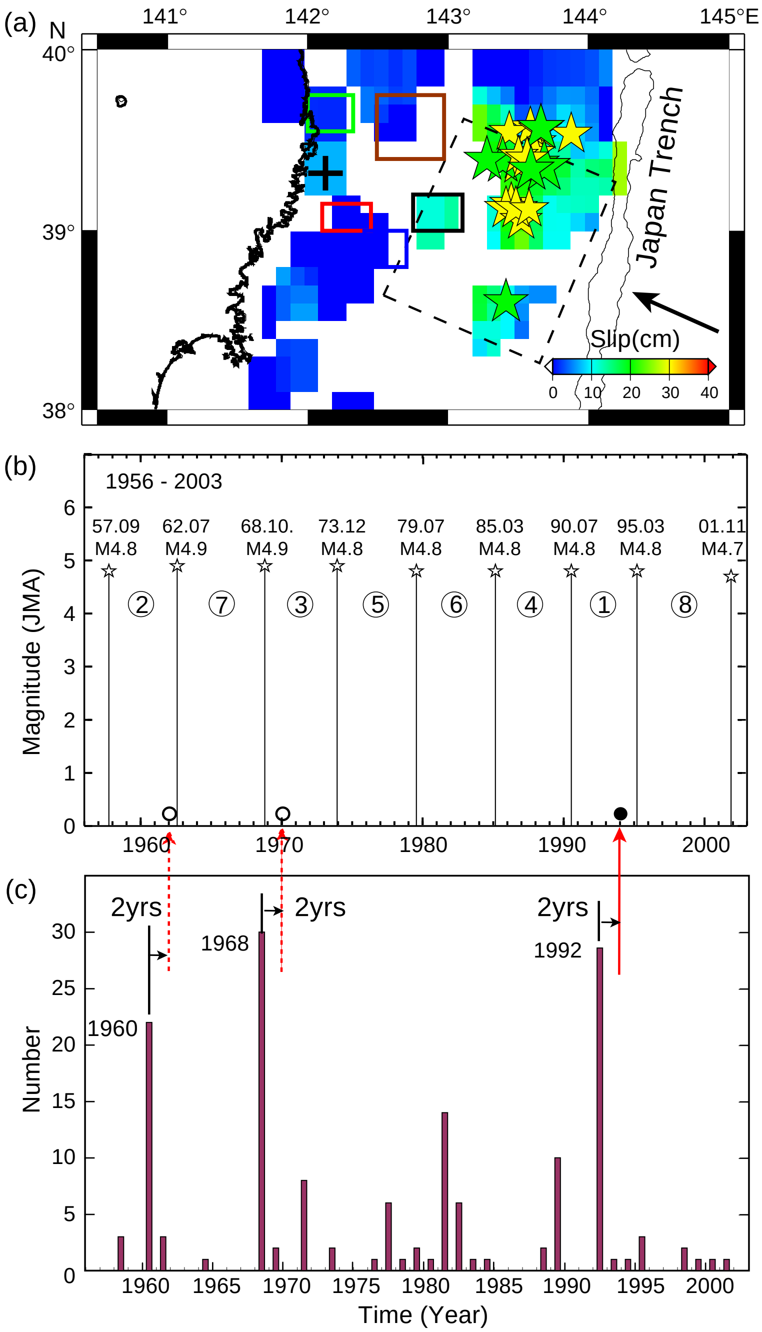

Fig. 5. (a) Creep distribution for the period involving the 1992 earthquake swarm (July 8 to October 26, 1992). The amount of slip for each window in which three or more groups are included is shown by a color scale. Green and yellow stars denote the epicenters of earthquakes of $M \geq 6$ and $6 > M \geq 5$, respectively. The cross symbol denotes the location of the off-Kamaishi M4.8±0.1 events and bold rectangles are the same as Fig. 4a. The arrow denotes the direction of the relative plate motion. (b) M–T diagram of the off-Kamaishi M4.8±0.1 events from 1956 to 2003. The numerals between the earthquakes indicate the ranking of recurrence intervals in ascending order. (c) Frequency distribution of earthquakes with magnitude 5 or larger for every year in the dashed rectangle in panel a. Red arrow and solid circle indicate the time of estimated creep acceleration after the 1992 earthquake swarm. Dotted arrows and open circles indicate the time two years after the 1960 and 1968 earthquake swarms.

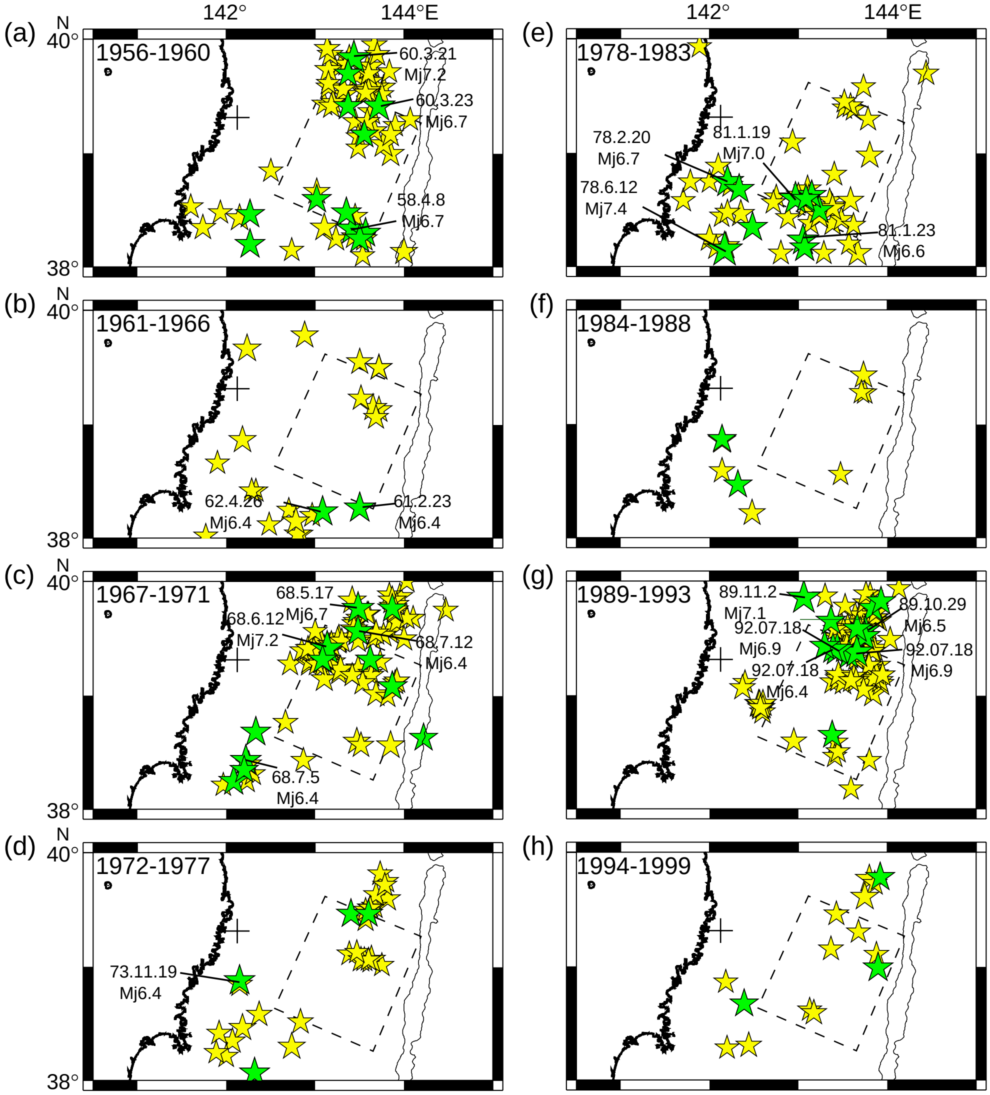

Fig. 6. Epicenter distributions of $M\geq5$ earthquakes off-Kamaishi for (a) 1956–1960, (b) 1961–1966, (c) 1967–1971, (d) 1972–1977, (e) 1978–1983, (f) 1984–1988, (g) 1989–1993, (h) 1994–1999. Shallow (depth≤60 km) earthquakes by JMA catalogue are plotted. Yellow stars, green stars, and dashed rectangles are the same as in Fig. 5a.

large creep accelerations that cover the whole area of the rectangle probably existed in 1968.

In 1981, several earthquakes had occurred at the southern area of the rectangle, however there were no distinctive activities at the northern part (Fig. 6e). We infer that there was no large acceleration of creeps that affected the M4.8±0.1 events in 1981. There are no other periods that show similar epicenter distributions except for 1958–1960 and 1968. It is likely that extensive creep accelerations during the 1958–1960 and 1968 earthquake swarms advanced the occurrences of the 1962 and 1973 M4.8±0.1 events.

4. Discussion

We found significant creep acceleration and its migration from the east (shallower part of the plate boundary) to west (deeper part) during the period from 1992 to 1994 along the plate boundary off-Kamaishi. The creep acceleration (afterslip) was probably produced by stress increase due to the destruction of several large asperities (corresponding to M6 events) although we cannot rule out the possibility of small creep acceleration preceding the M6 events [20]. $M \geq 5$ earthquakes in window C in Fig. 4 (denoted by yellow stars) were also activated correlating with the creep migration during the period from 1992 to 1994. Those events were estimated to be interplate events [20] and thus probably physically related to the migration of the creep acceleration. However, in the periods of 1958–1960 and 1968 which had significant swarm events near the trench, there are only few $M \geq 5$ events located in this area. One of the possible explanations for the lack of $M \geq 5$ events is that the amount of creep accelerations in the episodes of the 1958–1960 and 1968 were not sufficient to produce many $M \geq 5$ events.

Near the asperity of the M4.8±0.1 events, creep accelerations were estimated preceding three events in 1962, 1973, and 1995 that occurred after the three shortest recurrence intervals. As Okada et al. [8] investigated, the relative amplitude of the waveforms for the 1985, 1990, and 2001 events were within 0.9–1.2 times the 1995 event, and magnitude differences estimated by the Japan Metrological Agency (JMA) were within 0.1 for all events. Upper estimations of the differences in co-seismic slip for these events correspond to 2 cm at most. Therefore the slip variations of the M4.8±0.1 events are negligible compared to the fluctuation in the recurrence interval (about 1.5 yrs) that correspond to a slip of 12 cm if we assume an 8 cm/yr constant displacement increase (the same rate as the relative plate motion). This suggests the recurrence intervals of the M4.8±0.1 events are governed by temporal changes in creep around the asperity, given that the failure strength of the asperity does not change. If this is the case, the longer recurrence intervals may contain additional information on the creep rate around the M4.8±0.1 events.

The 2001 event that occurred after the longest recurrence interval was followed by the 1995 event that occurred after the shortest recurrence interval. The same relationship can be seen before and after the 1962 and 1973 events (Fig. 2b). Fig. 7 illustrates one

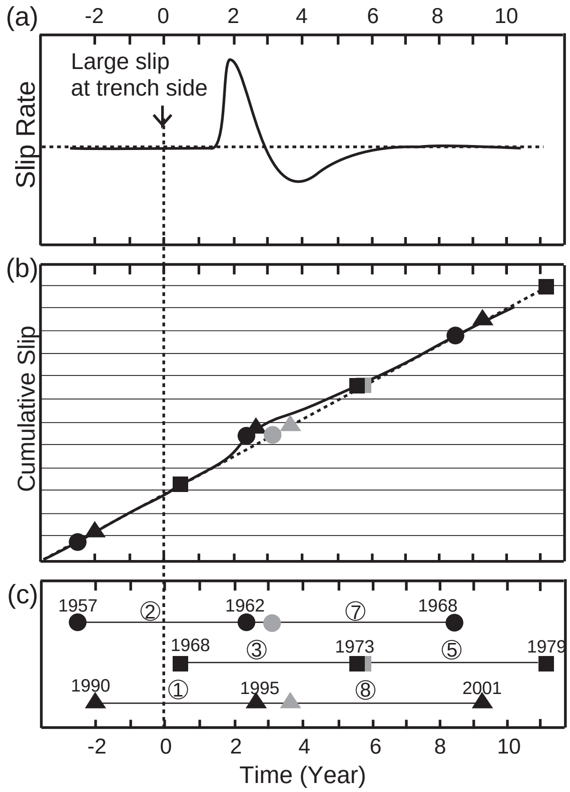

Fig. 7. Schematic diagram showing interpretation of the relation between slip rate change and the recurrence intervals. (a) Temporal change of slip rate around the asperity. (b) A cumulative slip around the asperity. Circles, squares, and triangles indicate the off-Kamaishi events. (c) Occurrence times of the off-Kamaishi M4.8±0.1 events with reference to the estimated occurrence times of large slip at the trench side in 1960, 1968, and 1992. Gray symbols in panels b and c indicate expected occurrence times if slip rate is constant.

probable explanation for the pairs of shorter and longer recurrence intervals. Here we assume that the M4.8±0.1 asperity was ruptured when the cumulative creep around the asperity (or the slip deficit of the asperity) become a certain value after the previous event, and that the same perturbation of creep rate occurred after the 1962, 1973, and 1992 earthquake swarms where the creep increase was inferred in the previous section. Fig. 7a and b, respectively, show the temporal changes in slip rate and cumulative slip around the asperity. The slip is accelerated around 2 yrs after the occurrence of the large creep on the trench side, and in addition deceleration follows the acceleration (Fig. 7a). The cumulative slip deviates from the constant rate increase (dashed line) by 2 yrs after the large slip at the trench side until it converges with the line about 7 yrs after the slip (Fig. 7b). The duration of fluctuation is not certain. If the duration is much larger than the averaged interval of the repeating earthquakes, successive two intervals of the repeating event sequence will not be compensated as observed. On the other hand, if the duration is much shorter than the one cycle, the fluctuation in the repeating interval will be seldom observed. Therefore we infer the duration of the creep fluctuation is around 5 yrs.

Fig. 7c shows three recurrence intervals that have shorter and longer pairs with reference to the estimated occurrence times of large slips on the trench side in 1960, 1968, and 1992. The advancement of the 1962 and 1995 events can be understood by the abrupt increase of cumulative slip around the asperity as shown in Fig. 7b. The longer recurrence intervals before the 2001 and 1968 events are explained by the relatively slow increases (deceleration) of cumulative slip during the intervals before the two events. The deceleration as described here is necessary because the event next to the advanced event should occur within a normal recurrence interval if the slip rate becomes normal after the acceleration. The relatively small advancement and delay before and after the 1973 event may also be explained by the approach of cumulative slip to the constant increase (dashed line) before the 1973 event (Fig. 7b). Therefore, these results suggest the existence of the deceleration of creep just after the accelerations. The decelerations of creep following the acceleration may come from temporal slip excess by the migration of slip acceleration, although further investigation is needed to reveal the nature of slip evolution in this area.

The model presented here offers important information on forecasting earthquakes other than a statistical one. We will be able to narrow the estimate range of a forecast by using the creep rate estimated from repeating earthquakes and/or other information. The next M4.8$\pm$0.1 event, which is estimated to occur in May 2007 $\pm$21 month with 99% probability [5], will occur earlier than May 2007 if extensive creep events occur by May 2005, although no significant creeps are observed from 1992 up to May 2004 from the repeating earthquakes and other moderate to large earthquakes.

5. Conclusions

Migration of acceleration in creep on the plate boundary was identified by repeating earthquake analysis from around 1992 to 1994 in the area off-Kamaishi, NE Japan, where the Pacific plate subducts from the Japan Trench. The migration was observed following extensive creep acceleration combined with an earthquake swarm near the Japan Trench in 1992. The acceleration of creep seemed to arrive about 1 yr before the 1995 off-Kamaishi quasi-periodic event, which was thought to be a recurrent rupture of an isolated asperity (1 km in width), which exists at a deeper position of the interplate main thrust zone. The acceleration of the creep rate near the asperity of the off-Kamaishi event is probably responsible for the early occurrence of the 1995 off-Kamaishi event.

We further found good correlation between large earthquake swarms near the Japan Trench that probably indicate the occurrence of large creep (quasi-static slip), and short recurrence intervals of off-Kamaishi events for the period from 1956 to 2003. Two earthquake sequences which have moderate to large earthquakes with a similar epicenter distribution as the 1992 earthquake swarm were observed in the period of 1958–1960 and in 1968, and shorter recurrence intervals of off-Kamaishi events followed the occurrences of these sequences. This suggests other extensive creep accelerations, their migration to near the off-Kamaishi events, and acceleration of the occurrence times of the events existed in these periods.

The present study strongly suggests the fluctuations of creeps near the asperity of the off-Kamaishi earthquakes are mainly controlling the occurrence times for the events. If this is the case, the shorter recurrence intervals following longer ones suggest decelerations of creep after the accelerations.

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