Occurrence of quasi-periodic slow-slip off the east coast of the Boso peninsula, Central Japan

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An analysis of Global Positioning System (GPS) data revealed south-southeastward transient deformation caused by the expected slow-slip near the Boso peninsula, central Japan, approximately 5 years after a similar event in 2002. An area of aseismic slip with a moment magnitude of 6.6 was estimated off the Boso peninsula, adjacent to the area of associated seismic activity. The 2007 aseismic slip started from around August 10, expanded slightly to the north, and gradually ceased activity over a period of about 10 days. This rupture process is different from those of the last two events in which the slow-slip area moved from north to south. However, the three slow-slip events detected by the GPS array verify the hypothesis that the Boso slow-slips occur quasi-periodically in a certain area, accompanied by seismic swarms. The factors causing the slight differences in the rupture process, magnitude, recurrence time, and slip area among the observed slow-slip events remain unclear.

Key words: Slow-slip, Boso peninsula, interplate coupling, quasi-periodicity, seismic activity.

1. Introduction

The Philippine Sea plate is subducting beneath the Boso peninsula, central Japan, and is underlain by the Pacific plate (Ishida, 1992) (see Fig. 1). The crustal deformation on the Boso peninsula, shown in Fig. 1(B) relative to the Yasato site for the period between 1997 and 1999, is mostly explained by coupling between the North American plate and the Philippine Sea plate off the east coast of the Boso peninsula.

The coupling rate between the Philippine Sea plate and the overriding plate becomes higher toward the south, as is expected from the ground velocity in Fig. 1(B) (Sagiya, 2004). Under this tectonic setting, ground motion that deviated from the steady deformation in Fig. 1(B) occurred in May 1996 and October 2002. Figure 2(A, B) shows the detrended transient crustal deformation at GPS stations relative to the Yasato station for the period between April 8 and June 10, 1996 (Japan Time) and between September 1 and December 2, 2002. Trend and annual components are estimated for the period between 1997 and 1999 and removed from the original time series. We call this procedure "detrending" in this paper. As shown in these figures, south-southeastward ground displacements are observed in contrast with the deformation in Fig. 1(B). From the observed crustal deformation shown in Fig. 2(A, B), slow-slips with rupture propagating to the south were estimated off the east coast of the Boso peninsula (Sagiya, 2004; Ozawa *et al.*, 2003). On the basis of the 6- to 7-year quasi-periodicity of the seismic swarm that seems to accompany the Boso slow-slip events (National Research Institute for Earth Science and Disaster Prevention (NIED), 2003), the next slow-slip was expected at a time span of around 5 years from the previous event. Earthquakes did in fact start occurring from around August 13, 2007, in an area similar to those of the seismic swarms associated with the 1996 and 2002 events.

In this paper, we report the observed transient crustal deformation, estimate the time evolution of the 2007 Boso slow-slip, and compare the 2007 event with the similar 1996 and 2002 events to investigate the nature of the Boso slow-slips.

2. Transient Crustal Deformation

Figure 2(C) shows detrended crustal deformation for the period between August 1 and August 26, 2007, in the eastern part of the Boso peninsula, revealing a south-southeastward transient motion with a maximum movement of 3 cm. The vertical motion does not show clear transient movements for the same period. The 2007 transient ground motion shows a similar pattern to that of the 1996 event shown in Fig. 2(A) and the 2002 event shown in Fig. 2(B), although there are two notable differences among Fig. 2(A–C). Firstly, the overall magnitudes of the ground displacements of the 2007 and 2002 events are 30–100% greater than that of the 1996 event. Secondly, transient motion in the northern part of the Boso peninsula is relatively large in the 2007 event compared with that in the 1996 and 2002 events.

In association with the 2007 transient crustal movements, a seismic swarm occurred off the coast of the Boso peninsula (see Figs. (2–4)) from August 13 (Fig. 3(D)), as was observed in 1996 and 2002. The locations of seismic swarms associated with the three transients are similar (Fig. 2). These earthquakes are regarded as activities near the upper surface of the Philippine Sea plate, with a focal depth of between 20 and 30 km (NIED, 2007). This focal depth corresponds to those of the repeating earthquakes in

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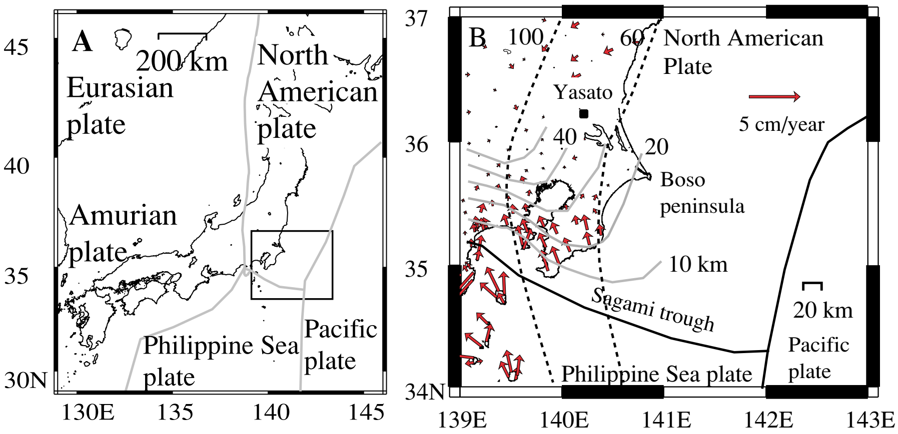

Fig. 1. (A) Tectonic settings in and around Japan. Thick gray lines indicate plate boundaries. (B) Magnified map of rectangular area in (A). Thick gray and dotted lines with numerals represent contours of the upper depths of the Philippine Sea plate and the Pacific plate, respectively. Depth contours are from figure 9 in Ishida (1992). Red arrows show average ground displacement rates for the period between 1997 and 1999 at GPS sites relative to the Yasato station.

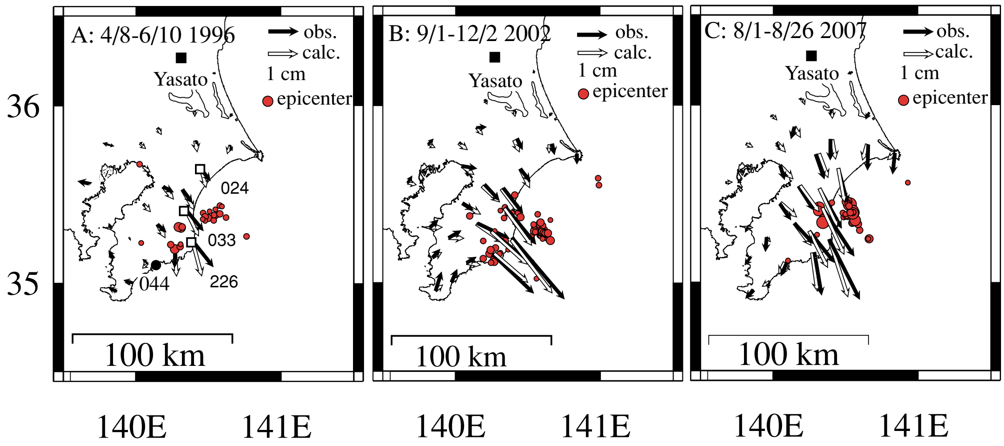

Fig. 2. Detrended ground displacements at GPS stations on the Boso peninsula relative to the Yasato station. Solid arrows represent ground displacements at GPS stations, while white arrows indicate values at GPS sites computed by Kalman filtering analysis. Small red dots represent epicenter with depth≤50 km and $M_{\mathrm{JMA}} \geq 2$ determined by the Japan Meteorological Agency (JMA). (A) April 8–June 10, 1996 (Japan Time). Open squares represent GPS sites whose time series are shown in Fig. 3. (B) September 1–December 2, 2002. (C) August 1–August 26, 2007.

the subducting Philippine Sea plate in a nearby area (NIED, 2007). Focal solutions show a low-angle thrust fault and north-northwest-south-southeast compresssion, which corresponds to the direction of the Phillipine Sea plate motion against the continental plate in this area (NIED, 2007). Uncertainties of the hypocenter are about 1 km for horizontal coordinates and 1 km for focal depth (Ozawa *et al.*, 2003).

Figure 3 shows time series of detrended ground displacements in 2007 at selected stations in Fig. 2(A). As shown, a transient event was observed from around August 10–20, 2007, followed by gradual subsidence. In the case of the 1996 and 2002 events, the time durations of the transient motion lasted for around 10 days, similarly to that of the 2007 event.

Considering the similarities among the 1996, 2002, and 2007 transient crustal deformation events and associated seismic swarms in Fig. 2, it is most likely that the 2007 transient crustal deformation was caused by the expected Boso slow-slip between the subducting Philippine Sea plate and the overriding North American plate.

3. Analytical Procedure

On the assumption that aseismic slip is the cause of the transient crustal deformation in the Boso peninsula, we infer the slip history between the Philippine Sea plate and the overriding plate for the 2007 event by employing a Kalman filter (Ozawa *et al.*, 2001) based on the time-dependent inversion method (Segall and Matthews, 1997) and the data in Figs. 2(C) and 3. We use daily east-west, north-south, and up-down detrended displacement data at 28 selected GPS sites (Fig. 2(C)) on the Boso peninsula with a weight ratio of 1:0.2 for horizontal and vertical motions. Trend components and annual changes are estimated for the period between 1997 and 1999 and subtracted from the raw time series. The raw position time series is available at http://terras.gsi.go.jp/ja/index.html. As a model region, we use the plate boundary estimated by Ishida (1992). Although we used Ishida's model, recent studies on the plate configuration in this Boso area do exist, such as that by Takeda *et al.* (2007), which shows a relatively steep increase in the depth of the plate interface off the east coast of the Boso peninsula toward the north-northwest direction com-

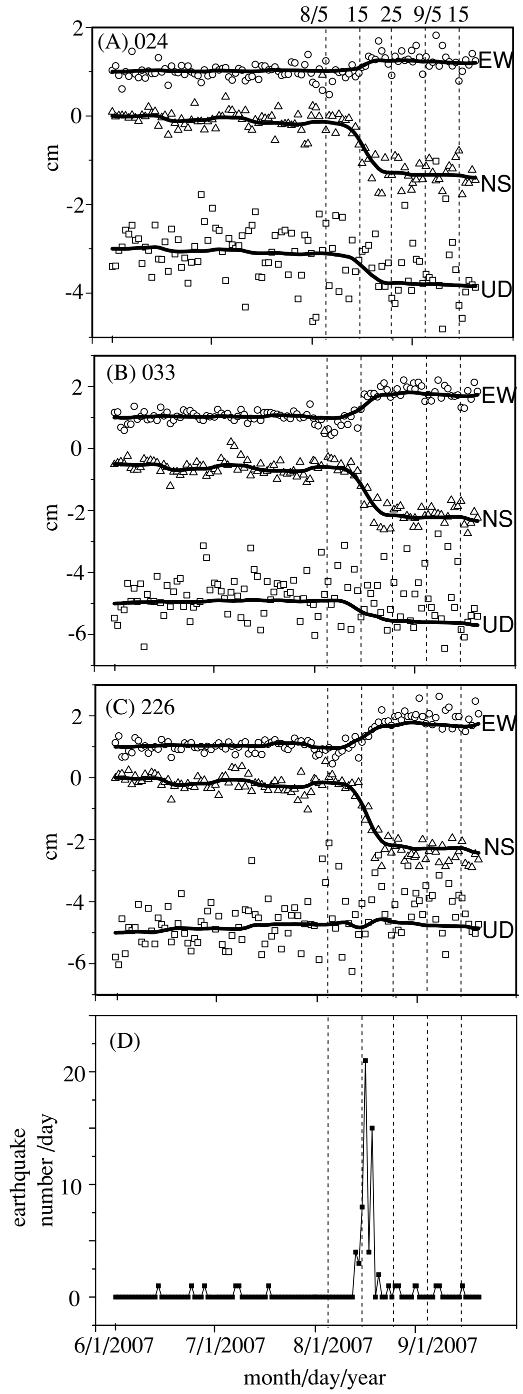

Fig. 3. Detrended time series of ground displacements at selected GPS stations in Fig. 2(A) relative to the Yasato station. EW, NS, and UD indicate east-west, north-south, and up-down components, with east, north, and up being positive. Circles, triangles, and squares represent EW, NS, and UD components, respectively. Solid lines represent values computed using the estimated model in Figs. 4 and 5(D). The vertical scale of (A) is different from those of (B) and (C) to emphasize transient movement at site 024. Sites (A) 024, (B) 033, and (C) 226. (D) Number of earthquakes that occurred in the area of the black rectangle in Fig. 4(A).

pared with Ishida's (1992) model. In order to estimate the effect of a plate boundary model, we used the plate boundary model of Takeda *et al.* (2007) as a check and found that the results have similar characteristic features to those obtained in this study using Ishida's plate boundary model.

Adopting Ishida's model region represented by spline surfaces (Ozawa *et al.*, 2001), we estimate the slip history between June 1 and September 20, 2007. We set slip components at zero at the edge of the fault patch as a boundary condition, considering that this region corresponds to the edge of the Philippine Sea plate. Furthermore, we restrict the direction of slip to be southward and eastward so as not to oppose the direction of plate convergence in this region (Ozawa *et al.*, 2003).

4. Results and Discussion

With regard to transient ground displacements in 2007, eastward movement at site 024 shows transient motion from around August 15, 2007, although it does seem that the east-west component at site 226 started transient motion from around August 10 (Fig. 3). Transient eastward movement increased at site 033 on August 16, preceded by around 5 days of small movement, although such a time evolution was not observed at site 226. These observations suggest a slight northward expansion of the slow-slip area with time.

Our time-dependent analysis for the 2007 Boso aseismic slip reveals an area of slip off the east coast of the Boso peninsula (Fig. 4). Figure 4(A–D) shows the estimated time evolution of the 2007 aseismic slip in the Boso peninsula in which an aseismic slip area off the east coast of the Boso peninsula is clearly visible from August 10 to August 15 (Fig. 4(B)). After August 15, the slip rate increases and the slip area expands slightly northward (Fig. 4(C)); activity lessens after August 20. A seismic swarm appears in the vicinity of the estimated slip area, as shown in Fig. 4. The difference in location between the seismic activity and aseismic slip area may indicate that the stress buildup in the neighboring area is the cause of the seismic swarm, as hypothesized for the last two events by Ozawa *et al.* (2003).

The ground displacements computed using the slip model are consistent with the observed displacements (Figs. 2(C) and 3).

We also estimated the total slip areas for the 1996 event and the 2002 event to compare them with that of the 2007 slow-slip under the same analytical conditions. Approximate 1σ uncertainty for the three events is shown in Fig. 5(A). The estimated slow-slip of the 2007 event is similar to those of the other two events (Fig. 5). In particular, the 2002 event is similar to the 2007 event in moment magnitude and slip area, although the slip area of the 2007 event shows slightly larger slippage in the northern part of the fault patch than that of the 2002 event. The center of aseismic slip of the 2007 slow-slip event is approximately 20 km further north of that of the 2002 slow-slip event (Fig. 5), reflecting the relatively large transient deformation in the northern part of the Boso peninsula in the 2007 event. In terms of slight differences in the estimated slip direction for the three events, we do not know if these differences are within the fluctuation of the Boso slow-slips or have tectonic meaning.

As for the spatial resolution, our solution for an area far offshore of southernmost Boso peninsula cannot be well constrained, since there are no offshore observations. At this point, we conducted a checkerboard test by the Yabuki and Matsu'ura's (1992) method and roughly recovered syn-

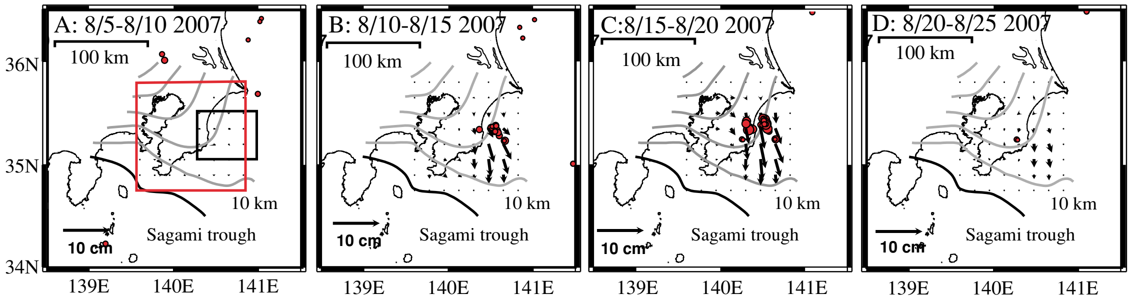

Fig. 4. Time evolution of the estimated aseismic slip on the plate boundary in August 2007 based on detrended time series. Gray lines represent isodepth contours of the plate boundary between the Philippine Sea plate and the North American plate (Ishida, 1992). Contour interval is 10 km. The red lines outline the area of the fault patch. Solid arrows represent slip of the North American plate against the Philippine Sea plate. Red dots represent epicenters with depth$\leq$50 km and $M_{\mathrm{JMA}} \geq 2$ determined by JMA. The number of earthquakes with depth$\leq$50 km and $M_{\mathrm{JMA}} \geq 2$ occurring in the rectangular area marked by the black lines in Fig. 4(A) is shown in Fig. 3(D). (A) August 5–10, 2007, (B) August 10–15, 2007, (C) August 15–20, 2007, and (D) August 20–25, 2007.

thesized slips from the synthesized data within one to three standard deviations of the estimated slip under the same boundary condition, fault patch, and station locations of this study.

Although there are slight differences among the three slow-slip events in their location, the overlap of their slip areas suggests that these events share characteristic features, as is often reported for characteristic radiative earthquakes in many areas (e.g., Matsuzawa *et al.*, 2002). In addition to the similarities in slip area among the 1996, 2002, and 2007 events, seismic swarms associated with the slow-slip events are reported in all three cases (see Figs. 5 and 6) (NIED, 2003). On the basis of the quasi-periodicity of seismic swarms, it was proposed that aseismc slips off the Boso peninsula may be characteristic events occurring at intervals of about 6–7 years (e.g., Ozawa *et al.*, 2003). This hypothesis of characteristic slow-slip off the coast of the Boso peninsula was verified by the 2007 event, which supports the hypothesis that the friction characteristics of the plate boundaries are time-stationary and regulate the occurrence of aseismic slip (e.g., Matsuzawa *et al.*, 2002; Shibazaki and Iio, 2003). The coupling state, which probably reflects the friction characteristics of a plate boundary, increases from 0 to 2 cm/year in the offshore area between GPS sites 033 and 044 (Fig. 2(A)) or from north to south (Sagiya, 2004). At this point, the results of our analyses of the three cases verify the hypothesis that a rupture of slow-slips tends to occur in a weakly coupled area, as was proposed by Ozawa *et al.* (2003).

With regard to rupture processes, Sagiya (2004) estimated the space-time slip distribution of the 1996 event and reported that aseismic slip of the 1996 event propagated from north to south, as was observed for the 2002 event (Ozawa *et al.*, 2003). In this point, the 2007 slip area expanded slightly to the north over time, and the seismic swarm expanded northward by a small amount. The above process is different from those of the 1996 and 2002 events, which occurred for similar durations (approx. 10 days) and were accompanied by the seismic swarms that propagated from north to southwest with time.

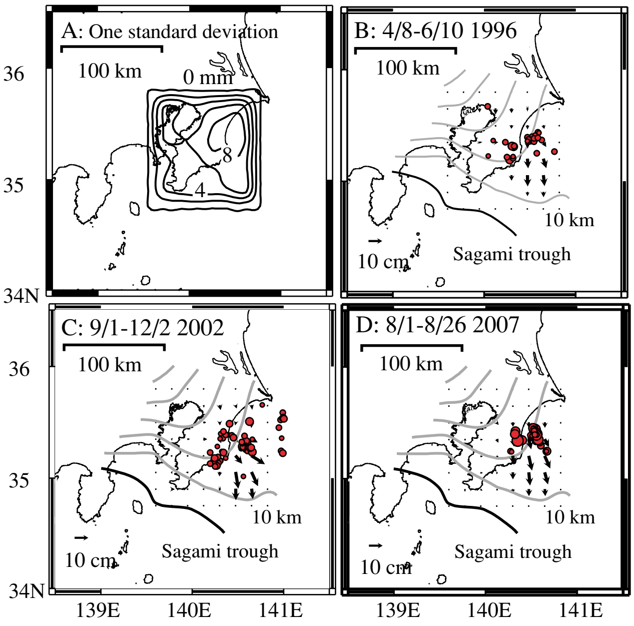

Fig. 5. Estimated slip distribution on the plate boundary. Nomenclatures are the same as those in Fig. 4. (A) 1σ uncertainty for data in Fig. 5(B–D). (B) Aseismic slip from April 8 to June 10, 1996 (C) Aseismic slip from September 1 to December 2, 2002. (D) Aseismic slip from August 1 to August 26, 2007.

The 2007 slow-slip event occurred 4 years and 10 months after the 2002 event. This recurrence interval is shorter than the 5 years and 5 months of the 1996 event, which was based on seismic swarm activity (NIED, 2003), and the 6 years and 5 months of the 2002 event. However, the moment of the 2007 event was 1.09×10^{19} N m with 1σ of 0.06×10^{19} N m, which is larger than the 0.59×10^{19} N m of the 1996 event ($1\sigma = 0.04 \times 10^{19}$ N m) and the 0.87×10^{19} N m of the 2002 event ($1\sigma = 0.10 \times 10^{19}$ N m) with 30 GPa rigidity, even though the trend components did not change after the transients, meaning that there was no change in coupling rates for the interseismic period. The cause of this variation in the total moment and recurrence intervals among the last three slow-slip events is not yet clear, although slight differences in slow-slip areas may partially contribute to this variation.

In terms of the associated seismic swarm, it remains unclear whether the seismic swarm or the slow-slip started first in the last three events. It has not been reported that

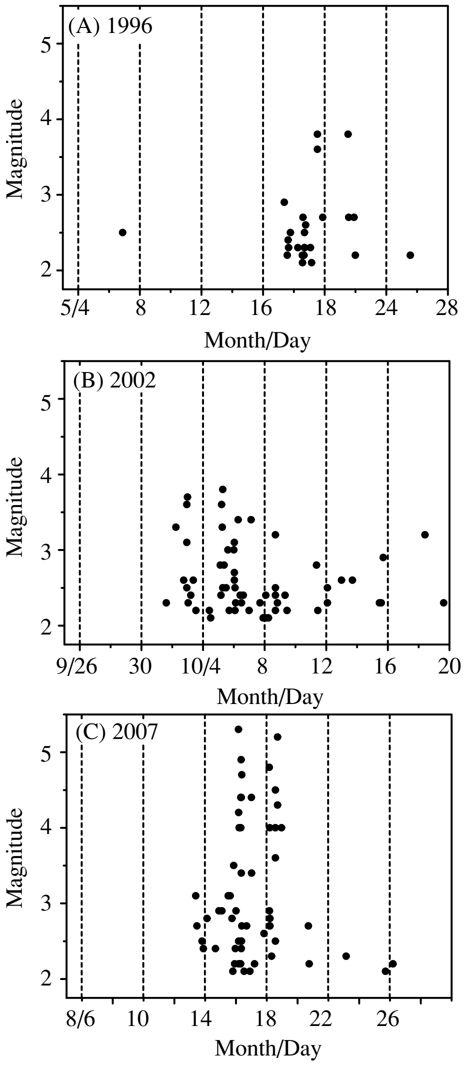

Fig. 6. Earthquake magnitude (M_{JMA}) versus time for the (A) 1996, (B) 2002, and (C) 2007 swarms, in the rectangular area marked by the black lines in Fig. 4(A), with $M_{\mathrm{JMA}} \geq 2$ and depth$\leq$50 km.

these seismic swarms are repeating patches. The total moment of the 2007 seismic swarm amounts to 3×10^{17} N m, while those of the 2002 and 1996 events are estimated to be around 0.04×10^{17} N m for the 2002 event and 0.03×10^{17} N m for 1996 event, indicating a relatively intense seismic activity for the 2007 event. Since the total moments of the asscoiated seismic swarms are much smaller than those of the estimated slow-slips, the slow-slips are the primary process driving eathquake swarms, as was the case of the previous Boso slow-slip events and the case of the Salton Trough, California, event (Loman and McGuire, 2007), even though the number of earthquakes was much larger in the latter case. Figure 6 shows the magnitude versus time for the last three events. Interestingly, the highest magnitude at the time of the 2007 event is around 5.3, which is larger than that of the 1996 and 2002 events, as was expected from the total moment of earthquakes in the three events. It is now possible to hypothesize that the northern part of the fault patch comprises small asperities of radiative earthquakes and slow-slip area, and that this latter area did not rupture to any great extent at the time of the 1996 and 2002 events. Subduction-related energy therefore accumulated for a longer time, finally releasing the energy in 2007 in the form of slow-slips and relatively large earthquakes. In Fig. 6, mild earthquakes preceded large ones at the time of the 1996 and 2007 events. Furthermore, a large earthquake had occurred for the relatively large aseismic deformation observed at site 033 on August 16, 2007 (Figs. 3(B) and 6), which cannot be explained by coseismic deformation of the earthquakes. These observations indicate a possibility of improving short-term earthquake forecasts for the Boso seismic swarm by using seismicity data, higher sampling geodetic data, and mechanical triggering models, as was first proposed by Lohman and McGuire (2007).

To clarify what factors control the small differences among the Boso slow-slip events, such as recurrence interval, variability in magnitude, rupture process, recurrence interval, time duration and slip area, more studies and the collection of both seismic and geodetic data in the Boso region are necessary.

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