Recurrent slow slip event likely hastened by the 2011 Tohoku earthquake

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Slow slip events (SSEs) are another mode of fault deformation than the fast faulting of regular earthquakes. Such transient episodes have been observed at plate boundaries in a number of subduction zones around the globe. The SSEs near the Boso Peninsula, central Japan, are among the most documented SSEs, with the longest repeating history, of almost 30 y, and have a recurrence interval of 5 to 7 y. A remarkable characteristic of the slow slip episodes is the accompanying earthquake swarm activity. Our stable, long-term seismic observations enable us to detect SSEs using the recorded earthquake catalog, by considering an earthquake swarm as a proxy for a slow slip episode. Six recurrent episodes are identified in this way since 1982. The average duration of the SSE interoccurrence interval is 68 mo; however, there are significant fluctuations from this mean. While a regular cycle can be explained using a simple physical model, the mechanisms that are responsible for the observed fluctuations are poorly known. Here we show that the latest SSE in the Boso Peninsula was likely hastened by the stress transfer from the March 11, 2011 great Tohoku earthquake. Moreover, a similar mechanism accounts for the delay of an SSE in 1990 by a nearby earthquake. The low stress buildups and drops during the SSE cycle can explain the strong sensitivity of these SSEs to stress transfer from external sources.

Boso Peninsula slow slip events | Philippine Sea plate | change in the Coulomb failure stress | global positioning system | tiltmeters

We suggest based on observational data that the great Tohoku earthquake (moment magnitude 9.0) on March 11, 2011 likely hastened the occurrence of the latest Boso Peninsula slow slip event (SSE) in central Japan. SSEs are another mode of fault deformation than the fast faulting of regular earthquakes and have been detected in a variety of tectonic environments (1–4). Because most SSEs in subduction zones occur at places adjacent to megathrust rupture zones, their slip behavior plays a critical role in earthquake hazard assessment because the size of an interplate earthquake and accompanying tsunami could become much larger if SSE areas slip seismically during the earthquake (5). The Boso SSEs are among the most documented such events, with the longest repeating history, of almost 30 y, and have a recurrence interval of 5 to 7 y (Fig. 1) (6–9). However, the latest episode in October 2011 occurred 4 y 2 mo after the previous episode in August 2007, which is the shortest interval among the five known so far. In between, the Tohoku earthquake occurred (10). Although the regular recurrence can be explained by a simple model with constant stress build-up rate and strength, the factors controlling the fluctuations in the recurrence interval are poorly known. Here we report on the possibility that the SSE recurrence cycle has been perturbed by the 2011 Tohoku earthquake as well as by a nearby large event in 1987.

The Kanto area in central Japan has a very complicated tectonic setting. From the south, the Philippine Sea plate (PHS) is moving toward the northwest and is subducting at the Sagami trough under the Japanese Islands (11), whereas from the east the Pacific plate (PA) is subducting beneath the PHS (Fig. 2). The Boso SSEs recur at the interface between the PHS and the overriding plate, close to the source area of the megathrust Kanto earthquakes beneath Tokyo (6, 12), and have moment magnitudes of 6.4 to 6.6 as observed by a dense global positioning system (GPS) network and borehole tiltmeters (6–9). For example, the latest episode in October 2011 caused tilt changes and surface displacements around the Boso Peninsula lasting for about 10 d (Fig. 3). A similar deformation is observed during each episode. A remarkable feature of the Boso SSEs is the accompanying earthquake swarm activity. Our stable and continuous seismic observations (13, 14) enable us to search the earthquake catalog for swarm activity back to early 1980s. Because the earthquake catalog is more complete and extends longer back in time compared to the continuous geodetic data, the swarm activity can be used as a proxy for detecting SSEs.

We define a typical Boso SSE episode from the clear crustal deformations observed quasi-periodically since 1996 at several GPS stations in the region (6–8). The earthquake swarms that accompany an SSE span each time about the same area, which extends about 50 km in the east-west and north-south directions, near the east coast of the Boso Peninsula (Fig. 2B). We identified two earlier swarm episodes in 1983 and 1990, which have a similar spatial distribution with the typical seismicity observed during the later SSE episodes. Slow crustal deformations are recorded by a nearby tiltmeter during these earlier swarms (9). We thus infer the occurrence of two SSE episodes in 1983 and 1990. In total, six SSEs with associated earthquake swarms are identified since 1982. The earthquakes during the 2011 SSE are located very close to the estimated SSE fault (Fig. 4). These observations suggest that an SSE directly triggers the associated swarm activity, similar to the SSE-earthquake interaction reported in the island of Hawaii (15). Moreover, they suggest that the SSEs and swarms recur almost at the same place every time (data analyses are described in Materials and Methods).

The SSE average recurrence interval is 68 mo, with a standard deviation (SD) of 16 mo (Fig. 1). The latest interval of 50 mo is more than one SD shorter than the average. Although the limited SSE observation history precludes rigorous statistical testing, this observation may suggest a possible effect of the Tohoku earthquake on the Boso SSE recurrence cycle. To test whether the Tohoku earthquake affected the occurrence of the last SSE, we assume that a positive (or a negative) Coulomb static stress change (ΔCFS) on the SSE source area shortens (or lengthens) the time until the next SSE (16) and evaluate the ΔCFS produced by the great earthquake on the plate interface where the Boso SSEs recur.

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Results and Discussion

$\Delta CFS$ is defined as $\Delta \tau + \mu \Delta \sigma_n$, where $\Delta \tau$ is the shear stress change, $\mu$ is the effective coefficient of friction, and $\Delta \sigma_n$ is the normal stress change. The stress changes in an elastic half-space are calculated with Okada’s formulation (17), assuming $\mu = 0.4$ and a rigidity of $4 \times 10^{10}$ Pa. The PHS configuration is based on the compilation of a number of seismic reflection surveys (18) and repeating earthquake studies (19). The slip direction on PHS with respect to the overriding plate is given in

![Fig. 2.](image)

Fig. 2. (A) Index map of the study area. Its location is indicated in the inset by dotted rectangle. The Tohoku earthquake coseismic slip and afterslip (until October 31, 2011) (10) are shown by continuous purple and dashed blue contours, respectively. Unit is meter. Thin dashed lines indicate the depth of the upper surface of the subducting Pacific plate. The focal mechanism of the 1987 Off-Chiba earthquake (22) is also shown. Pink dashed rectangle shows the area of earthquakes occurred during the six swarm episodes. Pink rectangle shows the fault area of the 2011 SSE. Dashed rectangle shows the area in which the seismicity is taken into account in Fig. 1.

![Fig. 3.](image)

Fig. 3. Observed records for the 2011 SSE around the Boso Peninsula. From top to bottom: Tilt (north and east tilting components at the Hi-net stations CH2H, CBAH, and KT2H) and GPS displacement records (north-south, east-west, and up-down components at the station 950226), daily numbers of earthquakes, the atmospheric pressure change, and the daily precipitations. Station locations are displayed in Fig. 4.
ref. (11). Because the Tohoku earthquake released not only a seismic moment corresponding to a magnitude 9.0 but has also been releasing additional moment as afterslip (10), we evaluate the ΔCFS caused by the sum of the coseismic slip (20) and the afterslip (21) distributions (Fig. 2B). The coseismic slip distribution is estimated from the onshore GPS data and seafloor GPS/ acoustic observations (22) and the afterslip distribution (moment magnitude 8.6) is based on the GPS data until October 30, 2011. In the following discussion, we use the average of the ΔCFS values evaluated at the four points near the northeastern corner of the SSE area (Fig. 5). Such a choice is justified by observations showing that every Boso SSE likely initiates from the east. The slow slip during the latest Boso SSE episode migrates from east to west (Fig. S1) and the earthquake swarms accompanying the SSEs always migrate in the same direction (Fig. S2), suggesting a characteristic east to west migration of the SSEs that could trigger the swarm activity.

The Tohoku earthquake coseismic slip and afterslip cause a Coulomb stress increase on the SSE source region of about 0.1 MPa (Fig. 3A), which is on the same order as the stress drop of a single Boso SSE (calculation details are described in Materials and Methods). Because the stress buildup and drop through the SSE cycle are of approximately the same amplitude and the stress increase corresponds to a large fraction of the stress buildup, the stress transfer from the great Tohoku earthquake could advance the occurrence timing of the latest SSE. It is worth noticing that the latest SSE did not occur at the time of the Tohoku earthquake but about 7 mo after the megathrust event. This might suggest that the stress increase on the order of 10 kPa due to the Tohoku coseismic slip (Figs. S3A and S4) was not enough for the failure of the SSE patch but caused a significant clock-advance effect (Materials and Methods) or, in other words, hastened the occurrence of the last SSE episode. In addition, the Tohoku afterslip, which produced a comparable stress increase on the SSE fault as the coseismic slip (Fig. S3B) likely contributed to the clock advance. Note that the comparable stress increases produced by the coseismic slip and the afterslip, regardless of the large difference of their seismic moment, are mainly due to the difference in their slip distributions. That is, the large afterslip patch close to the SSE source region (Fig. 2A) contributed significantly to the inferred stress transfer.

There is another recurrence interval, between 1983 and 1990 (Fig. 1), whose length falls outside of one SD from the average. During this interval of 91 mo, the December 17, 1987 Off-Chiba intraplate earthquake (magnitude 6.7) occurred within the subducting PHS, just beneath the SSE source region. The right-lateral strike-slip earthquake that occurred on a north-south striking subvertical fault, as estimated from its aftershock distribution (23), produced a Coulomb stress decrease of 0.2 MPa on the SSE area (Fig. 5B). This implies that the 1987 Off-Chiba earthquake delayed the following SSE episode (or in other words, caused a clock-delay) and made the corresponding recurrence interval the longest.

Other events that could cause Coulomb stress changes on the order of 0.1 MPa on the Boso SSE source area are not known. A candidate is the 2000 northern Izu volcanic activity (24). This large-scale dike intrusion episode caused horizontal displacements of several centimeters at the Boso Peninsula. The calculated ΔCFS is negative, and this might correspond to the second longest interval of 77 mo between 1996 and 2002; however, the stress change is on the order of 0.1 kPa, three orders of magnitude smaller than the stress drop of the SSE and one or two orders smaller than a typical stress modulation by earth tides, indicating that the stress change is too small to influence significantly the SSE timing.

Fig. 4. (A) Fault model for the 2011 Boso SSE (pink rectangle for the fault area and red arrow for the slip vector), observed (blue arrows) and calculated (open arrows) tilt change vectors, and earthquake epicenters occurred during the time windows (1) and (2) in Fig. 3. (B) Observed (green arrows) and calculated (open arrows) horizontal GPS displacements. Green triangle, orange square, and black solid square show the locations of the reference GPS station 93005, the atmospheric pressure observation station HAH2H, and the precipitation observation site Katsuura, respectively.

Fig. 5. ΔCFS around the SSE source area. (A) ΔCFS caused by the 2011 Tohoku earthquake and its afterslip. Dashed lines show the depth contours of the upper surface of the subducting PHS. Pink dashed rectangle shows the fault area of the 2011 SSE. White circles show the evaluation points of the ΔCFS values. (B) ΔCFS caused by the 1987 Off-Chiba earthquake. Gray rectangle shows the source fault of the intraslab earthquake.
Two other earthquake swarms were reported around the Boso Peninsula in June 1971 (25) and June 1977 (26). The hypocentral distribution for these sequences has a similar spatial extent with that of a typical SSE swarm (Fig. 2F), although the earthquake location uncertainties for these swarm episodes are larger than those in our earthquake catalog and there is no geodetic record for their accompanying SSEs. If these two episodes are also considered, the SSE average recurrence interval would be of 69 mo, with a SD of 13 mo. In such a case, the deviations of the two “anomalous” SSE interoccurrence intervals from the average cycle duration would become more prominent.

Data acquired during the modern seismic and geodetic observations in the last 30 y reveal large shortening or lengthening of the Boso SSE recurrence intervals that can be explained by stress changes, on the order of 0.1 MPa, caused by relatively large earthquakes. The strong sensitivity of the SSEs to stress transfer from external sources can be explained by the low stress buildups and drops during the SSE cycle. Our results suggest that SSEs can be used as stress indicators at depth and, hence, can help monitor the vicinity of megathrust earthquake rupture zones.

Materials and Methods

Earthquake Catalog. The earthquake catalog used in this study is a product of the Kanto–Tokai observation network (1982–2002) (13) and its successor, the high-sensitivity seismograph network (Hi-net; 2002–present) (14) operated by the National Research Institute for Earth Science and Disaster Prevention (NIED). The earthquake locations and origin times are determined from manual picks of P and S wave arrivals.

To characterize the seismicity associated with SSEs, we selected the earthquakes that occurred in the dashed rectangle area in Fig. 2B and are shallower than 28 km depth. Because it is difficult to extract only the associated seismicity, the catalog also contains the earthquake activity that is not directly related to the SSEs, such as a number of aftershocks of the 1987 Off-Chiba earthquake (Fig. 1, Figs. S5A and S6A).

The same catalog is used in the longitude versus time plots for each swarm episode in Fig. S2. A clear east to west migration of seismicity during each of the swarm episodes can be seen.

Geodetic Data and SSE Fault Inversion for the 2011 SSE. A typical NIED Hi-net station is equipped with a high sensitivity seismometer and a tiltmeter in a borehole. Fig. 3 shows the detrended and detided tilt records for the 2011 SSE at selected sites around the Boso Peninsula (Japan Standard Time is used throughout this paper). Tidal components and atmospheric pressure response in the tilt records were removed with the BAYTAP-G program (27). To estimate the source fault model of the 2011 Boso SSE, we use the tiltmeter data as well as the data on the solutions of GPS Earth Observation Network (GEONET) sites (the F3 solution) provided by the Geospatial Information Authority of Japan (28). The GPS data were referenced to the station 93005 (Fig. 4B). The detrended GPS data (Fig. 3) are used in the subsequent analysis.

We have applied a fault inversion method (29), based on a genetic algorithm, to the tilt changes and displacement data, assuming a rectangular fault in an elastic half-space (17). The pink rectangle in Fig. 2B shows the calculated fault for the 2011 SSE during the time windows (1) and (2) in Fig. 3. The SSE fault is centered eastern offshore of the peninsula with the epicenters around the northern edge of the fault (Fig. 2B). Most of the earthquakes during the swarm episodes are located on or close to the plate interface, at the top of the subducting PHS, suggesting that the slow slip on the plate interface could trigger the swarm-like seismicity. The estimated SSE seismic moment (\(M_s\)) is 9.3 \(\times\) 10\(^{38}\) Nm and the area of the fault (\(\Omega\)) is 2 \(\times\) 10\(^{16}\) km\(^2\). Based on these values, the stress drop of the SSE, \(\Delta\sigma\), is estimated as

\[\Delta\sigma = -2.5M_s/\Omega^{1/2} \approx 0.26 \text{ [MPa]}.\]

On the other hand, the tilt data show clear time variation indicating the source migration of the SSE. To determine the source migration, we estimated a fault model for each time interval indicated in Fig. 3, based on the inversion of only the tiltmeter data. Fig. 5 shows the estimated slow-slip faults for the time windows (1), (2), and (3) in Fig. 3. The results indicate that the slow slip and the associated earthquake swarm activity migrate from east to west.

Other Clustered Earthquake Sequences Around Boso Peninsula, Not Identified as SSE Episodes. We have identified the six Boso SSE episodes based on the similarities between the associated swarm seismicity and the signature in the geodetic records, as described in the main text. The spatio-temporal pattern of seismicity during the analyzed time period reveals three other clustered earthquake sequences: (A) December 1987 (mostly aftershocks of the 1987 Off-Chiba earthquake), (B) February 1994, and (C) March 2011. Several characteristics of these sequences (Figs. S5 and S6) suggest that they are different from the SSE-type swarm activity. The spatial extent of clusters (A) and (B) is much smaller than that of a typical SSE swarm (Fig. 2B) and the durations of (B) and (C) earthquake sequences are shorter than the typical SSE duration, of about one week. The earthquake spatial distribution just after the great Tohoku earthquake (C) shows some similarity with that of the SSE associated swarms. However, the GPS records at the two closest sites from the SSE source region do not show a southward movement larger than 2 cm for the 4 d of increased earthquake activity (Fig. S7A), which would be expected in the case of a typical SSE. In addition, the horizontal displacements during the same time period (Fig. S7B) do not show the expected spatial pattern during the SSE episodes (e.g., Fig. 4B); they reflect instead the afterslip of the Tohoku earthquake on the plate interface of the subducting PA (10, 21).

Using a Different Tohoku Earthquake Source Model. We calculated the \(\Delta\sigma\)CFS using another slip model for the 2011 Tohoku earthquake. Fig. 5A shows the result for the coseismic slip distribution estimated from strong motion seismograms (30). The average Coulomb stress increase is 30 kPa. Therefore, the discussion in the main text holds if we consider a different Tohoku earthquake source model. We did not use another afterslip model because, to our knowledge, there is no other such model available at this time. Because any afterslip distribution should be estimated from the same GPS data (10, 21), a significantly different afterslip model may not be expected. Note that the afterslip distributions estimated by ref. (21) at different times after the Tohoku mainshock show robust spatial characteristics: In all cases relatively large afterslip is imaged in the deeper portion of the Tohoku fault and to the southwest of the coseismic rupture (Fig. 2A).

Slip Budget on the SSE Area. The interplate slip deficit rate on the SSE area is estimated as approximately 2 cm/y (6). This implies that the elastic stress corresponds to about 11 cm in slip builds up during the average interval of 68 mo. On the other hand, the estimated slip during the 2011 SSE is about 11 cm (Fig. 4) and similar amounts are estimated for the previous episodes (6–8). This indicates that a single slow slip episode releases the entire strain accumulated during the preceding SSE interoccurrence interval, and hence, the stress buildup and drop through the SSE cycle are of approximately the same amplitude.

Relation Between \(\Delta\sigma\)CFS and the Clock Advance/Delay. A simple model with a constant failure stress and a constant stress build-up rate (Fig. 5B) predicts the relation \(\Delta\sigma\)CFS/\(\Delta\tau\text{max}\) = \(-\dot{\sigma}/\dot{\tau}\text{max}\), where \(\Delta\sigma\) is the stress drop of a slip event, assumed to be equal to the constant failure stress, \(\sigma_{\text{fr}}\). This suggests that if a stress change with amplitude equal to a large fraction of a stress drop is applied, the recurrence interval can change by the same fraction.

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