Supplementary Figure 1 | Results of the slip deficit rate inversions. Distributions of slip deficit rate (blue and purple contours) and horizontal deformation rates (pink arrows) in 1998 (Left) and 2008 (Right). Black arrows represent synthetic horizontal deformation rates computed from the slip deficit rate distribution. The white star denotes the hypocentre of the Tohoku earthquake. The dark green line denotes the Japan Trench. The Sagami Trough is located out of the map beyond its southern end.
Supplementary Figure 2 | Two-dimensional mechanical model. Upper: Two-dimensional shape of the JTSZ in and off central Tohoku. Numbers 1 to 10 indicate locations where simulated slip histories are shown in Supplementary Fig. 3. Lower: Distributions of the parameters $a-b$, $L$, and $\sigma_n^{\text{eff}}$ in the rate- and state-dependent friction law\textsuperscript{5} along the plate boundary.
Supplementary Figure 3 | Results of the seismic supercycle simulation. Simulated slip deficit histories at points 2, 4, 6, 8, and 10 in the upper diagram of Supplementary Fig. 2. In addition to $M_7$-class earthquakes (steps in slip deficit slopes), several very-long-term transient events (flat parts in slip deficit slopes) denoted by orange or red bars occur during a supercycle between megathrust earthquakes. The last very-long-term transient event (red bars) in each cycle occurs just before and leading to a megathrust earthquake.
Supplementary Figure 4 | Distribution of composite deformations and the result of an inversion for an extending source model. The purple contours represent the distribution of slip for all the three interseismic phenomena, which was obtained through the inversion of the composite deformations (pink arrows). The black arrows denote synthetic deformations computed for the inversion result. The coseismic slip distribution of the 2011 Tohoku earthquake is also displayed with the epicentre (white star) and Japan Trench (dark green line). The black bar at the bottom right denotes 100 km.
Supplementary Note 1

Slip deficit rate inversion

To recover the slip deficit field for each year, we fitted the following function to the time series of the $i$-th coordinate component of the $j$-th station in a least-squares sense.

$$x_{ij}(t) = \sum_{n=1996}^{2011} \left[ a_{ij}^n + b_{ij}^n (t - t^n) \right] B^n (t - t^n)$$

$$+ c_{ij} \sin(2\pi t / 365.25) + d_{ij} \cos(2\pi t / 365.25) + \sum_{k=1}^{m} e_{ij}^k H(t - t^k) + \sum_{k=1}^{m} f_{ij}^k L^k(t - t^k)$$

(1)

Here, $t$ is the number of days from the beginning of GEONET, and $t^n$ is $t$ for the first day in year $n$. The first summation of Supplementary Equation (1) represents yearly trends with time using the boxcar functions $B^n(t - t^n) = H(t - t^n) - H(t - t^{n+1})$. Because the deformations are continuous, $a_{ij}^{n+1}$ for the year $n + 1$ was calculated from $a_{ij}^n + b_{ij}^n(t^{n+1} - t^n)$ for year $n$. The coefficient $b_{ij}^n$ is an estimate of the deformation rate during year $n$.

The second and third terms of Supplementary Equation (1) correspond to an annual variation, while the fourth term denotes coseismic signals of nearby $M_w 6–8$ earthquakes. Coseismic signals are described as the sum of Heaviside functions $H(t - t^k)$, whereas $e_{ij}^k$ is the magnitude of the $k$-th event, which occurred at $t^k$. In the fifth term of Supplementary Equation (1), postseismic signals are described as the sum of logarithmic functions $L^k(t - t^k)$ and their magnitudes $f_{ij}^k$. We tested several characteristic times for each logarithmic function and found the optimal one by trial and error. All visible coseismic and postseismic signals were removed in this procedure.

We applied Supplementary Equation (1) to horizontal components and then estimated deformation rate components for all stations by finding least-squares solutions. It has been shown that the Tohoku district experiences small internal deformations only$^1$; thus,
we did not consider internal deformations in this study. The pink arrows in Supplementary Fig. 1 show horizontal deformation rate vectors in the Tohoku and Kanto districts in 1998 (left diagram) and 2008 (right diagram). Since any slip deficit should occur on almost the entire Pacific plate boundary along the Japan Trench, we distributed source faults on this plate boundary. Because significant deformation rates were also found in the Kanto district, we distributed source faults throughout the Philippine Sea plate boundary along the Sagami Trough. Then, we performed a source inversion of the deformation rates (see Methods of the main text). The two resultant distributions (blue and purple contours in Supplementary Fig. 1) represent the slip deficit rate distributions of 1998 and 2008 on the two plate boundaries. The black arrows show synthetic deformation rates computed from the slip deficit rate distributions.

The distributions on the Philippine Sea plate in 1998 and 2008 differed little from each other as a result of the small deviations in the Kanto district, shown in Fig. 2. Meanwhile, the difference between the distributions on the Pacific plate in 1998 and 2008 was so large that the peak in the slip deficit rate decreased and migrated northward from 1998 to 2008. These weakening and migration processes were caused by the very-long-term transient event and northern backslip source. The maximum slip deficit rate in 1998 was nearly equal to the velocity of the Pacific plate motion relative to the North American plate ($V_{pl} = 8.5$ cm per year), resulting in 100% interplate coupling at the peak in slip deficit rate.

The return period of a megathrust earthquake (seismic supercycle period) along the Japan Trench subduction zone (JTSZ) was shown previously to be about 600 years. A megathrust earthquake releases $3/4$ of the strain accumulated by the subduction during
this return period, while $M$ 7-class earthquakes release the remaining $1/4$. Using these values, we can calculate the regular slip deficit rate in the coupled area to be $35 \text{ m} \times \frac{4/3}{600} = 8 \text{ cm per year}$; 35 m is the maximum coseismic slip of the 2011 Tohoku earthquake\textsuperscript{4}. Since this regular rate is very similar to the rate observed in 1998, it can be assumed that the JTSZ of the pre-2002 period was in a regular state and that the pre-2002 parts of the time series in the Tohoku and Kanto districts represented regular deformations due to slip deficit.
Supplementary References


