

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

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9
10 **Various slow earthquakes (SEQs), including tremors, very-low-frequency events**
11 **(VLFs) and slow slip events (SSEs) occur along megathrust zones, which generate**
12 **catastrophic earthquakes¹⁻⁷. For comprehensive understanding of the megathrust**
13 **plate boundary, it is necessary to monitor such events not only on a land area (deep**
14 **plate boundary) but also on a sea area (shallow plate boundary). Many shallow**
15 **SEQs have been observed along pan-Pacific subduction zones⁸⁻¹¹, including the**
16 **Nankai Trough off southwestern Japan on which megathrust earthquakes are**
17 **predicted to occur¹²⁻¹³. However, a SSE with a duration on the order of a year (long-**
18 **term SSE) has not been detected in a sea area. Recently, we improved the Global**
19 **Navigation Satellite System (GNSS)-Acoustic combination technique (GNSS-A),**
20 **which had enabled monitoring of the seafloor absolute position, to a level that can**
21 **detect a transient crustal deformation. Here, we present the first detection of long-**
22 **term SSE signals from seafloor geodetic observation data and discuss timings,**
23 **approximate locations and magnitudes of SSEs along the Nankai Trough inferred**
24 **therefrom. The results suggest features of SSEs for the strong-coupling regions and**
25 **other SEQ activities, i.e., temporal synchronization with VLF and short-term SSE**
26 **activities, regional complementarity with coupling and VLF regions and recurrence**
27 **in the near region. Although these are similar to features observed even in deep**
28 **SSEs^{4,6,14}, the occurrence timing for VLF activity was different depending on each**
29 **generation region. The GNSS-A monitoring network that can detect SSEs will**
30 **provide new basic information to promote research on subduction geophysics and**
31 **megathrust earthquake disaster prevention.**

32

33 In the last two decades, many kinds of SEQs, including aseismic SSEs, have been
34 detected using onshore high-precision seismometers and GNSS networks¹⁻³. Along the
35 Nankai Trough in western Japan, where recurring interplate megathrust earthquakes have
36 occurred¹²⁻¹³ and which has a dense seismic and geodetic monitoring network, their
37 interrelationships were discussed and compared in detail³⁻⁶. Most SEQs occurred not in a
38 strong coupling region, but rather around such a region and have features of repeatedly
39 occurring and migrating. Different types of SEQs sequentially occurred in the
40 neighbouring region, and temporal synchronization with other SEQs was also observed.

41 Observation of deep and shallow SEQ analogies and differences has multidisciplinary
42 value with respect to physical process of the plate boundary, submarine geology and
43 earthquake disaster research. However, shallow SEQs cannot be easily monitored due to
44 the technological difficulty of observation. With recent advances in technology, shallow
45 SEQs, such as tremors, VLFs and short-term SSEs with durations on the order of days,
46 have been detected by high-precision onshore seismometers, seafloor seismometers,
47 ocean bottom pressure gauges and submarine borehole strainmeters⁷⁻¹¹. However, only
48 long-term SSEs with durations on the order of a year have not been detected in the group
49 of shallow SEQs. From the analogy of deep long-term SSEs, GNSS-like geodetic
50 observation is necessary to detect the shallow long-term SSEs.

51 A seafloor geodetic monitoring technique called as the GNSS-A was proposed in the
52 1980s and has been developed in the latest two decades. The GNSS-A seafloor geodetic
53 observation majorly constrained an interplate coupling condition¹⁵⁻¹⁶ along the Nankai
54 Trough subduction zone. Recently, we improved GNSS-A technology and upgraded
55 observation sensitivity¹⁷ in order to detect a transient crustal deformation with durations
56 on the order of a year. Then, the GNSS-A monitoring can reveal the occurrence of SSEs,
57 which cannot be observed by the onshore geodetic network, as shown in Extended Data
58 Fig. 2. The GNSS-A methodology is described in the Method section.

59 We first show SSE signals detected in the GNSS-A dataset in Fig. 1. Our data is listed
60 in Supplementary Table 1. Signal detection was carried out in the procedure shown in
61 Extended Data Fig. 3. Coseismic and postseismic effects resulting from the 2011 Tohoku-
62 oki earthquake were preliminarily deducted as similar to those described in ref. 15. If
63 there was no transient event, the time series can be simply approximated by a straight line.
64 When there is a temporal change due to SSEs in the time series, the time series can be
65 approximated by the piece-wise line. By estimating this piece-wise line, the timing and
66 scale of deformation can be determined. We fitted straight and piece-wise lines for the
67 time series of each site rotating a direction every 10 degrees. Since the GNSS-A sampling
68 rate is low, this detection is not so sensitive to the duration of the SSEs. Here, we set the

69 deformation slope of the piece-wise line to one year, which is a typical duration of a long-
70 term SSE^{14,18-19}. The significance of fitting by the piece-wise line to the straight line is
71 verified using the c-AIC (refs 20 and 21) based on the method of ref. 22. The c-AIC is
72 defined as the following function:

$$73 \quad \text{c-AIC} = n \ln(2\pi) + n \ln\left(\frac{RSS}{n}\right) + \frac{2nk}{n-k-1} \quad (1)$$

74 where n , k and RSS are the numbers of data, a model parameter and the residual sum of
75 squares, respectively. The maximum likelihood solution minimizes this parameter. After
76 removing a detected deformation signal, we carried out the same process once again.
77 When the difference ($\Delta\text{c-AIC}$) between c-AICs for the straight line and the piece-wise
78 line is greater than -6, the process terminated because there was no clear signal. The time
79 series of seafloor positions and $\Delta\text{c-AIC}$ s and signal detected periods were compared with
80 the time series of neighbour VLF activity⁷ in Figs 1a – e. Details of this process are
81 described in the Method section. Although the Tohoku-oki earthquake effects were
82 preliminarily deducted, the remaining effects due to model uncertainty are detected as
83 shown in Extended Data Fig. 5. Detected deformation vectors other than the Tohoku-oki
84 effects are judged as SSE signals and are shown in Fig. 1f. Direction of the signal at site
85 (7) in 2014 was not from south to east and was assumed to be due to deep SSE activity¹⁸
86 or error, and an SSE model was not estimated for this signal.

87 SSE signals at offshore sites of the Bungo and Kii deep SSEs¹⁸⁻¹⁹ were detected. Off
88 the Bungo channel, signals were detected after 2015. Off the Kii channel, signals were
89 detected in 2009 and after 2017. In addition, SSE signals at sites around the Kumano-
90 nada were detected in 2015 and 2017. A clear signal was not obtained for the offshore
91 regions of the Tokai deep SSE and Shikoku Island.

92 We discuss timings, approximate locations and magnitude scales of SSEs by
93 estimating rectangular fault models that can explain the detected signals at offshore sites
94 of the Bungo and Kii channels and the Kumano-nada by the grid search method. Details
95 of the grid search method and the results are described in the Method section and are
96 shown in Fig. 2 and Extended Data Fig. 6, respectively. Considering durations as about
97 one year, these undersea shallow SSE models roughly follow a SEQ scaling law whereby
98 the event magnitude is proportional to the logarithm of the duration⁴ and had no
99 significant difference from deep SSEs¹⁴.

100 In a deep region around the Bungo channel, SSEs repeatedly occurred^{19,23}. The most
101 recent SSEs occurred intermittently between 2013 and 2016. Shallow SSE signals
102 detected after 2015 indicate that the deep SSE after 2013 spread to the offshore region.
103 According to the grid search results, there were M_w 6.1 – 6.3 events that migrated away

104 from the Bungo channel. The north shallow SSEs in 2015 were believed to be the first
105 step in the spread of the deep SSE to the offshore region, and this SSE sequence ended
106 around site (4). This is the first observation of SSE migration activity connecting deep
107 and shallow regions that was predicted in previous studies³. The migration speed of the
108 shallow SSE was approximately 50 – 100 km/year. This speed is much lower than other
109 SEQs⁸ but similar with deep long-term SSEs¹⁴.

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

115 Off the Kii channel, according to the grid search result, the M_w 6.2 SSE and the M_w
116 6.6 SSE were estimated in 2009 and 2017 – 2018, respectively. These SSEs repeatedly
117 occurred at eight-year intervals. In this region, detailed shallow VLF source reanalysis
118 was performed considering the 3D structure²⁴. According to this analysis, VLFs were
119 strongly activated in 2009 and 2018. Although there was an activity in 2015, this activity
120 was smaller than other two cases. The VLF activity in 2009 was slightly closer to the
121 western side than in 2018, as shown in Fig. 2b. The 2009 SSE was also located in the
122 western part of the 2017 – 2018 SSE region, although spreading to the west cannot be
123 sufficiently constrained because there was no western site before 2011. This consistency
124 suggests the temporal synchronization and the spatial correlation between SSE and VLF
125 in this region. Unlike the Bungo case, the SSE appears to precede the VLF activity.

126 The M_w 6.1 SSEs estimated off Kumano-nada were in the vicinity of short-term SSE
127 activity¹⁰, although it is possible that the western SSE was due in part to an afterslip of
128 the M_w 5.8 earthquake on Apr. 1, 2016 that occurred below this region. Since total slip
129 amounts of short-term SSEs had been presumed small¹⁰, the detected long-term SSEs
130 were believed to be independent activities synchronous with the short-term SSE activity.
131 In this region, after the eastern long-term SSE occurred in 2015, VLF activity was
132 monitored around the area between the eastern and western long-term SSEs and was
133 believed to be associated with short-term SSEs¹¹. In this case, long-term SSEs occurred
134 both before and after this VLF activity.

135 The relationship with a strong coupling region is similar to deep SSEs. Deep SSEs
136 have a feature to occur on the deep side adjacent to a strong coupling region and a
137 historical slip region^{18-19,25}. The detected shallow SSEs are also roughly adjacent on the
138 shallow side. This indicates that the edge areas of strong coupling regions may have two

139 periods that accumulate coupling and release at least a part of the coupling both by a deep
140 SSE and a shallow SSE.

141 Among sites other than the eight sites, no clear SSE signal was detected. The SSE
142 signal has not been detected even by the closest site (13) to the Tokai deep SSE region²⁵,
143 although this site, which has only an approximately seven-year observation period, may
144 not yet have adequate resolution. Regions off Shikoku Island and off Tokai deep SSE are
145 locations where strong coupling regions¹⁵⁻¹⁶ overlapped assumed and historical
146 seismogenic zones¹²⁻¹³. The absence of SSEs during our observation period indicates the
147 possibility that these are main slip regions of the Nankai Trough megathrust zone.

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

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156 **References**

- 157 (1) Dragert, H., Wang, K. & James, T. S. A silent slip event on the deeper Cascadia
158 subduction interface. *Science* **292**, 5521, 1525-1528, doi:10.1126/science.1060152
159 (2001).
- 160 (2) Ozawa, S. *et al.* Detection and Monitoring of Ongoing Aseismic Slip in the Tokai
161 Region, Central Japan. *Science* **298**, 5595, 1009–1012, doi:10.1126/science.1076780
162 (2002).
- 163 (3) Hirose, H., Asano, Y., Obara, K., Kimura, T., Matsuzawa, T., Tanaka, S. & Maeda,
164 T. Slow earthquakes linked along dip in the Nankai subduction zone. *Science* **330**,
165 1502, doi:10.1126/science.1197102 (2010).
- 166 (4) Ide, S., Beroza, G. C., Shelly, D. R. & Uchide, T. A scaling law for slow earthquakes.
167 *Nature* **447**, 76–79, doi:10.1038/nature05780 (2007).
- 168 (5) Ruiz, S. *et al.* Intense foreshocks and a slow slip event preceded the 2014 Iquique M_w
169 8.1 earthquake. *Science* **345**, 6201, 1165-1169, doi:10.1126/science.1256074 (2014).
- 170 (6) Obara, K. & Kato, A. Connecting slow earthquakes to huge earthquakes. *Science* **353**,
171 6296, 253-257, doi:10.1126/science.aaf1512 (2016).
- 172 (7) Asano, Y., Obara, K. & Ito, Y. Spatiotemporal distribution of very-low frequency
173 earthquakes in Tokachi-oki near the junction of the Kuril and Japan trenches

- 174 revealed by using array signal processing. *Earth Planet. Space* **60**, 871–875,
175 doi:10.1186/BF03352839 (2008).
- 176 (8) Yamashita, Y. *et al.* Migrating tremor off southern Kyushu as evidence for slow slip
177 of a shallow subduction interface. *Science* **348**, 6235, 676–679,
178 doi:10.1126/science.aaa4242 (2015).
- 179 (9) Wallace, L. M., *et al.* Slow slip near the trench at the Hikurangi subduction zone, New
180 Zealand. *Science* **352**, 701–704, doi:10.1126/science.aaf2349 (2016).
- 181 (10) Araki, E., *et al.* Recurring and triggered slow-slip events near the trench at the Nankai
182 Trough subduction megathrust. *Science* **356**, 1157–1160,
183 doi:10.1126/science.aan3120 (2017).
- 184 (11) Nakano, M., Hori, T., Araki, E., Kodaira, S. & Ide, S. Shallow very-low-frequency
185 earthquakes accompany slow slip events in the Nankai subduction zone. *Nature*
186 *Comm.* **9**, 984, doi:10.1038/s41467-018-03431-5 (2018).
- 187 (12) Ando, M. Source mechanism and tectonic significance of historical earthquakes
188 along the Nankai Trough, Japan. *Tectonophysics* **27**, 119–140, doi:10.1016/0040-
189 1951(75)90102-X (1975).
- 190 (13) Sagiya, T. & Thatcher, W. Coseismic slip resolution along a plate boundary
191 megathrust: The Nankai Trough, southwest Japan. *J. Geophys. Res.* **104**, B1, 1111–
192 1129, doi:10.1029/98JB02644 (1999).
- 193 (14) Takagi, R., Uchida, N. & Obara, K. Along-strike variation and migration of long-
194 term slow slip events in the western Nankai subduction zone, Japan. *J. Geophys. Res.*,
195 doi:10.1029/2018JB016738 (2019).
- 196 (15) Yokota, Y., Ishikawa, T., Watanabe, S., Tashiro, T. & Asada, A. Seafloor geodetic
197 constraint for interplate coupling along the Nankai Trough megathrust zone. *Nature*
198 **534**, 374–377, doi:10.1038/nature17632 (2016).
- 199 (16) Nishimura, T., Yokota, Y., Tadokoro, K. & Ochi, T. Strain partitioning and interplate
200 coupling along the northern margin of the Philippine Sea plate, estimated from
201 Global Navigation Satellite System and Global Positioning System-Acoustic data.
202 *Geosphere* **14**(2), doi:10.1130/GES01529.1 (2018).
- 203 (17) Yokota, Y., Ishikawa, T. & Watanabe, S. Gradient field of undersea sound speed
204 structure extracted from the GNSS-A oceanography. *Mar. Geophys. Res.*
205 doi:10.1007/s11001-018-9362-7 (2018).
- 206 (18) Kobayashi, A. Objective detection of long-term slow slip events along the Nankai
207 Trough using GNSS data (1996–2016). *Earth Planet. Space* **69**, 171,
208 doi:10.1186/s40623-017-0755-7 (2017).

- 209 (19) Ozawa, S. Long-term slow slip events along the Nankai trough subduction zone after
210 the 2011 Tohoku earthquake in Japan. *Earth Planet. Space* **69**, 56,
211 doi:10.1186/s40623-017-0640-4 (2017).
- 212 (20) Akaike, H. A new look at the statistical model identification. *IEEE Trans. Auto.*
213 *Control* **19**, 716-723, doi:10.1109/TAC.1974.1100705 (1974).
- 214 (21) Sugiura, N. Further analysts of the data by Akaike's information criterion and the
215 finite corrections. *Communications in Statics – Theory and Methods* **7**(1), 13-26,
216 doi:10.1080/03610927808827599 (1976).
- 217 (22) Nishimura, T., Matsuzawa, T. & Obara, K. Detection of short-term slow slip events
218 along the Nankai Trough, southwest Japan, using GNSS data. *J. Geophys. Res. Solid*
219 *Earth* **118**, 3112–3125, doi:10.1002/jgrb.50222 (2013).
- 220 (23) Ozawa, S., Suito, H., Imakiire, T. & Murakmi, M. Spatiotemporal evolution of
221 aseismic interplate slip between 1996 and 1998 and between 2002 and 2004, in
222 Bungo channel, southwest Japan. *J. Geophys. Res.* **112**, B05409,
223 doi:10.1029/2006JB004643 (2007).
- 224 (24) Takemura, S., Matsuzawa, T., Noda, A., Tonegawa, T., Asano, Y., Kimura, T. &
225 Shiomi, K. Structural characteristics of the Nankai Trough shallow plate boundary
226 inferred from shallow very low-frequency earthquakes. *Geophys. Res. Lett.*
227 doi:10.1029/2019GL082448 (2019).
- 228 (25) Ozawa, S., Tobita, M. & Yarai, H. A possible restart of an interplate slow slip
229 adjacent to the Tokai seismic gap in Japan. *Earth Planet. Space* **68**, 54,
230 doi:10.1186/s40623-016-0430-4 (2016).
- 231 (26) Colombo, O. L. Long range kinematic GPS, in *GPS for Geodesy, 2nd Edition*,
232 Kleusberg, A. & Teunissen, P., Editors. Springer-Verlag (1998).
- 233 (27) Colombo, O. L., Sutter, A. W. & Evans, A. G. Evaluation of precise, kinematic GPS
234 point positioning, *Proceedings of ION GNSS-2004*, Long Beach, California,
235 September (2004).
- 236 (28) Iwasaki, T., Sato, H., Shinohara, M., Ishiyama, T. & Hashima, A. Fundamental
237 structure model of island arcs and subducted plates in and around Japan. *2015 Fall*
238 *Meeting, American Geophys. Union, San Francisco*, Dec. 14-18, T31B-2878 (2015).
- 239 (29) Lindquist, K. G., Engle, K., Stahlke, D. & Price, E. Global Topography and
240 Bathymetry Grid Improves Research Efforts, *Eos Trans. AGU*, **85**(19), 186,
241 <http://onlinelibrary.wiley.com/doi/10.1029/2004EO190003/abstract> (2004).
- 242 (30) Altamimi, Z., Collilieux, X., Legrand, J., Garayt, B. & Boucher, C. ITRF2005: a new
243 release of the International Terrestrial Reference Frame based on time series of

244 station positions and Earth Orientation Parameters. *Geophys. J. Int.* **112**, B09401,
245 doi:10.1029/2007JB004949 (2007).

246

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

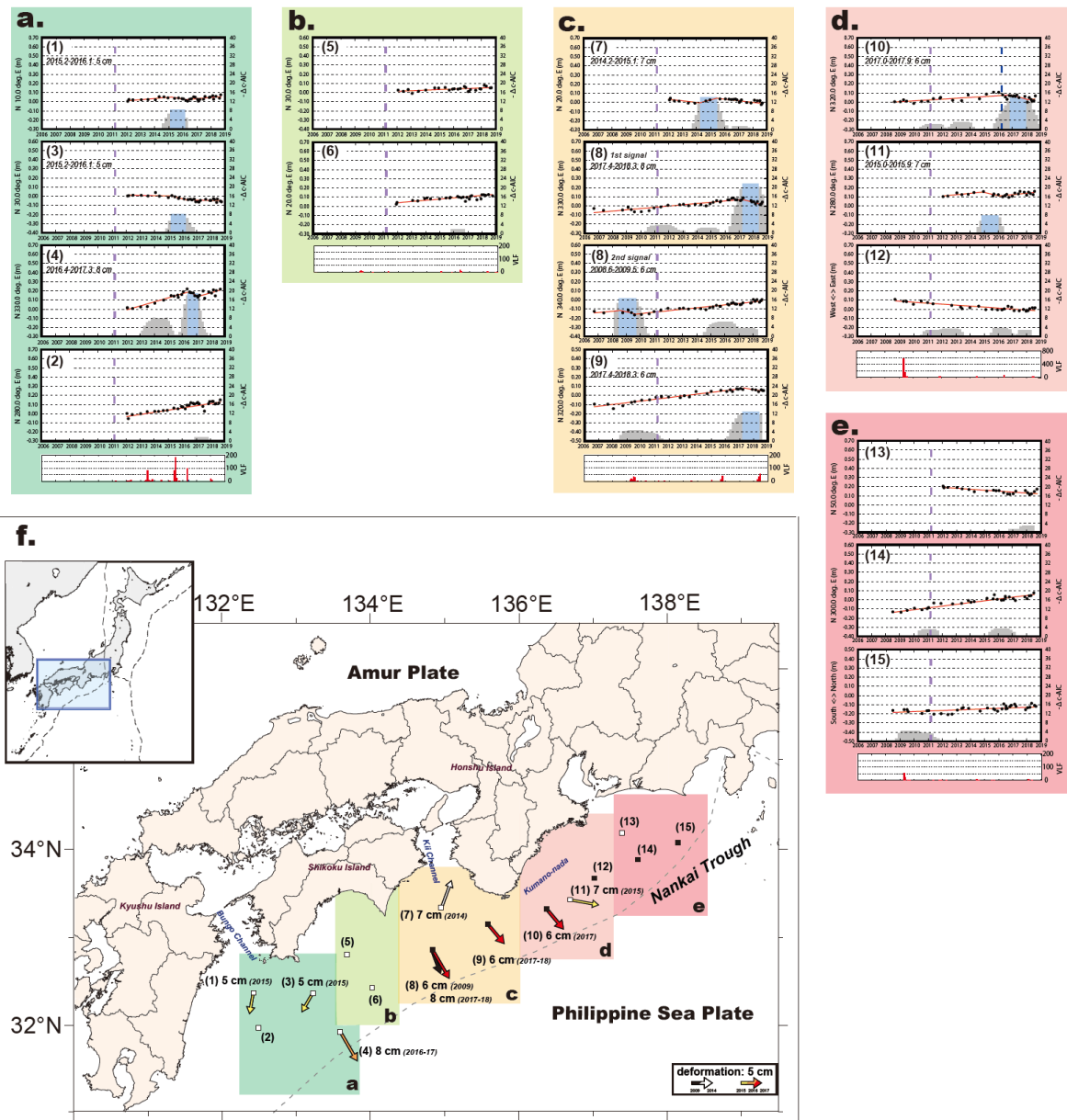
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269 **Author Information**

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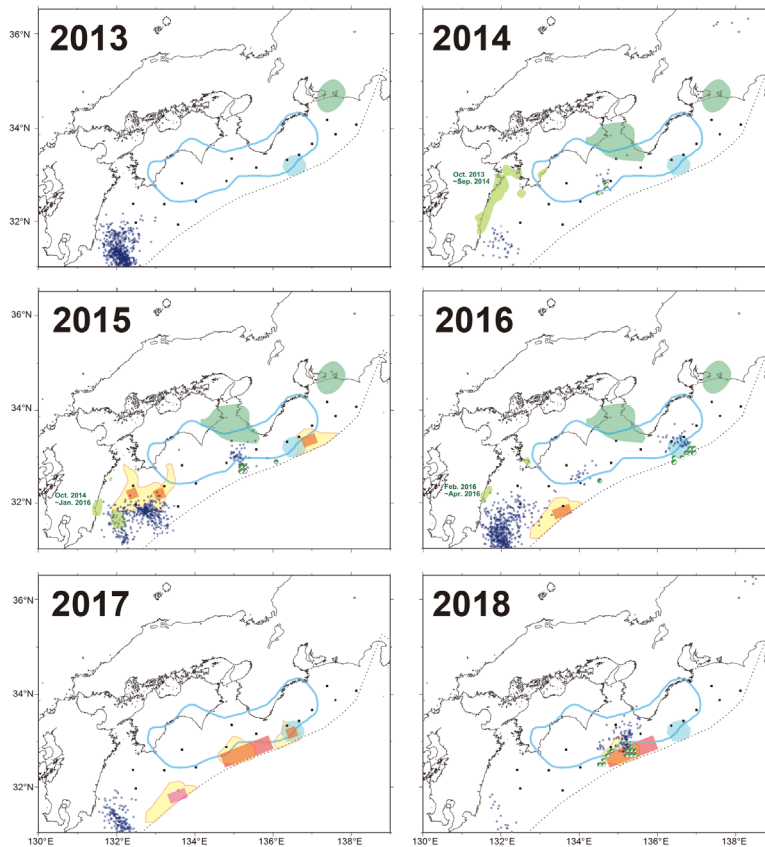
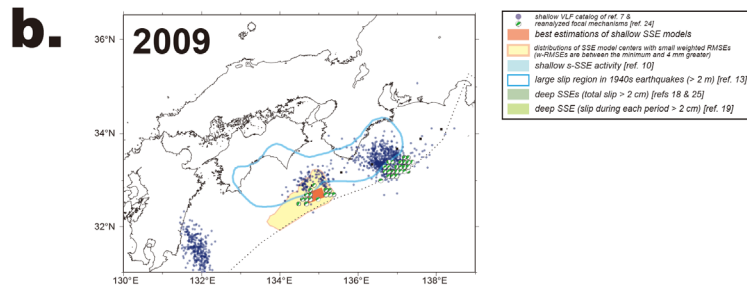
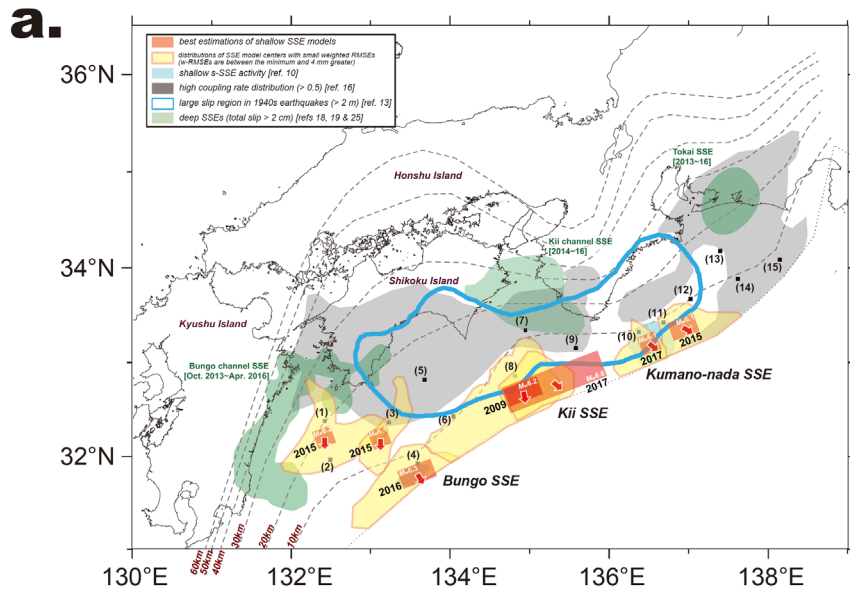
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275



277 **Fig. 1 | Results of the SSE signal detection process. a – e, time series of seafloor**
 278 **crustal deformations in the sites in coloured regions drawn in f. The maximum**
 279 **likelihood straight and piece-wise lines in the sites where SSE signals were detected and**
 280 **were not detected, respectively, were displayed. In site (8), two detected cases were**
 281 **displayed. Each time series was plotted in the direction for the case of the maximum**
 282 **likelihood solution in the SSE signal detection process. The reference frame is**
 283 **International Terrestrial Reference Frame (ITRF) 2005 (ref. 30). Red lines indicate**
 284 **straight and piece-wise lines estimated as the maximum likelihood solutions. Grey**
 285 **histograms are Δc -AIC time series (bin range: one year) every 0.2 years. Each light-blue**

286 bin is the case that was judged as an SSE signal. Bottom red histograms are shallow VLF
287 numbers⁷ within coloured regions in **f** every month. Purple and blue dashed lines indicate
288 the 2011 Tohoku-oki earthquake and the 2016 M_w 5.8 earthquake in the Kumano-nada
289 region, respectively. **f, Seafloor crustal deformations detected in the SSE signal**
290 **detection process.** Vectors indicated seafloor crustal deformations detected in the GNSS-
291 A data. Closed and open squares are the seafloor observation sites set before and after
292 2011, respectively.
293
294



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

296 **distribution and deep SSEs along the Nankai Trough.** Red rectangles and vectors are
297 shallow SSE models and slip angles, respectively, estimated by the grid search. The
298 yellow regions show distributions of SSE model centres with weighted RMSEs calculated
299 in the range between the minimum and 4 mm greater than the minimum. The light-blue
300 polygon indicates the Kumano-nada short-term SSE activity region detected by
301 submarine borehole monitoring¹⁰. The grey contour map indicates high coupling rate
302 distribution¹⁶ (rate: more than 0.5). The light-blue solid line indicates the most recent
303 seismogenic region¹³ (slip: more than 2 m). Green regions indicate deep SSE regions¹⁸⁻
304 ^{19,25} (total slip: more than 2 cm). Dashed lines indicate the depths of the plate boundary
305 of refs 28 and 29. Closed squares are the seafloor observation sites. **b, Snapshots of**
306 **detected shallow SSEs in 2009 and 2012 - 2018.** Blue dots indicate shallow VLF
307 activities⁷ in each year. Green focal mechanisms of VLFs (134.5°E – 137.5°E) were
308 estimated in ref. 24 by reanalysis of a part of the VLF catalogue of ref. 7 in consideration
309 of the 3D structure. Green regions indicate deep Kii and Tokai SSE regions^{18,25} (total slip:
310 more than 2 cm). Light-green regions indicate deep Bungo SSE regions¹⁹ (slip during
311 each period: more than 2 cm).
312

313 **Methods**

314 **Seafloor geodetic observation.** Seafloor movements are determined combining the
315 GNSS observation above the sea and the acoustic ranging system under the sea. This
316 method is called the GNSS-A, which is a unique approach to monitor the absolute
317 horizontal movement directly above the offshore interplate boundary. This technique was
318 proposed in the 1980s (ref. 31) and established after the 1990s. We have been developing
319 observation techniques³²⁻³⁴ and have provided valuable data for geodesy and seismology,
320 e.g., the pre-, co- and post-seismic seafloor crustal deformations of the 2011 Tohoku-oki
321 earthquake³⁵⁻³⁷ and the interseismic coupling condition along the Nankai Trough¹⁵.

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

329

330 **Slow slip event detectability of the GNSS-A.** Detectability for SSEs was verified based
331 on the method proposed in ref. 41. We verified whether crustal deformations calculated
332 using the SSE fault models set on the plate boundary are observable in the onshore and
333 seafloor geodetic monitoring networks. We assumed crustal deformations for the
334 horizontal component in all of the sites using Green's functions calculated using the
335 formulation of ref. 42 considering a homogeneous elastic half-space. The fault models
336 were set depending on the magnitude of every 0.1 and were deployed every 0.1 degree
337 on the plate boundary model (refs 28 and 29), which dip angles at shallower part than 10
338 km were set to roughly match seismic survey results in ref. 43. The fault size of each
339 magnitude was set according to scaling law using in ref. 41, assuming a rigidity of 10
340 GPa. The strike angle of the fault model was set to 249° in most areas and was adjusted
341 in an area where the trough axis angle was largely different. The rake angle was set to
342 90°.

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

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

352

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

361 We detected an SSE signal in these time series based on the method of ref. 22 using c-
362 AIC (refs 20 and 21). We fitted straight and piece-wise lines for the time series and
363 compared each c-AIC to determine if a time series contains SSE-like transient
364 deformation. We rotated a direction of time series every 10 degrees to extract the
365 maximum deformation angle. A deformation duration of the piece-wise line was set to
366 one year which is a typical timescale for long-term SSE. This piece-wise line was fitted
367 for the time series data for all periods. The residual sums of squares (RSSs) in Eq. (1)
368 were calculated for the straight and piece-wise lines for the data for the whole periods.
369 The start timing and scale of deformation were estimated every 0.2 years and every 1 cm
370 between 1 and 20 cm, respectively, and were chosen to minimize c-AIC. We defined Δc -
371 AIC as a difference between c-AICs for the straight line and the piece-wise line. When a
372 deformation signal of Δc -AIC < -6 was detected by the piece-wise line, after removing
373 this detected deformation, the same process was performed. When a signal of Δc -AIC <
374 -6 was not detected, the process ended because there was no clear signal. Signals detected
375 between 2011 and Dec. 2013 were considered to be a remaining influence due to the 2011
376 Tohoku-oki earthquake, even after the deduction process. We identified a signal other
377 than this type of signal as an SSE signal.

378

379 **Grid search process to determine SSE models.** Each SSE fault model that explains the
380 deformation fields determined in the c-AIC detection process was estimated using a grid
381 search technique. We set rectangular fault models for a grid every 0.1 degree on the plate
382 boundary to estimate the weighted RMSEs for the data in the region delimited. The strike
383 angle was set to 249° . The fault length, width, slip and rake angles were properly changed
384 every 10 km between 20 and 100 km, every 10 km between 20 and 50 km in the dip

385 direction, every 4 cm between 2 and 78 cm and every 10° between 70° and 130°,
386 respectively. The dip angle was set along the plate boundary model described in the above
387 section “SSE detectability of the GNSS-A”. Crustal deformations were also calculated
388 using the method and setting described in the above section. We calculated crustal
389 deformations for the horizontal component at seafloor sites and the neighbour onshore
390 GNSS sites of the GEONET. Considering the observation abilities, the weighted RMSE
391 was calculated by multiplying the onshore data by nine times the weight of the seafloor
392 data.

393 Refs 14 and 19 showed unsteady crustal deformation fields detected by GEONET
394 around the Bungo channel and suggested that there was no deformation fields over 5 mm
395 in 2015 and after Apr. 2016. Crustal deformation fields¹⁸ detected by GEONET around
396 the Kii channel and the Kumano-nada also suggested that there was no deformation field
397 over 5 mm in the time periods for calculating SSE models. Then, onshore crustal
398 deformations were assumed to be less than about 5 mm in estimations. Signals off the
399 Bungo channel in 2015 (sites (1) and (3)) and off the Kii channel in 2017 (sites (8) and
400 (9)) were synchronized and were considered to cause each SSE sequence. However, off
401 the Bungo channel, since it was not possible to estimate a single rectangular fault model
402 with an onshore deformation of less than about 5 mm, a rectangular fault was estimated
403 for each site observation. Off the Kii channel, one rectangular fault model was estimated.

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

411

412 **Data availability.** The dataset of seafloor positions is provided in Supplementary Table
413 1.

414

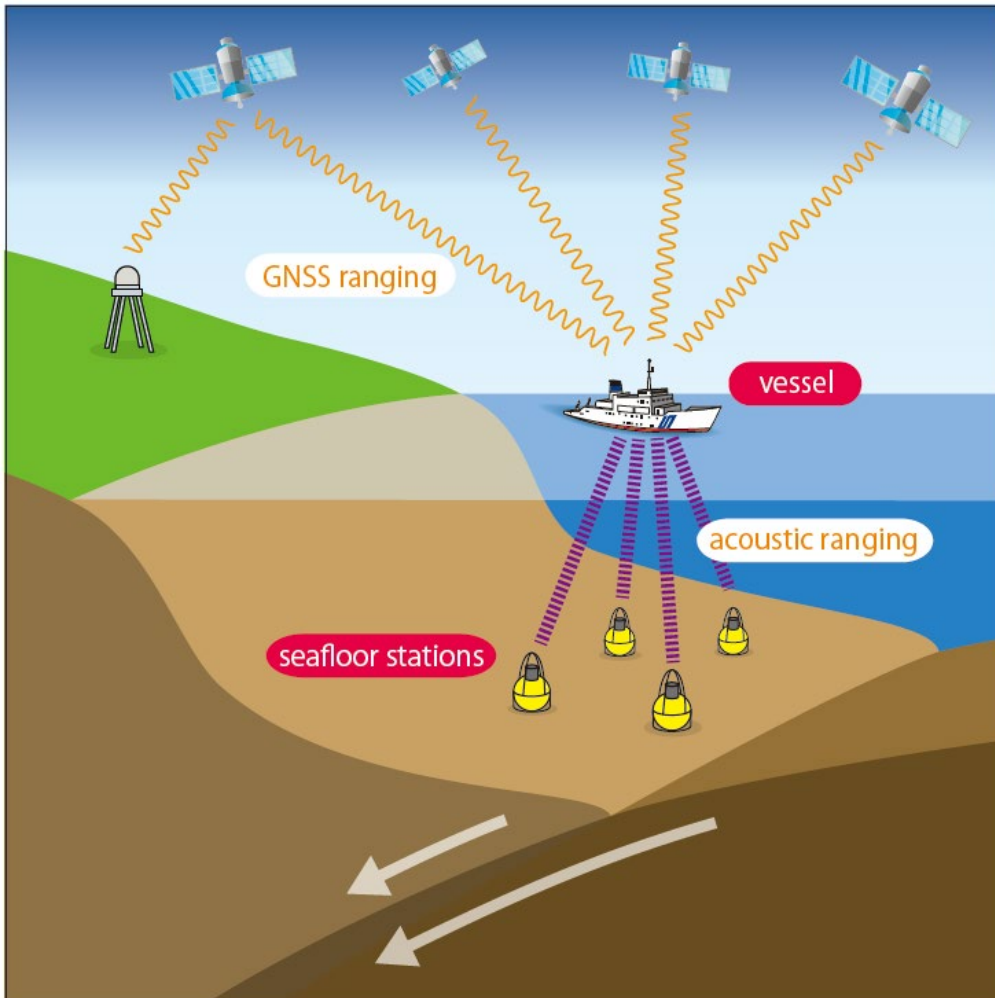
415

416 **References**

- 417 (31) Spiess, F. N. *et al.* Precise GPS/Acoustic positioning of seafloor reference points for
418 tectonic studies. *Phys. Earth Planet. Inter.* **108**, 101–112 (1998).
- 419 (32) Asada, A. & Yabuki, T. Centimeter-level positioning on the seafloor. *Proc. Jpn Acad.*
420 *Ser. B* **77**, 7–12 (2001).
- 421 (33) Fujita, M. *et al.* GPS/acoustic seafloor geodetic observation: method of data analysis
422 and its application. *Earth Planet. Space* **58**, 265–275, doi:10.1007/s00190-013-
423 0649-9 (2006).
- 424 (34) Ishikawa, T. & Yokota, Y. Detection of seafloor movement in subduction zones
425 around Japan using a GNSS-A seafloor geodetic observation system from 2013 to
426 2016. *J. Disaster Res.* **13**(3), 511–517, doi:10.20965/jdr.2018.p0511 (2018).
- 427 (35) Sato, M. *et al.* Interplate coupling off northeastern Japan before the 2011 Tohoku-
428 oki earthquake, inferred from seafloor geodetic data. *J. Geophys. Res.* **118**, 1–10,
429 doi:10.1002/jgrb.50275 (2013).
- 430 (36) Sato, M. *et al.* Displacement above the hypocenter of the 2011 Tohoku-oki
431 earthquake. *Science* **332**, 1395, doi:10.1126/science.1207401 (2011).
- 432 (37) Watanabe, S. *et al.* Evidence of viscoelastic deformation following the 2011 Tohoku-
433 oki earthquake revealed from seafloor geodetic observation. *Geophys. Res. Lett.* **41**,
434 5789–5796, doi:10.1002/2014GL061134 (2014).
- 435 (38) Yokota, Y., Tashiro, T. & Shimomura, H. Implementation of multi-acoustic ranging
436 system. *Rep. Hydro. Ocean Res.* **55**, 32–37 (2017).
- 437 (39) Matsushita, M. & Koike, M. Improving efficiency in seafloor geodetic observation
438 system using a multi-acoustic ranging method. *Rep. Hydro. Ocean Res.* **56**, 46–49
439 (2018).
- 440 (40) Yokota, Y., Ishikawa, T. & Watanabe, S. Seafloor crustal deformation data along the
441 subduction zones around Japan obtained by GNSS-A observations. *Scientific Data*
442 **5**, 180182, doi:10.1038/sdata.2018.182 (2018).
- 443 (41) Suito, H. Detectability of interplate fault slip around Japan, based on GEONET daily
444 solution F3, *Journal of Geod. Soc. Japan* **62**(3), 109–120 (2016).
- 445 (42) Okada, Y. Internal deformation due to shear and tensile faults in a half-space. *Bull.*
446 *Seis. Soc. Am.* **82**(2), 1018–1040 (1992).
- 447 (43) Kimura, G., Kitamura, Y., Hashimoto, Y., Yamaguchi, A., Shibata, T., Ujiie, K. &
448 Okamoto, S. Transition of accretionary wedge structures around the up-dip limit of
449 the seismogenic subduction zone. *Earth Planet. Sci. Lett.* **255**, 471–484,
450 doi:10.1016/j.epsl.2007.01.005 (2007).

- 451 (44) Iinuma, T., *et al.* Coseismic slip distribution of the 2011 off the Pacific Coast of
452 Tohoku Earthquake (M9.0) refined by means of seafloor geodetic data. *J. Geophys.*
453 *Res.* **117**, B07409, doi:10.1029/2012JB009186 (2012).
- 454 (45) Sun, T. *et al.* Prevalence of viscoelastic relaxation after the 2011 Tohoku-oki
455 earthquake. *Nature* **514**, 84–87, doi:10.1038/nature13778 (2014).
- 456 (46) Sun, T. & Wang, K. Viscoelastic relaxation following subduction earthquakes and
457 its effects on afterslip determination. *J. Geophys. Res.* **120**, 1329–1344,
458 doi:10.1002/2004JB011707 (2015).
- 459

460 **Extended Data legends**

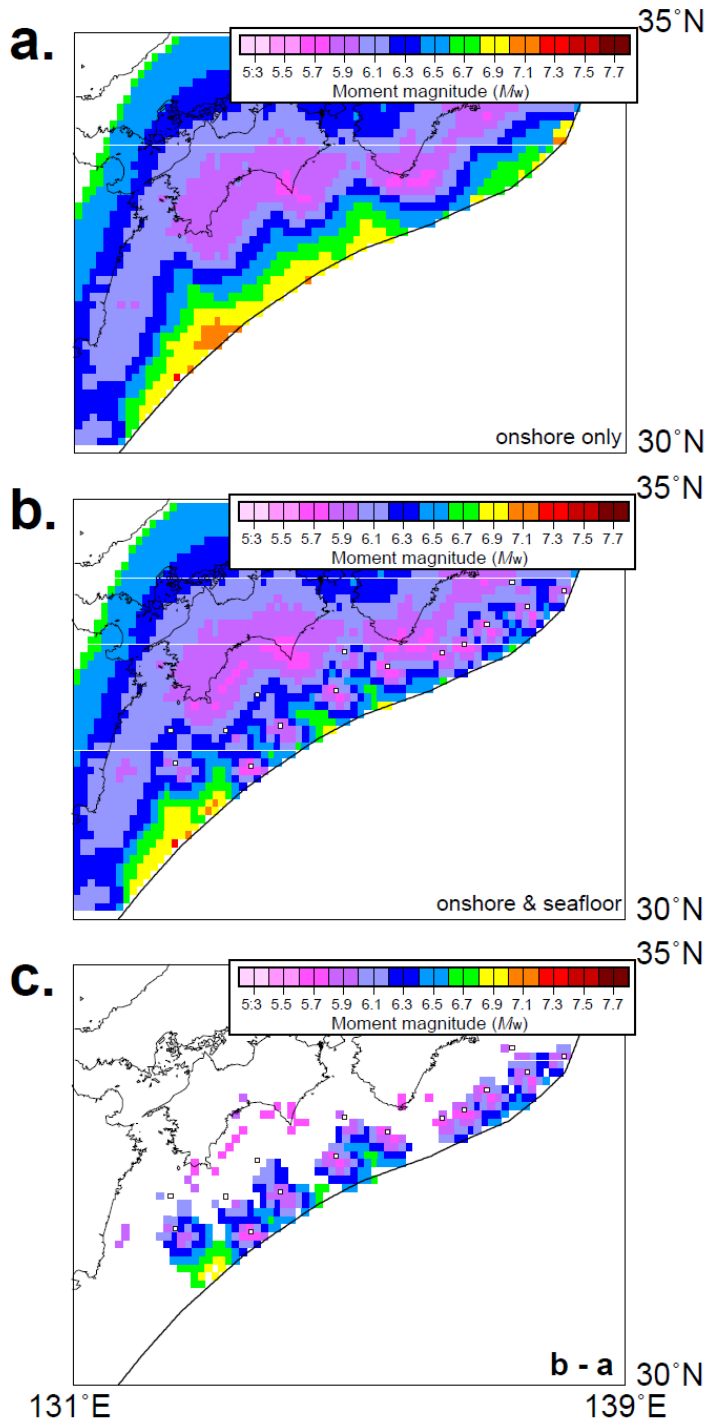


461 **Extended Data Figure 1 | Schematic diagram of the GNSS-A seafloor geodetic**
462 **observation system.** This figure is modified from refs 15, 17, 32, 33 and 34.

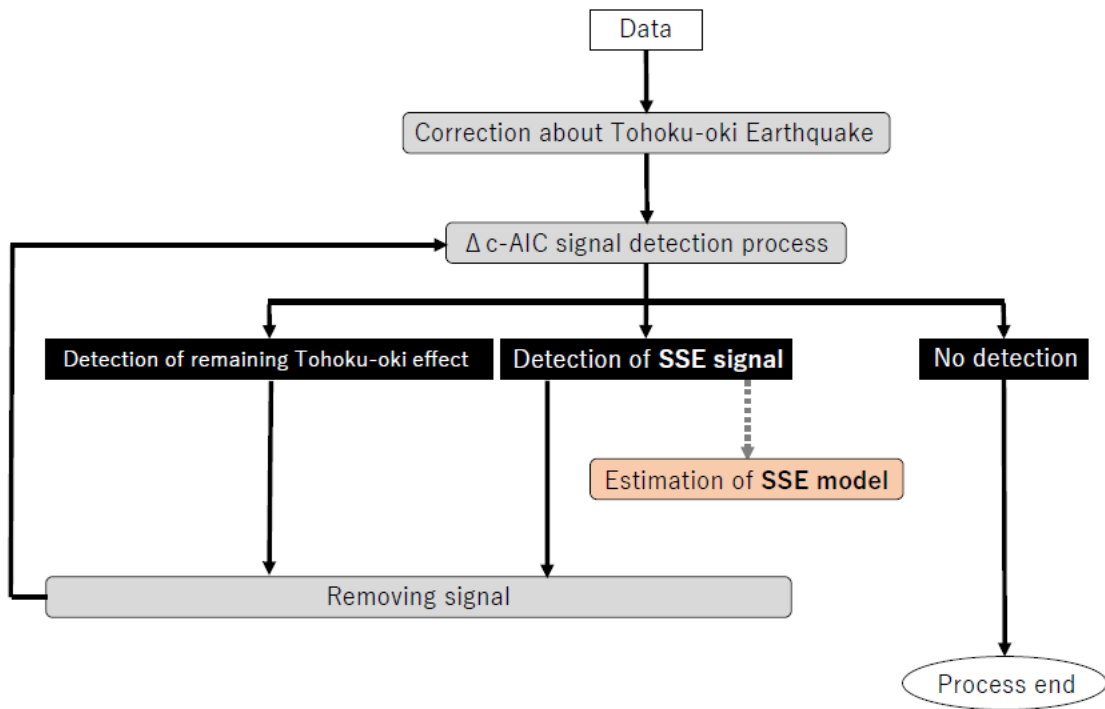
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464

465



466 **Extended Data Figure 2 | Maps representing SSE detectability constructed using, a,**
 467 **the onshore GNSS network only and, b, onshore and seafloor GNSS-A networks. c,**
 468 **Maps representing SSEs which can be detected only by the seafloor GNSS-A**
 469 **network.** Colour contours indicate the magnitude of detectable minimum events at each
 470 grid on the plate boundary.
 471

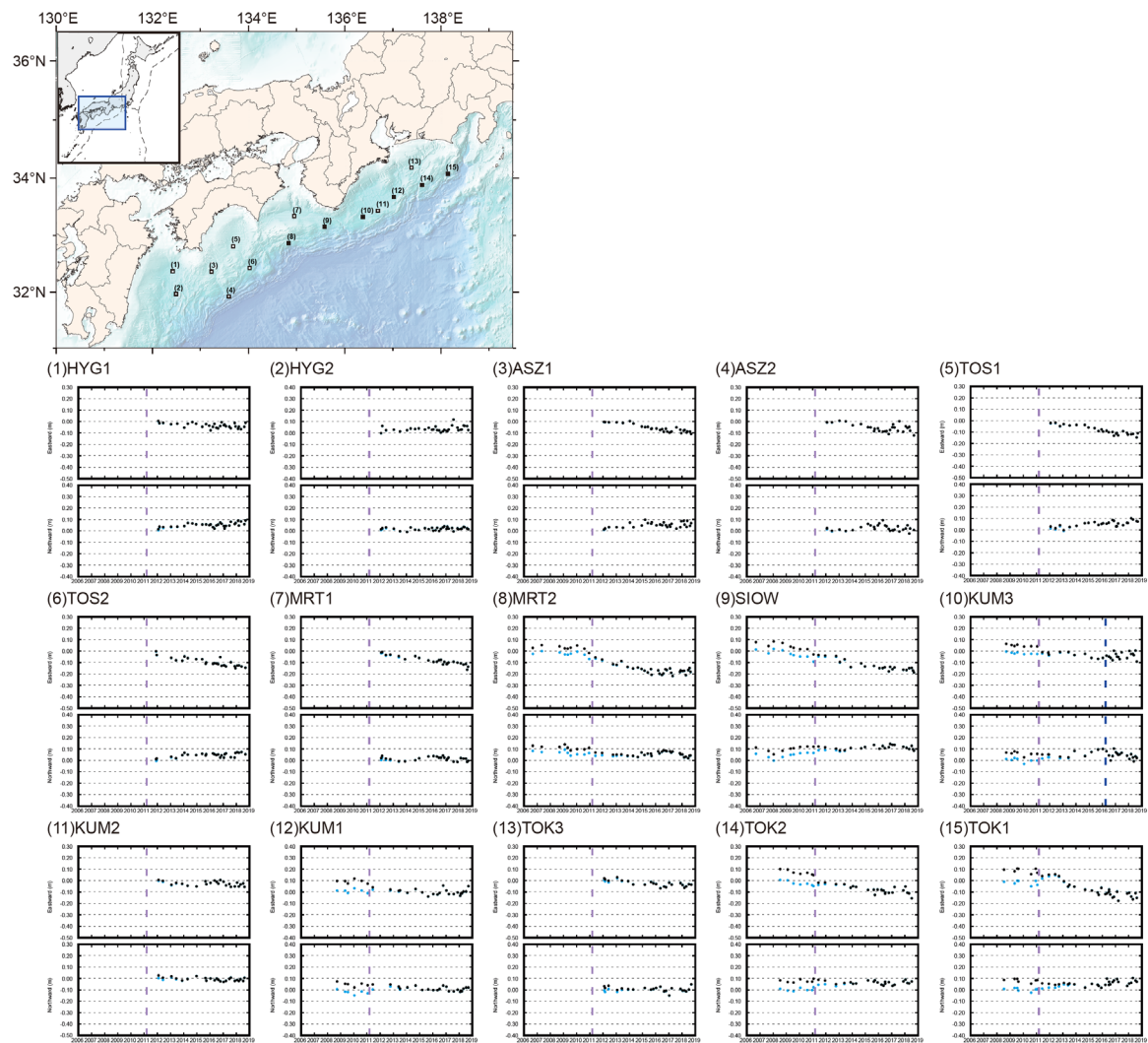


472 **Extended Data Figure 3 | Flow of the SSE signal detection process.**

473

474

475

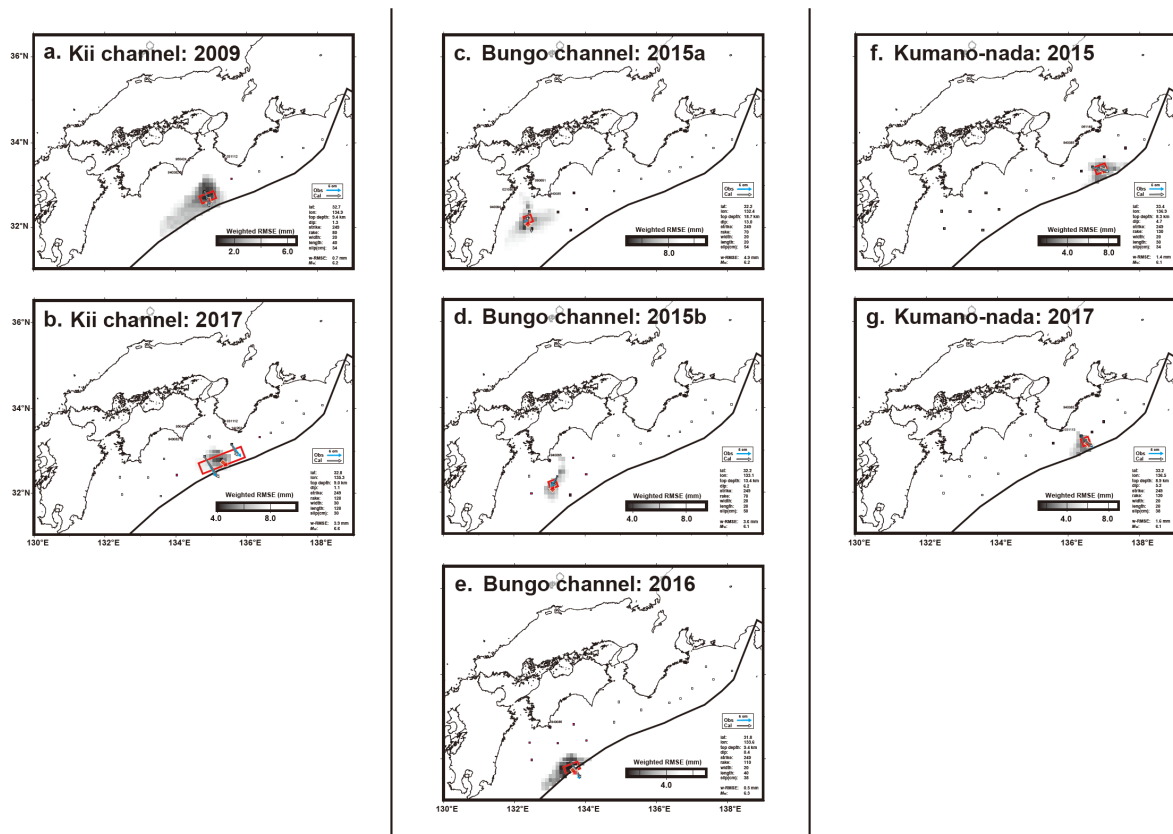


476 **Extended Data Figure 4 | Time series of horizontal components of seafloor GNSS-A**
 477 **data.** Black circles indicate seafloor positions after deduction of deformations due to the
 478 2011 Tohoku-oki earthquake based on refs 44, 45 and 46. Blue circles indicate raw data
 479 before deduction. The reference frame is ITRF2005 (ref. 30).

480
 481



483 **series.** Each time series was described in the direction with the maximum likelihood
 484 solution in the SSE signal detection process. The reference frame is ITRF2005 (ref. 30).
 485 The results for each step were obtained in order from the left. Red lines indicate straight
 486 and piece-wise lines estimated as the maximum likelihood solutions. Grey histograms are
 487 Δ c-AIC time series (bin range: one year) in the process every 0.2 years. Light-blue and
 488 green bins are Δ c-AIC in the cases that were judged as SSE signals and as remaining
 489 influences due to the 2011 Tohoku-oki earthquake, respectively. Purple and blue dashed
 490 lines indicate the 2011 Tohoku-oki earthquake and the 2016 M_w 5.8 earthquake in the
 491 Kumano-nada region, respectively.
 492



493 **Extended Data Figure 6 | Grid search results for estimating SSE models; a and b,**
 494 **off the Kii channel in 2009 and after 2017, c - e, off the Bungo channel around site**
 495 **(1) and site (3) in 2015 and in 2016 and f and g, around Kumano-nada in 2015 and**
 496 **2017.** Grey regions indicate distributions of SSE model centres with weighted RMSEs
 497 calculated in the range between the minimum and 4 mm greater than the minimum. Red
 498 rectangles indicate the final obtained rectangular fault models in the results. Blue and
 499 white vectors are observed and calculated movements for the sites, respectively. Fault
 500 parameters are listed at the right bottom. Pink and light-blue squares and light-blue circles

501 are the seafloor sites moved due to SSEs, unmoved sites and onshore GEONET sites used
502 in the grid search, respectively. GEONET site codes are described beside the sites. Open
503 squares are the seafloor sites that were not used in the grid search.

504

505 **Supplementary Table legends**

506 **Supplementary Table 1 | Time series of seafloor positions.** The reference frame is
507 ITRF2005 (ref. 30). The first column shows an observation epoch. Eastward and
508 Northward components (second and third columns) indicate the data corrected the
509 coseismic and postseismic effects due to the Tohoku-oki earthquake. $East_{raw}$ and
510 $North_{raw}$ components (forth and fifth columns) are raw data before March 2014.

511

(1) HYG1

Epoch (year)	Eastward (m)	Northwar d (m)	East _{raw} (m)	North _{raw} (m)
2012.077	0	0	0	0
2012.162	-0.02	0.022	-0.02	0.023
2012.447	-0.018	0.019	-0.017	0.022
2013.044	-0.03	0.022	-0.029	0.028
2013.518	-0.024	0.022	-0.023	0.031
2014.047	-0.059	0.026	-0.057	0.038
2014.318	-0.025	0.054		
2014.66	-0.011	0.05		
2014.942	-0.025	0.041		
2015.411	-0.051	0.04		
2015.696	-0.029	0.041		
2015.94	-0.042	0.035		
2016.044	-0.083	0.04		
2016.219	-0.052	0.018		
2016.334	-0.026	0.005		
2016.485	-0.061	0.032		
2016.608	-0.066	0.039		
2016.775	-0.046	0.057		
2016.877	-0.013	0.046		
2017.047	-0.037	0.026		
2017.104	-0.033	0.006		
2017.208	-0.047	0.027		
2017.466	-0.051	0.03		
2017.575	-0.065	0.064		
2017.874	-0.019	0.044		
2017.94	-0.049	0.054		
2018.129	-0.069	0.073		
2018.192	-0.051	0.031		
2018.351	-0.072	0.068		
2018.605	-0.052	0.042		
2018.696	-0.017	0.074		

(2) HYG2

Epoch (year)	Eastward (m)	Northwar d (m)	East _{raw} (m)	North _{raw} (m)
2012.074	0	0	0	0

2012.17	0.062	0.011	0.062	0.011
2012.452	0.025	0.017	0.025	0.019
2013.047	0.03	0.006	0.03	0.011
2013.518	0.016	-0.017	0.017	-0.01
2014.049	0.025	-0.025	0.026	-0.016
2014.321	0.04	0.015		
2014.658	0.036	-0.005		
2014.94	0.041	-0.008		
2015.408	0.032	0.01		
2015.699	0.046	0.001		
2015.948	0.029	0.012		
2016.044	0.033	-0.013		
2016.216	0.058	-0.009		
2016.337	0.026	0.013		
2016.488	0.024	-0.015		
2016.611	0.003	0.004		
2016.775	0.016	0.016		
2016.877	0.028	0.026		
2017.047	0.02	0.004		
2017.107	0.016	0.023		
2017.208	0.032	0.006		
2017.466	0.068	0.011		
2017.575	0.119	-0.019		
2017.874	0.049	0.008		
2017.942	0.025	0		
2018.132	0.029	0.003		
2018.195	0.031	0.006		
2018.345	0.067	0.021		
2018.4	0.063	0.019		
2018.605	0.061	0.008		
2018.699	0.027	0.001		

(3) ASZ1

Epoch (year)	Eastward (m)	Northward (m)	East _{raw} (m)	North _{raw} (m)
2012.077	0	0	0	0
2012.159	-0.002	0.01	-0.002	0.011
2012.455	-0.003	0.021	-0.003	0.025
2013.036	-0.004	0.02	-0.002	0.027

2013.512	-0.01	0.015	-0.008	0.025
2014.044	0.008	0.06	0.011	0.072
2014.315	-0.014	0.02		
2014.945	-0.041	0.035		
2015.195	-0.045	0.085		
2015.405	-0.043	0.056		
2015.663	-0.061	0.05		
2015.701	-0.058	0.062		
2016.058	-0.058	0.037		
2016.334	-0.071	0.043		
2016.49	-0.063	0.037		
2016.614	-0.085	0.062		
2016.773	-0.06	0.038		
2016.877	-0.085	0.022		
2017.047	-0.095	0.038		
2017.107	-0.092	0.025		
2017.208	-0.084	0.049		
2017.575	-0.047	0.008		
2017.871	-0.069	0.021		
2017.942	-0.098	0.073		
2018.129	-0.077	0.075		
2018.195	-0.071	0.042		
2018.351	-0.095	0.023		
2018.397	-0.083	0.076		
2018.608	-0.084	0.032		
2018.69	-0.106	0.056		

(4) ASZ2

Epoch (year)	Eastward (m)	Northward (m)	East _{raw} (m)	North _{raw} (m)
2012.082	0	0	0	0
2012.088	-0.003	0.003	-0.002	0.003
2012.463	-0.002	-0.021	-0.001	-0.019
2013.033	0.012	-0.01	0.013	-0.005
2013.51	0.008	-0.022	0.009	-0.015
2014.041	-0.027	-0.017	-0.025	-0.007
2014.666	-0.018	0.011		
2015.197	-0.043	0.038		
2015.403	-0.045	0.026		

2015.666	-0.079	0.012
2015.704	-0.058	-0.006
2015.951	-0.055	0.026
2016.06	-0.077	0.044
2016.332	-0.083	0.07
2016.501	-0.079	0.025
2016.614	-0.078	0.018
2016.773	-0.105	-0.005
2016.874	-0.069	-0.022
2017.049	-0.044	-0.017
2017.107	-0.02	-0.02
2017.211	-0.046	-0.012
2017.466	-0.076	0.018
2017.578	0.009	-0.028
2017.871	-0.084	-0.011
2018.068	-0.036	-0.001
2018.197	-0.051	0.027
2018.332	-0.041	-0.046
2018.397	-0.075	-0.001
2018.688	-0.116	-0.015

(5) TOS1

Epoch (year)	Eastward (m)	Northward (m)	East _{raw} (m)	North _{raw} (m)
2012.074	0	0	0	0
2012.444	0.002	-0.014	0.003	-0.011
2012.786	-0.028	0.012	-0.026	0.018
2013.068	-0.011	-0.032	-0.008	-0.023
2013.521	-0.022	-0.003	-0.018	0.009
2014.038	-0.018	0.006	-0.013	0.021
2014.668	-0.018	0.029		
2014.951	-0.04	0.032		
2015.414	-0.046	0.038		
2015.707	-0.071	0.014		
2015.937	-0.056	0.022		
2016.055	-0.076	0.029		
2016.321	-0.068	0.024		
2016.49	-0.083	0.033		
2016.778	-0.08	0.056		

2016.879	-0.112	0.05
2017.049	-0.094	0.001
2017.104	-0.087	0.002
2017.205	-0.109	0.027
2017.581	-0.071	0.012
2017.877	-0.087	0.032
2017.945	-0.103	0.031
2018.192	-0.1	0.072
2018.329	-0.096	0.062
2018.608	-0.127	0.047
2018.69	-0.09	0.043

(6) TOS2

Epoch (year)	Eastward (m)	Northward (m)	East _{raw} (m)	North _{raw} (m)
2011.904	0	0	0	0
2011.951	-0.033	0.008	-0.033	0.008
2013.055	-0.058	0.022	-0.056	0.031
2013.419	-0.079	0.009	-0.076	0.021
2013.899	-0.083	0.036	-0.079	0.05
2014.06	-0.046	0.056	-0.043	0.072
2014.312	-0.061	0.04		
2014.948	-0.071	0.035		
2015.4	-0.071	0.047		
2015.668	-0.11	0.032		
2015.704	-0.098	0.043		
2016.222	-0.11	0.05		
2016.329	-0.106	0.043		
2016.479	-0.108	0.036		
2016.616	-0.113	0.041		
2016.773	-0.052	0.014		
2016.874	-0.129	0.033		
2017.049	-0.124	0.013		
2017.118	-0.128	0.043		
2017.211	-0.134	0.05		
2017.578	-0.096	0.017		
2017.868	-0.132	0.014		
2017.932	-0.149	0.055		
2018.068	-0.127	0.062		

2018.197	-0.125	0.057
2018.395	-0.134	0.063
2018.688	-0.146	0.043

(7) MRT1

Epoch (year)	Eastward (m)	Northwar d (m)	East _{raw} (m)	North _{raw} (m)
2012.09	0	0	0	0
2012.156	0.003	0.018	0.003	0.02
2012.438	-0.023	-0.005	-0.021	0
2012.775	-0.019	-0.011	-0.016	-0.003
2013.425	-0.042	-0.029	-0.036	-0.014
2013.896	-0.061	-0.03	-0.053	-0.01
2014.674	-0.034	-0.02		
2014.967	-0.05	-0.003		
2015.674	-0.071	0.013		
2016.063	-0.084	0.017		
2016.318	-0.083	0.013		
2016.477	-0.069	0.002		
2016.627	-0.066	0.003		
2016.778	-0.105	0.021		
2016.879	-0.084	0.003		
2017.052	-0.103	-0.019		
2017.101	-0.101	-0.01		
2017.197	-0.089	0.003		
2017.581	-0.083	-0.032		
2017.877	-0.09	-0.034		
2018.126	-0.097	-0.001		
2018.329	-0.107	-0.006		
2018.515	-0.102	-0.006		
2018.611	-0.153	-0.034		
2018.685	-0.126	-0.026		

(8) MRT2

Epoch (year)	Eastward (m)	Northwar d (m)	East _{raw} (m)	North _{raw} (m)
2006.668	0	0	0	0
2007.351	0.025	-0.01	0.024	-0.009
2008.71	0.014	-0.011	0.013	-0.011

2009.11	-0.003	0.012	-0.004	0.012
2009.332	-0.006	-0.017	-0.006	-0.017
2009.556	0.002	-0.042	0.001	-0.041
2010.049	0.021	-0.029	0.02	-0.029
2010.603	-0.006	-0.032	-0.007	-0.031
2010.956	-0.044	-0.019	-0.045	-0.018
2011.441	-0.084	-0.06	-0.04	-0.043
2011.951	-0.102	-0.064	-0.056	-0.039
2012.784	-0.142	-0.079	-0.093	-0.046
2013.058	-0.147	-0.078	-0.099	-0.042
2013.422	-0.115	-0.077	-0.065	-0.038
2013.893	-0.167	-0.088	-0.116	-0.046
2014.304	-0.181	-0.089		
2014.671	-0.173	-0.105		
2014.953	-0.184	-0.054		
2015.178	-0.199	-0.082		
2015.425	-0.215	-0.07		
2015.671	-0.186	-0.07		
2015.715	-0.235	-0.09		
2016.225	-0.197	-0.05		
2016.318	-0.226	-0.069		
2016.504	-0.237	-0.054		
2016.619	-0.225	-0.042		
2016.77	-0.188	-0.043		
2016.871	-0.194	-0.048		
2017.121	-0.18	-0.049		
2017.211	-0.218	-0.06		
2017.321	-0.245	-0.051		
2017.877	-0.21	-0.066		
2017.932	-0.197	-0.076		
2018.071	-0.203	-0.077		
2018.2	-0.2	-0.102		
2018.329	-0.239	-0.097		
2018.512	-0.194	-0.11		
2018.611	-0.177	-0.088		
2018.685	-0.21	-0.086		

Epoch (year)	Eastward (m)	Northwar d (m)	East _{raw} (m)	North _{raw} (m)
2006.693	0	0	0	0
2007.647	-0.034	-0.03	-0.034	-0.03
2008.038	0.006	-0.059	0.006	-0.059
2008.71	-0.006	-0.028	-0.006	-0.029
2009.323	-0.039	-0.009	-0.039	-0.009
2009.553	-0.05	-0.005	-0.05	-0.006
2010.047	-0.061	0.006	-0.061	0.005
2010.603	-0.061	0.01	-0.061	0.01
2011.063	-0.107	0.008	-0.107	0.008
2011.441	-0.112	0.01	-0.062	0.03
2011.948	-0.119	0.003	-0.065	0.032
2012.778	-0.122	-0.009	-0.065	0.03
2013.063	-0.174	-0.026	-0.116	0.017
2013.427	-0.15	-0.023	-0.091	0.023
2013.89	-0.218	-0.003	-0.157	0.048
2014.682	-0.185	-0.006		
2014.973	-0.212	0.005		
2015.655	-0.208	0.022		
2016.071	-0.228	-0.01		
2016.315	-0.227	0.014		
2016.474	-0.22	-0.005		
2016.781	-0.256	0.003		
2016.882	-0.216	0.032		
2017.058	-0.237	0.024		
2017.214	-0.222	0.023		
2017.879	-0.242	0.007		
2018.123	-0.244	-0.002		
2018.326	-0.228	-0.013		
2018.515	-0.226	0.015		
2018.614	-0.248	-0.014		
2018.682	-0.264	-0.028		

(10) KUM3

Epoch (year)	Eastward (m)	Northwar d (m)	East _{raw} (m)	North _{raw} (m)
2008.707	0	0	0	0
2009.112	-0.009	-0.007	-0.009	-0.008

2009.334	-0.018	0.011	-0.018	0.01
2009.551	-0.006	0.002	-0.006	0.002
2010.06	-0.022	-0.042	-0.022	-0.043
2010.6	-0.02	-0.012	-0.02	-0.013
2011.058	-0.021	-0.012	-0.021	-0.012
2011.438	-0.071	-0.017	-0.015	0.005
2011.899	-0.075	-0.016	-0.015	0.015
2011.945	-0.093	-0.017	-0.033	0.015
2012.795	-0.069	-0.036	-0.006	0.008
2013.43	-0.07	-0.042	-0.004	0.009
2013.888	-0.097	0.015	-0.029	0.07
2014.685	-0.087	-0.031		
2015.175	-0.122	0.005		
2015.677	-0.13	0.027		
2016.038	-0.122	0.031		
2016.312	-0.103	0.012		
2016.507	-0.11	-0.026		
2016.633	-0.123	-0.069		
2016.781	-0.141	-0.031		
2016.882	-0.058	0.035		
2017.033	-0.087	0.004		
2017.121	-0.111	-0.009		
2017.214	-0.114	-0.02		
2017.318	-0.133	-0.016		
2017.468	-0.072	-0.002		
2017.879	-0.123	-0.028		
2018.058	-0.06	-0.057		
2018.189	-0.088	-0.015		
2018.326	-0.087	-0.043		
2018.392	-0.098	-0.077		
2018.518	-0.057	-0.033		
2018.616	-0.154	-0.046		

(11) KUM2

Epoch (year)	Eastward (m)	Northward (m)	East _{raw} (m)	North _{raw} (m)
2012.093	0	0	0	0
2012.427	-0.009	-0.02	-0.008	-0.015
2013.074	-0.043	-0.009	-0.039	0.005

2013.433	-0.027	-0.028	-0.021	-0.01
2013.885	-0.033	-0.045	-0.026	-0.023
2014.299	-0.051	-0.032		
2014.975	-0.057	-0.007		
2015.652	-0.012	-0.024		
2015.723	-0.037	-0.047		
2016.036	-0.026	-0.028		
2016.348	-0.006	-0.044		
2016.507	-0.017	-0.028		
2016.633	-0.032	-0.039		
2016.784	0	-0.052		
2017.03	-0.015	-0.057		
2017.214	-0.048	-0.048		
2017.468	-0.035	-0.031		
2017.584	-0.062	-0.02		
2017.882	-0.057	-0.049		
2018.058	-0.024	-0.041		
2018.192	-0.058	-0.049		
2018.323	-0.04	-0.034		
2018.521	-0.03	-0.049		
2018.616	-0.062	-0.021		

(12) KUM1

Epoch (year)	Eastward (m)	Northwar d (m)	East _{raw} (m)	North _{raw} (m)
2008.729	0	0	0	0
2009.337	0	-0.02	-0.001	-0.02
2009.551	-0.02	-0.024	-0.021	-0.024
2010.041	0.021	-0.053	0.021	-0.053
2010.597	0.001	-0.018	0.001	-0.018
2011.055	-0.022	-0.034	-0.022	-0.034
2011.438	-0.056	-0.027	0.011	0
2012.773	-0.074	-0.027	0.003	0.025
2013.408	-0.086	-0.045	-0.006	0.015
2013.507	-0.081	-0.063	0	-0.002
2014.066	-0.103	-0.052	-0.019	0.016
2014.69	-0.07	-0.036		
2015.2	-0.099	-0.074		
2015.647	-0.136	-0.069		

2016.036	-0.113	-0.076
2016.351	-0.118	-0.076
2016.51	-0.104	-0.066
2016.784	-0.039	-0.036
2017.03	-0.082	-0.046
2017.216	-0.113	-0.085
2017.584	-0.113	-0.086
2017.882	-0.1	-0.072
2018.074	-0.128	-0.091
2018.121	-0.109	-0.081
2018.203	-0.108	-0.086
2018.323	-0.092	-0.064
2018.521	-0.092	-0.053
2018.701	-0.044	-0.053

(13) TOK3

Epoch (year)	Eastward (m)	Northward (m)	East _{raw} (m)	North _{raw} (m)
2012.096	0	0	0	0
2012.153	-0.01	-0.015	-0.01	-0.014
2012.422	-0.022	0.004	-0.019	0.012
2013.077	0.009	-0.032	0.017	-0.013
2013.436	-0.02	-0.02	-0.009	0.005
2013.91	-0.025	-0.026	-0.009	0.006
2014.293	-0.055	-0.028		
2015.17	-0.056	-0.015		
2015.644	-0.032	-0.029		
2015.825	-0.044	-0.024		
2016.033	-0.05	-0.015		
2016.353	-0.088	-0.004		
2016.636	-0.073	-0.045		
2016.786	-0.079	-0.04		
2017.03	-0.04	-0.081		
2017.216	-0.056	-0.018		
2017.885	-0.042	-0.024		
2018.044	-0.06	-0.038		
2018.181	-0.083	-0.037		
2018.321	-0.072	-0.045		
2018.521	-0.052	-0.029		

2018.704 -0.056 0.017

(14) TOK2

Epoch (year)	Eastward (m)	Northwar d (m)	East _{raw} (m)	North _{raw} (m)
2008.529	0	0	0	0
2009.104	-0.003	-0.014	-0.003	-0.014
2009.548	-0.03	-0.019	-0.031	-0.019
2010.063	-0.04	0.011	-0.04	0.011
2010.595	-0.032	-0.01	-0.032	-0.01
2010.964	-0.047	-0.01	-0.047	-0.01
2011.066	-0.053	0.014	-0.053	0.014
2011.436	-0.119	0.006	-0.045	0.037
2011.942	-0.118	-0.002	-0.036	0.043
2012.77	-0.13	-0.033	-0.044	0.026
2013.405	-0.131	-0.023	-0.041	0.045
2013.882	-0.162	-0.016	-0.069	0.057
2014.068	-0.149	-0.029	-0.055	0.047
2014.296	-0.157	-0.027		
2015.203	-0.182	0		
2015.641	-0.18	-0.01		
2015.726	-0.226	0.001		
2015.932	-0.18	-0.019		
2016.227	-0.181	-0.039		
2016.378	-0.188	-0.046		
2016.512	-0.206	-0.028		
2016.501	-0.214	-0.012		
2016.784	-0.208	-0.016		
2017.06	-0.206	-0.048		
2017.216	-0.157	-0.04		
2017.885	-0.186	-0.009		
2018.044	-0.152	0.007		
2018.192	-0.207	-0.024		
2018.321	-0.212	-0.026		
2018.523	-0.255	-0.009		

(15) TOK1

Epoch (year)	Eastward (m)	Northwar d (m)	East _{raw} (m)	North _{raw} (m)
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2008.54	0	0	0	0
2009.34	-0.014	0.009	-0.014	0.009
2009.545	0.009	0.009	0.009	0.009
2009.627	0.007	-0.014	0.007	-0.014
2010.595	-0.039	-0.032	-0.04	-0.032
2010.948	0.008	-0.003	0.008	-0.004
2011.068	-0.028	-0.002	-0.028	-0.002
2011.436	-0.056	-0.029	0.027	0.005
2011.942	-0.045	-0.034	0.048	0.014
2012.419	-0.04	-0.044	0.056	0.013
2012.71	-0.056	-0.038	0.042	0.024
2013.085	-0.102	-0.027	-0.002	0.041
2013.403	-0.148	-0.038	-0.046	0.035
2013.501	-0.132	-0.03	-0.03	0.044
2013.879	-0.15	-0.038	-0.045	0.041
2014.693	-0.176	-0.067		
2015.205	-0.184	-0.034		
2015.641	-0.201	-0.043		
2015.726	-0.221	-0.052		
2015.923	-0.16	-0.069		
2016.23	-0.214	-0.044		
2016.356	-0.208	0.011		
2016.515	-0.176	-0.016		
2016.504	-0.195	-0.044		
2016.597	-0.218	-0.04		
2016.786	-0.245	-0.019		
2016.885	-0.239	-0.005		
2017.123	-0.193	0.007		
2017.219	-0.275	-0.017		
2017.888	-0.209	-0.053		
2018.041	-0.203	-0.031		
2018.195	-0.237	-0.026		
2018.318	-0.261	0.017		
2018.523	-0.207	-0.006		
2018.619	-0.247	-0.016		