

Supporting Information

Data preprocessing

We estimated the linear trend and the annual and semiannual periodic components for the period between 1996 and 2011 before the Tohoku earthquake by regressing the function

$$y(t) = y_0 + v_0 t + b_1 \sin 2\pi t + b_2 \sin 4\pi t + c_1 \cos 2\pi t + c_2 \cos 4\pi t + \sum_{i=1}^r d_i H(t - t_i), \quad (1)$$

where t indicates time (1 year=1), y_0 is the initial position, and v_0 is the secular velocity. b_1 , b_2 , c_1 , and c_2 relate to annual and semiannual seasonal variations. $H[t-t_i]$ is a Heaviside function that represents offsets of Boso SSEs and earthquakes at time t_i with an amplitude of d_i . r is the number of Boso SSEs and earthquakes.

We removed the components of the linear trend and the trigonometric functions from the position time series for the entire period. For the events after the Tohoku earthquake, we regressed the logarithm and exponential functions to the above position time series whose annual and semiannual components and the linear trend has been removed, considering the postseismic deformation of the 2011 Tohoku earthquake, using the following function:

$$y(t) = h \log \left(1 + \frac{t-t_0}{d} \right) + p \left(1 - \exp \left(-\frac{t-t_0}{g} \right) \right), \quad (2)$$

where t_0 indicates the date of the Tohoku earthquake, h is the amplitude and d is the time constant of the logarithm function, and p is the amplitude and g is the time constant of the exponential function. We removed the logarithm and exponential components from the position

time series whose annual, semiannual, and linear trend components has been removed. Since the annual and semiannual periodic components changed after 2012 because of the replacement of the antennas in 2012, we estimated the annual and semiannual components for the period between 2015 and 2018 and removed them from the position time series in the analysis of the 2014 and 2018 events.

Modified time-dependent inversion method

We used the square-root information filter (e.g., Kitagawa and Gersch 1996) instead of the Kalman filter for the time-dependent inversion since it is more convenient for incorporating spatial smoothing in a transition equation. We adopted the following state in the square-root information filter in the time-dependent inversion:

$$\mathbf{x}(t) = (u_1, v_1, \dots, u_k, v_k, \dots, u_L, v_L, e_1, \dots, e_i, \dots, e_N, f_{EW}, f_{NS}, f_{UD}), \quad (3)$$

where u_k indicates the slip and v_k indicates the slip velocity at the k -th grid on the plate interface, which is represented by the spline surface of a total of L grids, and e_i represents the offset of the i -th position time series out of a total of N positions. This offset is used to estimate the zero position of the position time series since we do not know the zero position of each time series. f_{EW} , f_{NS} , and f_{UD} are the common mode errors in the east-west, north-south, and up-down components, respectively (e.g., Fukuda 2018).

The transition equation of the square-root information filter, which contains the

hyperparameter τ used in temporal smoothing, is described in Kitagawa and Gersch (1996) as follows:

$$\mathbf{v}_{n|n-1} = \mathbf{F} \mathbf{v}_{n-1|n-1} + \boldsymbol{\omega}_1, \quad (4)$$

where $\mathbf{v}_{n|n-1}$ is the predicted slip velocity at time n based on the data until time $n-1$. $\mathbf{v}_{n-1|n-1}$ is the state at time $n-1$ based on the data until time $n-1$. $\mathbf{F}$ is the transition matrix described in Ozawa et al. (2001). $\boldsymbol{\omega}_1$ is the Gaussian noise of the system with zero mean and variance τ .

We incorporated the following equation of spatial roughness in the transition equation:

$$\mathbf{M} \mathbf{v}_{n|n-1} = \boldsymbol{\omega}_2, \quad (5)$$

where $\mathbf{M}$ is the roughness matrix described in Ozawa et al. (2001). $\boldsymbol{\omega}_2$ is the Gaussian noise of the system with zero mean and variance λ .

The hyperparameter λ used in spatial smoothing and τ used in temporal smoothing in the transition equation were determined by maximizing the log-likelihood of the system (e.g., Kitagawa and Gersch 1996).

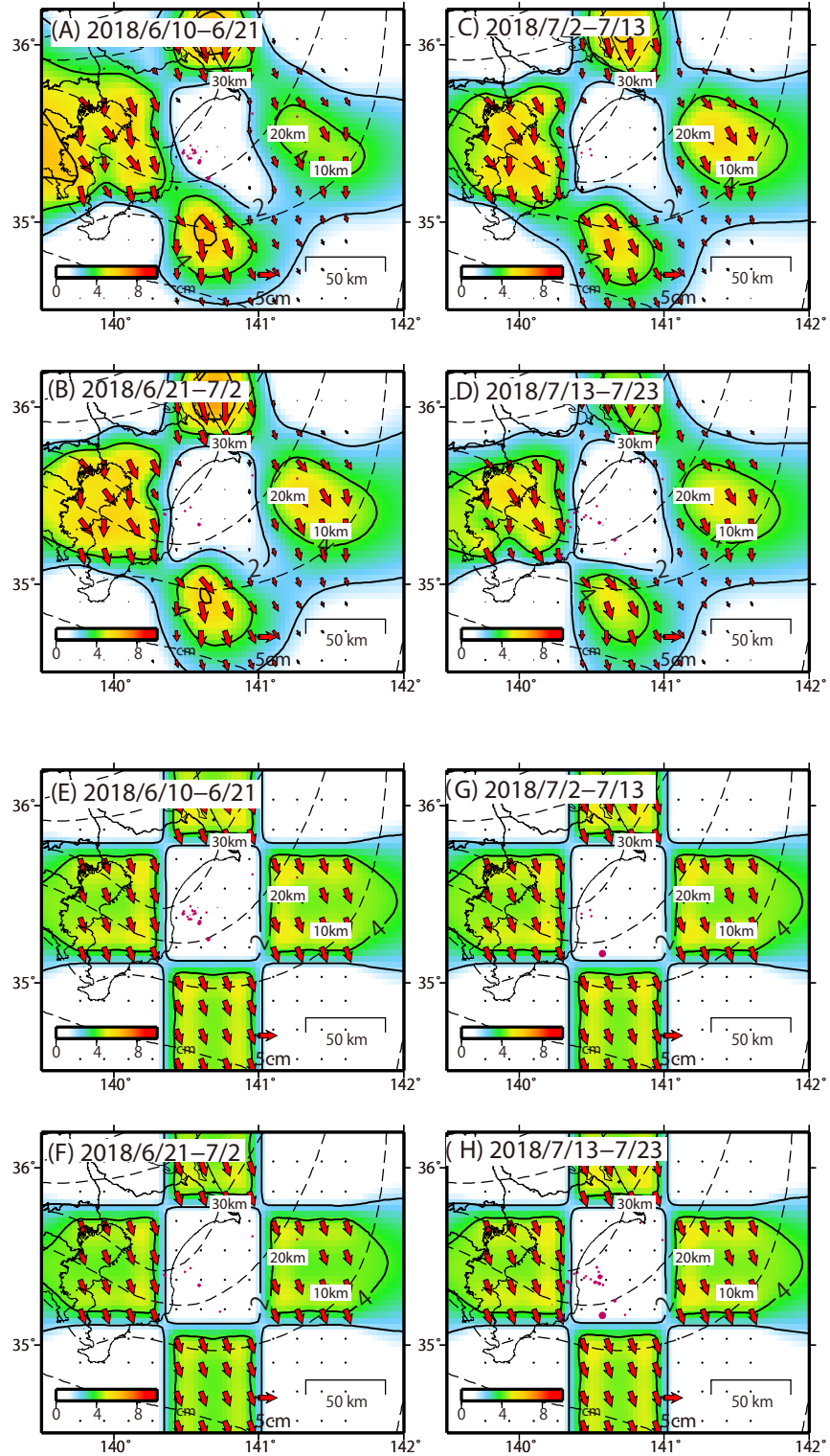


Fig. S1A (A)-(D) Inverted slip distributions based on synthetic data. The synthetic data are produced by adding a 1 mm Gaussian standard error to horizontal components and a 5 mm error to vertical components in the calculation from the synthetic slip. (E)-(H) Synthetic slip.

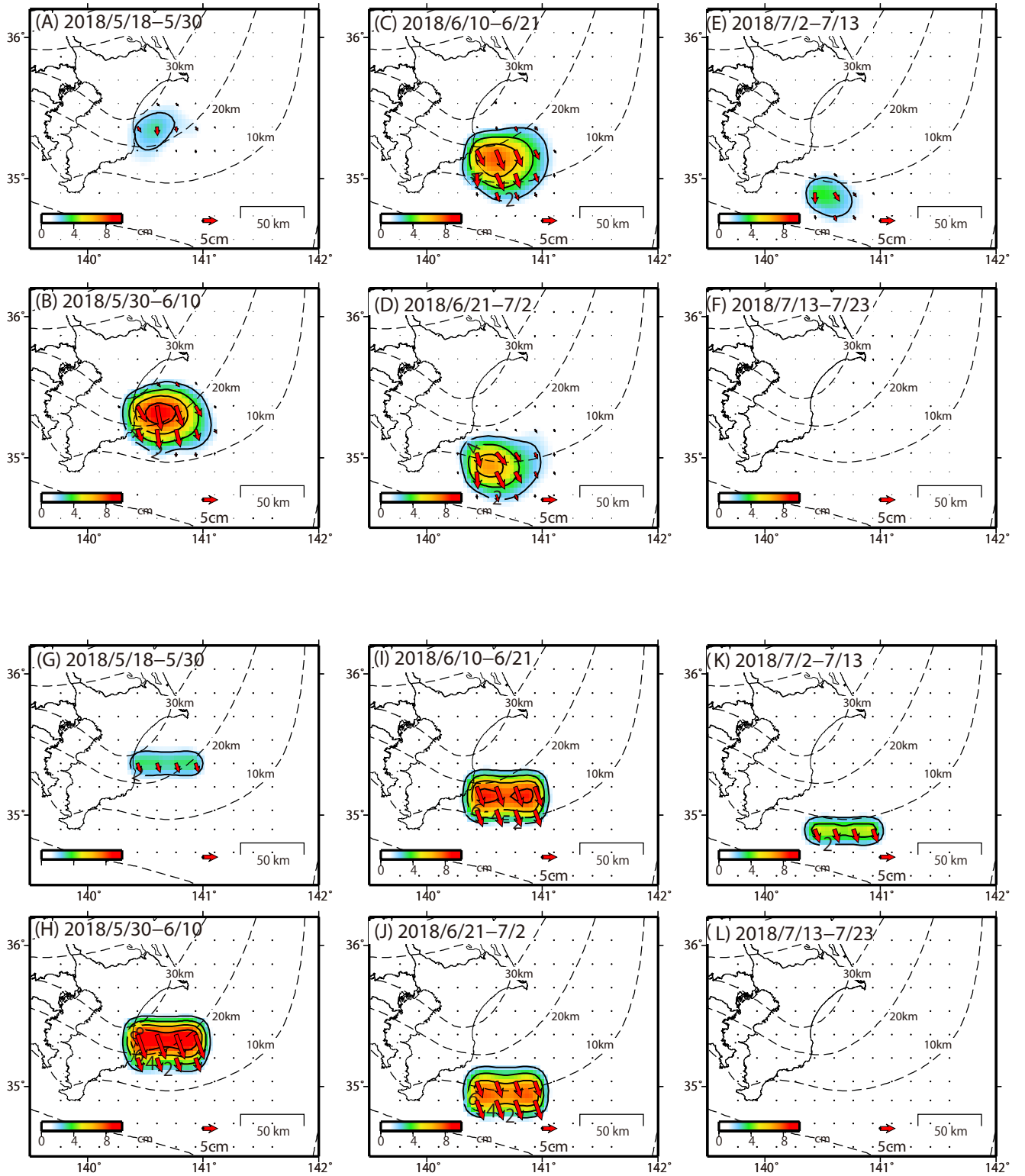


Fig. S1B. (A)-(F) Inverted slip distributions based on synthetic data. The synthetic data are produced in the same way as that in Fig. S1A. Southward slip propagation is detected. (G)-(L) Synthetic slip.

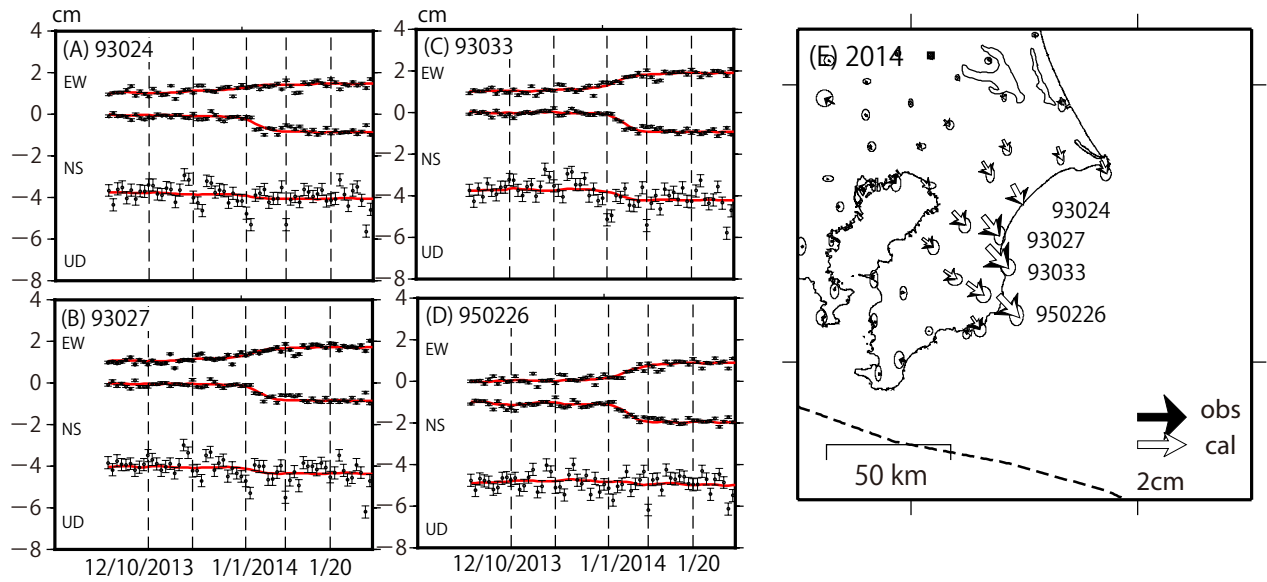


Fig. S2A. (A) Detrended position time series at site 93024. (B) 93027. (C) 93033. (D) 950226. (E) Total southeastward transient for the period between December 23, 2013 and January 30, 2014. The nomenclature is the same as that in Fig. 2.

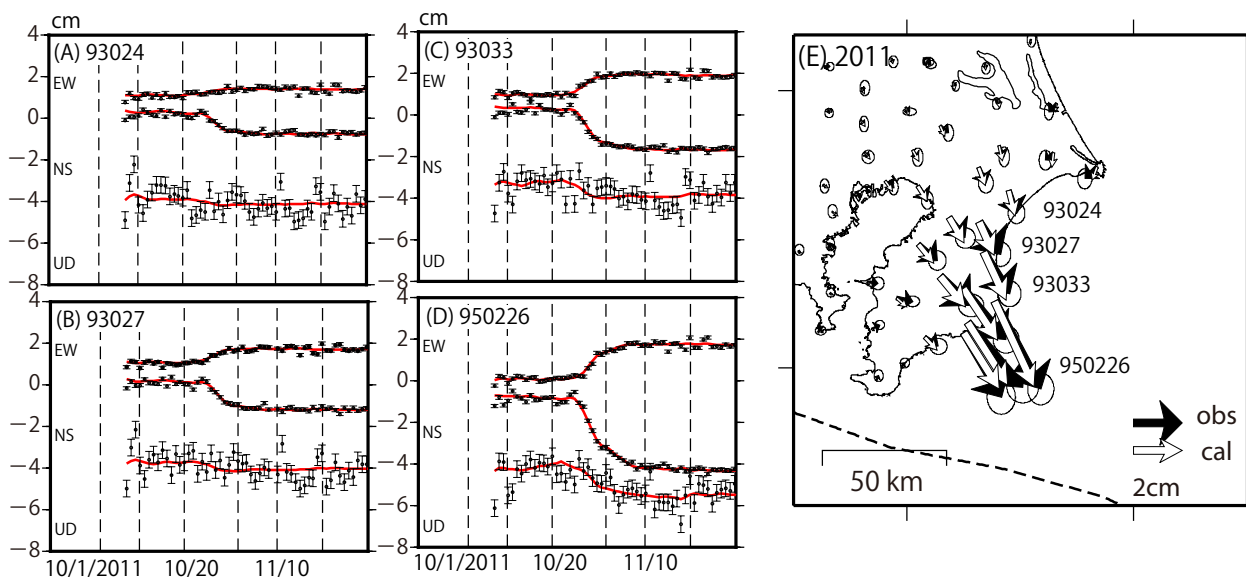


Fig. S2B. (A) Detrended position time series at site 93024. (B) 93027. (C) 93033. (D) 950226. (E) Total southeastward transient for the period between October 12 and December 10, 2011. The nomenclature is the same as that in Fig. 2.

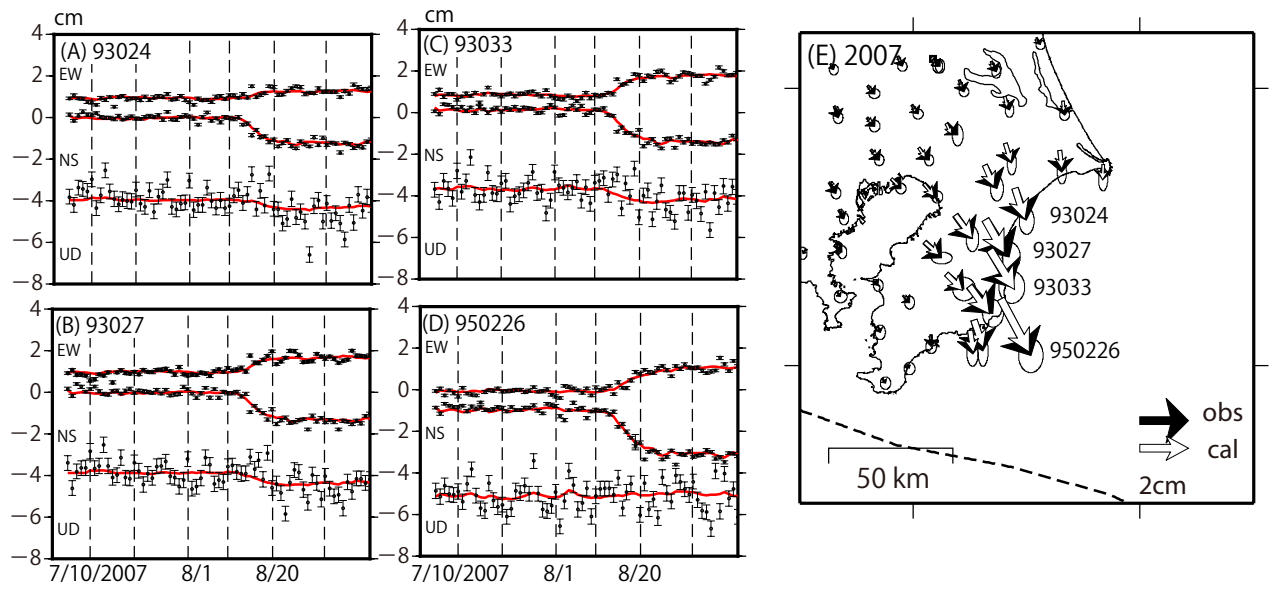


Fig. S2C. (A) Detrended position time series at site 93024. (B) 93027. (C) 93033. (D) 950226. (E) Total southeastward transient for the period between August 3 and September 7, 2007. The nomenclature is the same as that in Fig. 2.

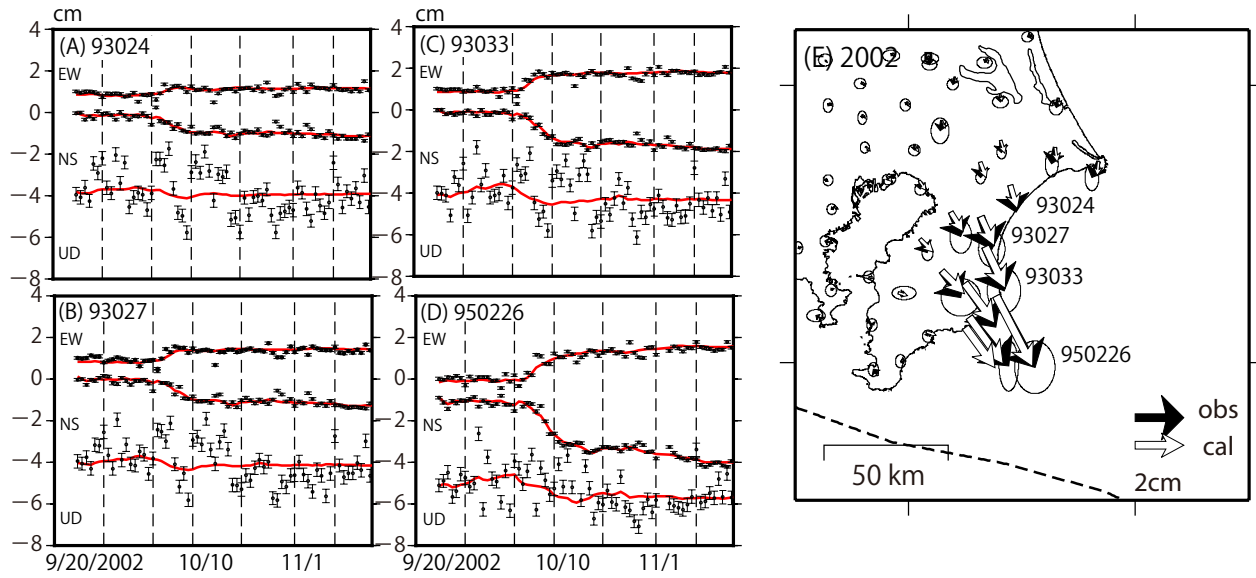


Fig. S2D. (A) Detrended position time series at site 93024. (B) 93027. (C) 93033. (D) 950226. (E) Total southeastward transient for the period between September 23 and November 30, 2002. The nomenclature is the same as that in Fig. 2.

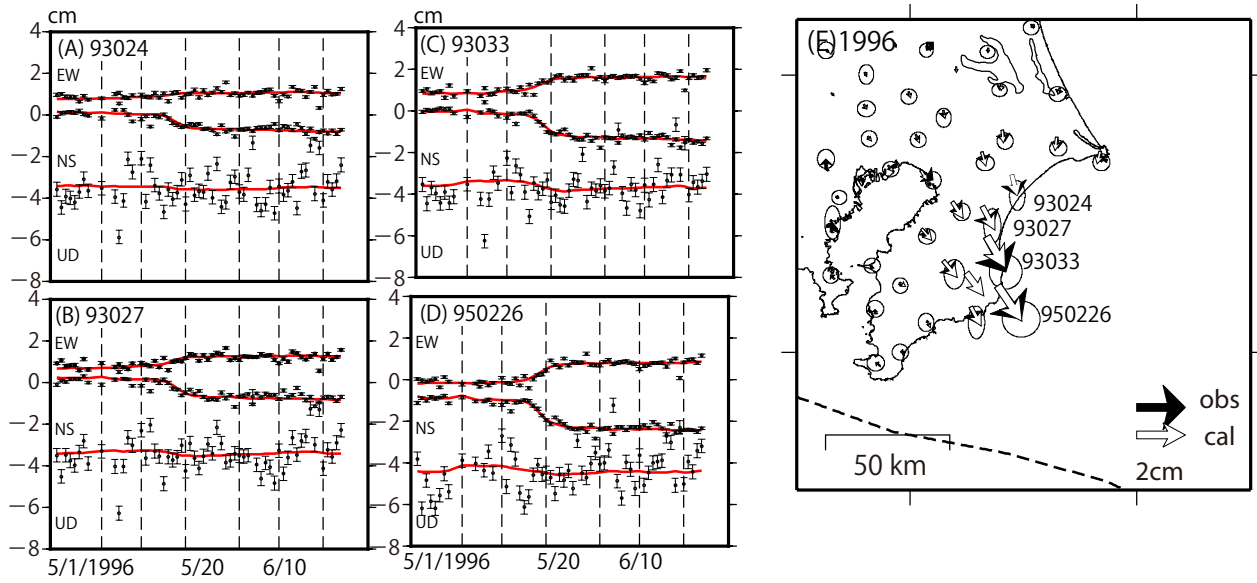


Fig. S2E. (A) Detrended position time series at site 93024. (B) 93027. (C) 93033. (D) 950226. (E) Total southeastward transient for the period between May 7 and June 24, 1996. The nomenclature is the same as that in Fig. 2.

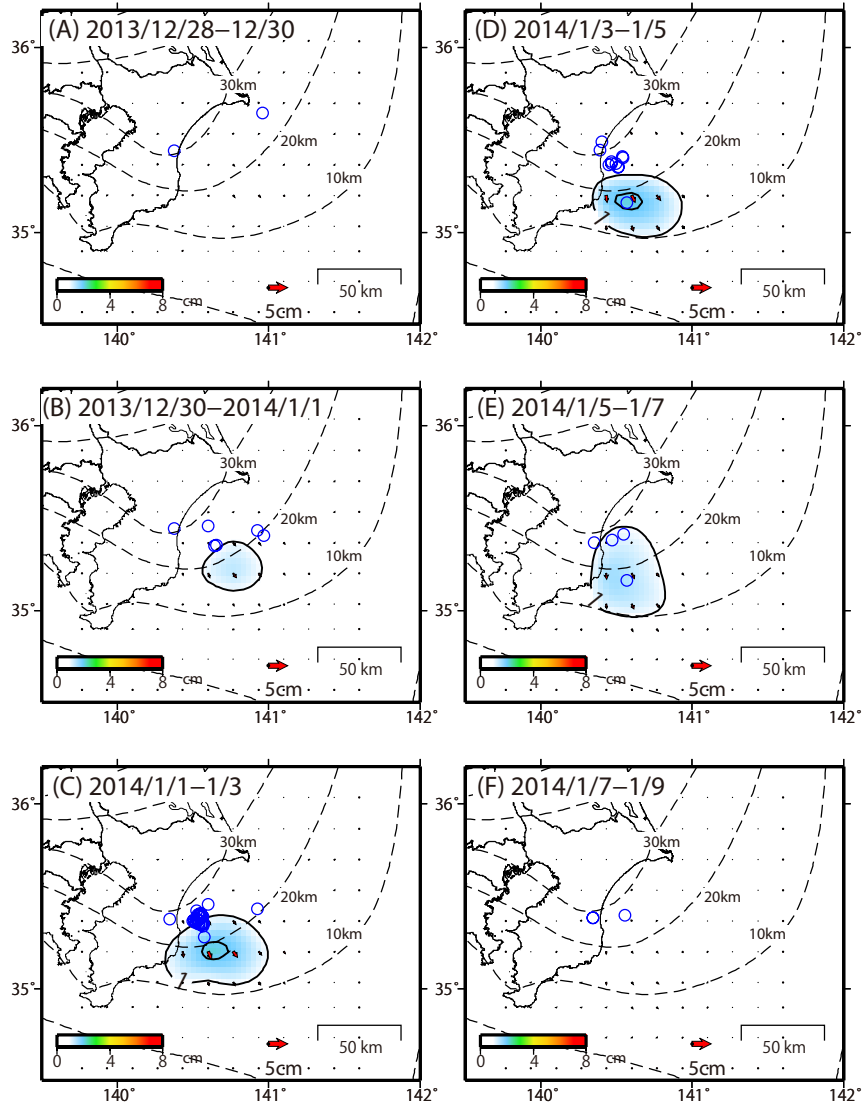


Fig. S3A. Estimated interplate aseismic slip at the time of the 2014 event. The nomenclature is the same as that in Fig. 3.

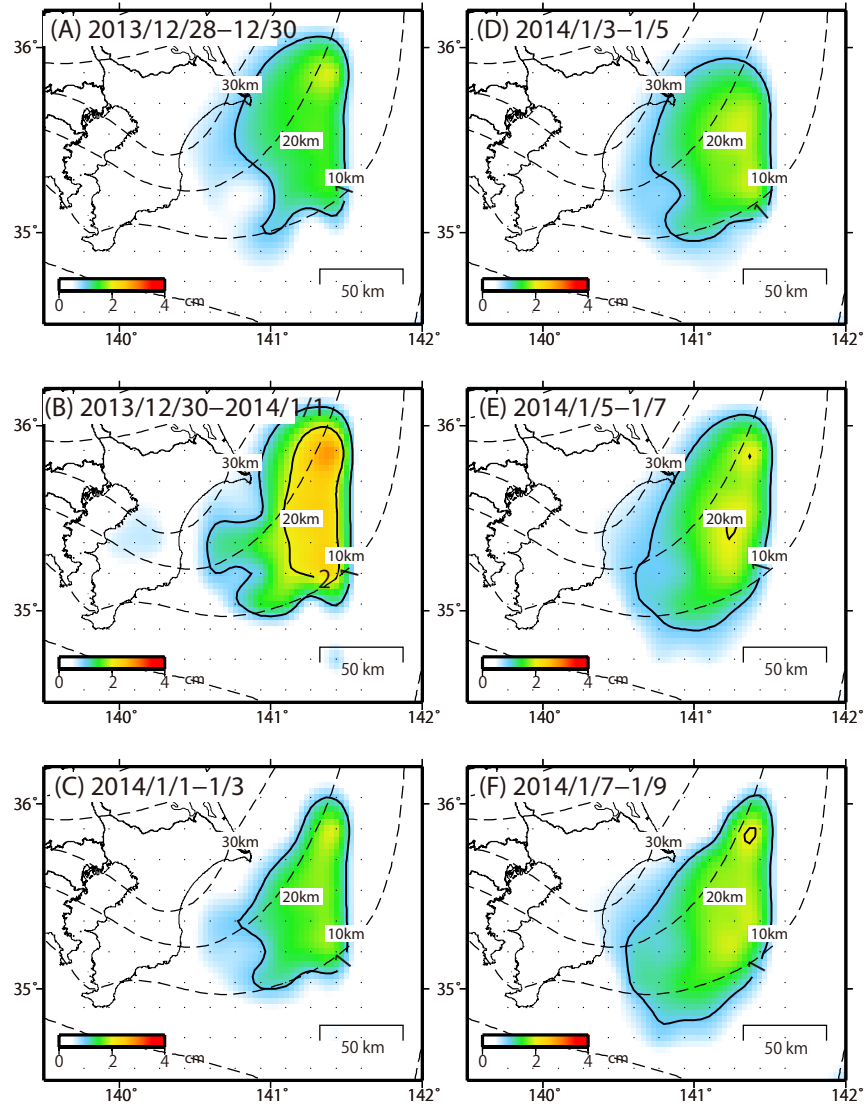


Fig. S3B. Standard deviation of the estimated interplate aseismic slip for the periods in Fig. S3A.

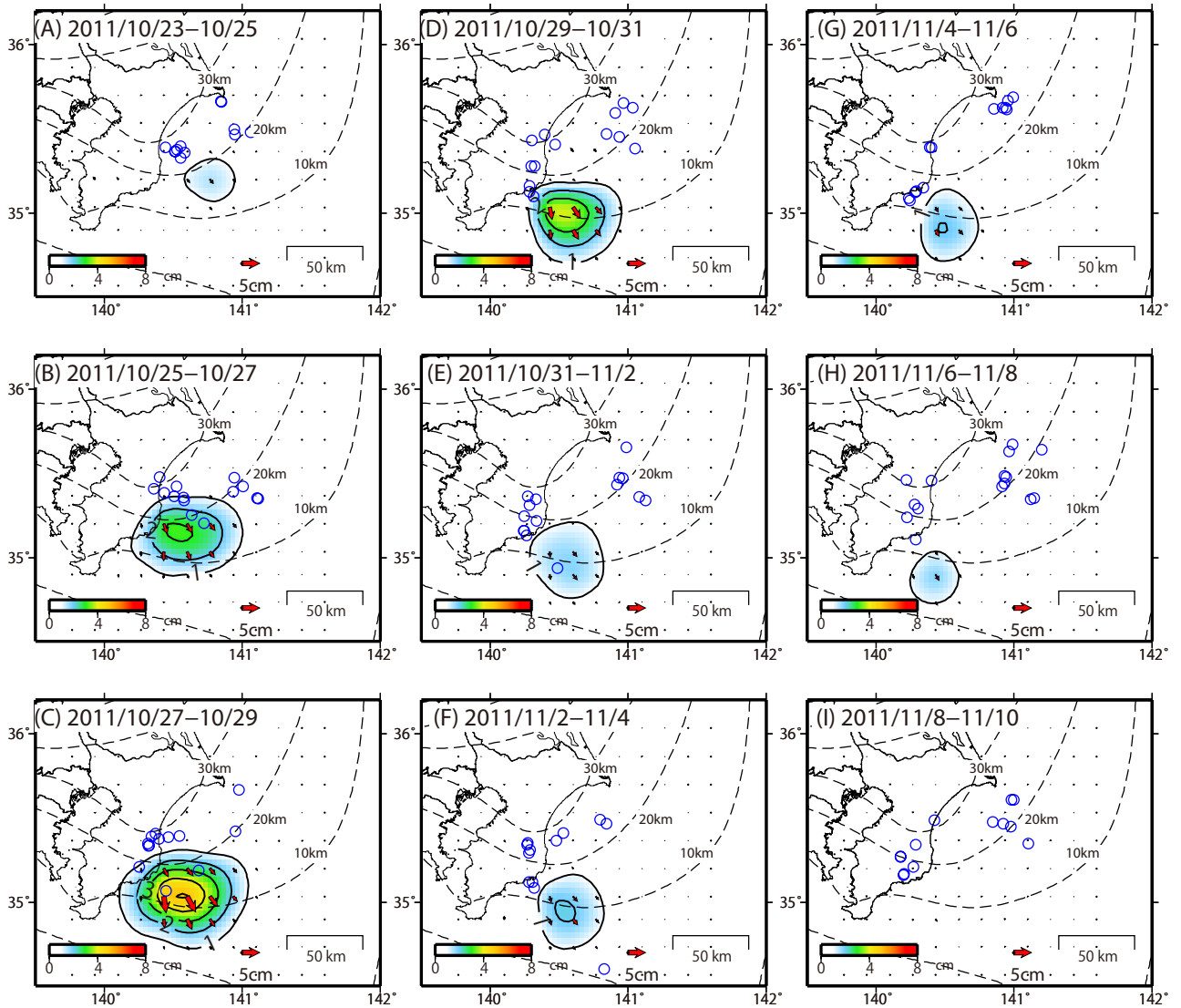


Fig. S3C. Estimated interplate aseismic slip at the time of the 2011 event. The nomenclature is the same as that in Fig. 3.

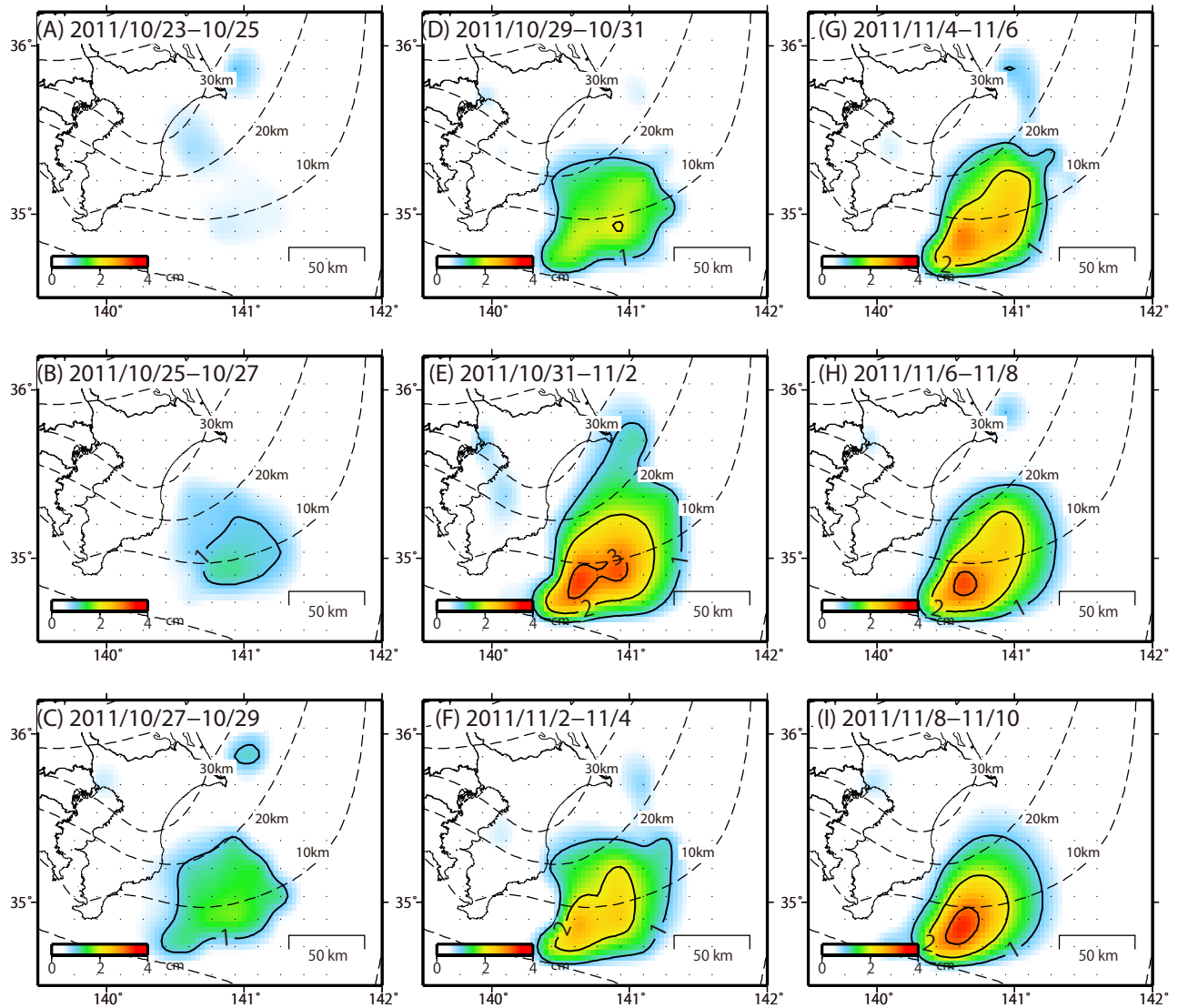


Fig. S3D. Standard deviation of the estimated interplate aseismic slip for the periods in Fig. S3C.

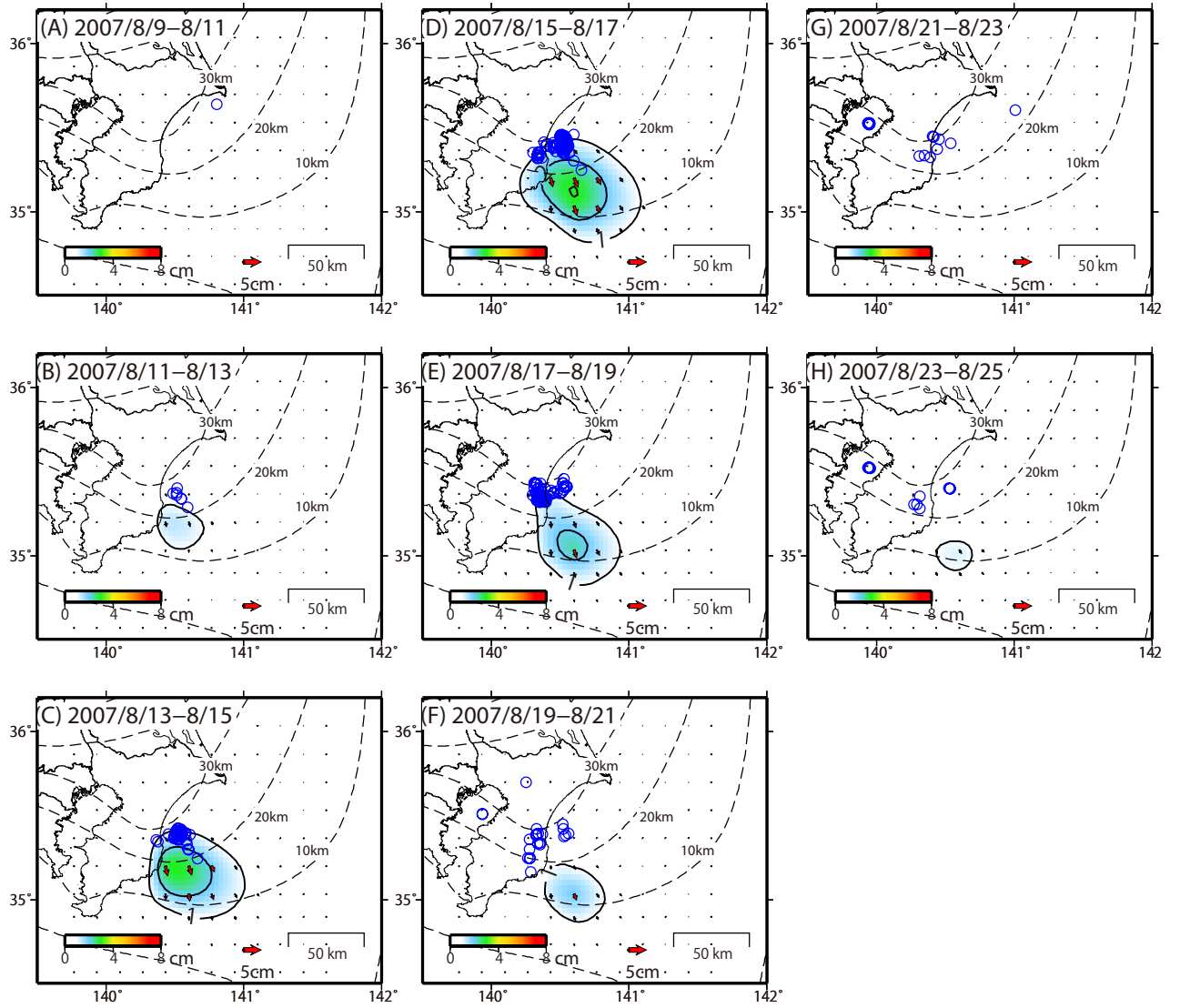


Fig. S3E. Estimated interplate aseismic slip at the time of the 2007 event. The nomenclature is the same as that in Fig. 3.

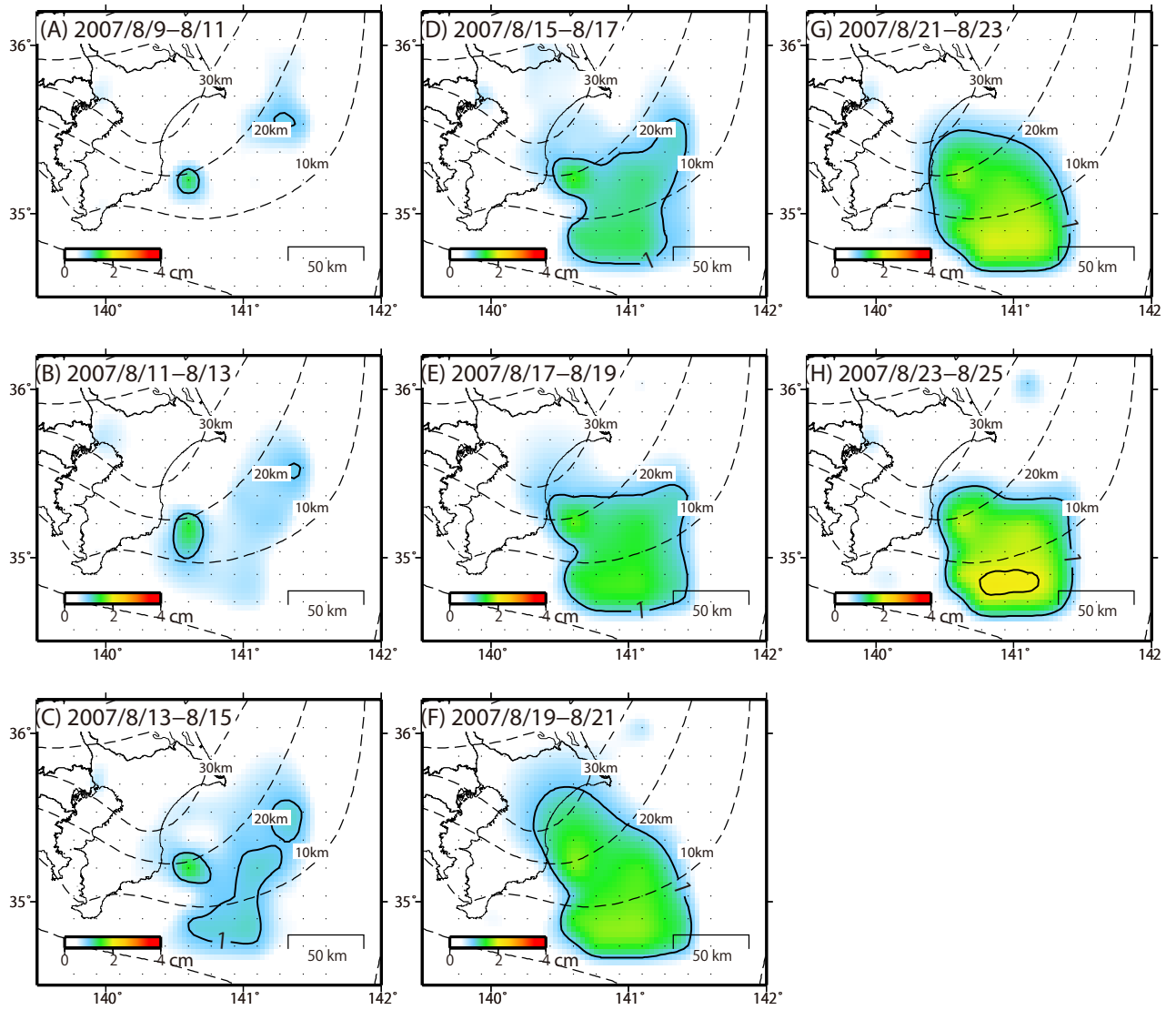


Fig. S3F. Standard deviation of the estimated interplate aseismic slip for the periods in Fig. S3E.

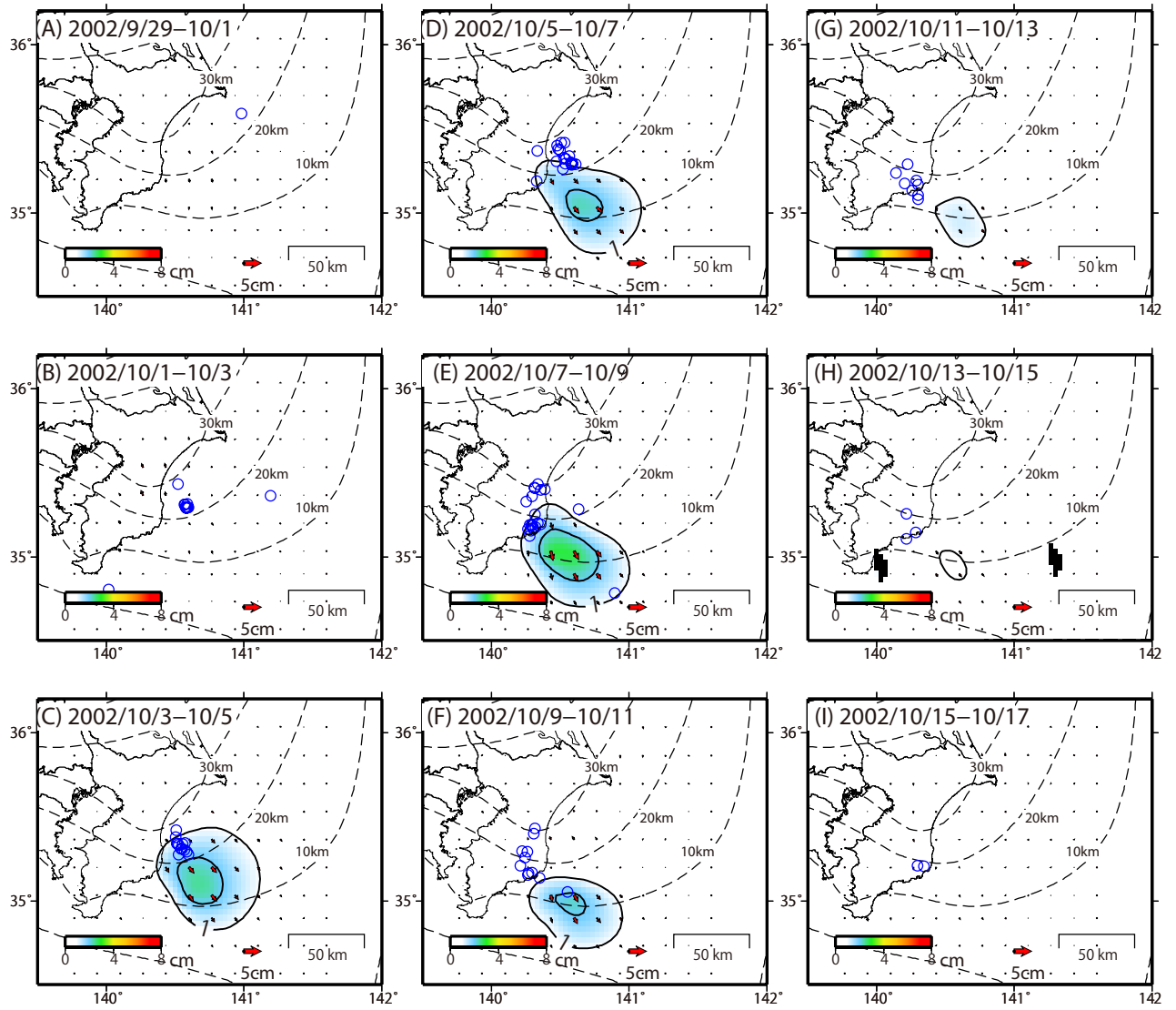


Fig. S3G. Estimated interplate aseismic slip at the time of the 2002 event. The nomenclature is the same as that in Fig. 3.

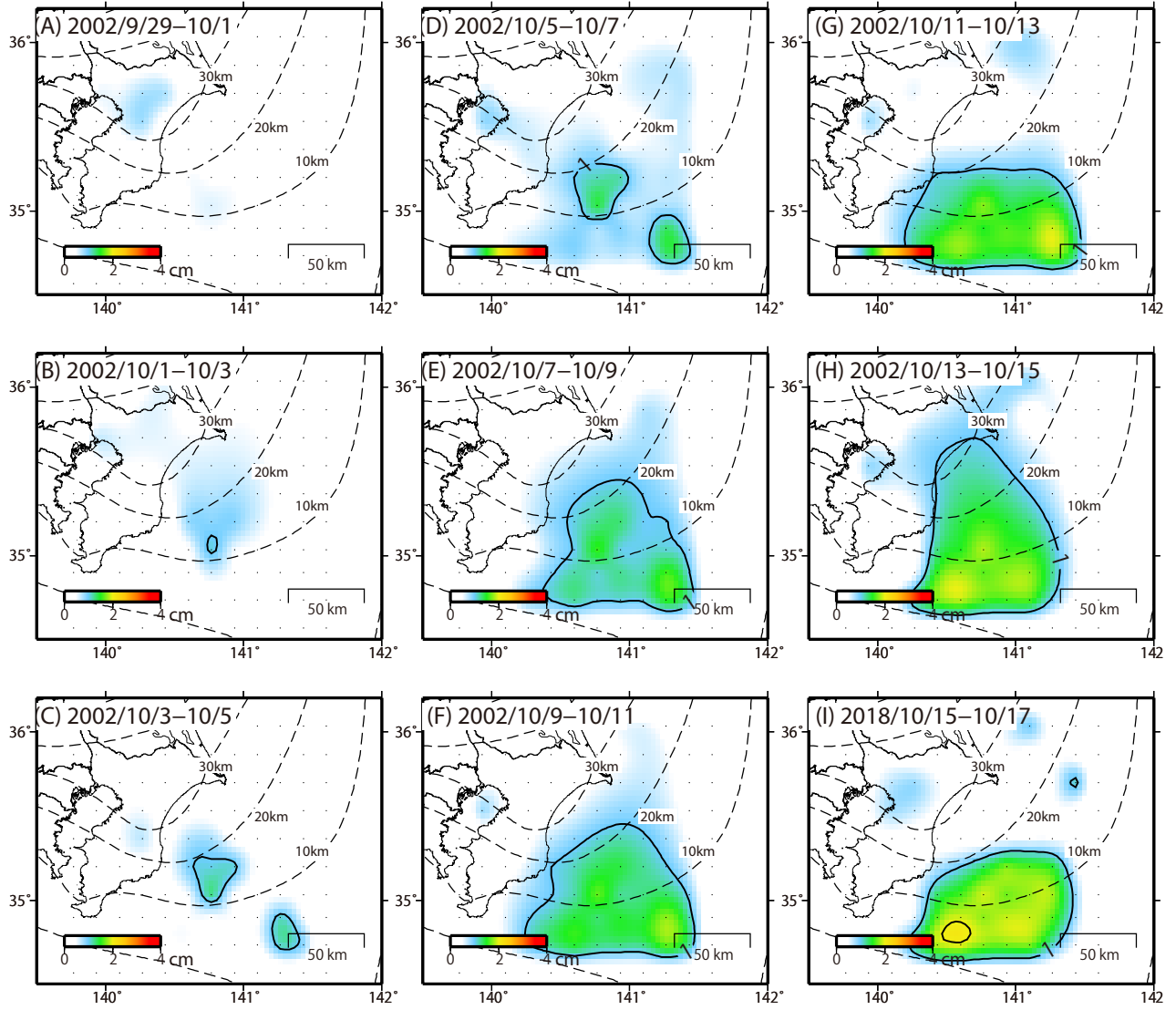


Fig. S3H. Standard deviation of the estimated interplate aseismic slip for the periods in Fig. S3G.

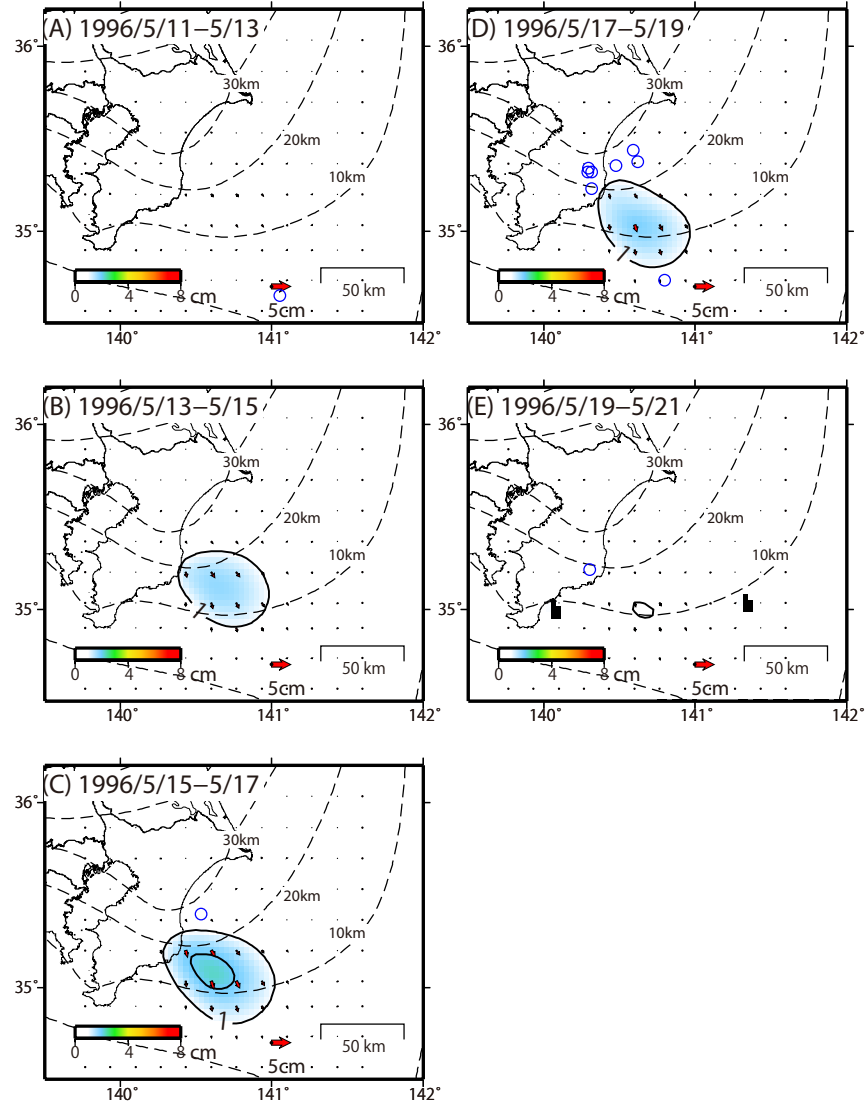


Fig. S3I. Estimated interplate aseismic slip at the time of the 1996 event. The nomenclature is the same as that in Fig. 3.

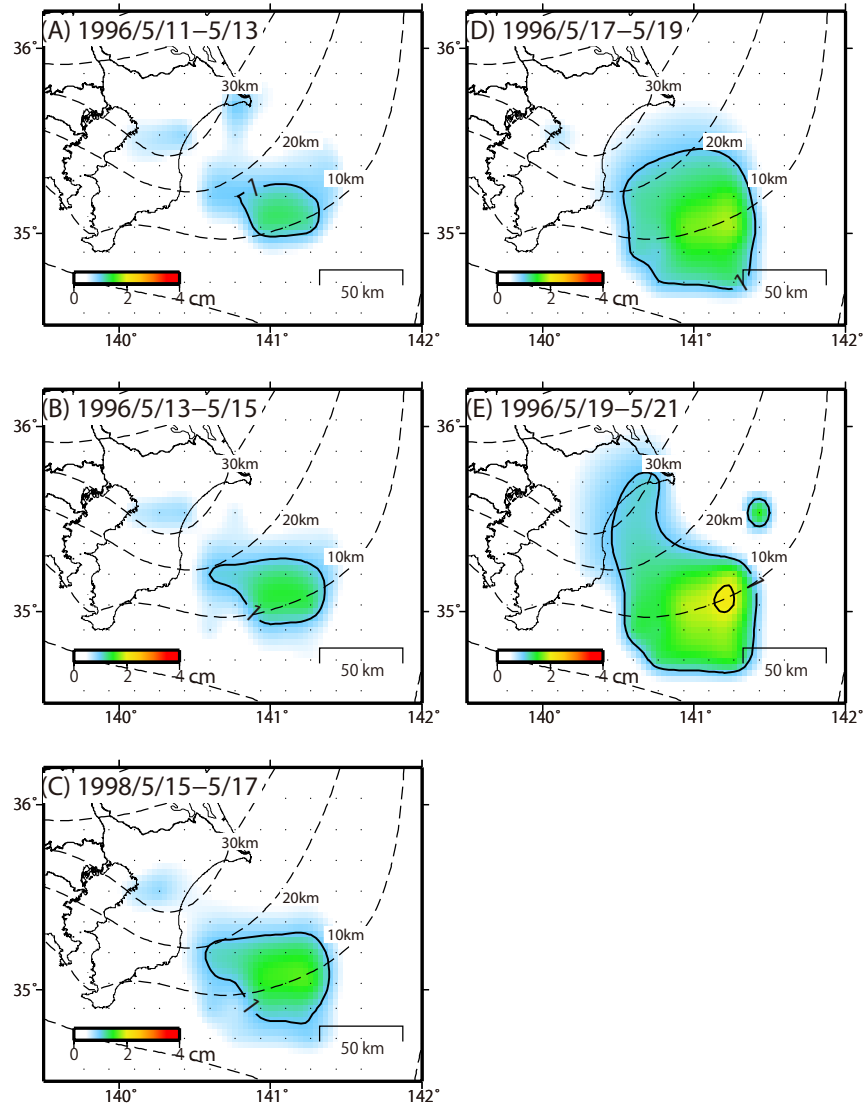


Fig. S3J. Standard deviation of the estimated interplate aseismic slip for the periods in Fig. S3I.

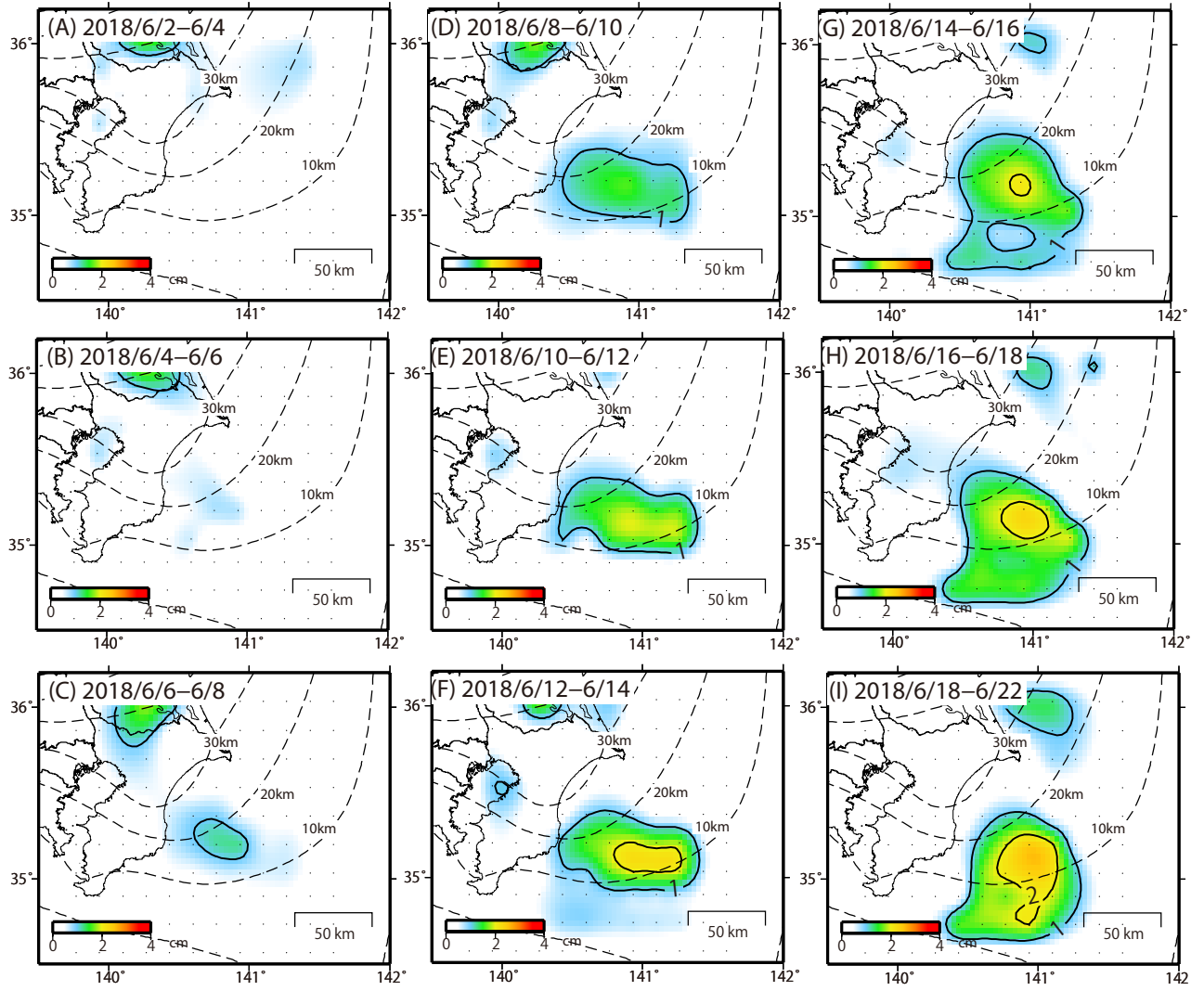


Fig. S4. Standard deviation of the estimated interplate aseismic slip for the periods in Fig. 3.

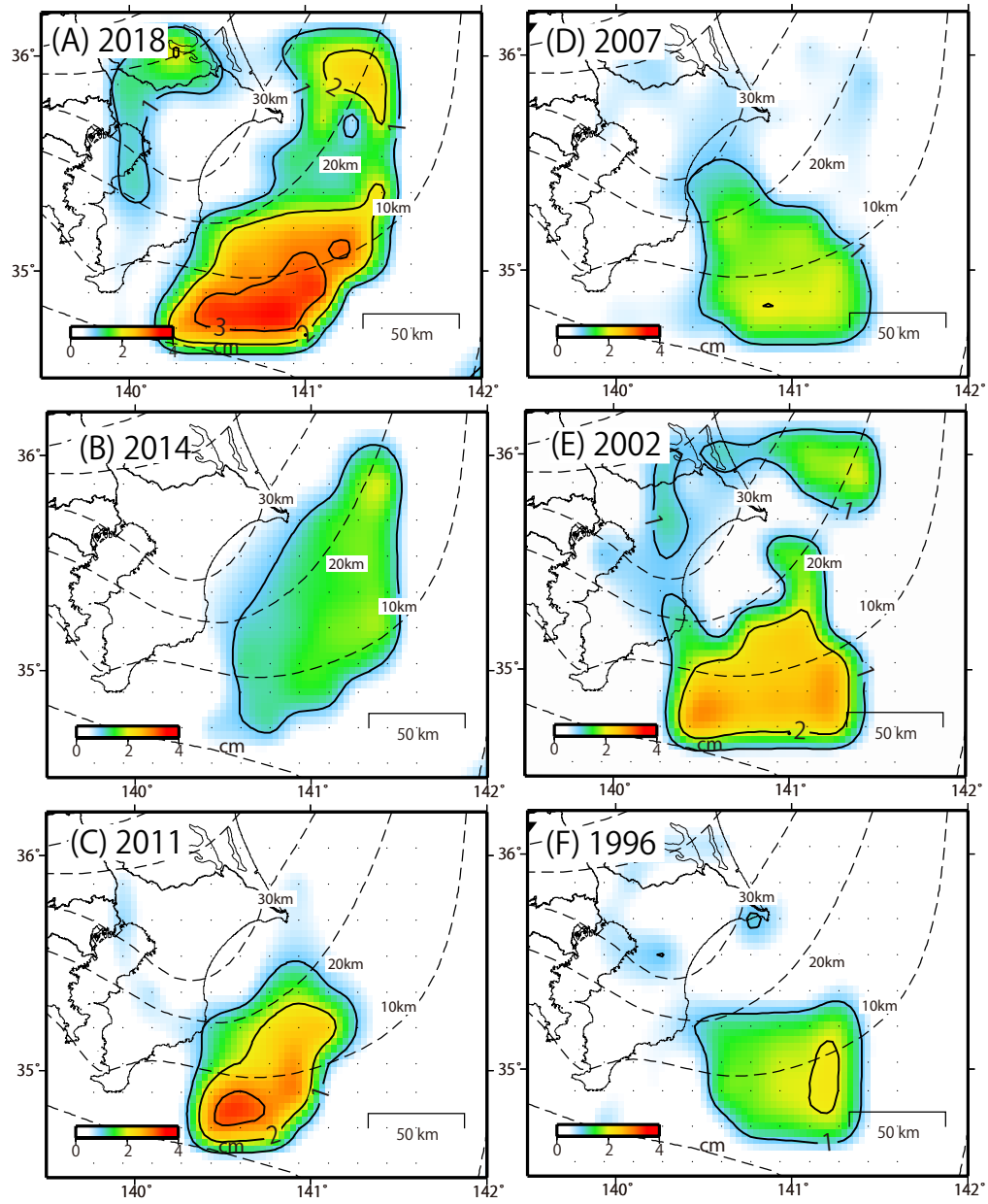


Fig. S5. Standard deviation of the estimated interplate aseismic slip for the periods in Fig. 4.

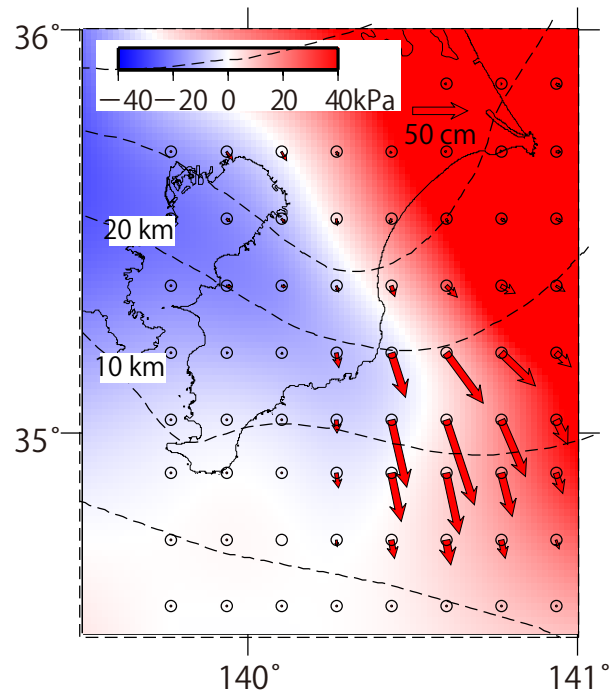


Fig. S6. Δ CFS on the plate interface between the Philippine Sea plate and the CJP according to the 2011 Tohoku earthquake model (Ozawa et al. 2012). The dashed lines indicate isodepth contours of the plate interface with an interval of 10 km. Red arrows indicate the total Boso slow slip from 1996 to 2018.

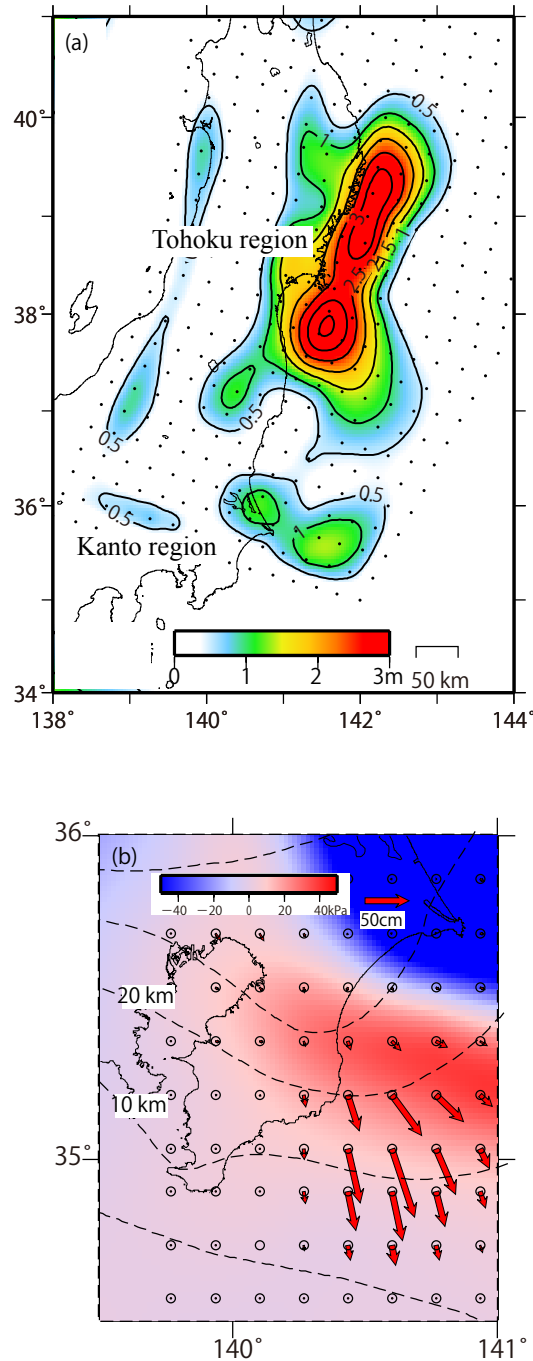


Fig. S7. (a) Afterslip model proposed by Ozawa et al. (2012) for the period between March 2011 and October 2011. Since this model does not take into account viscoelastic relaxation, the afterslip area off the Tohoku region is overestimated. However, the estimated afterslip near the Kanto region is not so different from that in Sun et al. (2014), which takes into account viscoelastic relaxation, since the postseismic deformation near the Kanto region seems to be mainly caused by afterslip for this period. (b) ΔCFS obtained by the afterslip model in (a). The slip direction and friction coefficient in the ΔCFS calculation were the same as those used in the ΔCFS calculation for the 2011 Tohoku earthquake model. The nomenclature is the same as that in Fig. S6. ΔCFS near the Boso SSE area is mainly caused by afterslip near the Kanto region, which is not so different from the model proposed by Sun et al. (2014). Even if we exclude the afterslip off the Tohoku region from the computation, the main feature in the Boso SSE area does not change. ΔCFS ranges up to 50 kPa in the Boso SSE area.

Reference

Sun, T., Wang, K., Iinuma, T., Hino, R., He, J., Fujimoto, H., Kido, M., Osada, Y., Miura, S., Ohta, Y., Hu, Y. (2014) Prevalence of viscoelastic relaxation after the 2011 Tohoku-oki earthquake. *Nature* 514:84-87. doi:10.1038/nature13778.

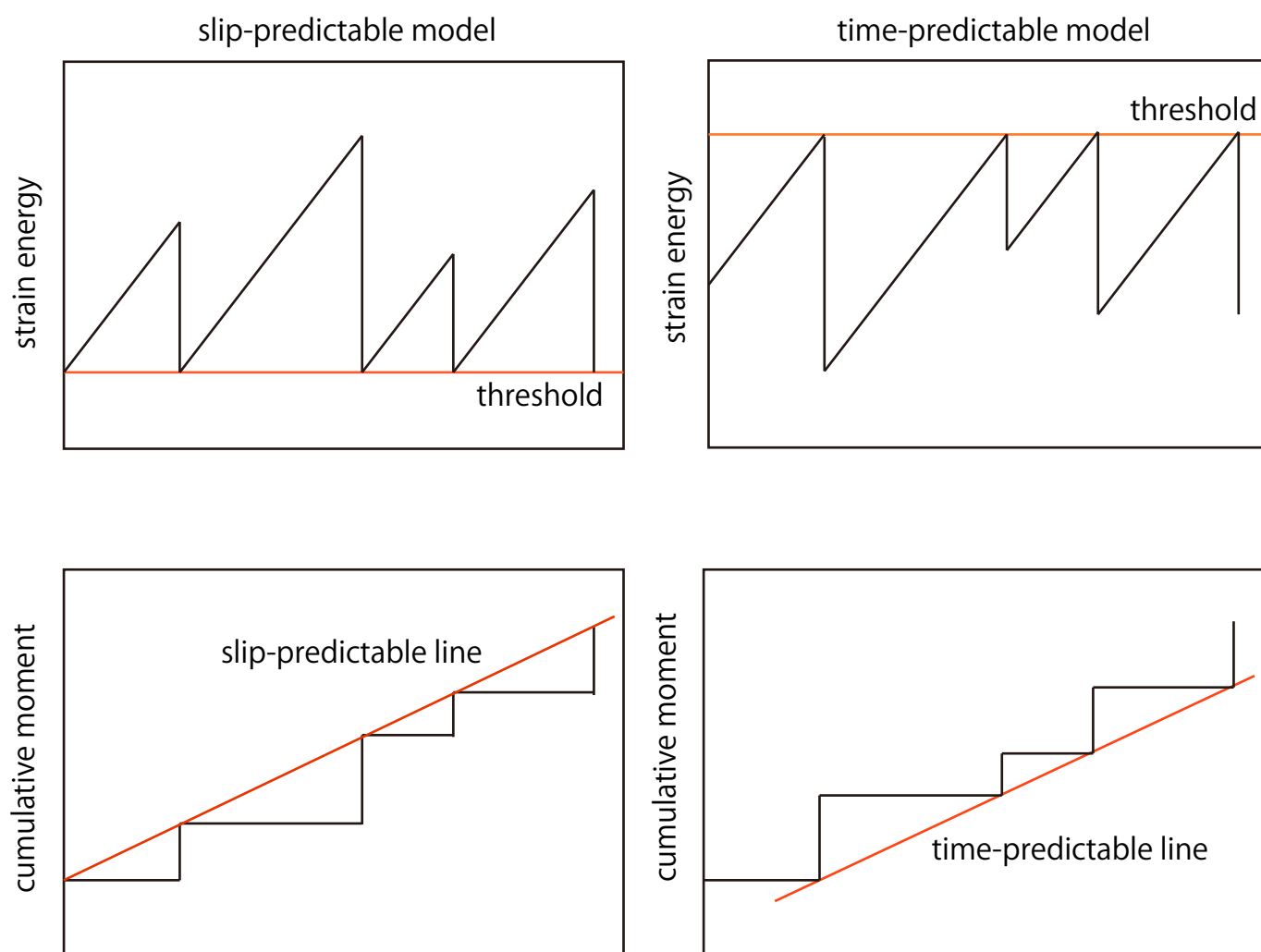


Fig. S8. As schematically shown in the top figures, in the slip-predictable model, strain energy above some threshold is released when fault rupture occurs, while fault rupture occurs in the time-predictable model when accumulated strain energy reaches some threshold. The slip-predictable line and time-predictable line fitting the cumulative moment are schematically shown in the bottom figures.

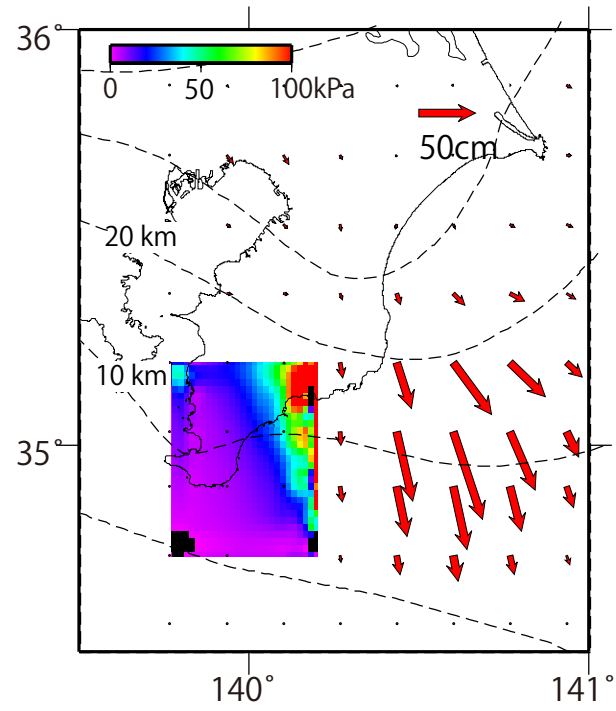


Fig. S9. Total ΔCFS on the plate interface between the Philippine Sea plate and the CJP from 1996 to 2018. The nomenclature is the same as that in Fig. S6.