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Interplate quasi-static slip off Sanriku, NE Japan, estimated from repeating earthquakes

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[1] Space-time distribution of quasi-static slip on the plate boundary off Sanriku, northeastern (NE) Japan, was estimated by using small repeating earthquakes. We found 2509 repeating earthquakes occurring on the plate boundary for the last 17 years. Based on the interpretation that these events are caused by repeating slips of small asperities surrounded by stable sliding area, we regarded these repeating events as creepmeters embedded on the plate boundary. The results show that deeper portions of the plate boundary are sliding almost stably and earthquakes with magnitudes more than 6 are accompanied by quasi-static slips in the surrounding areas. *INDEX TERMS:* 7209 Seismology: Earthquake dynamics and mechanics; 7223 Seismology: Seismic hazard assessment and prediction; 7230 Seismology: Seismicity and seismotectonics; 8150 Tectonophysics: Plate boundary—general (3040). **Citation:** Uchida, N., T. Matsuzawa, T. Igarashi, and A. Hasegawa, Interplate quasi-static slip off Sanriku, NE Japan, estimated from repeating earthquakes, *Geophys. Res. Lett.*, *30*(15), 1801, doi:10.1029/2003GL017452, 2003.

1. Introduction

[2] Off Sanriku, northeastern (NE) Japan, the Pacific plate is subducting with a rate of about 8 cm/year from the Japan Trench. The seismic coupling coefficient for the plate boundary in this region is estimated to be about 25% [*Pacheco et al.*, 1993; *Peterson and Seno*, 1984]. Therefore, about 75% of the total slip along the plate boundary must be released by aseismic slips. These aseismic slips probably play a crucial role in stress concentration on large asperities (source regions of future large earthquakes). However, the process related to aseismic slip on the plate boundary is not well known yet. Recently, Global Positioning System (GPS) data have revealed a broad pattern of the interplate coupling in this region [*Heki et al.*, 1997; *Nishimura et al.*, 2000; *Kawasaki et al.*, 2001]. However, installations of GPS stations are limited to the land area, although the major collision zone lies below the Pacific Ocean. Therefore, estimation of highly resolved slip distributions for the area far from the shore is difficult from GPS data alone. Repeating earthquake analysis also provides information about the quasi-static slip on the plate boundary [*Ellsworth*, 1995; *Nadeau and McEvilly*, 1999; *Igarashi et al.*, 2003]. It has the possibility to estimate with higher spatial resolution, especially for the area far from the shore, than the geodetic data analysis.

[3] Repeating earthquake sequence is a series of earthquakes regularly occurring on a patch of the fault plane. Repeating earthquakes have been found in Stone Canyon [*Ellsworth*, 1995], Parkfield [*Nadeau and McEvilly*, 1997] and NE Japan subduction zone [*Igarashi et al.*, 2003; *Matsuzawa et al.*, 2002]. *Igarashi et al.* [2003] reported almost all the repeating earthquakes found in NE Japan are occurring on the plate boundary. These earthquakes are thought to be caused by repeated ruptures of small asperities surrounded by stably sliding area. Figure 1 schematically shows spatial distribution of small and large asperities surrounded by aseismic slip area on the plate boundary off Sanriku. Because of the relative plate motion, each large asperity ruptures repeatedly as large earthquakes at long time intervals. On the other hand, each small asperity ruptures at short time intervals and generates almost identical waveforms, i.e. repeating earthquakes. If small asperities are sparsely distributed on the plate boundary and the coupling is strong only at those asperities, activities of the repeating earthquakes (ruptures of the small asperities) are governed by the aseismic slip rate in the surrounding areas. That is, the cumulative slip of repeating earthquakes for an asperity reflects the cumulative quasi-static slip occurring in the area surrounding that asperity. If the asperity always slips seismically, we can estimate quasi-static slip distribution on the plate boundary from the spatial distribution of slips by repeating earthquakes [*Nadeau and Johnson*, 1998; *Igarashi et al.*, 2003].

[4] In this paper, we estimated detailed space-time distribution of quasi-static slip on the subducting plate boundary from repeating earthquake analysis, independent of GPS data analysis.

2. Repeating Earthquake Analyses

[5] We identified repeating earthquakes based on similarity of seismograms. We calculated cross-correlation coefficient of waveforms for events observed at each station following *Igarashi et al.* [2003]. We band-pass filtered seismograms from 1 to 4 Hz and calculated cross-correlation coefficients for all the pairs whose epicenter separations are less than 30 km. We treated an earthquake pair as a pair of repeating earthquakes when the two events showed quite

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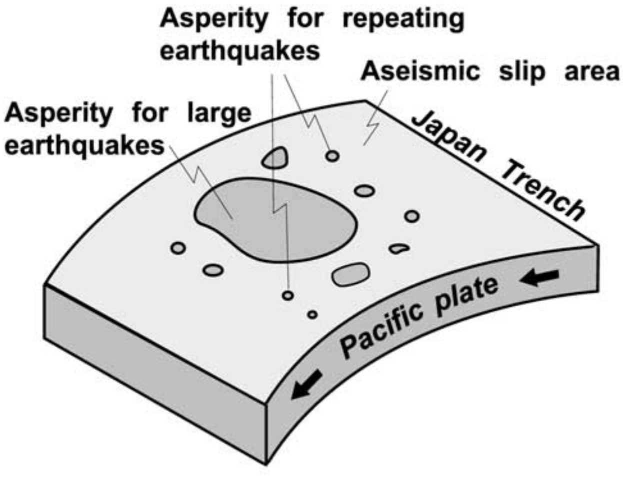

Figure 1. Schematic diagram showing the distribution of asperities on the plate boundary off Sanriku, northeastern Japan.

similar waveforms at two or more stations. The criteria for the similarity were that the cross-correlation coefficients of the two waveforms were larger than 0.95 for 40s window containing both P and S waves. Then, a pair (group) of repeaters was linked with another if the two pairs (groups) shared the same earthquake. In other words, if an event was found to belong to two different groups, we re-classified all the events belonging to the both groups into a new large group. This grouping procedure was iterated. Slip amount of each repeating earthquake sequence was estimated by using the relationship between slip (d; cm) and seismic moment (M_0; dyne.cm) proposed by *Nadeau and Johnson* [1998].

$$\log(d) = -2.36 + 0.17\log(M_0). \quad (1)$$

Scalar moment for each event was estimated from magnitude determined by Research Center for Prediction of Earthquakes and Volcanic Eruptions (RCPEV), Tohoku University, using the relationship between magnitude and scalar moment [*Hanks and Kanamori*, 1979].

[6] We used digital seismograms recorded by the microearthquake observation network of RCPEV, Tohoku University, for the period from July 1984 to October 2001. The sampling frequency was 100Hz and most of the seismometers were of 1 Hz velocity type. We selected 21 stations that have been continuously operated since 1984. In total, we searched about 23,000 shallow (depth < 70km) earthquakes with magnitude 2.0 or larger. The magnitude range and analyzed period are wider than *Igarashi et al.* [2003]. We calculated cross-correlation coefficients for about 36,000,000 waveform pairs. As a result, we detected 2,509 repeating earthquakes that were grouped into 600 sequences for the off-Sanriku region (rectangle in Figure 2a). About 10% of the events have been identified as repeating earthquakes, and each sequence contains about 4 earthquakes on the average for the period of 17 years. Magnitudes of these repeating earthquakes range from 2.0 to 5.1 and the average is 3.0. The earthquakes that have not been identified as the repeating earthquakes probably correspond to earthquakes rupturing different combination of asperities from event to event, intraplate earthquakes, and earthquakes occurring when noise levels were accidentally high. The existence of intraplate events in both subducting and overriding plates has been pointed out by *Hino et al.* [2000].

[7] Figure 2b shows the spatial distribution of the repeating earthquake sequences (groups) thus identified for the rectangle in Figure 2a. We use a moving spatial window of 0.3 by 0.3 degrees to count the number of repeating earthquake sequences. The window is repeatedly moved by an increment of 0.1 degrees. The number of the sequences located within each window is represented by a color patch of 0.1 by 0.1 degrees at the center of the window. Black line shows the western limit of low-angle thrust type earthquakes [*Igarashi et al.*, 2001]. The plate boundary is thought to be completely decoupled to the west of this line. There are many repeating earthquake sequences close to the line and to the Japan Trench. In the figure, the large moment release area of the 1994 M7.6 Far-off Sanriku earthquake is shown by contours [*Nagai et al.*, 2001], which probably

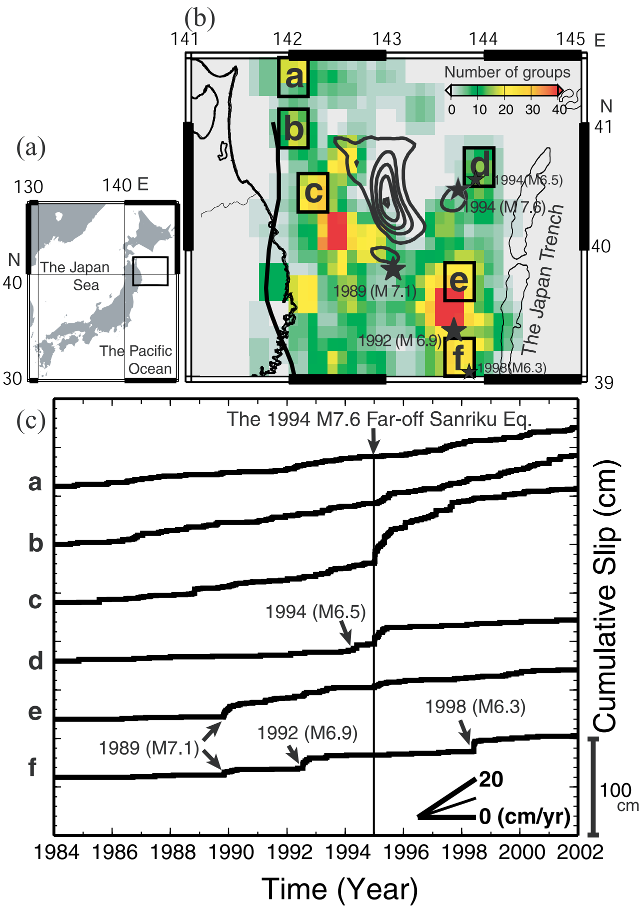

Figure 2. (a) Location of study area (off-Sanriku region). (b) Distribution of repeating earthquake sequences. Heavy line shows the western limit of low-angle thrust type earthquake occurrence [*Igarashi et al.*, 2001]. Stars denote epicenters of the 1994 Far-off Sanriku earthquake and other major events indicated in Figure 2c. Six areas shown in Figure 2c are indicated by rectangles. Contours show the moment release distribution of the 1994 Far-off Sanriku earthquake [*Nagai et al.*, 2001]. (c) Averaged slip histories in the six areas indicated in Figure 2b. The occurrence time of the five major earthquakes are indicated by arrows.

corresponds to the location of a large asperity. There are very few sequences inside the contours. This feature is consistent with our model (Figure 1).

3. Space-Time Distribution of Quasi-Static Slip

[8] We calculated a cumulative slip history for each sequence and then averaged (stacked) the cumulative slips for the sequences located within each window in order to obtain reliable slip history at each window. There might be asperities located closely and combination of ruptured asperities may be different from event to event. In such a case, cumulative slip will be overestimated or underestimated depending on the cross-correlation coefficients between the combinations. However we expect that these effects would be cancelled to some extent by the stacking, assuming that the possibilities of overestimation and underestimation would be almost the same. On the other hand, if small asperities are located close to a very large asperity, the small asperities are likely to slip together with the large asperity. Thus, it should be noted that the cumulative slips estimated from such asperities might be underestimated by the occurrences of very large events. Averaged cumulative slips for six rectangles in Figure 2b are shown in Figure 2c as examples. These cumulative slips can be interpreted as quasi-static slips occurring in those six regions. In window 'a', the plate boundary seems to be slipping with an almost constant rate of about 4 cm/year. Note that the window is located near the western limit of low-angle thrust type earthquakes and far from the asperity that caused the 1994 Far-off Sanriku earthquake. In windows 'b', 'c' and 'd' the quasi-static slip was accelerated after the 1994 Far-off Sanriku earthquake. This quasi-static slip acceleration probably represents an afterslip of the earthquake. The afterslip is large on the landward side of the source area (window 'c') and it lasted about one year. On the trenchward side of the source area (window 'd') the afterslip is also observed, but its amplitude and time constant are smaller than those for window 'c'. In this region, a small afterslip for the April 8, 1994 event (M6.5) is also seen. In southern regions, windows 'e' and 'f', quasi-static slip rates changed abruptly associated with the 1989 (M7.1), 1992 (M6.9) and 1998 (M6.3) events. Geodetic data analyses [*Kawasaki et al.*, 2001; *Heki et al.*, 1997; *Nishimura et al.*, 2000] have revealed that the 1989, 1992 and 1994 (M7.6) events were followed by large afterslips. However, afterslips for the 1994 (M6.5) and 1998 (M6.3) events have not been found from those analyses.

[9] To examine space-time distribution of quasi-static slip, we estimated distribution of slip rate for every two years (Figure 3). The slip rate estimated from repeating earthquake sequences within a moving window of 0.3 by 0.3 degrees is indicated by a color patch of 0.1 by 0.1 degrees at the center of the window. Slip rates for windows in which three or more sequences are contained are shown here. In the periods A and B, slips with a rate of about 5 to 10 cm/year (light blue to green) are seen along the western limit of low angle thrust type earthquake (heavy line in Figure 3). This slip rate is comparable to the subduction rate (8 cm/year) of the Pacific plate in this region, which is not inconsistent with the interpretation that the plate boundary is decoupled to the west of this line. In the periods C and D, two earthquake swarms including M7.1 and 6.9 events

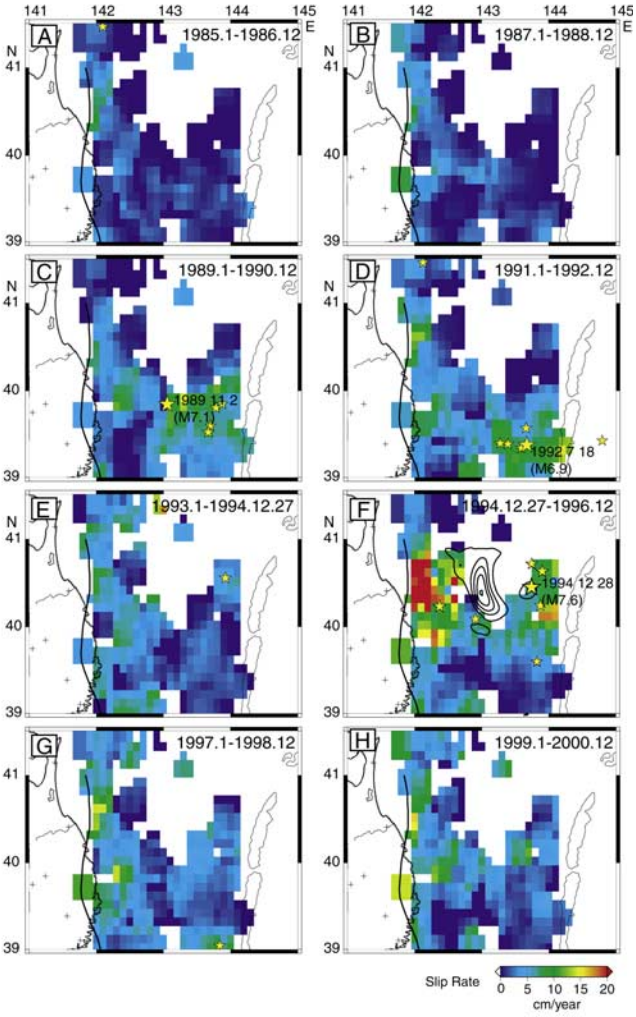

Figure 3. Slip rate distribution for every two years (periods A to H). Slip rate for each window in which three or more sequences are included is shown by color scale. Note that the end of the period E is set just before the 1994 Far-off Sanriku event and the start of the period F is set just after the event. Stars denote epicenters of earthquakes with magnitude 6 or larger. In the period F, contours show the moment release distribution for the 1994 Far-off Sanriku earthquake [*Nagai et al.*, 2001].

occurred, respectively. In these periods, the quasi-static slip rate was accelerated widely in the southern part. The main parts of quasi-static slip areas for the two events seem to be complementary. The period E was set from 1993 to just before the 1994 Far-off Sanriku earthquake (M7.6). In this period, an event with magnitude 6.5 occurred in April 1994 close to the trench preceding the 1994 M7.6 event. The quasi-static slip was accelerated locally in the area near this event. This slip was also seen in the window 'd' of Figure 2c. In the period F, the 1994 Far-off Sanriku earthquake occurred and the quasi-static slip was accelerated in a wide area. The quasi-static slip was distributed not only to the west of the source region but also to the east of it, which was not clearly seen in the results of GPS data analyses [*Nishimura et al.*, 2000] because of poor resolution in the regions far from the land. Major aftershocks (yellow stars in Figure 3 for period F) are distributed within the afterslip region. In the period G, the quasi-static slip associated with an event with magnitude 6.3 is seen in the southern part. No major event occurred in the period H. Spatial pattern of the quasi-static slip in this period is similar to that in the periods A and B, although the absolute value of slips was slightly different.

4. Discussion

[10] Our analyses using repeating earthquakes showed that the quasi-static slips are distributed especially in deeper and shallower parts of the plate boundary. This result is consistent with the idea that the plate boundary is decoupled in deeper and shallower parts due to the thermal condition and existence of unconsolidated sediment [*Hyndman and Wang*, 1993; *Oleskevich et al.*, 1999]. As shown in Figure 2b, there exist relatively large number of repeating sequences in the southern region (39–40.3 N), which means that the plate coupling coefficient in the southern region is smaller than the northern region (40.3–41.5 N). Furthermore, the distribution of repeating earthquake sequences complementary to large asperities as shown in the 1994 event case suggests that the distribution of repeating earthquakes can give information on the locations of large asperities. In the deeper part of the plate boundary, slips are almost stable for all the analyzed periods. The coincidence of the quasi-static slip rate presently estimated with the plate convergence rate in this area enhanced the reliability of the slip estimation from repeating earthquake analyses. Although the scaling relationship might be different between the shallower and deeper parts of the plate boundary, it is certain that the quasi-static slip (afterslip) took place following the 1994 event and other M > 6 events in the areas near the Japan Trench. In the shallow part (to the west of the Japan Trench) the occurrence of the quasi-static slip seems to be episodic.

[11] As mentioned above, it is difficult to correctly estimate the quasi-static slip distribution near the trench from GPS data alone. However, repeating earthquake analyses can reveal the nature of the quasi-static slip in those areas. In the area off Sanriku, most of interplate earthquakes with magnitude 6 or larger (yellow stars in Figure 3) were followed by afterslips. These quasi-static slips accompanying moderate earthquakes are important in the stress concentration to large asperities near those events. For example, the quasi-static slip after the April 1994 M6.5 event may have influenced the occurrence of the 1994 M7.6 event. The quasi-static slip observed here probably plays an important role in accelerating the occurrences of nearby larger earthquakes as well as in generating the aftershocks and swarm activities.

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