Detailed Spatial Slip Distribution for Short-term Slow Slip Events along the Nankai Subduction Zone, Southwest Japan

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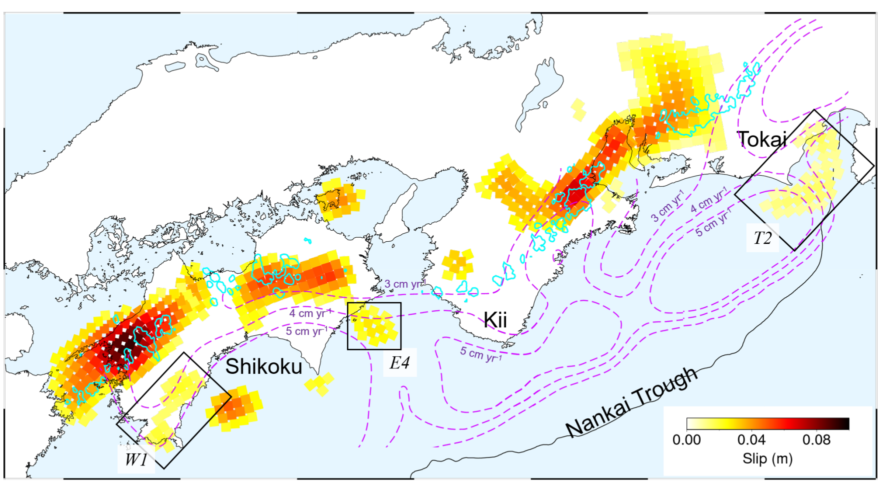
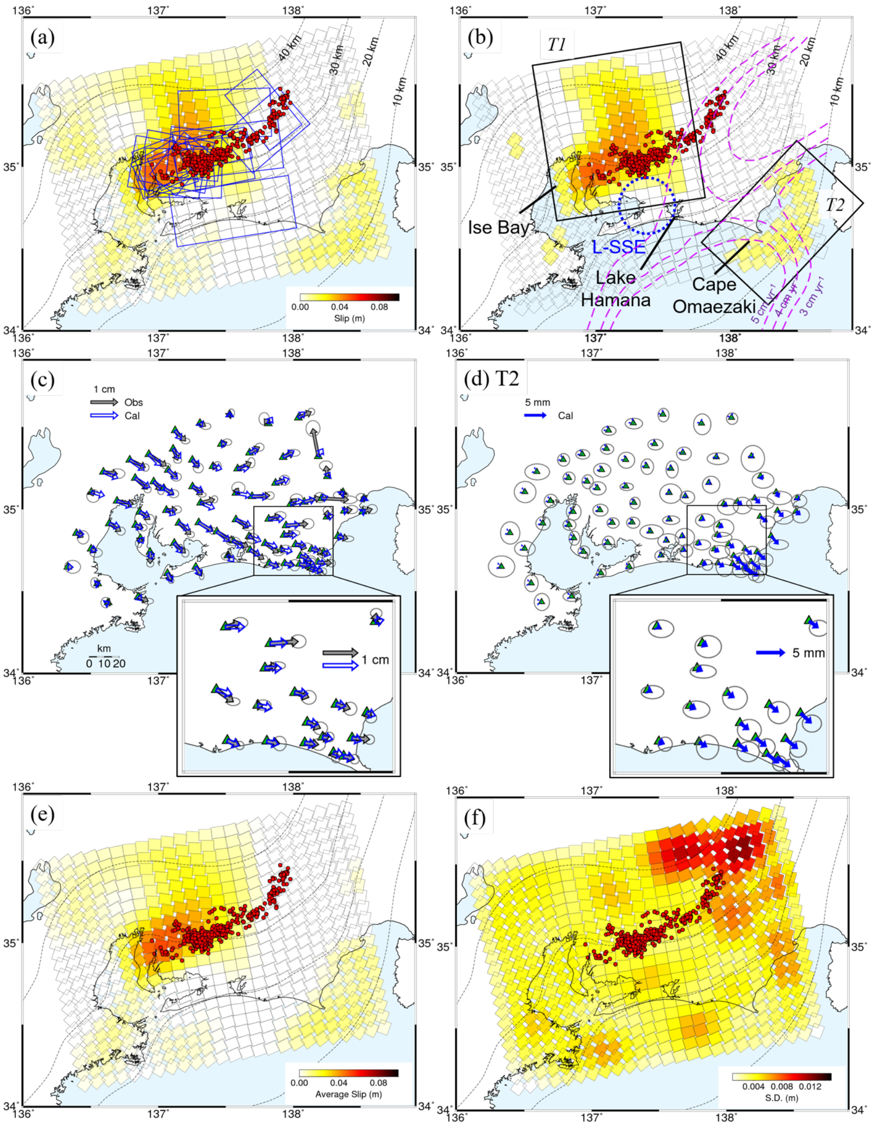
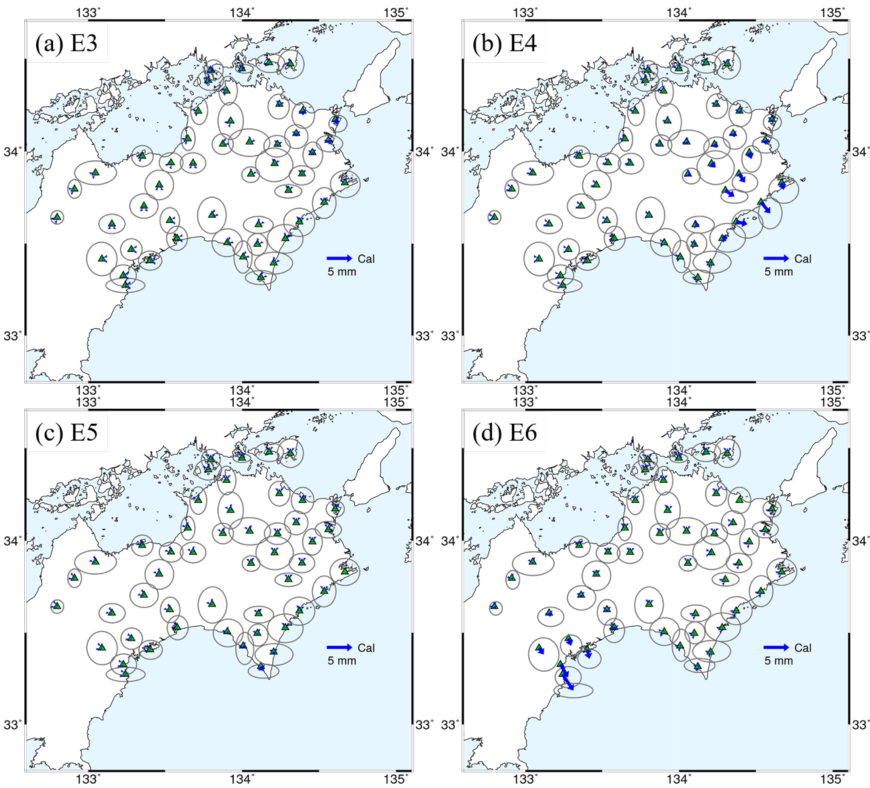
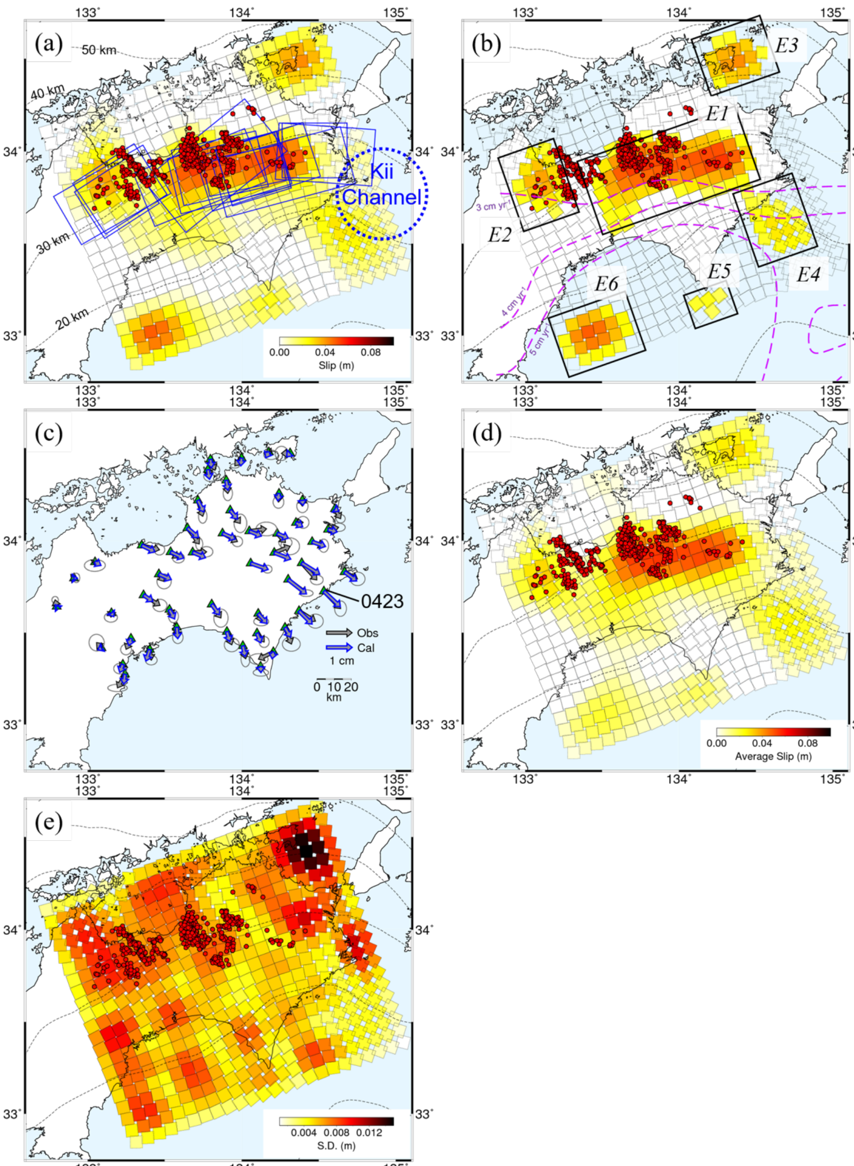
Abstract

Short-term slow slip events (S-SSEs) intensively occur at the transition zone along the Nankai subduction zone, southwest Japan. Because crustal deformation due to a single S-SSE is small, the source fault is often represented using a planar uniform single-fault slip model, resulting to little constraint on the spatial heterogeneity in amounts of fault slip. To comprehensively investigate the detailed cumulative spatial distribution of S-SSEs in the entire Nankai subduction zone, we adopted a stacking approach of Global Navigation Satellite System (GNSS) data using low-frequency earthquakes as reference. We extracted cumulative displacements due to a series of S-SSEs from 2004 to 2009; coherent signals in almost opposite direction of plate subduction were obtained. The inverted slip indicated significant slip patches laterally elongated along the transition zone at ˜30–35 km depth, and small patches in the shallow portions at ˜15–20 km and ˜10–15 km depth in eastern Shikoku and in Tokai as well as western Shikoku, respectively. The shallow patches in Shikoku were located on the downdip edge of the coseismic slip area of the 1946 Nankai earthquake, while the Tokai small slip was located on the shallower side of the anticipated source area of a large earthquake. Large slip patches of S-SSEs were complementary to the spatially dense low-frequency earthquake areas; in major S-SSE areas, the number of low-frequency earthquakes is small. This spatial dependence of fault slip style even within the transition zone provides new insights regarding the generation mechanism of slow earthquakes.

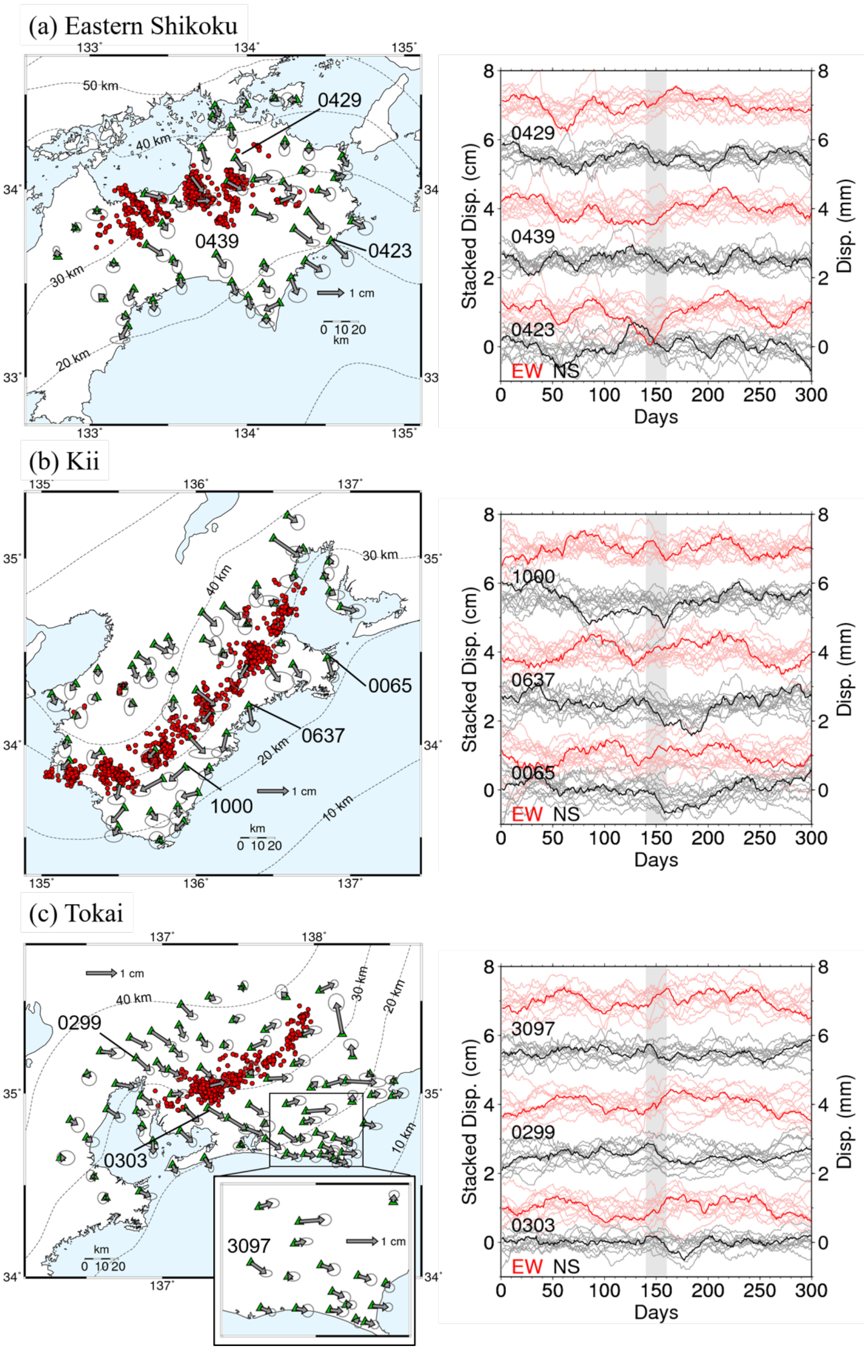



(a)
40 km
30 km
20 km
10 km
Slip (m)
0.00 0.04 0.08
(b)
T1
T2
Ise Bay
L-SSE
Lake Hamana
Cape Omaezaki
(c)
1 cm
Obs
Cal
km
0 10 20
(d) T2
5 mm
(e)
Average Slip (m)
(f)
S.D. (m)
0.004 0.008 0.012
136°
137°
138°
34°
35°


(a) E3
(b) E4
(c) E5
(d) E6
133˚
134˚
135˚
34˚
33˚
Cal
5 mm



(a)
50 km
40 km
30 km
20 km
Kii
Channel
0.00 0.04 0.08
Slip (m)
(b)
E1
E2
E3
E4
E5
E6
3 cm yr⁻¹
4 cm yr⁻¹
5 cm yr⁻¹
(c)
0423
Obs
Cal
1 cm
0 10 20
km
(d)
0.00 0.04 0.08
Average Slip (m)
(e)
0.004 0.008 0.012
S.D. (m)
133°
134°
135°
34°
33°



(a) Eastern Shikoku
133°
134°
135°
34°
33°
50 km
40 km
30 km
20 km
0429
0439
0423
1 cm
0 10 20
km
Stacked Disp. (cm)
Disp. (mm)
EW
NS
Days
(b) Kii
135°
136°
137°
35°
34°
30 km
40 km
20 km
10 km
1000
0637
0065
1 cm
km
0 10 20
(c) Tokai
137°
138°
35°
34°
1 cm
40 km
30 km
20 km
10 km
0299
0303
3097
km
0 10 20

Detailed Spatial Slip Distribution for Short-term Slow Slip Events along the Nankai Subduction Zone, Southwest Japan

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Key Points: (140 char.)

- Detailed cumulative slip distribution for short-term slow slip events (S-SSEs) is estimated in the Nankai subduction zone, southwest Japan (140)
- S-SSEs are inferred not only deep transition zones but shallow areas along the plate interface in eastern Shikoku and Tokai (124)
- Large slip areas of S-SSEs are possibly separated in space from the active areas of low-frequency earthquakes (111)

Abstract

Short-term slow slip events (S-SSEs) intensively occur at the transition zone along the Nankai subduction zone, southwest Japan. Because crustal deformation due to a single S-SSE is small, the source fault is often represented using a planar uniform single-fault slip model, resulting to little constraint on the spatial heterogeneity in amounts of fault slip. To comprehensively investigate the detailed cumulative spatial distribution of S-SSEs in the entire Nankai subduction zone, we adopted a stacking approach of Global Navigation Satellite System (GNSS) data using low-frequency earthquakes as reference. We extracted cumulative displacements due to a series of S-SSEs from 2004 to 2009; coherent signals in almost opposite direction of plate subduction were obtained. The inverted slip indicated significant slip patches laterally elongated along the transition zone at ~30–35 km depth, and small patches in the shallow portions at ~15–20 km and ~10–15 km depth in eastern Shikoku and in Tokai as well as western Shikoku, respectively. The shallow patches in Shikoku were located on the downdip edge of the coseismic slip area of the 1946 Nankai earthquake, while the Tokai small slip was located on the shallower side of the anticipated source area of a large earthquake. Large slip patches of S-SSEs were complementary to the spatially dense low-frequency earthquake areas; in major S-SSE areas, the number of low-frequency earthquakes is small. This spatial dependence of fault slip style even within the transition zone provides new insights regarding the generation mechanism of slow earthquakes.

1. Introduction

In these decades, slow earthquakes characterized by longer duration compared to ordinary earthquakes (Ide et al., 2007) have been discovered one after another in tectonic zones worldwide (e.g., Schwartz & Rokosky, 2007; Obara & Kato, 2016). Although slow earthquakes alone do not result in significant seismic damage because of their slow fault rupture, their source locations have been often identified near seismogenic zones where huge earthquakes previously occurred or are expected to occur. Thus, slow earthquakes can perturb seismiogenic zones by loading tectonic stress. In fact, prior to large earthquakes, slow earthquake have been often observed adjacent to their source areas (Graham et al., 2014; Ito et al., 2013; Kato et al., 2012; Ozawa et al., 2012; Radiguet et al., 2016; Ruiz et al., 2014; Socquet et al., 2017; Voss et al., 2018; Yokota & Koketsu, 2015). Therefore, investigating activities of slow earthquakes provides important information regarding tectonic processes during earthquake cycles.

Among the various types of slow earthquakes, slow slip events (SSEs) are geodetic signatures of slow fault rupture that are fundamentally recognized by observing slow crustal deformation using geodetic instruments such as Global Navigation Satellite System (GNSS) (Hirose et al., 1999), tiltmeters (Sekine et al., 2010), strainmeters (Itaba et al., 2010), ocean bottom pressure gauges (Ito et al., 2013; Wallace et al., 2016), and Synthetic Aperture Radar (Hooper et al., 2012; Bekaert et al., 2015). SSEs are often classified into two types depending on their durations: long-term SSEs (L-SSEs) last for months to years (Hirose et al., 1999), whereas short SSEs (S-SSEs) last for days to weeks (Obara et al., 2004). The amplitudes of crustal deformations associated with L-SSEs are sufficiently large, and can be used in investigating their source processes (Ozawa et al., 2001). On the other hand, those of S-SSEs are often too small, and can be hidden in the background observational noise. The extraction of such small signals is an important issue for capturing the features of S-SSE activities.

Several studies have developed the methodology to extract small crustal deformation due to S-SSEs (Bartlow, 2020; Frank, 2016; Frank et al., 2015; Haines et al., 2019; Nishimura et al., 2013; Rousset et al., 2017). One approach is fitting a specific function to the GNSS data. Nishimura et al. (2013) assumed a linear function with and without a step due to an S-SSE and comprehensively detected S-SSEs in the Nankai subduction zone, southwest Japan, when linear functions with a step better explained the observation data in terms of Akaike's information criteria. Another approach is stacking GNSS data to increase the signal-to-noise ratio by compromising on temporal resolution. Frank et al. (2015) utilized low-frequency earthquakes (LFEs) as an in situ monitoring tool of SSEs, assuming that the quantity of LFEs reflects a background slow fault slip, to extract signals from a series of S-SSEs in the Guerrero subduction, Mexico. When LFE bursts occurred, detrended GNSS displacements were stacked, following which cumulative surface displacement for seven episodes were obtained. They clarified that the locations of S-SSEs are deeper than L-SSEs. This stacking approach is useful in capturing the overall spatial characteristics of S-SSEs.

In the Nankai subduction zone (Fig. 1), the Philippine Sea plate subducts beneath the Amurian plate at a rate of ~67 mm yr^{-1} (Miyazaki & Heki, 2001). Large megathrust earthquakes with moment magnitudes (M_w) of ~8 rupture the plate interface at a depth of < ~20 km with a recurrence interval of 90–200 years (Ando, 1975). L-SSEs with M_w of ~7 repeatedly inferred below the seismogenic zone at the Bungo Channel (Hirose et al., 1999; Ozawa et al., 2013), Kii Channel (Kobayashi, 2014), and Tokai area (Miyazaki et al., 2006; Ochi & Kato, 2013; Ozawa et al., 2016). In addition, relatively smaller (M_w of ~6.0–6.6) L-SSEs are identified just below the seismogenic zone in western Shikoku (Takagi et al., 2019). These L-SSEs lasted for a duration of months and are usually detectable by GNSS observation. On the deeper side of these L-SSEs, S-SSEs with M_w of 5.4–6.2 frequently occur at ~35 km depth at intervals of several months (Hirose & Obara, 2010), concordant with the tectonic tremors referred to as episodic tremor and slip (ETS) (Obara et al., 2004). Since the magnitude of crustal deformation due to S-SSEs was small, tiltmeters were usually utilized to identify S-SSEs and to elucidate a spatio-temporal evolution of the slip during a few major S-SSEs (Hirose & Obara, 2010; Obara et al., 2004; Sekine et al., 2010). With the advancements in detection methods (Nishimura et al., 2013), GNSS data became recently available to identify small signals of S-SSEs and source locations of more than 100 S-SSEs have been estimated over 15 years. However, the source locations were determined as a single planar rectangular fault model assuming a spatially uniform slip. Therefore, the detailed spatial distributions of the slip from S-SSEs were not clarified. In addition, it is difficult to estimate multiple source locations in principle.

To comprehensively investigate the spatial distribution of S-SSEs, Kano et al. (2019) applied the stacking method (Frank et al., 2015) to the GNSS data in western Shikoku, and succeeded to extract the cumulative displacements due to 12 S-SSEs previously detected by GNSS (Nishimura et al., 2013) and/or tiltmeters (Sekine et al., 2010). The inverted slip indicated two slip patches: a large patch at ~35 km depth and a small patch at ~20 km depth. The deep large patch was located at a well-documented ETS source area in previous studies (Hirose et al., 2010; Nishimura et al., 2013; Sekine et al., 2010). The estimated seismic moment was comparable to that expected from these studies, showing the applicability of the stacking method of Frank et al. (2015). Additionally, a small but significant slip was simultaneously inferred at the bottom of the strongly coupled region where little interseismic slip was previously considered to occur. This shallow slow slip transient was possibly excited by the ETS episodes and may reflect the unlocking process of the seismogenic zone. This finding was attributed to the detailed estimation of the slip of a series of S-SSEs. Following the case study in western Shikoku (Kano et al., 2019), this study aims to image the detailed cumulative spatial distribution of S-SSEs in the entire Nankai subduction zone, i.e., eastern Shikoku, Kii, and Tokai regions (Fig. 1), and discuss the overall features of S-SSEs.

2. Extraction of GNSS signals due to S-SSEs

This study attempts to extract cumulative GNSS displacements due to 12, 11, and 14 S-SSEs with LFE bursts in eastern Shikoku, Kii, and Tokai region from April 2004 to March 2009 (Table 1), respectively, which have been already identified through the analysis of tiltmeters (Sekine et al., 2010) and/or GNSS (Nishimura et al., 2013). The signal extraction is conducted by referencing the numbers of LFEs using the stacking method originally proposed by Frank et al. (2015), and the detailed procedures of the method is the same as Kano et al. (2019) that adopted Frank et al. (2015)'s method to the S-SSEs in western Shikoku.

Firstly, we defined the reference date for each S-SSE when maximum number of LFEs occurred during the period of 5 days before and 15 days after the onset of each S-SSE determined by Sekine et al. (2010) and/or Nishimura et al. (2013) (Table 1). The LFE catalog was systematically obtained by the matched-filter technique (Shelly et al., 2007; Kato et al., 2013) utilizing waveforms of template events detected by the Japan Meteorological Agency (the details of estimation are summarized in Kano et al., 2019). We used continuous three-component velocity seismograms retrieved by a nationwide high-sensitivity seismograph network (Hi-net) from April 2004 to March 2009. As template events, we selected 4,219 LFEs in southwest Japan (from western Shikoku to Tokai regions) with relatively high signal-to-noise ratios as identified by the Japan Meteorological Agency (JMA). The continuous and template waveforms were preprocessed by using bandpass filtering between 2 and 6 Hz and decimating the sampling from 100 to 20 Hz. We then extracted a 6.0 s data window, starting 3.0 s prior to the arrival of synthetic S-wave. The synthetic arrivals were calculated using the one-dimensional velocity structure of the JMA. The event detection threshold was set at 9 times the median absolute deviation of the average correlation coefficient calculated over the day of interest. We assigned the location of the detected event to that of a template event. For multiple detections in each ±6.0 s window, we used the template event location with the highest mean correlation coefficient. After removing multiple detections, we detected ~220,000 LFEs located at 30–35 km depths with some clusters during our analysis, (Fig. 2). The obtained LFE catalog was referred to determine the reference dates as the center of the period for stacking the GNSS time series.

The daily crustal movements on the Earth's surface have been monitored by the GNSS Earth Observation Network System (GEONET) in Japan, which has been operated by the Geospatial Information Authority of Japan (GSI) since 1997. We analyzed the GEONET F3 solution (Nakagawa et al., 2009) to obtain the daily coordinates in two horizontal components at 49, 54, and 76 stations in eastern Shikoku, Kii, and Tokai regions, respectively, for the following analysis (Fig. 2). After correcting the offsets due to antenna displacements and large earthquakes, the daily coordinates averaged over the three stations (0462, 0691, and 0692 in Fig. 1) in the islands of west-off Kyushu, were subtracted from time series in each station. This indicates the removal of common mode errors from the original time series and the resulting daily displacements are the movement relative to the Amurian plate. Then, we calculated the 20-day moving averages for each time series. After preprocessing, we focused on the 300-day period based on the reference date for each S-SSE and subtracted the linear trend in each GNSS time series. Finally, the detrended time series were respectively stacked over the multiple SSEs in each region. Figure 2 summarizes examples of stacked GNSS time series, showing a transient movement around day 150. The time series for the other stations can be seen in Figs. S1–S3. This stacking approach by increasing the signal-to-noise ratio enables the extraction of the cumulative displacements due to S-SSEs as already verified in Guerrero (Frank et al., 2015) and western Shikoku (Kano et al., 2019).

Displacements due to a series of S-SSEs defined as the differences of the stacked time series between days 140 and 160 are shown in Fig. 2. The ellipsoids in each vector indicate a standard deviation of the residuals calculated by respectively fitting the linear trend to the stacked time series from days 50 to 100 and days 200 to 250. In eastern Shikoku, most of the stations exhibit coherent south to southeast signals. The amplitude of displacement vectors are large in southeastern part of the region with a maximum amplitude of ~0.94 cm at station 0423 (Fig. 2a). The displacement vectors in Kii are oriented from southwest to southeast and are more scattered compared to those in eastern Shikoku (Fig. 2b). Large signals of ~0.6–0.8 cm can be identified at stations above the isodepth contour of ~30 km. GNSS stations located in the western part of Tokai moves southeast, while those in the eastern part moves eastward (Fig. 2c). The magnitudes of displacements are relatively large (~0.6 cm) around stations 0303 and 3097. The extracted displacement vectors lie in a direction nearly opposite to that of the subduction of the Philippine Sea plate relative to the Amurian plate. Therefore, we considered these signals as originating from tectonic processes.

3. Estimation of cumulative spatial distribution of S-SSEs

3.1. Inversion analysis

The surface displacements extracted in the previous section are projected onto a cumulative fault slip on the plate interface following the inversion scheme of Nishimura (2009). Firstly, we generated a model of the geometry of the upper surface of the subducting Philippine Sea plate using the depth contours of the plate interface estimated by Baba et al.

(2002), Hirose et al. (2008), and Nakajima & Hasegawa (2007). Then, the plate interface was divided into planar subfaults in both strike and dip directions so that each modeled region respectively covers the whole eastern Shikoku, Kii, and Tokai regions. Each subfault was determined to be 7.5 × 7.5 km when projected on the ground surface. The numbers of subfaults were 24 × 21 in eastern Shikoku, 26 × 17 in Kii, and 25 × 21 in Tokai. Additional subfaults with zero slip were assigned surrounding the model fault region that are not represented in each figure. As a prior constraint, spatial smoothing of slip in adjacent faults for both strike and dip directions was adopted. With spatial smoothing and additional zero slip subfaults, the estimated slip varied smoothly and the slip at the edge of the model region became smaller. The slip direction of each subfault was fixed at N125E, which is in an approximately an opposite direction of the subduction of the Philippine sea plate relative to the Amurian plate (Miyazaki & Heki, 2001); thus, the rake angles in each subfault were adjusted to match the slip direction. The displacement response on the Earth's surface at the GNSS stations due to a unit fault slip on each subfault was calculated by assuming an elastic homogenous half-space (Okada, 1992). With this setting, the amounts of slip and their corresponding errors were estimated via the following equations:

$$s(\mathbf{a}) = (\mathbf{d} - \mathbf{Ha})^{\mathrm{T}} \mathbf{E}^{-1} (\mathbf{d} - \mathbf{Ha}) + \alpha^2 \mathbf{a}^{\mathrm{T}} \mathbf{Ga}, \tag{1}$$

$$\mathbf{C} = \frac{s(\hat{\mathbf{a}})}{(N + P - M)} (\mathbf{H}^{\mathrm{T}} \mathbf{E}^{-1} \mathbf{H} + \alpha^2 \mathbf{G})^{-1}, \tag{2}$$

where **d** is the observed displacement vector, **H** is the matrix consisting of an elastic response, **a** is the model parameter (the amounts of slips), **E** is the covariance matrix for the observed errors, and **G** is the smoothing operator. The slip distributions were optimized by minimizing equation (1) consisting of a data misfit and smoothness constraint terms. The hyperparameter α^2 that controls the balance of the data misfit and spatial smoothing terms is determined by minimizing Akaike's Bayesian information criterion (Akaike, 1980). The estimation errors for the obtained slip are the diagonal elements of the error covariance matrix **C**, which are calculated using the optimum model parameter $\hat{\mathbf{a}}$ by equation (2), where N is the number of GNSS data, P is the rank of the smoothing operator **G**, and M is the number of model parameters to be determined. This inversion scheme was adopted individually for the observed vectors in eastern Shikoku, Kii, and Tokai regions (Fig. 2) to estimate the cumulative spatial distributions of S-SSEs.

3.2. Eastern Shikoku

The spatial distribution of cumulative fault slip due to 12 S-SSEs in eastern Shikoku (Fig. 3a) showed several slip patches. Focusing on the slips that exceeded their estimation errors (Fig. 3b), we identified one large slip patch (E1) and five relatively smaller patches (E2–E6). For all subfaults exceeding the errors, a cumulative seismic moment of 100.4×10^{17} Nm corresponding to M_w 6.60 was calculated by assuming a rigidity of 40 GPa. The displacement vectors calculated from the estimated slip on all subfaults showed good agreement with the observed data (Fig. 3c).

E1 patch is elongated at a depth of ~30 km in the strike direction with the maximum slip of ~5.5 cm located on its eastern side. E2 patch is located on the western side of E1 patch at a similar depth. The source areas of these patches are identified within the ETS zone and are roughly consistent with the rectangular fault models inferred by Sekine et al. (2010) and Nishimura et al. (2013). A total seismic moment of 64.1×10^{17} Nm (M_w 6.47) is obtained summing up the subfaults exceeding 1-σ estimation errors (hereafter, the seismic moment values or M_w indicate only the contributions of the subfaults where their slips exceeded the 1-σ estimation errors in the regions of interest). This value is approximately half of that estimated by summing up the previously estimated values of 118.1×10^{17} Nm (M_w 6.65) in

Sekine et al. (2010) and Nishimura et al. (2013). This difference may be attributed to the estimation discrepancy of the fault model since we assumed a detailed spatial distribution of the slip, while previous studies assumed a uniform slip model with a single fault.

The other four small patches (E3–E6) are identified outside the ETS zone. To confirm the validity of their estimated slips, we conducted additional jackknife test with random resampling technique. We performed inversion analysis for 100 cases using the displacements at randomly selected 39 stations, i.e., 80 % of the total stations and estimated the average slip distributions and their standard deviations for 100 cases (Figs. 3d & 3e). The slip areas indicated by the average slip distribution were almost similar to those obtained by all 49 stations (Fig. 3a). However, there are less peak slips in small patches (E2–E6), especially in E6 patch where the peak slip decreased to ~37 % of the initial amount. If a slip in a patch is sensitive only to a few stations and its observed vectors there are not used for inversion in the jackknife test, the estimated slip in the patch becomes smaller, resulting in a smaller average slip than that when all stations are used. Therefore, we considered that the fault slip in E6 patch largely relied on a small number of stations.

To investigate the detectability of the small slip patches E3–E6, we calculated the surface displacement due only to the slip within each individual patch (Fig. 4). For E3 patch (Fig. 4a), the fault slip is hardly detectable even in the stations near the patch which moves < 1.0 mm because the slipping area is deep (> 40 km). On the other hand, E4–E6 patches are located at the shallower depth of ~15–20 km. The transient slip in E4 patch ranged ~1.8–2.7 cm with a moment magnitude of 8.5×10^{17} Nm (M_w 5.89). Although the amount of slip is small, the shallow fault depth resulted in surface displacements of > 2 mm at four GNSS stations, comparable to 2-σ observation errors (Fig. 4b). At these stations near the eastern coast line, the slips in E4 patch explained one-fourth to one-third of the total calculated displacements in their amplitudes (Fig. 3c). In addition, the standard deviations of the fault slip in E4 patch is relatively smaller within the entire fault (Fig. 3e) with more significant estimated slips of ~1.8–2.7 cm compared to their standard deviations. Therefore, despite its weak detection, a small amount of transient slip likely occurred in this shallow small E4 patch, which can explain the observed vectors in the southeastern part of the Shikoku region. E5 patch is located on the western side of E4 patch. However, even though the slip patch exists at a shallow depth, its slip is too small (~2 cm) to be detected as a signal at stations close to the patch (Fig. 4c). There are relatively larger fault slips (2.1–4.6 cm) in E6 patch located offshore the southwestern edge of the fault region. The surface displacements of ~2–4 mm due to this patch (Fig. 4d) are comparable to the 2-σ observation errors at the three southern stations. In two of these stations, quite a large fraction (87–99 %) of the amplitudes of the calculated vectors due to all subfaults (Fig. 3b) can be explained by the slip in E6 patch. This means, as mentioned in the last paragraph, the amount of fault slip in E6 patch largely depends on whether the observed vectors at these two stations are utilized in the inversion. Additional analyses using more S-SSEs during a longer period and more stations in the western part will improve the signal-to-noise ratio to support any shallow slip in E6 patch if it exists. However, this is beyond the scope of the present study.

3.3 Kii

In the Kii region, spatial distribution accumulated for 14 S-SSEs consists of an eastern large patch (K1) and a western small patch (K2) (Figs. 5a and 5b), with a cumulative seismic moment of 82.6 × 10^{17} Nm corresponding to M_w 6.54. The estimated slip distribution quantitatively reproduced the displacement vector that matched the observed vectors (Fig. 5c).

The large patch K1 is located at depths of ~35 km elongating to ~110 km in the strike direction. In K1 patch, two peak slips are estimated – a peak slip of ~6.9 cm at its center and ~5.8 cm at its northeastern edge of below the Ise Bay. The source region of K1 patch corresponded to the ETS zone where the source models were inferred by Sekine et al. (2010) and Nishimura et al. (2013). A total seismic moment of 116.6 × 10^{17} Nm (M_w 6.64) is obtained, roughly comparable to that of our inversion result of 77.2 × 10^{17} Nm (M_w 6.53). In addition, the slip zone extended to deeper faults (> 40 km depth) at the southwestern edge of K1 patch. The slips of 2.0–3.9 cm are relatively smaller than those in the shallower slip region.

At a location southwest of K1 patch, a small slip patch (K2) at ~40 km depth is observed. K2 patch is slightly deeper than the previously inferred source area in western Kii. However, it rarely contributed to the calculated displacements (< 0.6 mm) that are smaller than the 2-σ observation errors (Fig. 5d); thus, it is not further discussed in the present study.

3.4. Tokai

We derived a cumulative slip distribution for 11 S-SSEs in the Tokai region (Figs. 6a & 6b), where two major slip patches were imaged (T1 & T2). The displacement vectors calculated from all subfaults showed a good agreement with those from observations (Fig. 6c).

The large slip in T1 patch locating eastern side of the Ise Bay occurred at a depth of ~ 30 km with amplitudes of ~ 5.0 cm. The slip zone extended to ~ 80 km in the strike direction within the ETS zone and ~ 80 km in the dip direction up to a depth ~ 40 km. A seismic moment of 67.7 × 10^{17} Nm (M_w 6.49) was obtained in T1 patch. The source region and seismic moment are consistent with those detected by Sekine et al. (2010) and Nishimura et al. (2013) shown by blue rectangles in Fig. 6a with a seismic moment of 68.3 × 10^{17} Nm (M_w 6.49). In addition, the ETS zone is complementary distributed on the deeper side of L-SSE, which mainly slips below the western side of Lake Hamana (Fig. 5b) (Miyazaki et al., 2006; Ozawa et al., 2016), indicating a depth dependence of the slip style.

Notably, a small fault slip is inferred in a wide area off Cape Omaezaki at shallow depths of 10–15 km (T2 patch). This slip patch caused significant crustal movement of > 2 cm at 11 stations exceeding the 2-σ observation errors (Fig. 6d). To further confirm this slip in T2 patch, additional slip inversion is performed for 100 cases, randomly selecting 80 % of the total stations (61 stations) (jackknife test). The slip distribution averaged for 100 cases (Fig. 6e) is quite similar to that using all observed displacements (Fig. 6a) in terms of the overall characteristics and quantity of slips even in T2 patch. However, the standard deviations of the slip at the northern part of T2 patch is slightly larger (~ 0.6 mm). The above validation suggests that the GNSS stations densely distributed around Cape Omaezaki contributed in illuminating the small but significant slip in T2 patch on the shallow depth of the plate interface.

4 Discussion

4.1 Shallow slip patches

Figure 7 summarizes the cumulative slip distributions for S-SSEs detected from 2004 to 2009 in southwest Japan revealed by Kano et al. (2019) (western Shikoku) and in this study (eastern Shikoku, Kii, and Tokai). The main slip areas are laterally elongated in the ETS zone, while shallow minor patches are inferred in western and eastern Shikoku and Tokai areas.

In eastern Shikoku, the small slip patch (E4 patch) is estimated to be present just updip side of the L-SSE source area in the Kii Channel (Fig. 3b), where M_w 6.6–6.7 class L-SSEs occurred repeatedly in 1996–1997 (Kobayashi, 2014), 2000–2003 and 2014–2017 (Kobayashi, 2017). During our analysis period, there have been no reports of L-SSEs; hence, we cannot discuss any temporal correlation between L-SSE region and E4 patch. However, both source regions do not seem to overlap at the plate interface. The slow slip transient in the E4 patch occurs within the moderately coupled region with a slip deficit rate of ~ 2–3 cm yr^{-1} (Yokota et al., 2016; Nishimura et al., 2018) and the area which experienced a relatively smaller coseismic slip in 1946 Nankai earthquake (Figs. 1 & 3b) (Sagiya & Thatcher, 1999). This suggests that small slow slip transient sometimes causes gradual unlocking at the bottom of the strongly coupled zone. Similar transient slow slip has been also inferred in western Shikoku region (W1 patch in Fig. 7) (Kano et al., 2019).

The shallow slip transients occur without LFEs in eastern and western Shikoku (Fig. 7). The small S-SSEs that were not associated with LFEs below the locked megathrust were also identified in northern Cascadia (Hall et al., 2018). The slow slip extends ~ 15 km to the updip side of the ETS zone. Hall et al. (2018) proposed that the lack of LFEs on the updip S-SSEs can be explained by an along-dip variation of rheological properties and/or fault strength. These two mechanisms expect along-dip changes of frictional properties or effective normal stress and thus, such mechanisms would explain the preference for slow slip instead of LFEs on the shallow slip patches in eastern and western Shikoku.

In addition, because our method extracts GNSS signals generated due to known ETS episodes at a depth of ~ 30 km, the subfaults in the shallower E4 patch simultaneously move with those in the deep E1 patch. Considering that the observed vectors are obtained from the difference of displacements during 20 days and that the stacked GNSS data is smoothed using 20-days moving averages, a time lag of slow slip occurrence between E1 and E4 patches is at most a few tens of days. Although we cannot conclusively ascertain the mechanisms functioning here, direct stress transfer from E1 patch to E4 patch or an updip fluid migration along the plate interface as proposed in the case of western Shikoku (Kano et al., 2019) may explain this almost simultaneous occurrence of transient slip.

While the small slip patches are estimated on the downdip portion of the locked megathrust region in eastern and western Shikoku, the small slip patch (T2 patch) is estimated within the shallower portion of the anticipated source area of Tokai earthquake (Figs. 1 & 6b) that is proposed by the Central Disaster Management Council (2001) where no large M~8 class earthquakes have occurred for more than 150 yrs (Ando, 1975). This small slip transient may represent a cumulative slip of shallow S-SSEs that are first revealed in Tokai region. In the off-Kii region, several shallow S-SSEs with slips of 1–4 cm were recurrently detected at depths of 4–10 km on the offshore side of the rupture area of the M_w 8.1 Tonankai earthquake, which occurred in 1944 (Fig. 1), as pore pressure changes at the seafloor borehole stations (Araki et al., 2017). These shallow S-SSEs contribute to releasing 30–55 % of stress accumulation due to the plate subduction near the trench. On the other hand, the fault slips in T2 patch ranging from 0.7 to 1.5 cm for 5 yrs accommodate 5–15 % of relative plate motion of 2–3 cm/yr in Tokai (Miyazaki & Heki, 2001), which is smaller than the off-Kii region. However, because the estimated slip is accumulated only for the period of S-SSEs occurrence in the deeper portion within the ETS zone, we may underestimate the slip amount of the shallow S-SSEs. Recent onshore and offshore geodetic studies indicated a smaller slip deficit rate compared to the adjacent seismogenic zone (Fig. 6b) (Yokota et al., 2016; Nishimura et al., 2018) and thus, this weaker coupling could be partly explained by the S-SSEs detected by the present study. An additional time-series analysis over a longer time period will provide further clarification regarding detailed features of the shallow S-SSE in T2 patch.

The mechanism for the simultaneous occurrence of both deep and shallow S-SSEs with a gap of anticipated seismogenic area is enigmatic. If an upward migration of over-pressurized fluid is a dominant mechanism that could trigger shallow S-SSEs during the deep S-SSEs as in the case of western Shikoku, temporal changes in pore pressure may promote shallow minor slow slips. In western Shikoku, the spatial gap corresponds to the L-SSE source region (Takagi et al., 2019). Considering that L-SSE regions exhibit mixed fault behavior of friction and viscous deformation (Gao & Wang, 2017) and are less sensitive to the migrated fluid, Kano et al. (2019) proposed a fluid migration model as a possible mechanism. However, because unlike the case of western Shikoku, the spatial gap in Tokai corresponds to the anticipated seismogenic area, namely brittle frictional regime, and can be sensitive to fluid migration, fluid migration model is not applicable in Tokai. It may be possible that both shallow and deep S-SSEs occur independently, and the shallow S-SSEs revealed in the present study are just a fraction of the entire activity that occurred in the timing of deep S-SSEs. A time-dependent inversion analysis using a time series of a dense GNSS network consisting of GEONET and additional stations deployed around Cape Omaezaki and Lake Hamana (Sakaue et al., 2019) will reveal the detailed temporal changes in shallow S-SSEs.

4.2 Complementary distribution between large S-SSE patches and LFEs within the ETS zone

Focusing on the ETS zone at depths of ~30–35 km, the maximum slip of S-SSEs in each region is estimated to occur in locations where LFE densities calculated from the JMA catalog are low (Fig. 7). This characteristic is clear in eastern Shikoku and Tokai. The maximum slip in E1 patch occurs on the eastern side of the LFE clusters in eastern Shikoku (Fig. 3b), and the large slip is located on the western side of the LFE clusters in T1 patch in Tokai (Fig. 6b). The depths of these maximum slips are similar to those of the LFEs. In Kii, the peak slip is located between the two LFE clusters in K1 patch (Fig. 5b), and the second peak slip is located at the northeastern edge of K1 patch below the Ise Bay, where few LFEs occur. In the case of western Shikoku, the maximum slip is inferred slightly deeper side of the LFE clusters. This feature means that, even at a similar depth, fault slips on the plate interface in some regions are detected as geodetic signals, i.e., SSEs, while those in other regions are seismically identified as LFEs.

From a geological standpoint, the deformation of subduction mélange shear zones is related to the occurrence of SSEs and LFEs. A subduction mélange typically consists of strong brittle clasts that potentially result in LFEs embedded in a weak ductile matrix (Fagereng et al., 2014; Behr et al., 2018). Geological surveys have indicated that the slip behavior along the plate interface in shear zones is fundamentally controlled by the ratio of strong brittle clast to weak ductile matrix (Fagereng & Sibson, 2010). Beall et al. (2019) demonstrated through numerical simulations that SSEs occur when the proportion of the ductile matrix to the total media is high, or when force concentration of clasts is temporarily inactive after clast failure even when this proportion is low. Therefore, one possible explanation for complementary distribution of areas with large slips and high LFE densities in the Nankai subduction zone is the spatial heterogeneity of the ratio of strong brittle clasts and weak ductile matrix within the shear zones.

Another possibility is a spatial variation of fault instability in the framework of a rate and state friction. In this framework, SSEs occur when the elastic stiffness of the surrounding material is close to the critical stiffness of the fault, while the fault yields to undergo dynamic brittle failure when the elastic stiffness is smaller than the critical stiffness (Ruina, 1983; Yoshida & Kato, 2003). Since the critical stiffness is determined by frictional parameters and effective normal stress, the spatial heterogeneity of frictional parameters or pore pressure or both would be a possible mechanism for the complementary distribution of S-SSEs and LFEs. Both possibilities might be feasible, and in each case, spatial heterogeneities in fault strength are expected so that the spatial distribution of the preference of fault slip style might be determined by the heterogeneity in fault strength.

5. Conclusions

We have herein estimated the detailed spatial slip distribution for S-SSEs in southwest Japan from 2004 to 2009. The significant SSEs are inferred along the well-known ETS zone at depths of ~30–35 km. In addition, small slow slips are estimated in offshore shallower portions such as in eastern Shikoku and Tokai. The slip deficit rates in these areas are relatively smaller than those of the adjacent strongly coupled seismogenic zone, and therefore slow slip partially releases the slip deficit accumulated along the plate interface. Especially, the shallow slip area in Tokai is located on the shallower side of the anticipated seismogenic zone, which is similar to the case of the shallow SSEs detected on the offshore side of the 1946 Tonankai earthquake revealed by Araki et al. (2017). Further analysis using GNSS time series with time-dependent geodetic inversion will more clearly reveal the detailed spatio-temporal evolutions of such small slip events. In addition, the number of LFEs is low in major slow slip areas. This represents the preference of fault slip style, i.e., whether ductile or brittle behavior is dominant depends on regions, within the transition zone where slow earthquakes occur intensively. The present results will contribute to improve the understanding of generation mechanisms of slow earthquakes.

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Research Program. The inversion code used throughout this study was provided by T. Nishimura. We used the EIC computer system of the Earthquake Research Institute, the University of Tokyo. Generic Mapping Tools by Wessel & Smith (1998) is used to generate figures. The GEONET F3 solutions are provided by the GSI and available at http://datahouse1.gsi.go.jp/terras/terras_english.html. We use seismic data in the Hi-net (NIED, 2019) for estimating LFE locations. The JMA catalog of LFEs (Katsumata & Kamaya, 2003) was downloaded from "Slow Earthquake Database" (Kano et al., 2018; http://www-solid.eps.s.u-tokyo.ac.jp/~sloweq/) supported by JSPS KAKENHI Grant Number JP16H06472 in Scientific Research on Innovative Areas "Science of Slow Earthquakes."

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Tables

Table 1. *List of onsets and moment magnitudes of S-SSEs detected by tiltmeters (Sekine et al. 2010) and GNSS (Nishimura et al., 2013). The reference dates (see section 2) is set when maximum numbers of LFEs occurred around each onset of S-SSEs in (a) eastern Shikoku, (b) Kii, and (c) Tokai regions.*

(a) Eastern Shikoku

Onset of S-SSEs		**LFE_max (Reference date)**	**Moment magnitude (× 10^{17} Nm)**	
Tiltmeters*	**GNSS****		**Tiltmeters***	**GNSS****
	2004/10/21	2004/10/27		11.5

	2004/12/17	2004/12/19		6.1
	2005/11/05	2005/11/07		10.4
	2006/02/21	2006/02/16		8.5
	2006/06/24	2006/06/24		5.3
2006/11/07	2006/11/11	2006/11/09	9.9	13.4
	2007/03/19	2007/03/18		3.4
	2007/05/10	2007/05/06		16.8
	2007/06/21	2007/06/22		6.3
	2007/10/17	2007/10/14		15.0
2008/02/13	2008/02/14	2008/02/15	13.5	9.8
	2008/10/14	2008/10/15		11.5

(b) Kii

Onset of S-SSEs		**LFE_max (Reference date)**	**Moment magnitude (× 10^{17} Nm)**	
Tiltmeters*	**GNSS****		**Tiltmeters***	**GNSS****
2004/11/29		2004/11/29	7.3	
	2005/01/04	2005/01/03		7.3
2005/07/09		2005/07/10	8.3	
2006/01/07	2006/01/10	2006/01/10	13.8	23.6
	2006/03/17	2006/03/15		6.8
2006/05/29		2006/06/01	5.6	
	2006/07/25	2006/07/28		5.8
2006/11/04	2006/11/11	2006/11/05	9.3	15.3
2007/03/23	2007/03/23	2007/03/24	3.7	4.9
	2007/07/23	2007/07/19		11.5
2007/10/16		2007/10/17	2.8	
	2007/11/14	2007/11/15		7.9
2008/03/05	2008/03/07	2008/03/06	7.6	9.0
2008/06/15	2008/06/21	2008/06/18	6.4	13.0

(c) Tokai

Onset of S-SSEs		**LFE_max (Reference date)**	**Moment magnitude (× 10^{17} Nm)**	
Tiltmeters*	**GNSS****		**Tiltmeters***	**GNSS****
2004/12/17	2004/12/20	2004/12/21	6.3	8.8
2005/07/20	2005/07/29	2005/07/20	5.3	6.0

2006/01/16 2006/01/19		2006/01/21	2.2 1.5	
	2006/07/20	2006/07/16		6.0
2006/08/27		2006/08/30	4.8	
2007/02/04	2007/02/09	2007/02/05	4.0	10.2
	2007/08/28	2007/08/29		6.5
2007/09/25 2007/10/05	2007/10/09	2007/10/09	2.8 3.6	7.2
2007/12/31		2008/01/03	7.9	
2008/05/14		2008/05/16	3.9	
	2008/08/21	2008/08/31		8.4

Note. *Sekine et al. (2010), **Nishimura et al. (2013)

Figure Captions

Figure 1. The study area in southwest Japan is indicated by a large rectangle in the inset. The Philippine Sea plate is subducting northeastward beneath the Amurian plate along the Nankai Trough. The black contours indicate the iso-depths of the upper surface of the subducting Philippine Sea plate with an interval of 10 km (Baba et al., 2002; Nakajima & Hasegawa, 2007; Hirose et al., 2008). The red rectangles are the eastern Shikoku, Kii, and Tokai areas, where S-SSEs are investigated in this study. The green lines are the source areas of the 1944 Tonankai and 1946 Nankai earthquakes (Sagiya & Thatcher, 1999) and the aniticipated source area in Tokai proposed by the Central Disaster Management Council (2001). The blue circles indicate the locations of L-SSEs in the Bungo Channel (Hirose et al., 1999), Kii Channel (Kobayashi, 2014), Tokai (Miyazaki et al., 2006), and shallow SSE southeast of Kii (Araki et al., 2017). The black dots show the locations of GEONET stations used in this study.

Figure 2. (Left) Stacked displacement with 2-σ observation errors and (right) examples of detrended GNSS time series in the 4-digit in the left panel in (a) eastern Shikoku, (b) Kii, and (c) Tokai. The red dots are the LFE epicenters. The red and black lines indicate the time

series for the EW and NS components, respectively, cumulated for all S-SSEs detected during the analysis period, while the light red and grey lines are the time series for the individual S-SSE. The displacement vectors during the grey shaded period in the right panel is indicated in the left panel. The detrended time series for all GNSS stations are summarized in Figures S1–S3.

Figure 3. (a) Cumulative slip distribution for 12 S-SSEs in eastern Shikoku inferred by using all stations. The blue rectangles are the fault models from Sekine et al. (2010) and/or Nishimura et al. (2013). The blue circle indicates an L-SSE source area (Kobayashi, 2014). The red dots are LFE epicenters. (b) Same as (a), but the faults where the slips exceeded the estimation error are represented and separated into six (E1–E6) fault patches. The purple lines indicate the contours of the slip deficit rate (Yokota et al., 2016). (c) The comparison between the observed (black arrows) and calculated (blue arrows) displacement vectors. (d) Average slip distribution and (e) its standard deviation for 100 cases, each of which is inverted by randomly choosing 80 % of the GNSS stations.

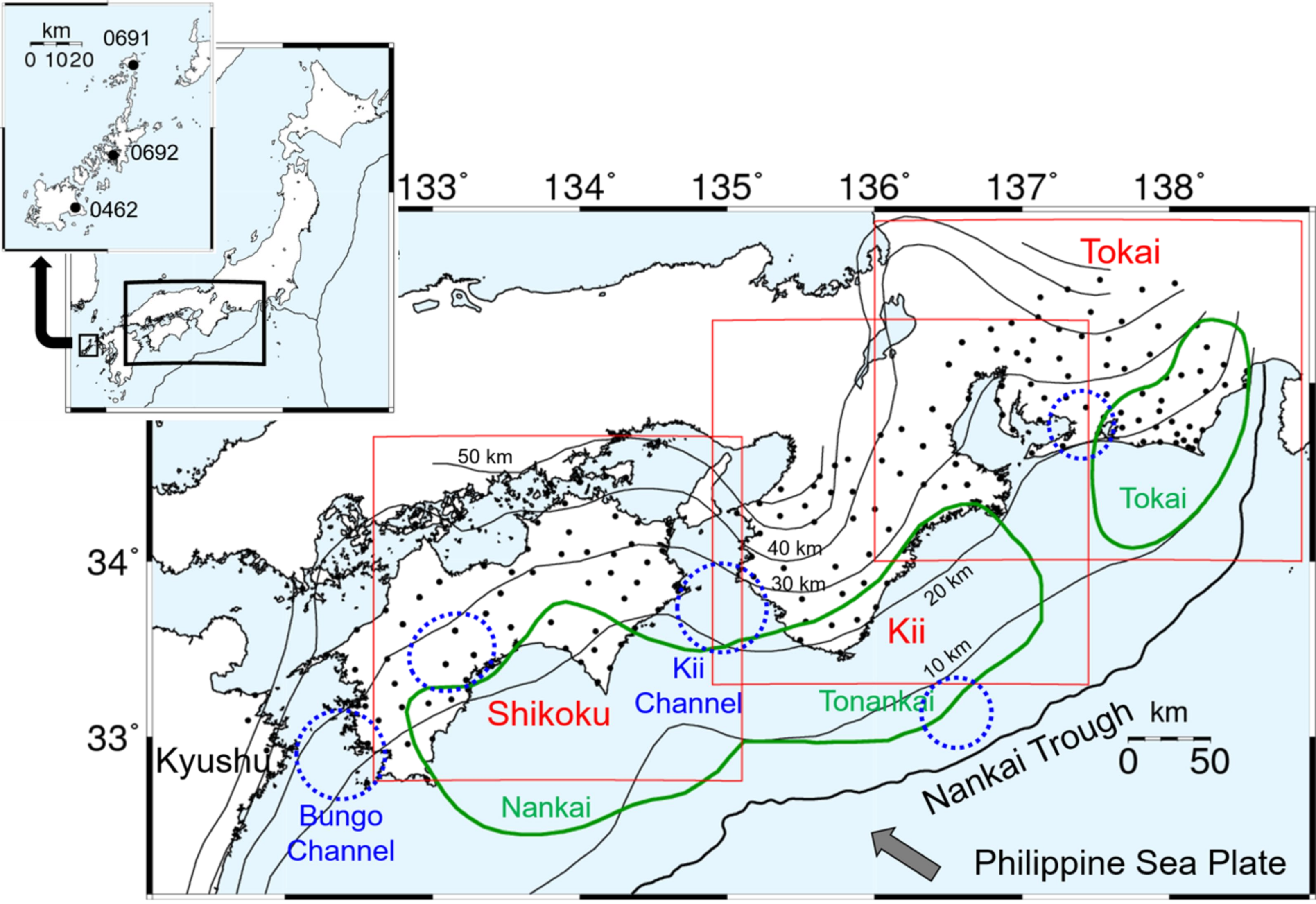
Figure 4. Calculated displacements due only to the fault slip in (a) E3, (b) E4, (c) E5, and (d) E6 patch, respectively.

Figure 5. (a) Cumulative slip distribution for 14 S-SSEs in Kii region. The blue rectangles are the fault models from Sekine et al. (2010) and/or Nishimura et al. (2013). The red dots represent the LFE locations. (b) Same as (a), but the faults where the slips exceeded the estimation error are represented and separated into two (K1–K2) fault patches. (c) Comparison between the observed (black arrows) and calculated (blue arrows) displacement vectors. (d) Calculated displacements due only to the slip in K2 patch.

Figure 6. (a) Fault slip distribution cumulated for 11 S-SSEs in Tokai region. The blue rectangles are the fault models from Sekine et al. (2010) and/or Nishimura et al. (2013). The red dots indicate the LFE locations. (b) Same as (a), but the subfaults where the slips exceeded the estimation error are indicated. The purple lines indicate the contours of the slip deficit rate (Yokota et al., 2016). The blue circle is the source area of Tokai L-SSE (Miyazaki et al., 2006). (c) Comparison of the observed (black arrows) and calculated (blue arrows) displacements. (d) Calculated displacements due only to the fault slip in the shallow (T2) patch. (e) Fault slip distribution averaged for 100 cases, each of which is inverted by using a random selection of 80 % of the GNSS stations and (f) its estimation error.

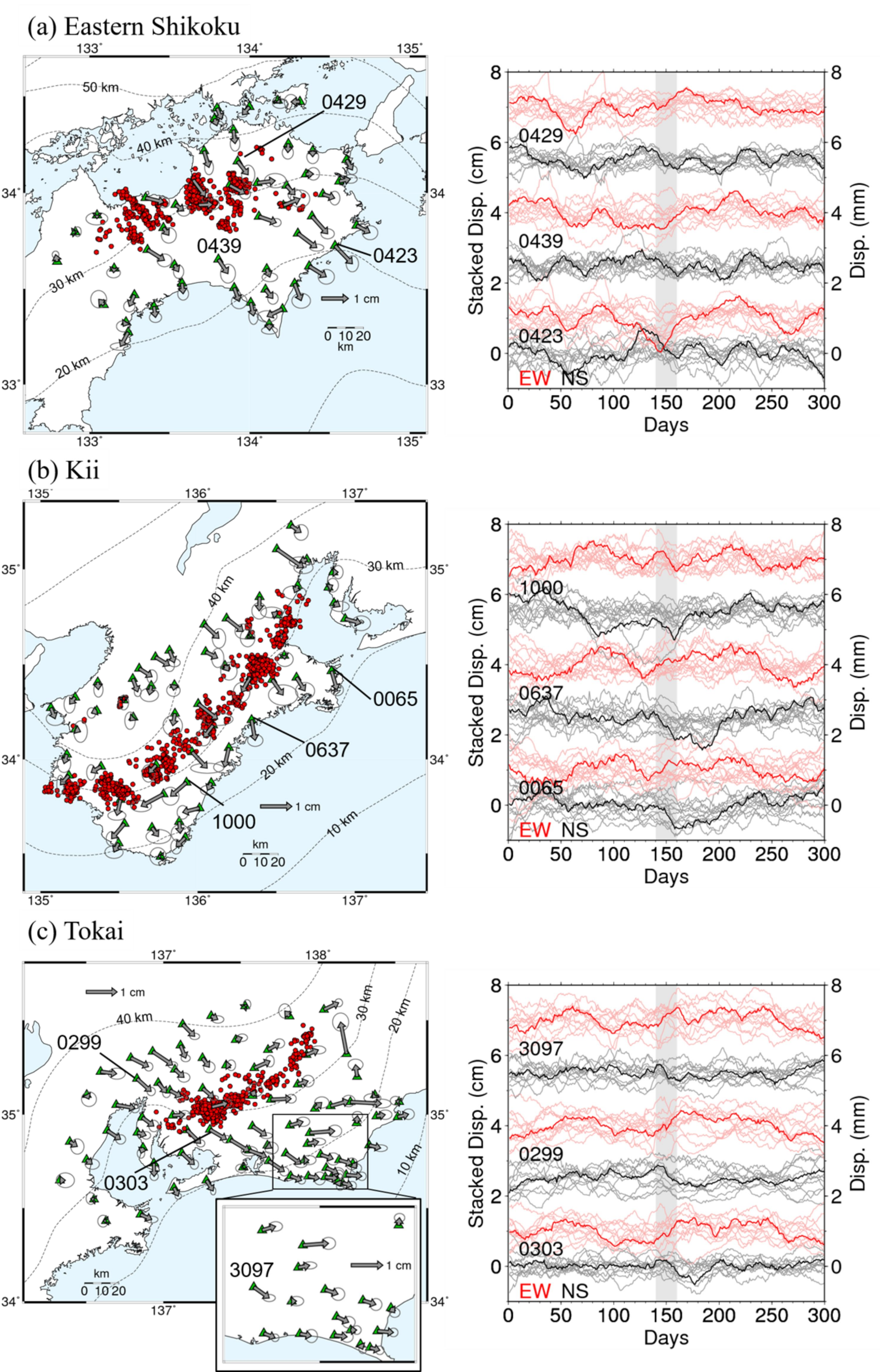
Figure 7. Summary of the cumulative slip distribution in southwest Japan and the LFE epicenters in the JMA catalog (Katsumata & Kamaya, 2003). The light blue lines indicate the contours of the LFE densities of 2 (counts) / 0.02 (degree) × 0.02 (degree). The purple lines indicate the contours of the slip deficit rate (Yokota et al., 2016).

Figure 1.



km
0 1020
0691
0692
0462
133°
134°
135°
136°
137°
138°
34°
33°
Tokai
Kii
Shikoku
Kyushu
50 km
40 km
30 km
20 km
10 km
Tokai
Tonankai
Nankai
Kii Channel
Bungo Channel
Nankai Trough
km
0 50
Philippine Sea Plate

Figure 2.



(a) Eastern Shikoku
133°
134°
135°
34°
34
33°
33
50 km
40 km
30 km
20 km
0429
0439
0423
1 cm
0 10 20
km
Stacked Disp. (cm)
Disp. (mm)
Days
EW NS
(b) Kii
135°
136°
137°
35°
34°
30 km
40 km
20 km
10 km
0065
0637
1000
1 cm
km
0 10 20
1000
0637
0065
Stacked Disp. (cm)
Disp. (mm)
Days
EW NS
(c) Tokai
137°
138°
35°
34°
1 cm
40 km
30 km
20 km
10 km
0299
0303
3097
km
0 10 20
Stacked Disp. (cm)
Disp. (mm)
Days
EW NS

Figure 3.

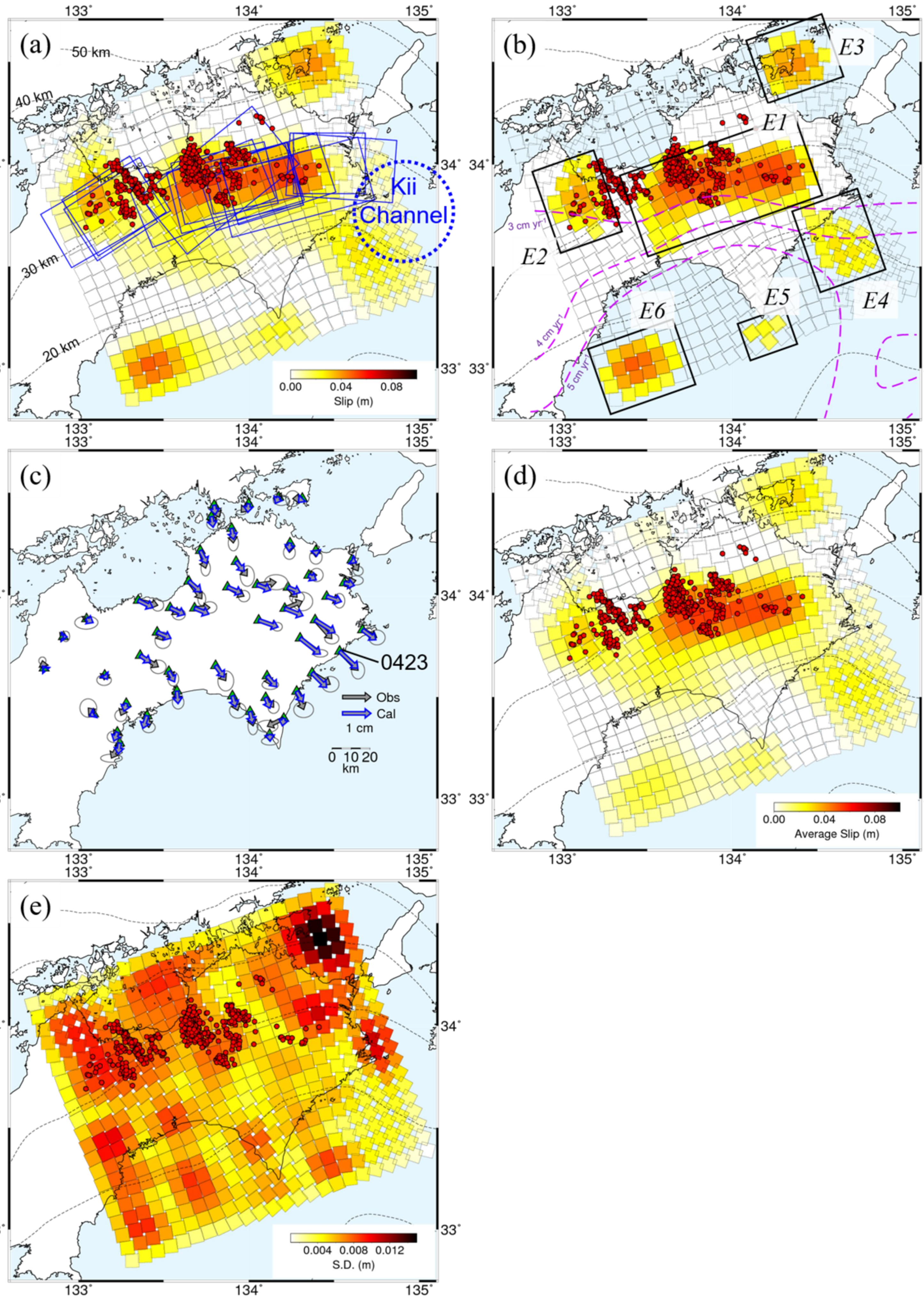
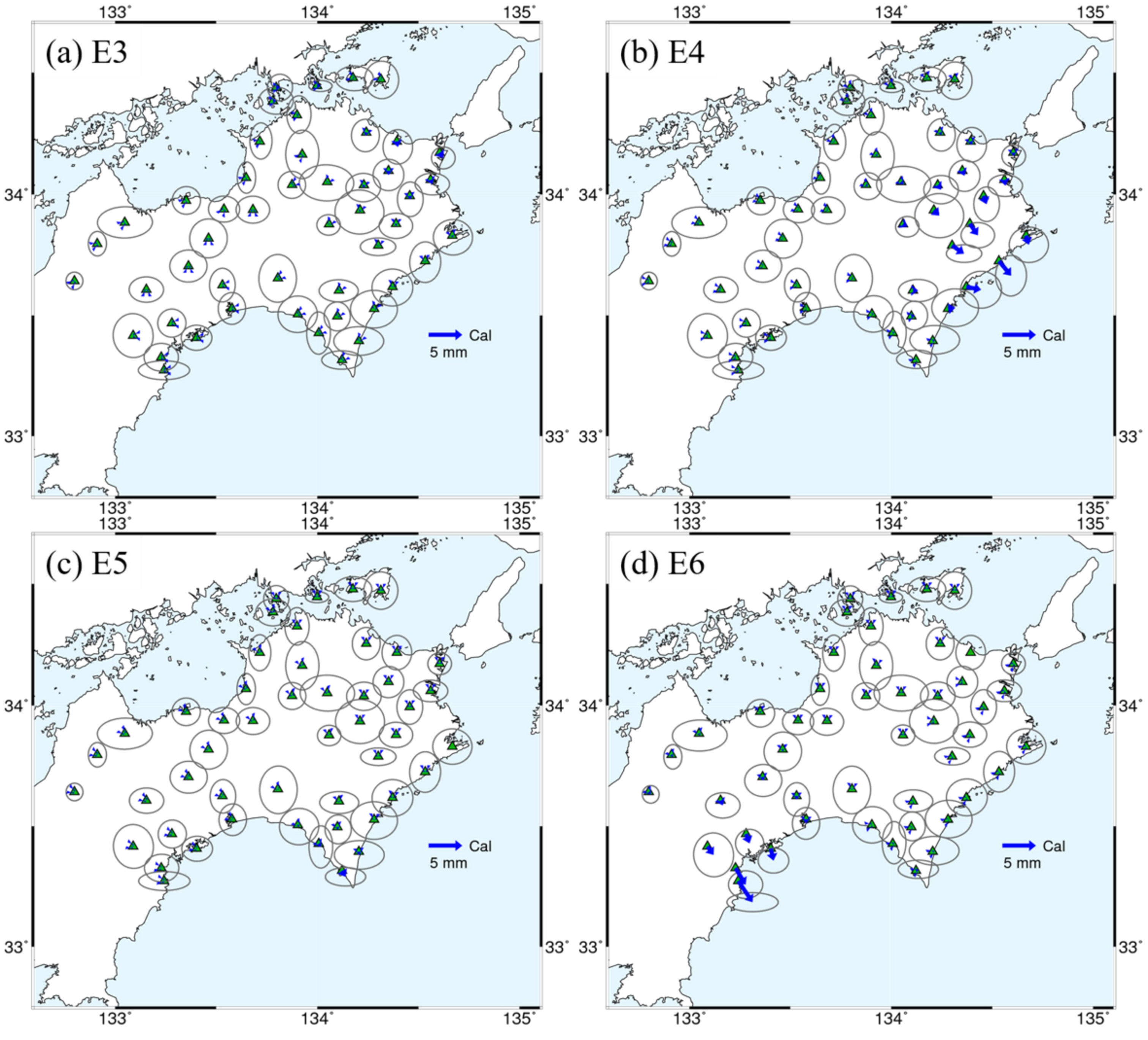
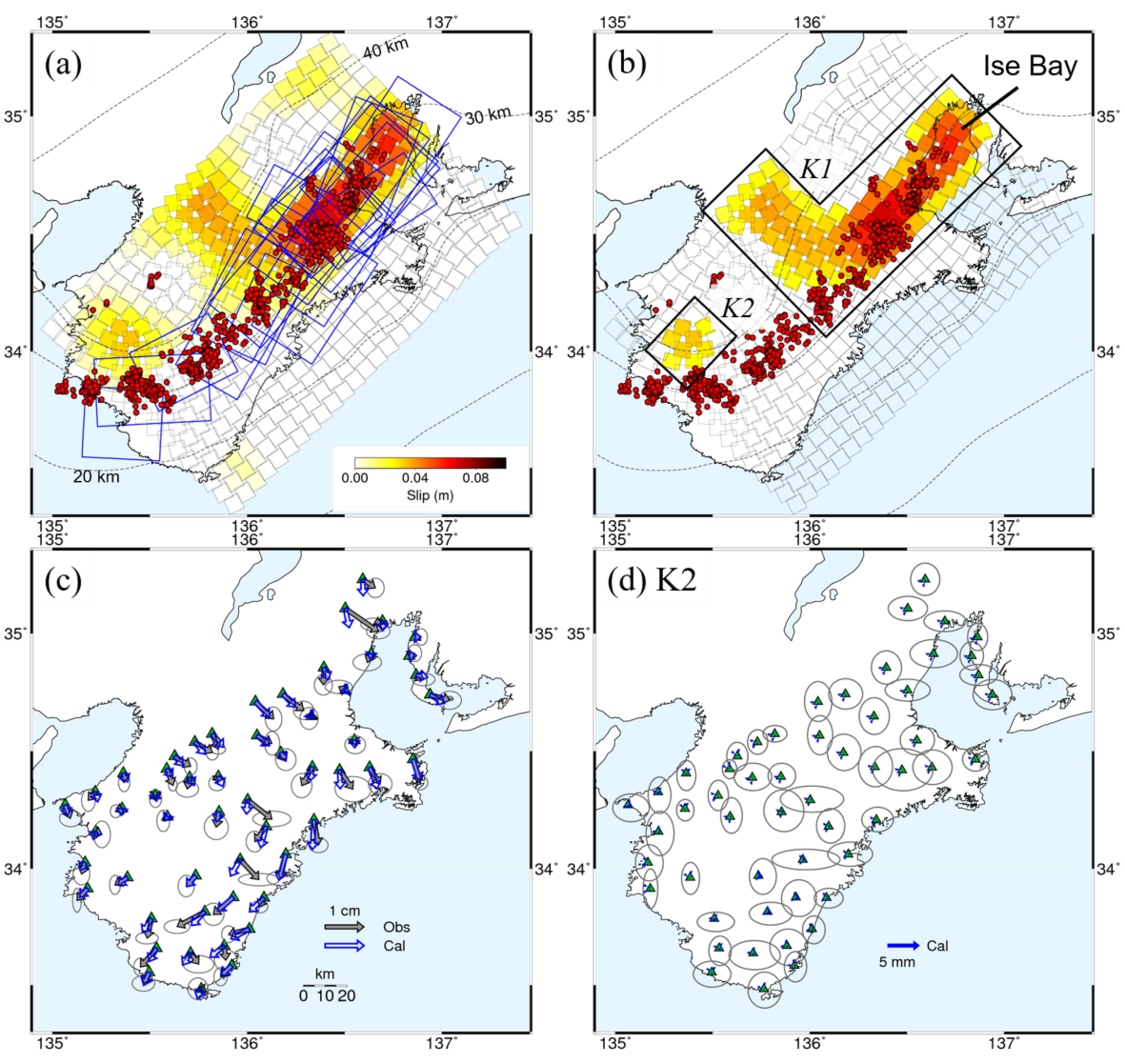

(a)
133°
134°
135°
34°
33°
50 km
40 km
30 km
20 km
Kii
Channel
0.00
0.04
0.08
Slip (m)
(b)
E1
E2
E3
E4
E5
E6
3 cm yr-1
4 cm yr-1
5 cm yr-1
(c)
0423
Obs
Cal
1 cm
0 10 20
km
(d)
0.00
0.04
0.08
Average Slip (m)
(e)
0.004
0.008
0.012
S.D. (m)

Figure 4.



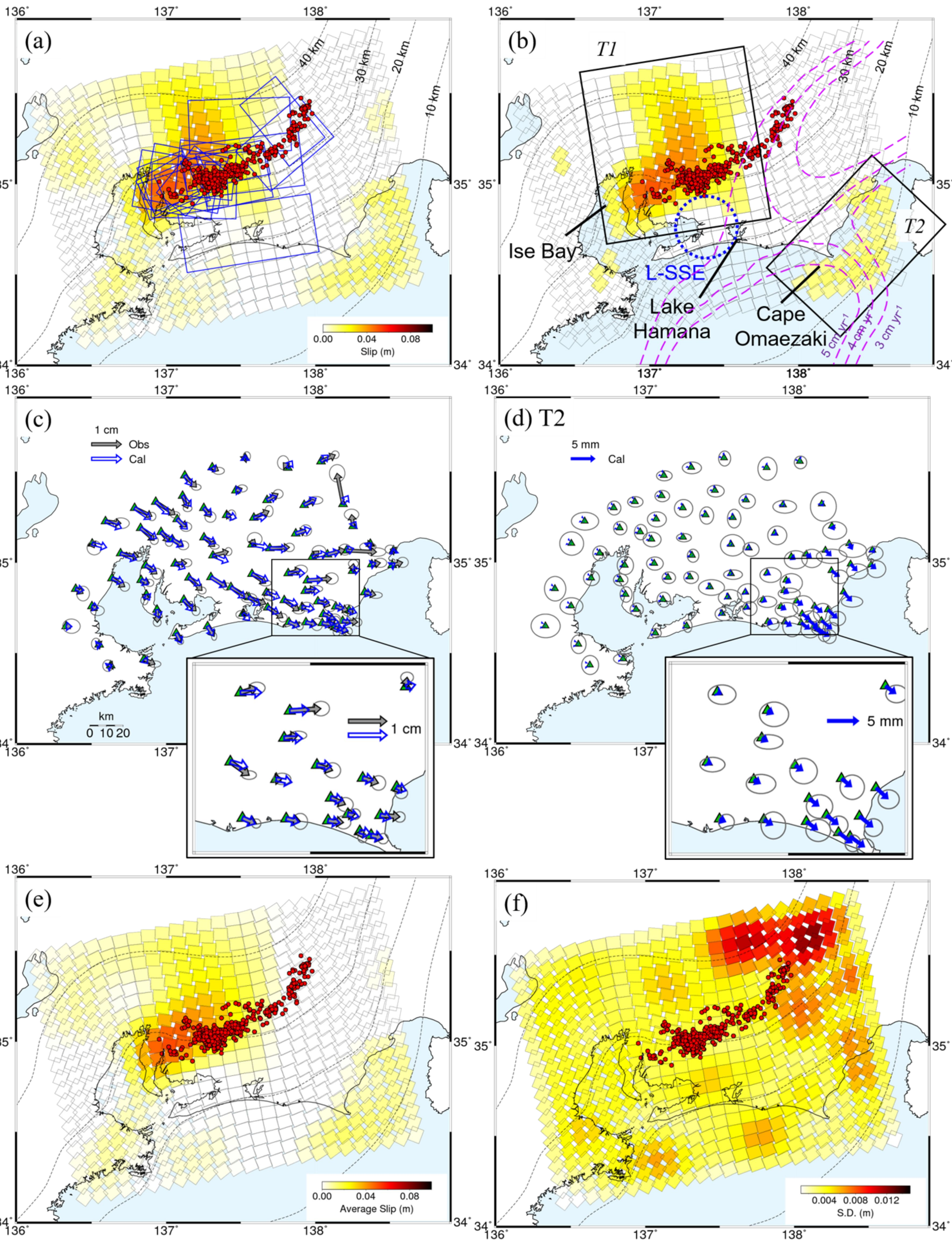
(a) E3
(b) E4
(c) E5
(d) E6
Cal
5 mm
133°
134°
135°
34°
33°

Figure 5.



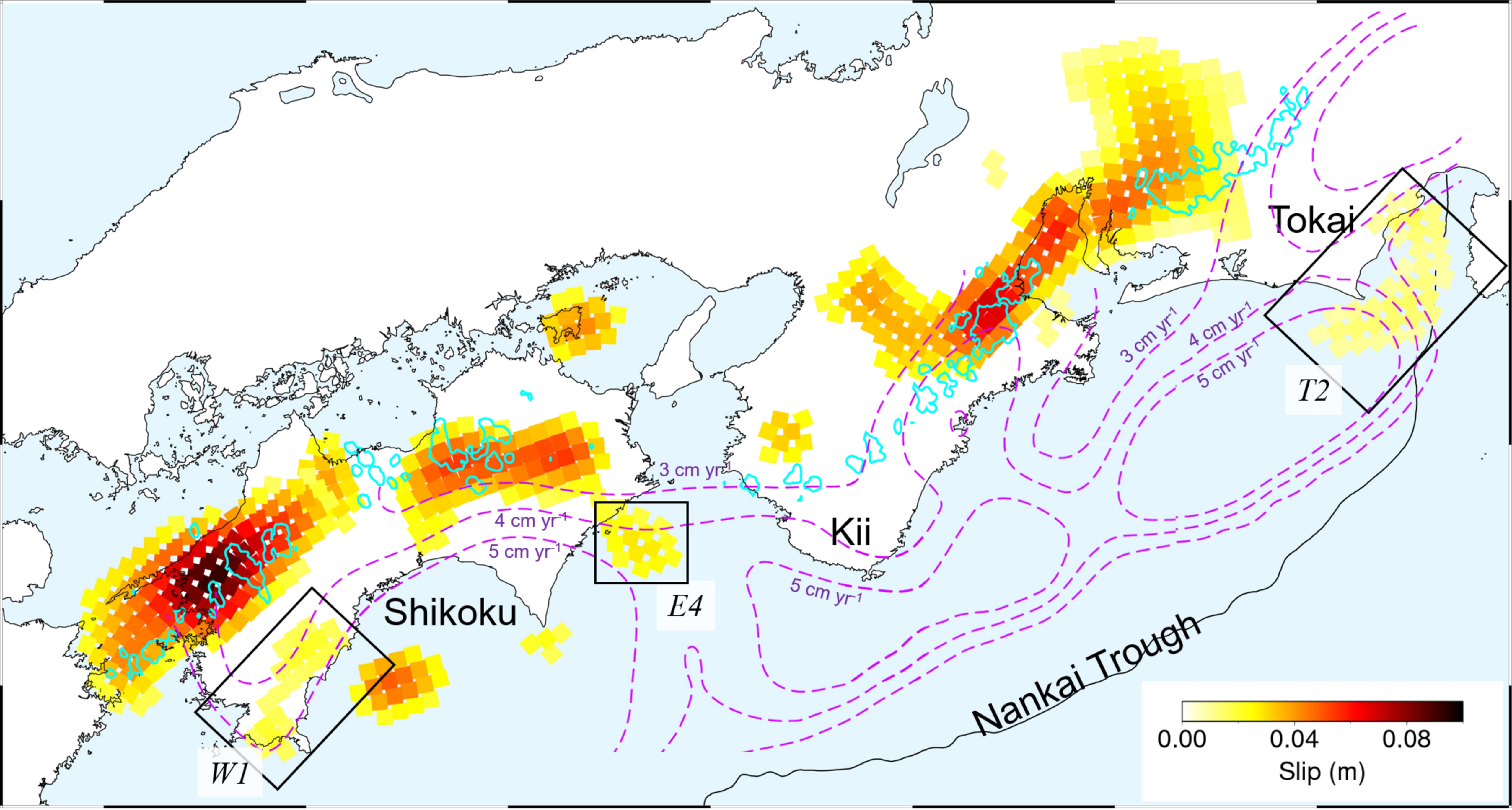
(a)
40 km
30 km
20 km
0.00
0.04
0.08
Slip (m)
(b)
Ise Bay
K1
K2
(c)
1 cm
Obs
Cal
km
0 10 20
(d) K2
Cal
5 mm
135°
136°
137°
35°
34°

Figure 6.



(a)
40 km
30 km
20 km
10 km
0.00 0.04 0.08
Slip (m)
(b)
T1
T2
Ise Bay
L-SSE
Lake Hamana
Cape Omaezaki
5 cm yr⁻¹
4 cm yr⁻¹
3 cm yr⁻¹
(c)
1 cm
Obs
Cal
km
0 10 20
1 cm
(d) T2
5 mm
Cal
5 mm
(e)
0.00 0.04 0.08
Average Slip (m)
(f)
0.004 0.008 0.012
S.D. (m)
136°
137°
138°
34°
35°

Figure 7.


Tokai
T2
3 cm yr-1
4 cm yr-1
5 cm yr-1
Kii
E4
Shikoku
W1
Nankai Trough
0.00
0.04
0.08
Slip (m)