Shallow long-term slow slip events along the Nankai Trough detected by the GNSS-A

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Various slow earthquakes (SEQs), including tremors, very-low-frequency events (VLFs) and slow slip events (SSEs) occur along megathrust zones, which generate catastrophic earthquakes[1-7]. For comprehensive understanding of the megathrust plate boundary, it is necessary to monitor such events not only on a land area (deep plate boundary) but also on a sea area (shallow plate boundary). Many shallow SEQs have been observed along pan-Pacific subduction zones[8-11], including the Nankai Trough off southwestern Japan on which megathrust earthquakes are predicted to occur[12-13]. However, a SSE with a duration on the order of a year (long-term SSE) has not been detected in a sea area. Recently, we improved the Global Navigation Satellite System (GNSS)-Acoustic combination technique (GNSS-A), which had enabled monitoring of the seafloor absolute position, to a level that can detect a transient crustal deformation. Here, we present the first detection of long-term SSE signals from seafloor geodetic observation data and discuss timings, approximate locations and magnitudes of SSEs along the Nankai Trough inferred therefrom. The results suggest features of SSEs for the strong-coupling regions and other SEQ activities, i.e., temporal synchronization with VLF and short-term SSE activities, regional complementarity with coupling and VLF regions and recurrence in the near region. Although these are similar to features observed even in deep SSEs[4,6,14], the occurrence timing for VLF activity was different depending on each generation region. The GNSS-A monitoring network that can detect SSEs will provide new basic information to promote research on subduction geophysics and megathrust earthquake disaster prevention.

In the last two decades, many kinds of SEQs, including aseismic SSEs, have been detected using onshore high-precision seismometers and GNSS networks[1-3]. Along the Nankai Trough in western Japan, where recurring interplate megathrust earthquakes have occurred[12-13] and which has a dense seismic and geodetic monitoring network, their interrelationships were discussed and compared in detail[3-6]. Most SEQs occurred not in a strong coupling region, but rather around such a region and have features of repeatedly occurring and migrating. Different types of SEQs sequentially occurred in the neighbouring region, and temporal synchronization with other SEQs was also observed.

Observation of deep and shallow SEQ analogies and differences has multidisciplinary value with respect to physical process of the plate boundary, submarine geology and earthquake disaster research. However, shallow SEQs cannot be easily monitored due to the technological difficulty of observation. With recent advances in technology, shallow SEQs, such as tremors, VLFs and short-term SSEs with durations on the order of days, have been detected by high-precision onshore seismometers, seafloor seismometers, ocean bottom pressure gauges and submarine borehole strainmeters[7-11]. However, only long-term SSEs with durations on the order of a year have not been detected in the group of shallow SEQs. From the analogy of deep long-term SSEs, GNSS-like geodetic observation is necessary to detect the shallow long-term SSEs.

A seafloor geodetic monitoring technique called as the GNSS-A was proposed in the 1980s and has been developed in the latest two decades. The GNSS-A seafloor geodetic observation majorly constrained an interplate coupling condition[15-16] along the Nankai Trough subduction zone. Recently, we improved GNSS-A technology and upgraded observation sensitivity[17] in order to detect a transient crustal deformation with durations on the order of a year. Then, the GNSS-A monitoring can reveal the occurrence of SSEs, which cannot be observed by the onshore geodetic network, as shown in Extended Data Fig. 2. The GNSS-A methodology is described in the Method section.

We first show SSE signals detected in the GNSS-A dataset in Fig. 1. Our data is listed in Supplementary Table 1. Signal detection was carried out in the procedure shown in Extended Data Fig. 3. Coseismic and postseismic effects resulting from the 2011 Tohoku-oki earthquake were preliminarily deducted as similar to those described in ref. 15. If there was no transient event, the time series can be simply approximated by a straight line. When there is a temporal change due to SSEs in the time series, the time series can be approximated by the piece-wise line. By estimating this piece-wise line, the timing and scale of deformation can be determined. We fitted straight and piece-wise lines for the time series of each site rotating a direction every 10 degrees. Since the GNSS-A sampling rate is low, this detection is not so sensitive to the duration of the SSEs. Here, we set the deformation slope of the piece-wise line to one year, which is a typical duration of a long-term SSE[14,18-19]. The significance of fitting by the piece-wise line to the straight line is verified using the c-AIC (refs 20 and 21) based on the method of ref. 22. The c-AIC is defined as the following function:

$$\text{c-AIC} = n\ln(2\pi) + n\ln\left(\frac{RSS}{n}\right) + \frac{2nk}{n-k-1} \qquad (1)$$

where n, k and RSS are the numbers of data, a model parameter and the residual sum of squares, respectively. The maximum likelihood solution minimizes this parameter. After removing a detected deformation signal, we carried out the same process once again. When the difference (Δc-AIC) between c-AICs for the straight line and the piece-wise line is greater than -6, the process terminated because there was no clear signal. The time series of seafloor positions and Δc-AICs and signal detected periods were compared with the time series of neighbour VLF activity[7] in Figs 1a – e. Details of this process are described in the Method section. Although the Tohoku-oki earthquake effects were preliminarily deducted, the remaining effects due to model uncertainty are detected as shown in Extended Data Fig. 5. Detected deformation vectors other than the Tohoku-oki effects are judged as SSE signals and are shown in Fig. 1f. Direction of the signal at site (7) in 2014 was not from south to east and was assumed to be due to deep SSE activity[18] or error, and an SSE model was not estimated for this signal.

SSE signals at offshore sites of the Bungo and Kii deep SSEs[18-19] were detected. Off the Bungo channel, signals were detected after 2015. Off the Kii channel, signals were detected in 2009 and after 2017. In addition, SSE signals at sites around the Kumano-nada were detected in 2015 and 2017. A clear signal was not obtained for the offshore regions of the Tokai deep SSE and Shikoku Island.

We discuss timings, approximate locations and magnitude scales of SSEs by estimating rectangular fault models that can explain the detected signals at offshore sites of the Bungo and Kii channels and the Kumano-nada by the grid search method. Details of the grid search method and the results are described in the Method section and are shown in Fig. 2 and Extended Data Fig. 6, respectively. Considering durations as about one year, these undersea shallow SSE models roughly follow a SEQ scaling law whereby the event magnitude is proportional to the logarithm of the duration[4] and had no significant difference from deep SSEs[14].

In a deep region around the Bungo channel, SSEs repeatedly occurred[19,23]. The most recent SSEs occurred intermittently between 2013 and 2016. Shallow SSE signals detected after 2015 indicate that the deep SSE after 2013 spread to the offshore region. According to the grid search results, there were M_w 6.1 – 6.3 events that migrated away from the Bungo channel. The north shallow SSEs in 2015 were believed to be the first step in the spread of the deep SSE to the offshore region, and this SSE sequence ended around site (4). This is the first observation of SSE migration activity connecting deep and shallow regions that was predicted in previous studies[3]. The migration speed of the shallow SSE was approximately 50 – 100 km/year. This speed is much lower than other SEQs[8] but similar with deep long-term SSEs[14].

This SSE activity proceeded around the northeastern edge of the shallow VLF activity region from north to southeast. The VLF activity also shifted to the northeast in 2015 and converged in 2016, as shown in Fig. 2b and was thought to jump across the SSE region around sites (3) and (4). The activities of these VLFs and SSEs synchronized in time, while their activity regions were complementary.

Off the Kii channel, according to the grid search result, the M_w 6.2 SSE and the M_w 6.6 SSE were estimated in 2009 and 2017 – 2018, respectively. These SSEs repeatedly occurred at eight-year intervals. In this region, detailed shallow VLF source reanalysis was performed considering the 3D structure[24]. According to this analysis, VLFs were strongly activated in 2009 and 2018. Although there was an activity in 2015, this activity was smaller than other two cases. The VLF activity in 2009 was slightly closer to the western side than in 2018, as shown in Fig. 2b. The 2009 SSE was also located in the western part of the 2017 – 2018 SSE region, although spreading to the west cannot be sufficiently constrained because there was no western site before 2011. This consistency suggests the temporal synchronization and the spatial correlation between SSE and VLF in this region. Unlike the Bungo case, the SSE appears to precede the VLF activity.

The M_w 6.1 SSEs estimated off Kumano-nada were in the vicinity of short-term SSE activity[10], although it is possible that the western SSE was due in part to an afterslip of the M_w 5.8 earthquake on Apr. 1, 2016 that occurred below this region. Since total slip amounts of short-term SSEs had been presumed small[10], the detected long-term SSEs were believed to be independent activities synchronous with the short-term SSE activity. In this region, after the eastern long-term SSE occurred in 2015, VLF activity was monitored around the area between the eastern and western long-term SSEs and was believed to be associated with short-term SSEs[11]. In this case, long-term SSEs occurred both before and after this VLF activity.

The relationship with a strong coupling region is similar to deep SSEs. Deep SSEs have a feature to occur on the deep side adjacent to a strong coupling region and a historical slip region[18-19,25]. The detected shallow SSEs are also roughly adjacent on the shallow side. This indicates that the edge areas of strong coupling regions may have two periods that accumulate coupling and release at least a part of the coupling both by a deep SSE and a shallow SSE.

Among sites other than the eight sites, no clear SSE signal was detected. The SSE signal has not been detected even by the closest site (13) to the Tokai deep SSE region[25], although this site, which has only an approximately seven-year observation period, may not yet have adequate resolution. Regions off Shikoku Island and off Tokai deep SSE are locations where strong coupling regions[15-16] overlapped assumed and historical seismogenic zones[12-13]. The absence of SSEs during our observation period indicates the possibility that these are main slip regions of the Nankai Trough megathrust zone.

The detected shallow SSEs led new knowledge and discussion about a diverse behaviour of SEQs and provide many academic targets about such as stress loading for the coupling region and difference in geological conditions in SSEs and coupling regions, to be solved by future seafloor and onshore geophysical monitoring. It is also necessary to enhance the seafloor geodetic observation system in order to upgrade the observation density and continuity for investigating a detail relation between SSEs and megathrust earthquakes.

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Author Contributions

Y.Y. and T.I. designed the study and performed the statistical processing. Y.Y. carried out the grid search analysis. Y.Y. and T.I. developed the GNSS-A seafloor geodetic observation system and wrote this manuscript.

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Figure legends

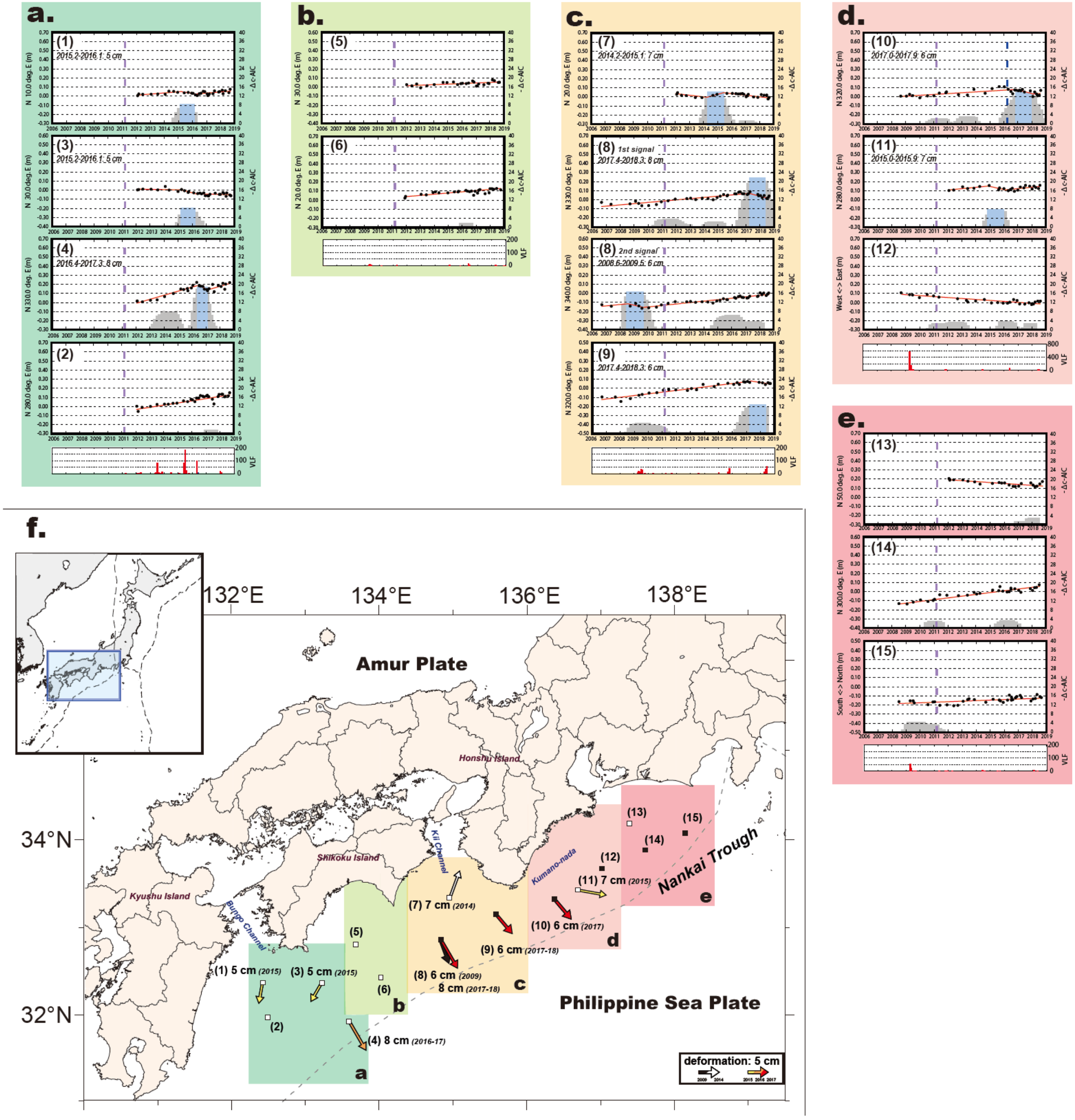
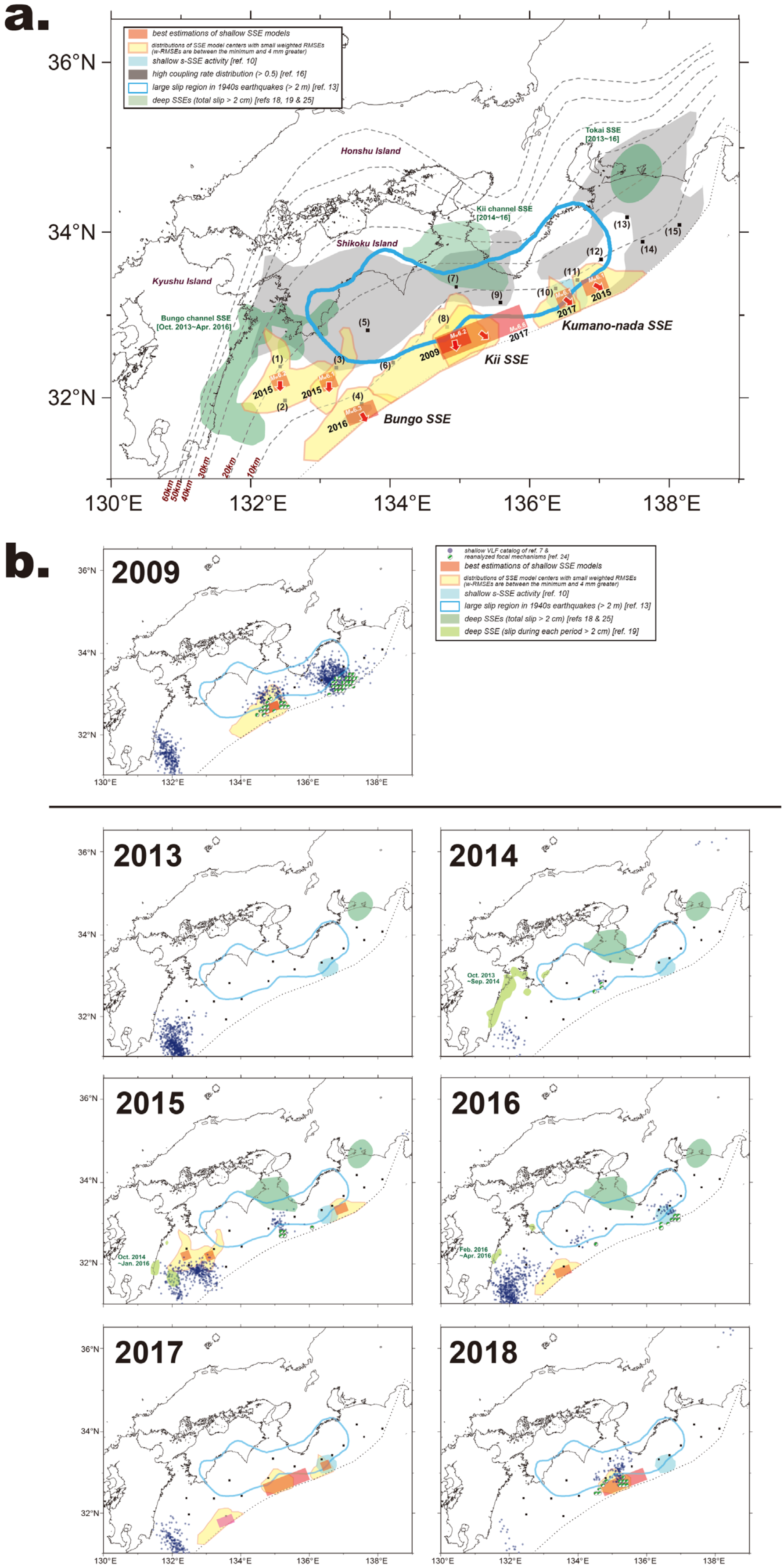


Fig. 1 | Results of the SSE signal detection process. a – e, time series of seafloor crustal deformations in the sites in coloured regions drawn in f. The maximum likelihood straight and piece-wise lines in the sites where SSE signals were detected and were not detected, respectively, were displayed. In site (8), two detected cases were displayed. Each time series was plotted in the direction for the case of the maximum likelihood solution in the SSE signal detection process. The reference frame is International Terrestrial Reference Frame (ITRF) 2005 (ref. 30). Red lines indicate straight and piece-wise lines estimated as the maximum likelihood solutions. Grey histograms are Δc-AIC time series (bin range: one year) every 0.2 years. Each light-blue bin is the case that was judged as an SSE signal. Bottom red histograms are shallow VLF numbers[7] within coloured regions in **f** every month. Purple and blue dashed lines indicate the 2011 Tohoku-oki earthquake and the 2016 M_w 5.8 earthquake in the Kumano-nada region, respectively. **f, Seafloor crustal deformations detected in the SSE signal detection process.** Vectors indicated seafloor crustal deformations detected in the GNSS-A data. Closed and open squares are the seafloor observation sites set before and after 2011, respectively.



293 **Fig. 2 | a, Spatial relationship between detected shallow SSEs, coupling rate**

distribution and deep SSEs along the Nankai Trough. Red rectangles and vectors are shallow SSE models and slip angles, respectively, estimated by the grid search. The yellow regions show distributions of SSE model centres with weighted RMSEs calculated in the range between the minimum and 4 mm greater than the minimum. The light-blue polygon indicates the Kumano-nada short-term SSE activity region detected by submarine borehole monitoring[10]. The grey contour map indicates high coupling rate distribution[16] (rate: more than 0.5). The light-blue solid line indicates the most recent seismogenic region[13] (slip: more than 2 m). Green regions indicate deep SSE regions[18-19,25] (total slip: more than 2 cm). Dashed lines indicate the depths of the plate boundary of refs 28 and 29. Closed squares are the seafloor observation sites. **b, Snapshots of detected shallow SSEs in 2009 and 2012 - 2018.** Blue dots indicate shallow VLF activities[7] in each year. Green focal mechanisms of VLFs (134.5°E – 137.5°E) were estimated in ref. 24 by reanalysis of a part of the VLF catalogue of ref. 7 in consideration of the 3D structure. Green regions indicate deep Kii and Tokai SSE regions[18,25] (total slip: more than 2 cm). Light-green regions indicate deep Bungo SSE regions[19] (slip during each period: more than 2 cm).

Methods

Seafloor geodetic observation. Seafloor movements are determined combining the GNSS observation above the sea and the acoustic ranging system under the sea. This method is called the GNSS-A, which is a unique approach to monitor the absolute horizontal movement directly above the offshore interplate boundary. This technique was proposed in the 1980s (ref. 31) and established after the 1990s. We have been developing observation techniques[32-34] and have provided valuable data for geodesy and seismology, e.g., the pre-, co- and post-seismic seafloor crustal deformations of the 2011 Tohoku-oki earthquake[35-37] and the interseismic coupling condition along the Nankai Trough[15].

A schematic diagram of the seafloor geodetic observation system is shown in Extended Data Fig. 1. Before 2015, the observation frequency was approximately two to three times/year. After 2016, the acoustic system has been improved in order to observe each site four to 10 times/year (refs 38 and 39). Details of the GNSS-A system and the data were described and published in ref. 40. Dataset used in the present study was improved from published data about the underwater sound speed structure error using the method of ref. 17.

Slow slip event detectability of the GNSS-A. Detectability for SSEs was verified based on the method proposed in ref. 41. We verified whether crustal deformations calculated using the SSE fault models set on the plate boundary are observable in the onshore and seafloor geodetic monitoring networks. We assumed crustal deformations for the horizontal component in all of the sites using Green's functions calculated using the formulation of ref. 42 considering a homogeneous elastic half-space. The fault models were set depending on the magnitude of every 0.1 and were deployed every 0.1 degree on the plate boundary model (refs 28 and 29), which dip angles at shallower part than 10 km were set to roughly match seismic survey results in ref. 43. The fault size of each magnitude was set according to scaling law using in ref. 41, assuming a rigidity of 10 GPa. The strike angle of the fault model was set to 249° in most areas and was adjusted in an area where the trough axis angle was largely different. The rake angle was set to 90°.

RMSs of GNSS and GNSS-A data are about 3 mm (ref. 41) and about 2 cm or more (ref. 40), respectively. In this study, considering these observation abilities, it is judged that SSEs can be detected when the horizontal movements in the onshore and seafloor networks exceed 5 mm and 5 cm which are about twice RMSs, respectively, even at one site. Extended Data Figs 2a and b show the resultant maps calculated using the onshore network only and using the onshore and seafloor networks, respectively. Extended Data

Fig. 2c indicates SSEs which can be detected only by the seafloor network. These results show that the seafloor network can detect M_w 6 class shallow SSEs that cannot be detected using only the onshore network.

Slow slip event signal detection process using Δc-AIC. We detected an SSE signal according to the process flow shown in Extended Data Fig. 3. Before the signal detection process, the same deductions as ref. 15 on effects resulting from the 2011 Tohoku-oki earthquake were performed for the dataset. Coseismic and postseismic effects were calculated based on the models established in refs 44, 45 and 46. Resultant time series of their locations in the sites along the Nankai Trough were listed in Extended Data Fig. 4 and Supplementary Table 1. The reference frame is International Terrestrial Reference Frame (ITRF) 2005 (ref. 30).

We detected an SSE signal in these time series based on the method of ref. 22 using c-AIC (refs 20 and 21). We fitted straight and piece-wise lines for the time series and compared each c-AIC to determine if a time series contains SSE-like transient deformation. We rotated a direction of time series every 10 degrees to extract the maximum deformation angle. A deformation duration of the piece-wise line was set to one year which is a typical timescale for long-term SSE. This piece-wise line was fitted for the time series data for all periods. The residual sums of squares (RSSs) in Eq. (1) were calculated for the straight and piece-wise lines for the data for the whole periods. The start timing and scale of deformation were estimated every 0.2 years and every 1 cm between 1 and 20 cm, respectively, and were chosen to minimize c-AIC. We defined Δc-AIC as a difference between c-AICs for the straight line and the piece-wise line. When a deformation signal of Δc-AIC < -6 was detected by the piece-wise line, after removing this detected deformation, the same process was performed. When a signal of Δc-AIC < -6 was not detected, the process ended because there was no clear signal. Signals detected between 2011 and Dec. 2013 were considered to be a remaining influence due to the 2011 Tohoku-oki earthquake, even after the deduction process. We identified a signal other than this type of signal as an SSE signal.

Grid search process to determine SSE models. Each SSE fault model that explains the deformation fields determined in the c-AIC detection process was estimated using a grid search technique. We set rectangular fault models for a grid every 0.1 degree on the plate boundary to estimate the weighted RMSEs for the data in the region delimited. The strike angle was set to 249°. The fault length, width, slip and rake angles were properly changed every 10 km between 20 and 100 km, every 10 km between 20 and 50 km in the dip direction, every 4 cm between 2 and 78 cm and every 10° between 70° and 130°, respectively. The dip angle was set along the plate boundary model described in the above section "SSE detectability of the GNSS-A". Crustal deformations were also calculated using the method and setting described in the above section. We calculated crustal deformations for the horizontal component at seafloor sites and the neighbour onshore GNSS sites of the GEONET. Considering the observation abilities, the weighted RMSE was calculated by multiplying the onshore data by nine times the weight of the seafloor data.

Refs 14 and 19 showed unsteady crustal deformation fields detected by GEONET around the Bungo channel and suggested that there was no deformation fields over 5 mm in 2015 and after Apr. 2016. Crustal deformation fields[18] detected by GEONET around the Kii channel and the Kumano-nada also suggested that there was no deformation field over 5 mm in the time periods for calculating SSE models. Then, onshore crustal deformations were assumed to be less than about 5 mm in estimations. Signals off the Bungo channel in 2015 (sites (1) and (3)) and off the Kii channel in 2017 (sites (8) and (9)) were synchronized and were considered to cause each SSE sequence. However, off the Bungo channel, since it was not possible to estimate a single rectangular fault model with an onshore deformation of less than about 5 mm, a rectangular fault was estimated for each site observation. Off the Kii channel, one rectangular fault model was estimated.

Observed and calculated deformation values in the best cases are compared in Extended Data Fig. 6. The distributions of SSE model centres with weighted RMSEs calculated in the range between the minimum and 4 mm greater than the minimum are drawn in Fig. 2 and Extended Data Fig. 6. A small RMSE region can be interpreted as the fault location estimation accuracy in each case. Small RMSE regions spread in the vicinity of the trough axis, where there is no site, so it is difficult to determine not only the fault position near the trench axis but also the upper end of the magnitude.

Data availability. The dataset of seafloor positions is provided in Supplementary Table 1.

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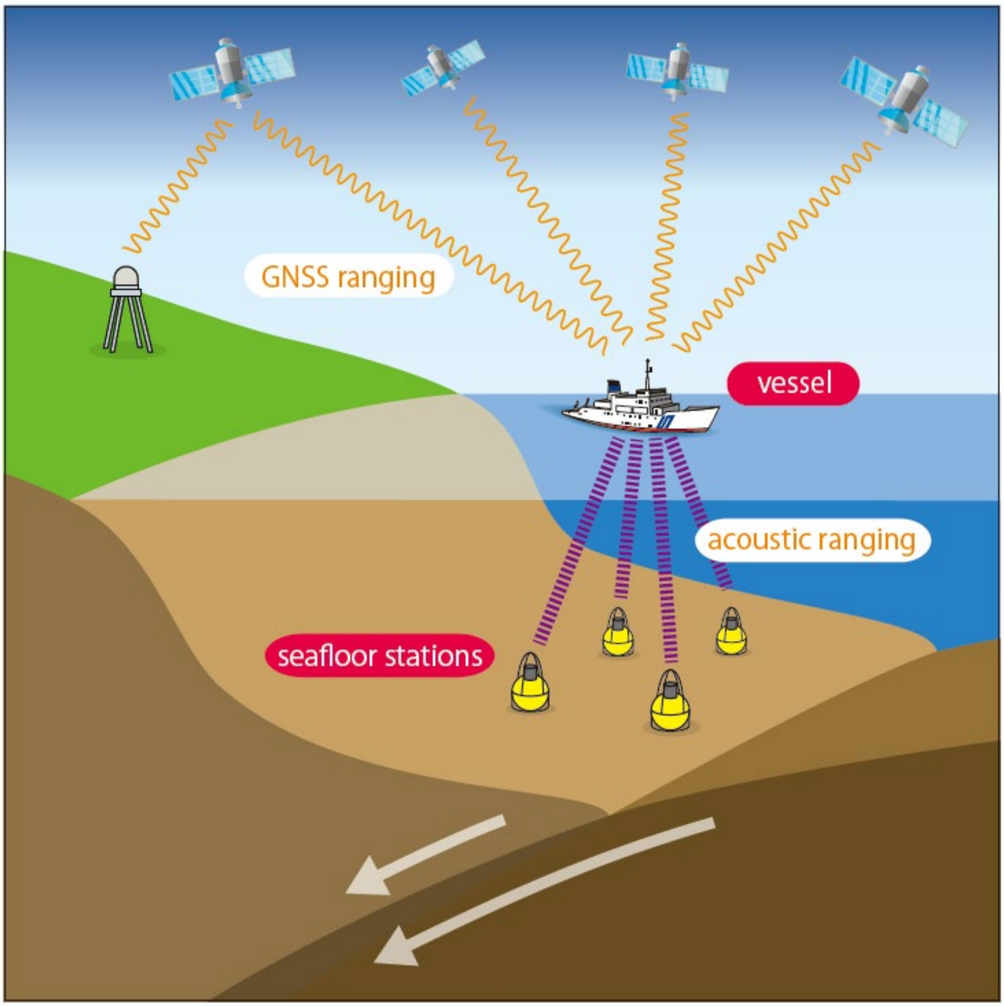
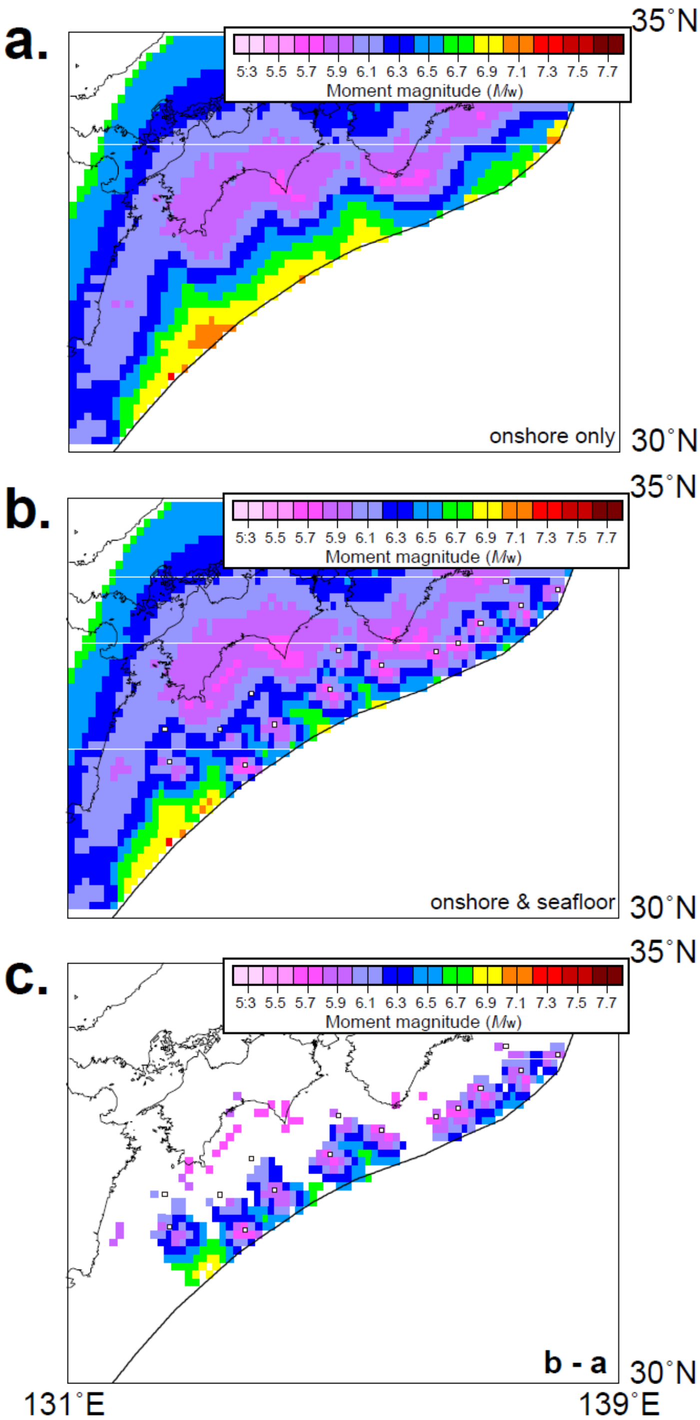
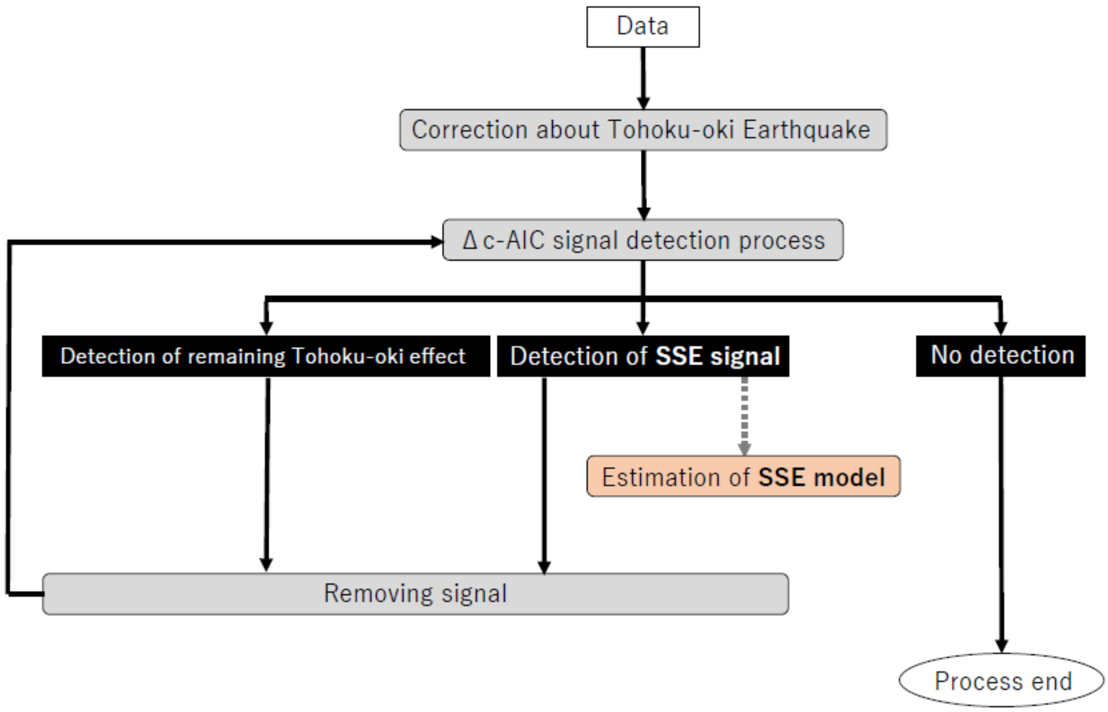
Extended Data legends



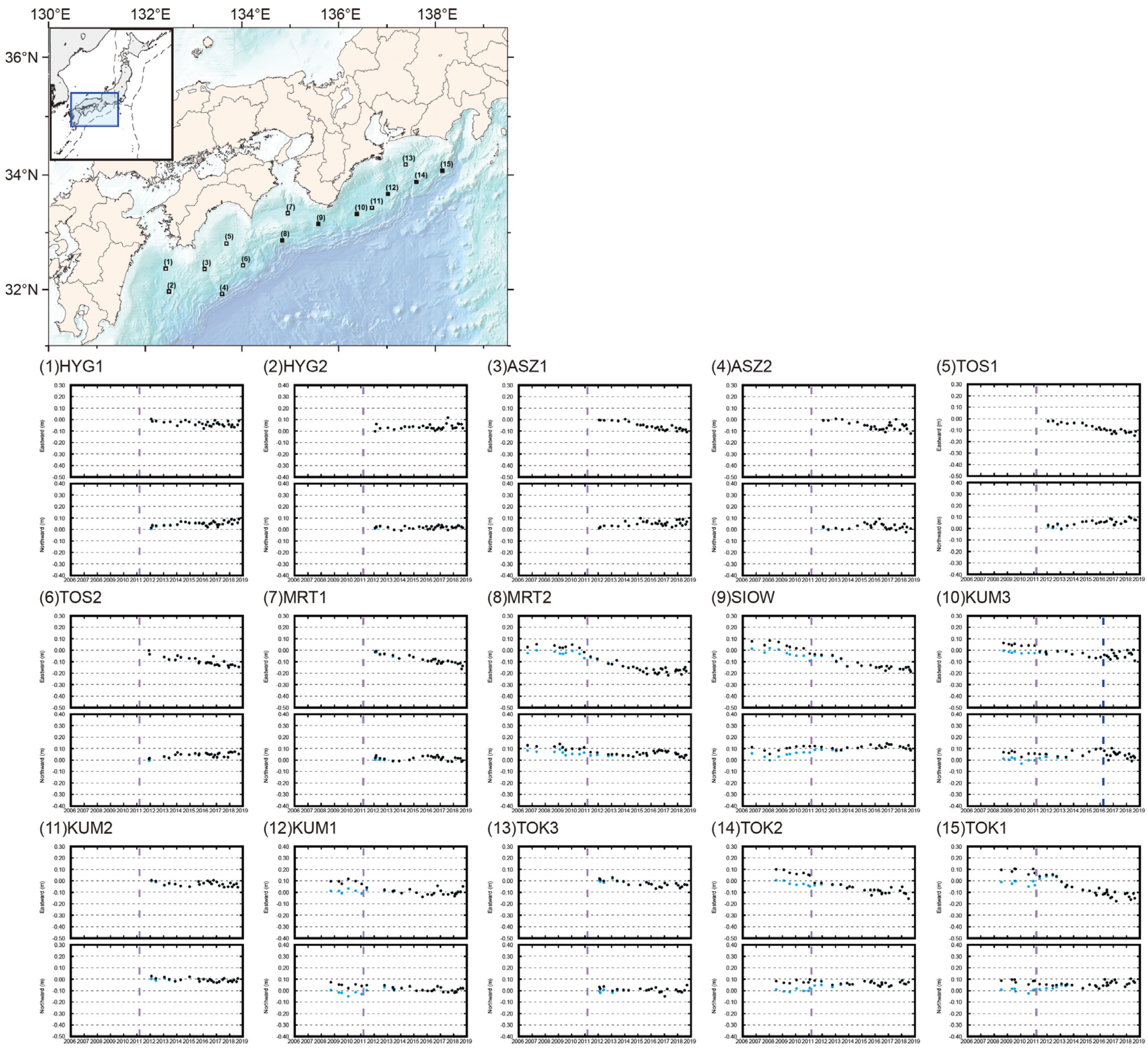
Extended Data Figure 1 | Schematic diagram of the GNSS-A seafloor geodetic observation system. This figure is modified from refs 15, 17, 32, 33 and 34.



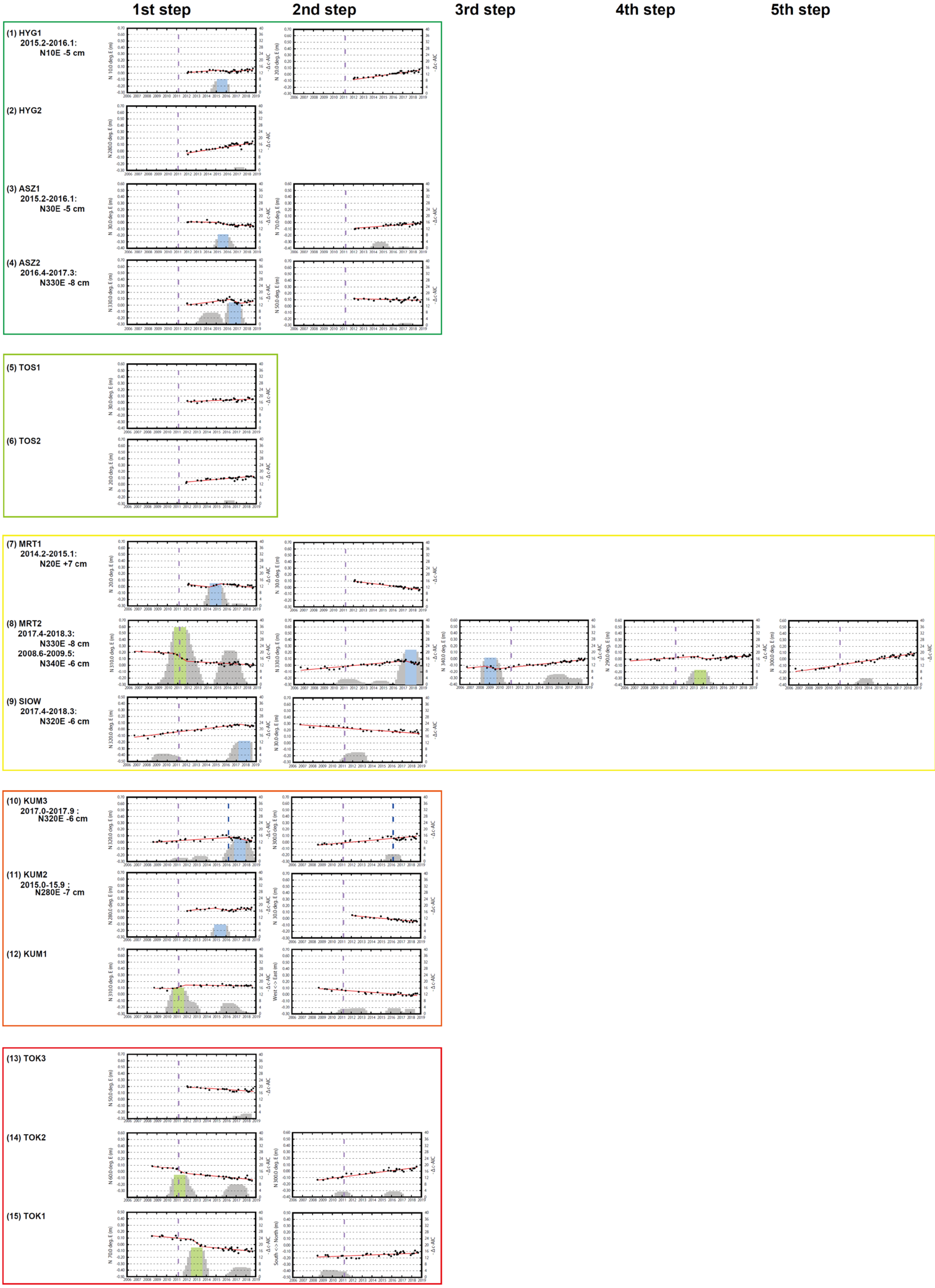
Extended Data Figure 2 | Maps representing SSE detectability constructed using, a, the onshore GNSS network only and, b, onshore and seafloor GNSS-A networks. c, Maps representing SSEs which can be detected only by the seafloor GNSS-A network. Colour contours indicate the magnitude of detectable minimum events at each grid on the plate boundary.



Extended Data Figure 3 | Flow of the SSE signal detection process.

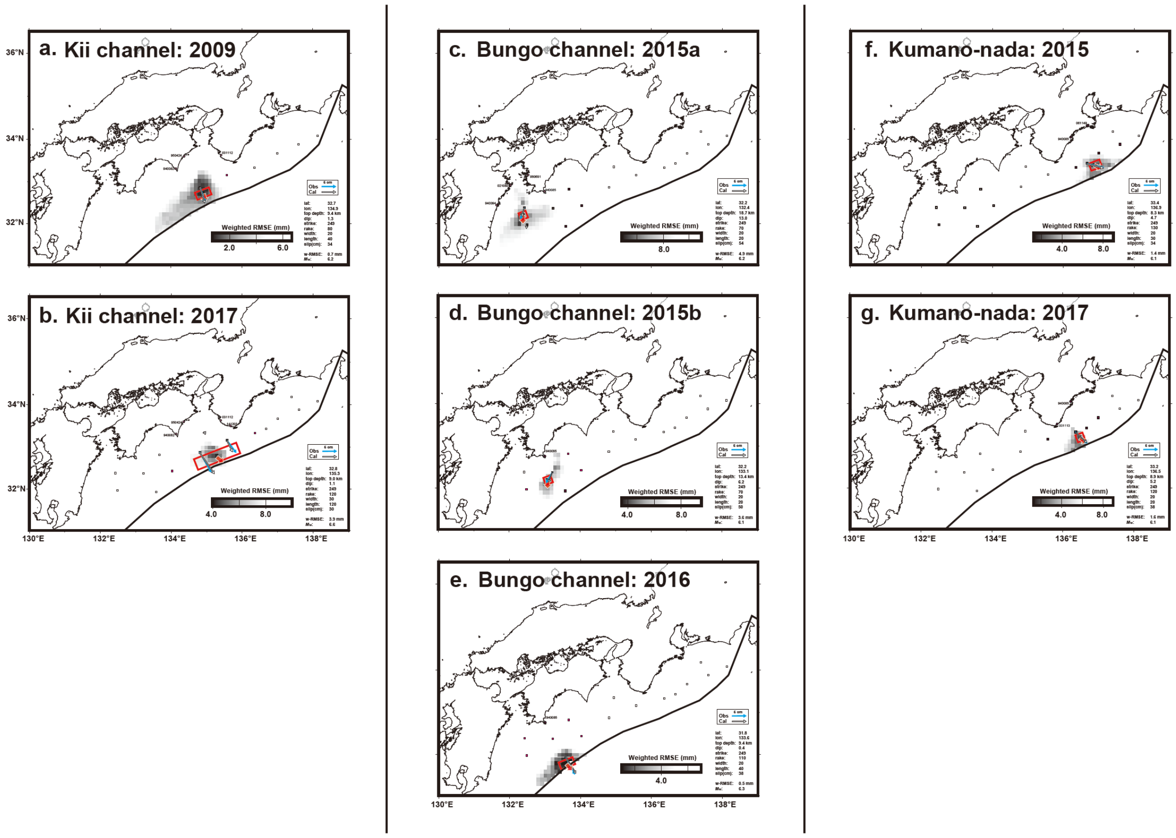


Extended Data Figure 4 | Time series of horizontal components of seafloor GNSS-A data. Black circles indicate seafloor positions after deduction of deformations due to the 2011 Tohoku-oki earthquake based on refs 44, 45 and 46. Blue circles indicate raw data before deduction. The reference frame is ITRF2005 (ref. 30).



480 **Extended Data Figure 5 | Results of the SSE signal detection process for all the time**

series. Each time series was described in the direction with the maximum likelihood solution in the SSE signal detection process. The reference frame is ITRF2005 (ref. 30). The results for each step were obtained in order from the left. Red lines indicate straight and piece-wise lines estimated as the maximum likelihood solutions. Grey histograms are Δc-AIC time series (bin range: one year) in the process every 0.2 years. Light-blue and green bins are Δc-AIC in the cases that were judged as SSE signals and as remaining influences due to the 2011 Tohoku-oki earthquake, respectively. Purple and blue dashed lines indicate the 2011 Tohoku-oki earthquake and the 2016 M_w 5.8 earthquake in the Kumano-nada region, respectively.



Extended Data Figure 6 | Grid search results for estimating SSE models; a and b, off the Kii channel in 2009 and after 2017, c - e, off the Bungo channel around site (1) and site (3) in 2015 and in 2016 and f and g, around Kumano-nada in 2015 and 2017. Grey regions indicate distributions of SSE model centres with weighted RMSEs calculated in the range between the minimum and 4 mm greater than the minimum. Red rectangles indicate the final obtained rectangular fault models in the results. Blue and white vectors are observed and calculated movements for the sites, respectively. Fault parameters are listed at the right bottom. Pink and light-blue squares and light-blue circles are the seafloor sites moved due to SSEs, unmoved sites and onshore GEONET sites used in the grid search, respectively. GEONET site codes are described beside the sites. Open squares are the seafloor sites that were not used in the grid search.

Supplementary Table legends

Supplementary Table 1 | Time series of seafloor positions. The reference frame is ITRF2005 (ref. 30). The first column shows an observation epoch. Eastward and Northward components (second and third columns) indicate the data corrected the coseismic and postseismic effects due to the Tohoku-oki earthquake. $East_{raw}$ and $North_{raw}$ components (forth and fifth columns) are raw data before March 2014.