Space Geodetic Observations of Repeating Slow Slip Events Beneath the Bonin Islands

Deasy Arisa¹ & Kosuke Heki¹

¹Department of Natural History Sciences, Graduate School of Science, Hokkaido University. 
N10 W8 Kita-ku, Sapporo-city, Hokkaido 060-0810, Japan

SUMMARY

Along the Izu-Bonin Trench subducts the Pacific Plate beneath the Philippine Sea Plate. We studied crustal movements at the Bonin Islands, using Global Navigation Satellite System and geodetic Very Long Baseline Interferometry data to reveal how the two plates converge in this subduction zone. These islands are located ~100 km from the trench, just at the middle between the volcanic arc and the trench, making these islands suitable for detecting signatures of episodic plate convergences, such as slow slip events (SSEs). During 2007-2016, we found five SSEs repeating quasi-periodically with similar displacement patterns. In estimating their fault parameters, we assumed that fault lies on the prescribed plate boundary, and optimized the fault sizes and dislocation vectors. Average fault slip was ~5 cm, and the average moment magnitude was ~6.9. We also found one SSE occurred in 2008 at the up-dip extension of the repeating SSE in response to an M6 class interplate earthquake. In spite of the frequent occurrence of SSEs, there are no long-term strain accumulation in the Bomin Islands that may lead to future megathrust earthquakes. The SSEs showed waveforms characterized by gradual start and stop, suggesting the temporal evolution of the active fault patch. Plate convergence in Mariana-type subduction zones may occur, to a large extent, episodically as repeating SSEs.

1 INTRODUCTION

The Izu-Bonin-Mariana Arc is the eastern margin of the Philippine Sea plate (PH), where the Pacific plate (PA) subducts westward, and a series of small islands exist along the volcanic arc (Fig.1a). The back-arc of the Izu Islands, the northernmost part of this arc, is considered to be in the
initial rifting stage, and Nishimura (2011) revealed its opening rate by space geodetic observations. Behind the Mariana Arc, the southern part of the arc, mature active back-arc spreading occurs (Kato et al., 2003). Behind the Bonin Islands, however, no active back-arc spreading occurs (e.g. Tamaki, 1985).

The Izu-Bonin-Mariana Arc is known as one end member (“Mariana type”) of comparative subductology (Uyeda & Kanamori, 1979), characterized by old, cold, and thick lithosphere, subducting at a high angle without large interplate thrust earthquakes. The PA-PH convergence rate is ~4 cm per year around the Bonin Islands. There have been no historic megathrust earthquakes there, and we do not even know how episodic or continuous the plate convergences are in such subduction zones.

Considering the lack of large earthquakes, episodic convergence may take a form of slow fault movements such as slow slip events (SSEs). Because faults move too slowly to radiate seismic waves in SSEs, they are observable only with geodetic sensors. However, in Mariana-type subduction zones, coverage of the land area is insufficient for geodetic observations. In most of the Izu-Bonin-Mariana Arc, the volcanic arc is ~200 km away from the boundary. Hence, it is difficult to detect crustal movements caused by locking and unlocking of the plate interface even if we can deploy modern space geodetic sensors on such volcanic islands. The Bonin Islands, non-volcanic frontal arc located just at the middle of the volcanic arc and the trench, offer a rare opportunity to monitor crustal movements from the place only ~100 km away from the trench. Here we take advantage of it, and study how plates converge there.

A clear SSE was first found in the Bungo Channel, Southwest Japan, with a dense array of Global Navigation Satellite System (GNSS) stations (Hirose et al., 1999). Later, similar SSEs are found to repeat fairly regularly every ~6 years at the same fault patch (Hirose et al., 2012). Quasi-periodic recurrence is a general feature of these SSEs. For example, SSEs under the Boso Peninsula, Kanto District, Japan, another well-studied series of SSEs (Ozawa et al., 2003), recur every 5-7 years, and those in the southwest Ryukyu Arc repeat biannually (Heki & Kataoka, 2008; Nishimura 2014). Fig. 1a shows the locations of these SSEs. Outside Japan, repeating SSEs are found, for example, in
Cascadia, Western North America (Dragert et al., 2001), Hikurangi, New Zealand (Douglas et al., 2005), and the Nicoya Peninsula, Costa Rica (Outerbridge et al., 2010).

Slow earthquakes have been studied focusing on various points, e.g. recurrence analogous to megathrust earthquakes, sensitivity to subtle change in the crustal stress, and mechanical interaction with other SSEs and regular earthquakes (e.g. see Obara & Kato, 2016). In this study, we first reveal if such SSEs occur beneath the Bonin Islands, then try to address these points of geophysical interests.

2 SPACE GEODETIC DATA IN THE BONIN ISLANDS

2.1 GNSS data

The GNSS Earth Observation Network (GEONET) is the permanent dense array of GNSS receivers operated by Geospatial Information Authority of Japan (GSI). To analyze SSE signatures, we used the F3 solution (Nakagawa et al., 2009), available from terras.gsi.go.jp. Coordinate jumps associated with antenna replacements (occurring once in ~10 years) are provided by GSI, and we corrected for these steps before analyzing the time series for SSE signals.

Two GNSS stations were installed in Hahajima (960603) and Chichijima (942003) of the Bonin Islands (Fig.1c) in 1990s. A new station in Chichijima (052007) started operation in 2007, but the older station (942003) stopped operation in 2011 March. The Hahajima station (960603) has been in operation throughout the studied period. Before 2007, the station coordinate time series are noisy (Fig.2a inset), and number of available stations are small. So we mainly analyzed ~10 years data from 2007.0 to 2016.5.

To reinforce the data set, we add data from another GNSS station located in Chichijima. This station was deployed by National Astronomical Observatory (NAO) of Japan, close to their radio telescope for astrometric VLBI (Very Long Baseline Interferometry). This data set spans from 2003 Feb. to 2016 Mar., and the coordinate solution is based on the Precise Point Positioning (PPP) technique (Zumberge et al., 1997). There was an antenna replacement in 2013, and a jump was estimated together with other parameters for SSEs.
Fig. 2 compares GNSS coordinate time series of the four stations (3 from GEONET, 1 from NAO). Standard deviation of the post-fit residuals were 2-4 mm for horizontal, and 8-10 mm for vertical components. The GEONET F3 solution is based on the baseline approach. The individual stations show smaller random noises, but the three stations often exhibit common systematic movements. On the other hand, the NAO GNSS coordinate time series are devoid of such systematic noises although their random noises are somewhat larger. For example, there are systematic disturbances in the second half of 2008 in GEONET stations. However, they are not seen in the NAO data, and we did not consider them to show real crustal movements.

2.2 Displacement signatures in the GNSS data

2.2.1 Regular earthquakes

According to the earthquake catalog by Japan Meteorological Agency (www.jma.go.jp), there were two relatively large earthquakes in the studied period (2007-2016) and area (Fig.1b), i.e. (1) M\text{w}6.2 inter-plate earthquake on February 27, 2008, and (2) M\text{w}7.4 normal-fault outer rise earthquake on December 22, 2010. In Fig.2a, they are marked with thin black vertical lines, respectively. We cannot see significant steps for the first earthquake, but it is immediately followed by slow eastward movement, due possibly to an afterslip that released much more seismic moment than the coseismic slip (discussed later in Section 3.4). The second earthquake is associated with significant westward coseismic steps at all the four stations (displacement vectors plotted on map in Fig.3g) with little postseismic deformation signals.

2.2.2 Repeating SSE signatures

Generally speaking, long distance from trench limits the chance of detecting SSEs to only large ones. For example, we detected a large SSE (M\text{w}>7.5), starting in 2004 July, in the northernmost part of the Izu-Bonin Arc (Arisa & Heki, 2016) at the Izu Islands ~200 km away from the trench. M\text{w}7 class SSEs, if any, would not have been caught by GNSS stations there. The Bonin Islands are located only ~100 km from the trench (Fig. 1b), and we expect to detect M\text{w}7 class SSEs there.
In Fig. 2a, we plot changes in east components of 4 GNSS stations in the Bonin Islands. We also show north (Fig. 2b) and vertical (Fig. 2c) coordinate changes for two of the stations. In Fig. 2, we removed the overall inter-SSE trends, composed of rigid movement of PH and inter-SSE strain accumulation. There, SSE signatures appear as episodic slow eastward movements, whose onsets are marked with thick gray vertical lines as SSE#1-#5. Their typical cumulative displacements are 1-2 cm, and each event lasts for a few months. Fig. 2 shows that displacements are mostly eastward, with small but significant north and up components.

We modeled the displacement \( u \) caused by SSE using an exponential function of time \( t \) (\( t=0 \) at the onset of SSE), i.e. \( u = A[1 - \exp(-t/\tau)] \). The time constant \( \tau \) for each event is optimized by grid-search with 0.01 year step using the east component, and the cumulative displacements \( A \) are estimated in all the three components using the same time constants. This resulted in 0.10 year uniform time constants for all SSEs, except somewhat shorter time constant (\( \tau = 0.05 \) year) for the 2008 SSE. We optimized the SSE onset times also by the grid-search method.

These five SSEs started approximately in 1) August, 2007, 2) July 2009, 3) February, 2011, 4) October, 2012, and 5) November, 2014. They have recurrence intervals of 20-25 months, with the average of ~1.8 years. We could not find any earthquakes that may have triggered these SSEs. The cumulative horizontal displacement vectors plotted in the map (Fig. 3a, c, d, e, f) are fairly uniform, and ranged from 12 mm to 17 mm.

The three GNSS stations in Chichijima showed displacements mostly consistent with each other. They moved mostly eastward, with small amounts of north components. In contrast to Chichijima stations, Hahajima showed south component as well as east components. In Fig. 3h, we show the average displacements of 5 repeating SSEs (the old Chichijima station had data of only 3 SSEs). We discuss fault models using these average vectors.

The 2008 SSE show different patterns in horizontal displacements (Fig. 3b), i.e. Chichijima/Hahajima showed southward/northward components in addition to east components. This reflects the difference in the slipped fault patch between the 2008 SSE and all other repeating SSEs. The 2008 SSE is therefore discussed separately in Section 3.4. The displacement vectors in
the 2011 SSE are somewhat different from the other 4 repeating SSEs (Fig. 3d). This is probably due
to the coseismic step by the 2010 Dec. 22 Mw7.4 outer rise earthquake (Fig. 3g). Because we had
only ~2 months between the two events, inter-parameter coupling of the 2010 Dec. coseismic step
and the cumulative displacements in the 2011 Feb. SSE increased their errors.

2.3 VLBI Data (VERA)

To reinforce GNSS results in the Bonin Islands, we examine distance change time series between
the VLBI stations at Chichijima and two other VLBI stations in SW Japan 2004.8 – 2015.4 (Fig. 4a).
In the Bonin Islands, first VLBI observations were carried out in 1980s using a mobile radio telescope
to detect the movement of PH (Matsuzaka et al., 1991). A new permanent VLBI station was installed
in Chichijima in 2003, which constitutes a part of the VERA (VLBI Exploration of Radio
Astrometry) array together with the other three stations, Mizusawa, NE Japan, Ishigaki in the Ryukyu
Islands, and Iriki, Kyushu (Fig. 4b).

Since 2004, routine geodetic VLBI observing sessions have been performed every 1-2 weeks in
addition to astrometric observations. Because the observations are not so dense in time as GNSS, the
VLBI data are less suitable for SSE studies than the GNSS data. In Fig. 4a, we plot the baseline
length (distance) time series of Chichijima-Iriki and Chichijima-Ishigaki pairs. There, we assumed
the same onset times and time constants of the SSEs as the GNSS data. The VLBI data show similar
SSE signatures and coseismic steps to the GNSS data. It also suggests another SSE in 2005, not
included in the GNSS data in Fig. 2.

3 FAULT MODELS

3.1 The repeating SSEs

We use the Okada’s (1992) model to calculate surface displacements due to a dislocation of a
rectangular fault in an elastic half-space. In general, we need parameters such as the location (latitude,
longitude, and depth), orientation (dip and strike), dimension (width and length), and slip vector
(vector length and rake) of the fault. With enough number of GNSS stations of sufficient spatial
coverage, e.g. in the case of the Bungo Channel, we could perform inversion analysis of the time-
variable fault slips (e.g. Yoshioka et al., 2015). In the present case, however, spatial coverage of the
observed displacement vectors is limited (i.e. two small islands), and we have to assume a simple
geometry of the fault for all the SSEs. We assumed two rectangular patches along the dip (to enable
different dip angles), and estimated the lengths of the fault dislocation vectors by least-squares
method using the three-dimensional displacement vectors of all the GNSS stations.

Other parameters were optimized by grid-search. We moved the horizontal position (latitude and
longitude) of the fault center to minimize the post-fit residuals between the calculated and observed
displacement vectors. We also assumed that the faults lie on the PA slab surface. Hence, if we give
the horizontal position of the fault centers, the orientation (strike and dip) and the depth of the faults
are given a-priori from a numerical model of the slab surface (earthquake.usgs.gov/data/slab).

We inferred fault dimension and slip direction also by grid-search. For the average displacement
vectors (Fig. 3h), the best model had the length and width of 136 and 121 km, respectively. The fault
dimension is negatively correlated with the estimated dislocation, i.e., assumption of too small faults
may result in the slip accumulation rate faster than the PA-PH plate convergence rate, which is ~3.8
cm/year beneath the Bonin Islands according to the MORVEL model (Argus et al., 2010). Fig.5
shows the estimated slips, 5.0 cm and 4.8 cm for the deeper and the shallower fault patches,
respectively. They are ~70% of the cumulative plate convergence over the average recurrence
interval (~1.8 years).

The optimum dislocation azimuth was N96E, only slightly different from the plate convergence
direction N101E from the MORVEL model. The estimated $M_w$ of the average SSE was ~6.9 (the
rigidity is assumed as 40 GPa). The $M_w$ and the duration of SSE (a few months) is consistent with
the scaling law by Ide et al. (2007) that the moment release of slow earthquakes are proportional to
their durations.

Next, the fault model of the average SSE is applied to individual SSEs (i.e. each SSE is assumed
to rupture the same patch in the same direction), and we estimated the lengths of the slip vectors.
They are fairly uniform as shown in Fig. 7, possibly due to the mechanical isolation of this SSE patch
from other seismogenic plate interface. The rhythm of some repeating SSEs in the Japanese mainland, such as those under the Boso Peninsula, was disturbed by the 2011 Tohoku earthquake (Ozawa, 2014; Hirose et al., 2012). On the other hand, the Bonin Island SSEs (Fig. 7) are not disturbed by this earthquake.

Information on the recurrence of the SSEs before 2007 is limited. However, the inset of Fig. 2a suggests that similar SSEs have occurred in 2005 March, 2003 January, 2000 November, and possibly in the middle of 1998. This suggests that the average recurrence interval before 2007 was ~2.3 years, somewhat longer than ~1.8 years after 2007.

3.4 SSE following an earthquake in February 27, 2008

As we recognized earlier, there was an SSE in 2008 (Fig. 2b), but this was not counted as one of the repeating SSEs in the Bonin Islands because of its different displacement pattern (Fig. 3b). This SSE started following an Mw 6.2 earthquake on February 27, 2008, at the plate boundary between the Bonin Islands and the trench axis (Fig. 1b).

We followed the same procedure as the average of the repeating SSEs to infer the fault geometry and slip. We found that the slipped fault is located at the up-dip side of the repeating SSE fault patch (Fig. 8a). Assuming the fault of 54 km length and 33 km width (the fault lie on the slab surface with the dip of 20°), we could well reproduce the observed displacements (Fig. 8). The fault slip in this SSE is 20.4 cm toward N99E. This is ~4 times as large as the repeating SSEs. Its recurrence interval would be much longer than 1.8 years, but is unknown because we did not find similar SSEs in the studied period.

Mw of this SSE is 6.7. This is somewhat smaller than the repeating SSE, but is much larger than the Feb. 27 earthquake of Mw 6.2. There was another Mw 6.0 event during the SSE (March 14, 2008), with epicenter close to the up-dip end of the slipping patch (Fig. 8c). It is known that SSEs are often accompanied by regular earthquakes with magnitudes up to M5, e.g. in the Boso Peninsula (Ozawa et al., 2007) and in Hikurangi (Wallace et al., 2012). In the 2008 case, the Mw 6.2 February earthquake
would have triggered the SSE, and then the SSE encouraged the occurrence of the $M_w$6.0 March
earthquake.

4 DISCUSSION AND CONCLUSION

4.1 Absence of long-term strain accumulation

Fig. 8 shows the time series of the distance from the Hahajima and Chichijima GNSS stations to
three stations, North-Daito, South-Daito, and Okinotorishima, all in the stable interior of PH. Although
the time series show many undulations due mainly to SSEs, their overall trend over the last 20 years is
less than 2 mm/year.

This means important facts about the plate convergence near the Bonin Islands. The first point is
the lack of long-term strain build-up for future megathrust earthquakes. Small amount of interplate
coupling at the Izu-Bonin Trench continuously build up compressional strain near the plate boundary,
but such strain is completely released by biennial SSEs as observed in this study. Secondly, this
justifies Arisa & Heki (2016), who used the Hahajima GNSS station to define the Euler vector of the
stable part of PH. Over the time scales of a few decades, we can assume that the Bonin Islands are
fixed to the stable interior of PH. The lack of extensional strain also means that active back-arc
rifting does not occur in this portion of the Izu-Bonin-Mariana Arc.

4.2 Waveform of various repeating SSEs

In Fig. 9 we compare the average waveforms of the repeating SSEs beneath the Bonin Islands with
those in other subduction zones in Japan (stars in Fig.1a). We show only one SSE from individual
series, but other SSEs occurring in the same fault patch tend to be similar in waveforms. For example,
the examples of the SSEs in the Boso Peninsula show a much smaller time constant than the Bungo
Channel, and this holds true for other SSEs in the same series.

Afterslips of large earthquakes have significant rates when they start, and the rates depend on $M_w$
(Mitsui & Heki, 2013). On the other hand, how SSEs start look diverse. For example, the top two in
Fig.9 (Bonin and Doto) seem to have indistinct start, i.e. the rate increase from zero to a certain
constant rate, while the bottom three (Bungo, Boso, and Iriomote) show distinct onsets. The stop of
the SSEs also seem to show some variations, i.e. the middle three (Dohoku, Bungo, and Bonin) show
clearer stops than the top and the bottom (Bonin, Iriomote).

It is not clear what governs the difference between SSEs with distinct and indistinct starts and
stops. When a slow deformation starts distinctly, a significant size of fault patch would have started
to slip as a whole. In the case like the Bonin Islands, a small patch of the fault may have started to
slip at first, and then the slip area may have grown larger over a finite time.

4.3 Concluding remarks

We analyzed the GNSS data over the last 10 years (2006 - 2016), and confirmed the occurrence
of 5 repeating SSEs, with Mw 6.8 – 7.0, beneath the Bonin Islands, at the depth 20-70 km, with the
recurrence interval of ~2 years. These SSEs were fairly uniform in recurrence intervals, time
constants, displacement vectors, possibly reflecting the mechanical isolation of this area due to the
lack of nearby seismogenic zones. Apart from these repeating SSEs, we found an occurrence of
another type of SSE with Mw 6.8 occurred in the up-dip extension of the plate interface following
the Mw6.2 interplate earthquake on February 27, 2008. We also confirmed the lack of long-term strain
accumulation, which is consistent with the absence of historical megathrust earthquakes in this
subduction zone.

These observations demonstrate that the plate convergence beneath the Bonin Islands is
accommodated significantly by repeating SSEs. The Bonin Islands are exceptional in their short
distance (~100 km) from the trench. Emergence of such a frontal arc might be due to the collision of
the Ogasawara Plateau on PA with the arc, and this makes it uncertain how far the case in the Bonin
Islands generally holds for other Mariana-type subduction zones. Deployment of seafloor geodetic
benchmarks and frequent measurements, as was done off the Pacific Ocean coast of the Japanese
Islands (e.g. Yokota et al., 2016), would eventually solve the problem in the future.

ACKNOWLEDGEMENTS
We thank Geospatial Information Authority of Japan for the F3 solution of the GEONET data. We obtained the GNSS and VLBI data of the VERA network from Yoshiaki Tamura and Takaaki Jike, National Astronomical Observatory of Japan, which is gratefully acknowledged. The paper has been improved by constructive reviews by XXXX and YYYY.

REFERENCES


Ozawa, S., Suito, H. & Tobita, M., 2007. Occurrence of quasi-periodic slow-slip off the east coast of

12


**Figure 1.** (a). Plate tectonic setting of the Japanese Islands. The four stars indicate the locations of repeating SSEs in Japan, to be compared with those beneath the Bonin Islands. The rectangle of blue dotted line shows the location of the Bonin Islands. It is magnified in (b), together with the epicenters of two regular earthquakes in the studied period (Mw6.2 on February 27, 2008, and Mw7.4 on December 22, 2010). Gray lines in (b) show depth contours of the PA slab surface (20 km interval). Chichijima and Hahajima constitutes the frontal arc located between the volcanic front (Nishinoshima and Kita-Iwojima are both volcanic islands) and the trench. A small rectangular region in (b) is magnified in (c), where we show positions of GNSS and VLBI stations in Chichijima and Hahajima.
Figure 2. (a) East component of the coordinate changes of the 4 GNSS stations in the Bonin Islands (average trends during non-SSE periods are removed). The north and up components of the two GNSS stations are shown in (b) and (c), respectively. The five thick vertical gray lines show repeating SSEs (SSE#1-#5). The SSE starting in February 2008 is not counted as one of the repeating SSEs. The 2010 December normal fault (outer rise) earthquake caused westward jumps (vectors shown in Fig.3g). Coordinate steps associated with antenna replacements, shown by short vertical dashed lines in (a), are corrected using values given a-priori for the GEONET stations and estimated for the NAO station. In the inset of (a), east component time series of the old Chichijima station 1996-2007 show four more possible SSEs.
Figure 3. (a-e) The cumulative horizontal displacement vectors of GNSS stations in the 6 SSEs from 2007 to 2014 shown in Fig. 2. Error ellipses show $2\sigma$. All SSEs (except the 2008 one) show similar displacement patterns, and are repeating SSEs. Average displacement of the five repeating SSEs are shown in (h), where the error ellipses indicate the standard deviation of the displacement vectors of the 5 events (the old Chichijima station covers only three SSEs). In (g) we show coseismic steps of the 2010 outer rise earthquake.

Figure 4. (a) Baseline length change 2004-2015 from the two pairs of the VERA VLBI stations (Chichijima-Iriki, Chichijima-Ishigaki). We fit the time series with the same model as the GNSS data (Fig. 2). (b) The map shows the positions of the four VLBI stations and baseline vectors used in this study.
Figure 5. Fault estimation for the average of the 5 repeating SSEs 2007-2014. Double rectangles in all panels are the surface projections of the assumed fault patches. Thick arrows show the slips estimated by least-squares method using the 3-dimensional displacement vectors of the 4 GNSS stations (errors are $2\sigma$). (a) and (b) show horizontal and vertical displacements of GNSS stations, respectively. In (c) and (d), horizontal and vertical displacements calculated at grid points are shown with light gray arrows and with colors (red shows uplift), respectively. The red arrow in (a) indicate the PA motion relative to PH over the average interval of the SSE recurrence (1.8 years).

Figure 6. Cumulative slip (weighted average of the slips of the two fault patches) of SSEs #1-#5 shown with blue squares is compared with the average PA-PH plate convergence rate in this region (3.8 cm/year). The $M_w$ (6.8-7.0) of individual SSEs are shown by red circles.
Figure 7. Fault model of the shallow SSE that started in February, 2008. For the detail of the four panels, see the caption of Fig. 5. For comparison, we show faults of the repeating SSEs with dashed lines in (a). In (c), we show mechanisms of the two interplate earthquakes that occurred at the onset of the SSE (Feb. 27, Mw6.2) and during the SSE (Mar. 14, Mw6.0). GNSS time series did not present significant steps related to these two earthquakes.

Figure 8. (a) Time series of the distance between stations in the Bonin Islands (Chichijima and Hahajima) and three GNSS stations on the stable interior of PH (North- and South-Daito Islands, and the Okinotorishima Island). A gray vertical line shows the 2010 December outer rise earthquake, whose coseismic steps are recognizable. See (b) for station positions. In spite of short-term undulations reflecting the SSEs, overall distance changes are negligible, suggesting that no long-term elastic strain accumulation takes place in this plate boundary.
Figure 9. Comparison of waveforms of the different series of (repeating) SSEs in Japan (see Fig. 1a for locations), from top to bottom, the Bonin Islands (this study), the Dohoku (northern Hokkaido) (Ohzono et al., 2014), the Bungo Channel (Hirose et al., 1999), the Boso Peninsula (Ozawa et al., 2003), and the Iriomote Island, Southwest Ryukyu (Heki & Kataoka, 2008). The station names, occurrence years, and the direction of the plotted components are given in the figure. Horizontal scale of 0.1 year and vertical scale of 1 cm are given to the right of the time series. Some repeating SSEs (e.g. Bungo, Boso) show distinct start and stop while the Bonin Islands SSEs show indistinct and gradual start and stop.