

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 earthquakes<sup>1-7</sup>. 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 zones<sup>8-11</sup>, including the**  
16 **Nankai Trough off southwestern Japan on which megathrust earthquakes are**  
17 **predicted to occur<sup>12-13</sup>. 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<sup>4,6,14</sup>, 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 networks<sup>1-3</sup>. Along the  
35 Nankai Trough in western Japan, where recurring interplate megathrust earthquakes have  
36 occurred<sup>12-13</sup> and which has a dense seismic and geodetic monitoring network, their  
37 interrelationships were discussed and compared in detail<sup>3-6</sup>. 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 strainmeters<sup>7-11</sup>. 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 condition<sup>15-16</sup> along the Nankai  
54 Trough subduction zone. Recently, we improved GNSS-A technology and upgraded  
55 observation sensitivity<sup>17</sup> 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<sup>14,18-19</sup>. 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  $\Delta\text{c-AICs}$  and signal detected periods were compared with  
80 the time series of neighbour VLF activity<sup>7</sup> 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 activity<sup>18</sup>  
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 SSEs<sup>18-19</sup> 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 duration<sup>4</sup> and had no  
99 significant difference from deep SSEs<sup>14</sup>.

100 In a deep region around the Bungo channel, SSEs repeatedly occurred<sup>19,23</sup>. 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 studies<sup>3</sup>. The migration speed of the  
108 shallow SSE was approximately 50 – 100 km/year. This speed is much lower than other  
109 SEQs<sup>8</sup> but similar with deep long-term SSEs<sup>14</sup>.

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 structure<sup>24</sup>. 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 activity<sup>10</sup>, 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 small<sup>10</sup>, 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 SSEs<sup>11</sup>. 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<sup>18-19,25</sup>. 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 region<sup>25</sup>,  
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 regions<sup>15-16</sup> overlapped assumed and historical  
146 seismogenic zones<sup>12-13</sup>. 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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263

### 264 **Author Contributions**

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.

268

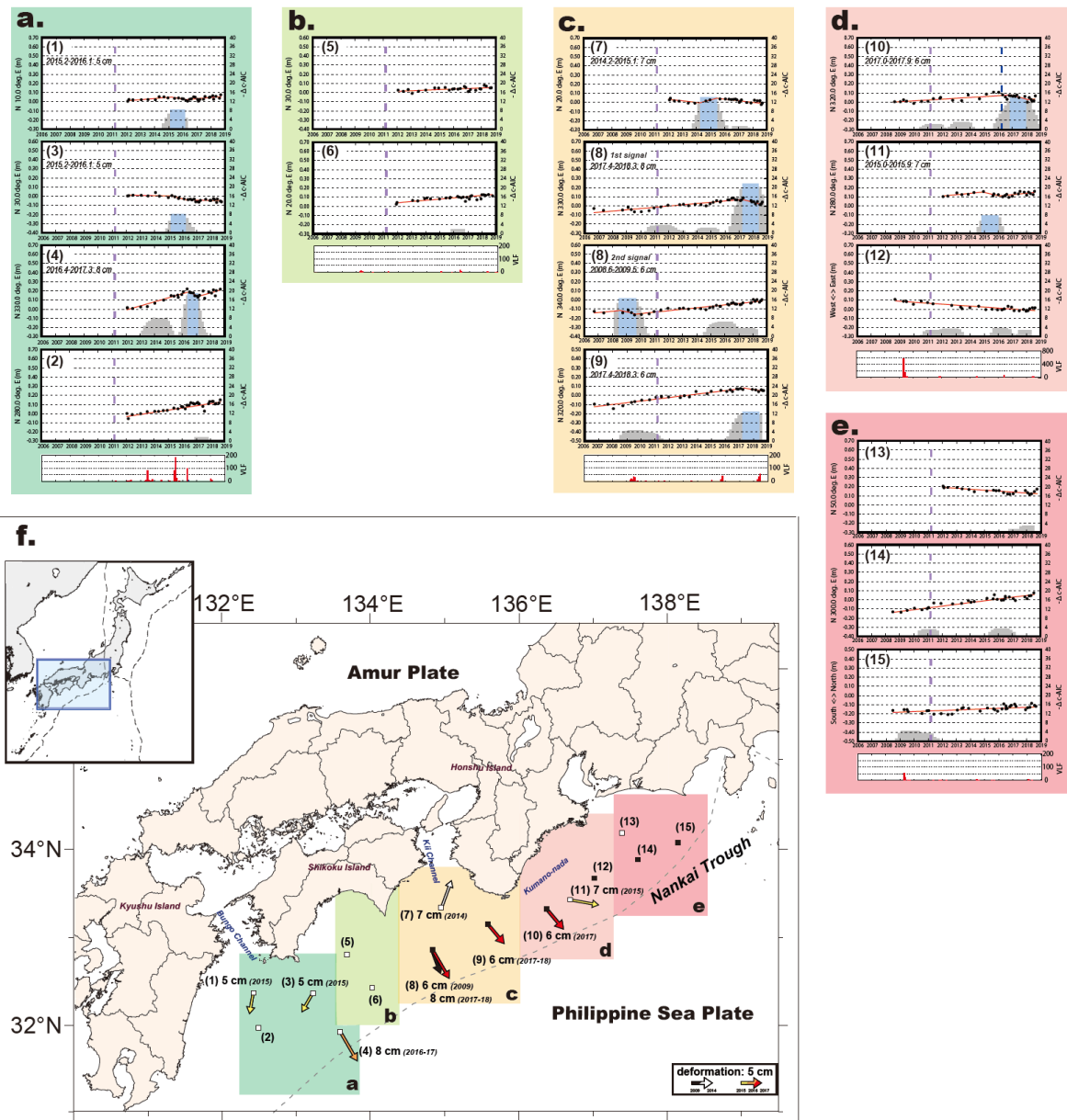
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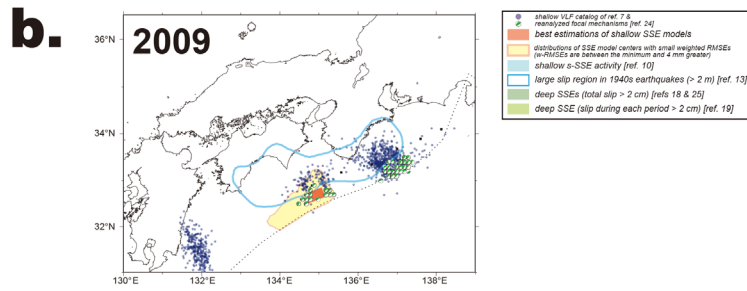
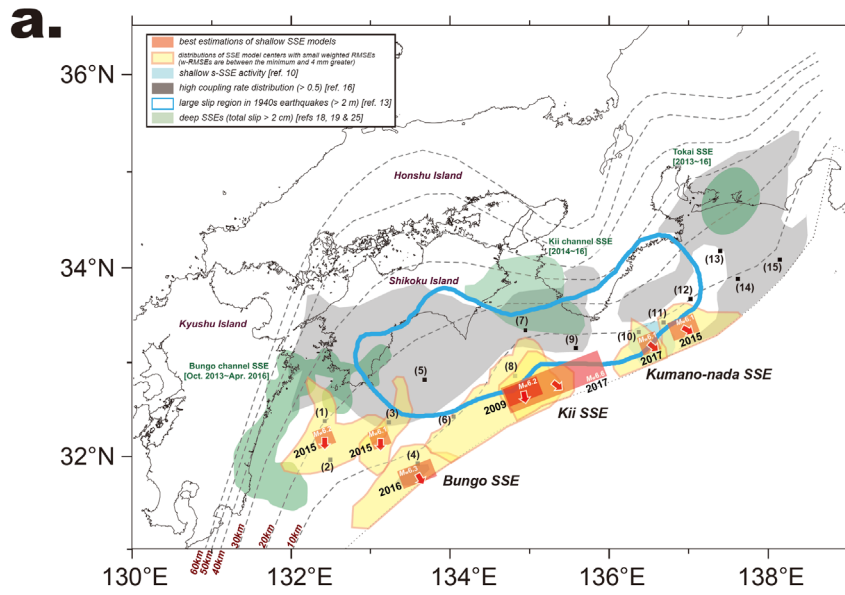
273





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

284 bin is the case that was judged as an SSE signal. Bottom red histograms are shallow VLF  
285 numbers<sup>7</sup> within coloured regions in **f** every month. Purple and blue dashed lines indicate  
286 the 2011 Tohoku-oki earthquake and the 2016  $M_w$  5.8 earthquake in the Kumano-nada  
287 region, respectively. **f, Seafloor crustal deformations detected in the SSE signal**  
288 **detection process.** Vectors indicated seafloor crustal deformations detected in the GNSS-  
289 A data. Closed and open squares are the seafloor observation sites set before and after  
290 2011, respectively.  
291  
292



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

294 **distribution and deep SSEs along the Nankai Trough.** Red rectangles and vectors are  
295 shallow SSE models and slip angles, respectively, estimated by the grid search. The  
296 yellow regions show distributions of SSE model centres with weighted RMSEs calculated  
297 in the range between the minimum and 4 mm greater than the minimum. The light-blue  
298 polygon indicates the Kumano-nada short-term SSE activity region detected by  
299 submarine borehole monitoring<sup>10</sup>. The grey contour map indicates high coupling rate  
300 distribution<sup>16</sup> (rate: more than 0.5). The light-blue solid line indicates the most recent  
301 seismogenic region<sup>13</sup> (slip: more than 2 m). Green regions indicate deep SSE regions<sup>18-</sup>  
302 <sup>19,25</sup> (total slip: more than 2 cm). Dashed lines indicate the depths of the plate boundary  
303 of refs 28 and 29. Closed squares are the seafloor observation sites. **b, Snapshots of**  
304 **detected shallow SSEs in 2009 and 2012 - 2018.** Blue dots indicate shallow VLF  
305 activities<sup>7</sup> in each year. Green focal mechanisms of VLFs (134.5°E – 137.5°E) were  
306 estimated in ref. 24 by reanalysis of a part of the VLF catalogue of ref. 7 in consideration  
307 of the 3D structure. Green regions indicate deep Kii and Tokai SSE regions<sup>18,25</sup> (total slip:  
308 more than 2 cm). Light-green regions indicate deep Bungo SSE regions<sup>19</sup> (slip during  
309 each period: more than 2 cm).  
310

311 **Methods**

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

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

327

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

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

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

350

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

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

376

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

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

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

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

409

410 **Data availability.** The dataset of seafloor positions is provided in Supplementary Table  
411 1.

412

413

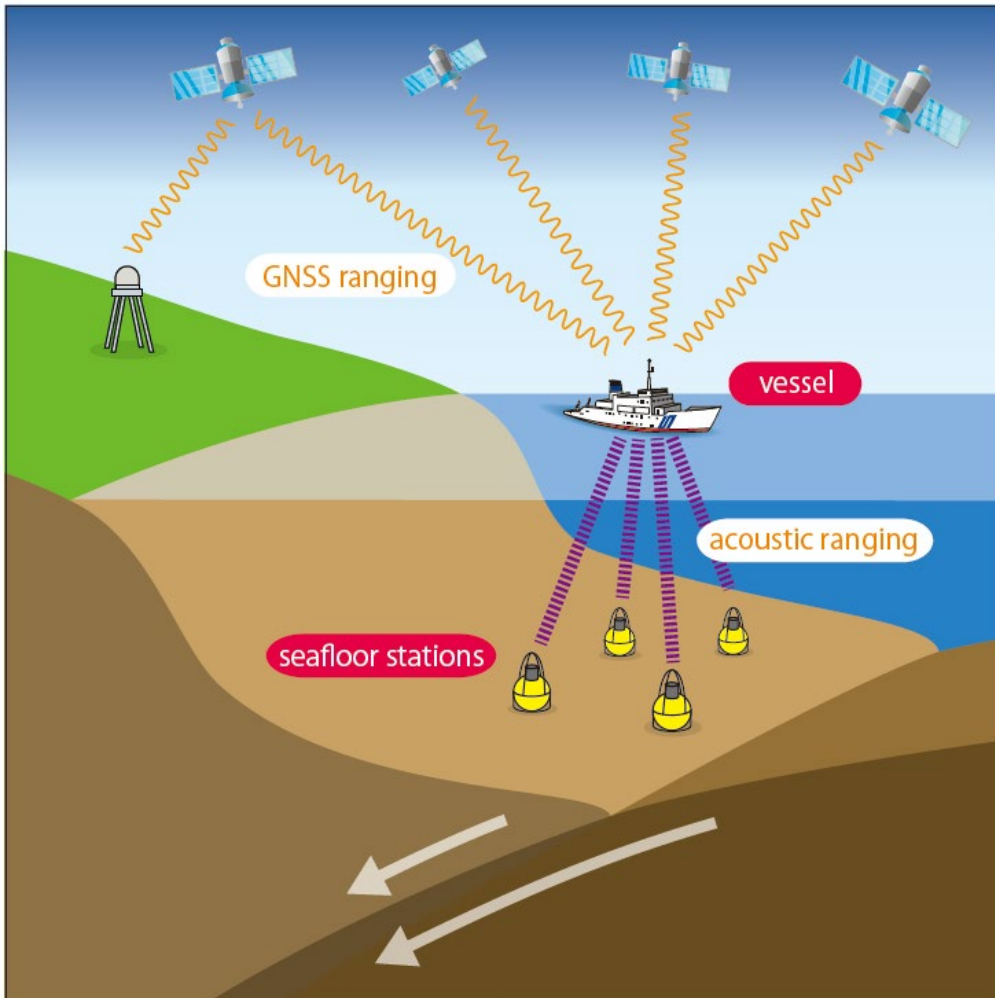
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453 earthquake. *Nature* **514**, 84–87, doi:10.1038/nature13778 (2014).
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455 its effects on afterslip determination. *J. Geophys. Res.* **120**, 1329–1344,  
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- 457

458 **Extended Data legends**

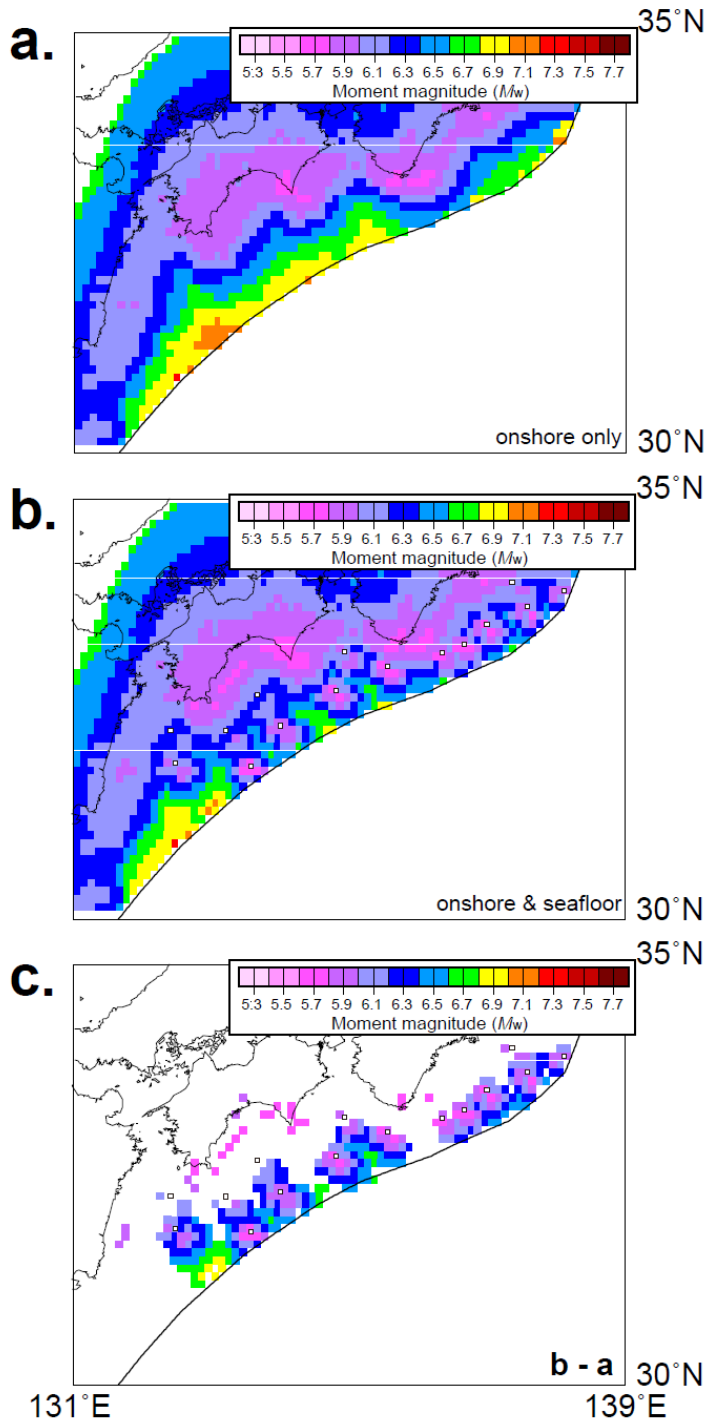


459 **Extended Data Figure 1 | Schematic diagram of the GNSS-A seafloor geodetic**  
460 **observation system.** This figure is modified from refs 15, 17, 32, 33 and 34.

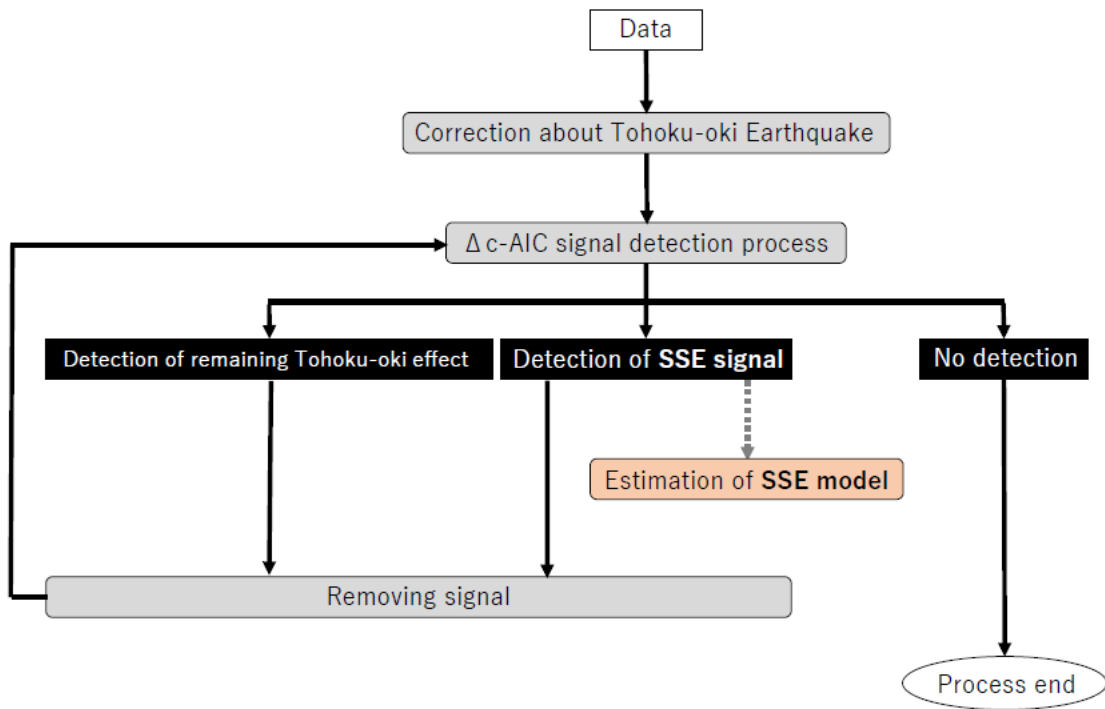
461

462

463



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

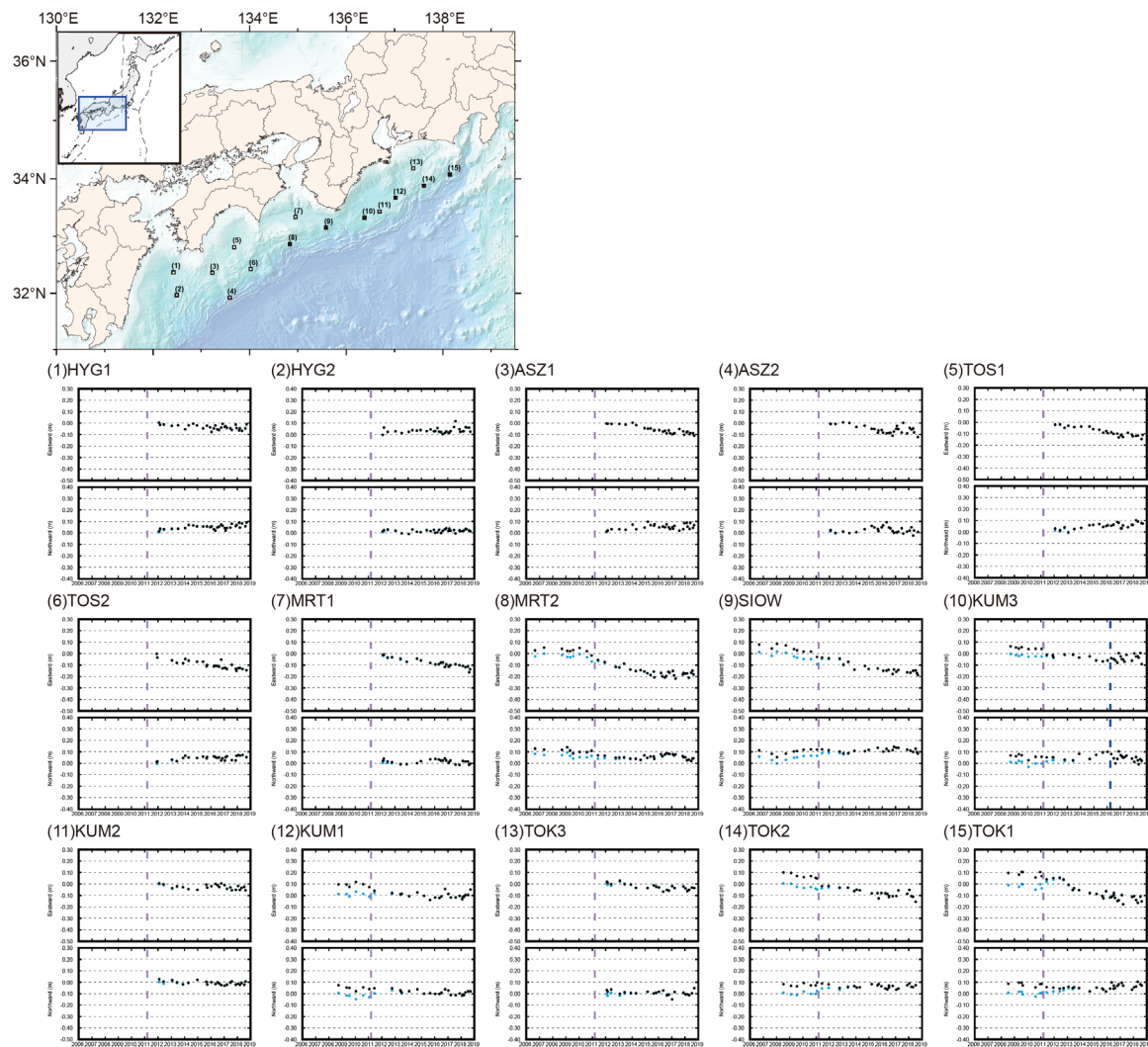


470 **Extended Data Figure 3 | Flow of the SSE signal detection process.**

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473



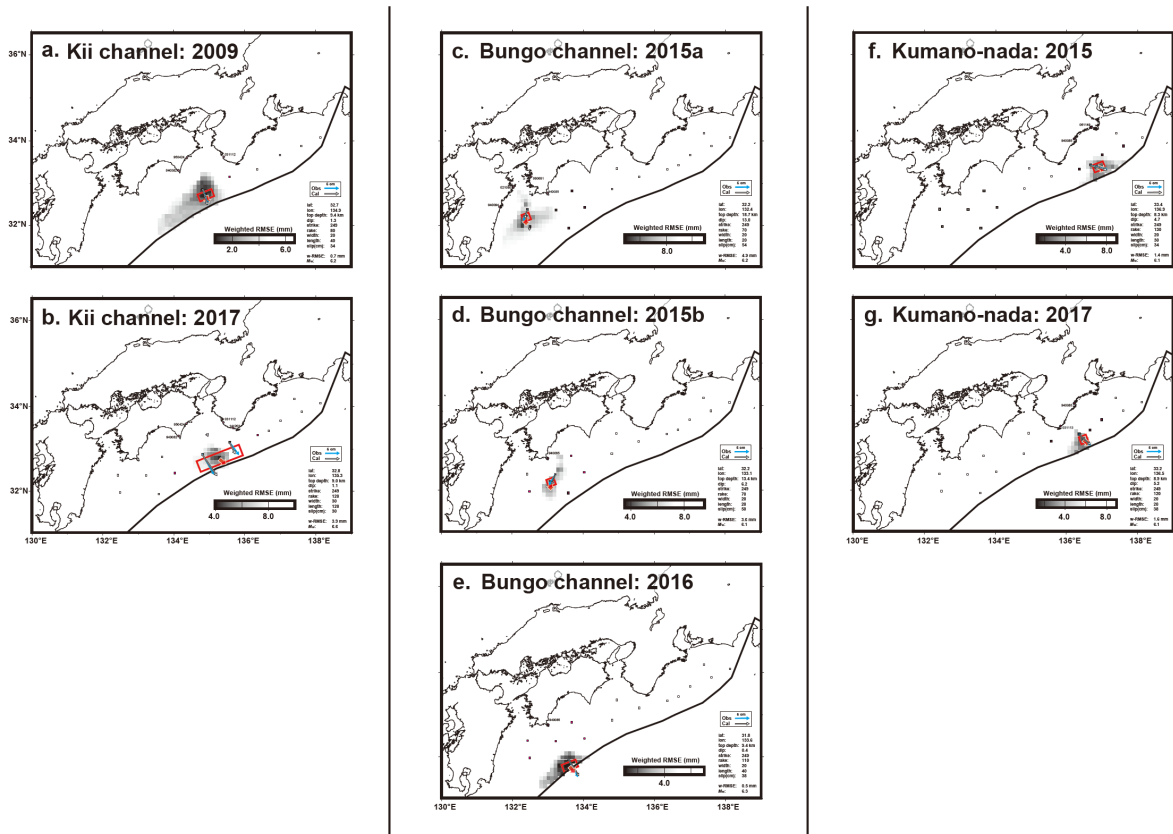
474 **Extended Data Figure 4 | Time series of horizontal components of seafloor GNSS-A**  
 475 **data.** Black circles indicate seafloor positions after deduction of deformations due to the  
 476 2011 Tohoku-oki earthquake based on refs 44, 45 and 46. Blue circles indicate raw data  
 477 before deduction.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

478  
 479



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

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



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

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

502

503 **Supplementary Table legends**

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

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(1) HYG1

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Epoch (year)	Eastward (m)	Northwar d (m)	East <sub>raw</sub> (m)	North <sub>raw</sub> (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		

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(2) HYG2

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Epoch (year)	Eastward (m)	Northwar d (m)	East <sub>raw</sub> (m)	North <sub>raw</sub> (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		

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(3) ASZ1

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Epoch (year)	Eastward (m)	Northward (m)	East <sub>raw</sub> (m)	North <sub>raw</sub> (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		

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(4) ASZ2

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Epoch (year)	Eastward (m)	Northward (m)	East <sub>raw</sub> (m)	North <sub>raw</sub> (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

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(5) TOS1

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Epoch (year)	Eastward (m)	Northward (m)	East <sub>raw</sub> (m)	North <sub>raw</sub> (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

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(6) TOS2

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Epoch (year)	Eastward (m)	Northward (m)	East <sub>raw</sub> (m)	North <sub>raw</sub> (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

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(7) MRT1

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Epoch (year)	Eastward (m)	Northwar d (m)	East <sub>raw</sub> (m)	North <sub>raw</sub> (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		

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(8) MRT2

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Epoch (year)	Eastward (m)	Northwar d (m)	East <sub>raw</sub> (m)	North <sub>raw</sub> (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 <sub>raw</sub> (m)	North <sub>raw</sub> (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		

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(10) KUM3

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Epoch (year)	Eastward (m)	Northwar d (m)	East <sub>raw</sub> (m)	North <sub>raw</sub> (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		

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(11) KUM2

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Epoch (year)	Eastward (m)	Northward (m)	East <sub>raw</sub> (m)	North <sub>raw</sub> (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		

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(12) KUM1

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Epoch (year)	Eastward (m)	Northwar d (m)	East <sub>raw</sub> (m)	North <sub>raw</sub> (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

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(13) TOK3

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Epoch (year)	Eastward (m)	Northward (m)	East <sub>raw</sub> (m)	North <sub>raw</sub> (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

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(14) TOK2

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Epoch (year)	Eastward (m)	Northwar d (m)	East <sub>raw</sub> (m)	North <sub>raw</sub> (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		

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(15) TOK1

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Epoch (year)	Eastward (m)	Northwar d (m)	East <sub>raw</sub> (m)	North <sub>raw</sub> (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		