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Key Points:
- Interplate creep history was estimated by the slip amount and slip direction of small repeating earthquakes
- Subduction rate of two oceanic plates beneath Kanto both increased after the 2011 Tohoku-oki earthquake
- Remarkably enhanced seismicity and frequent occurrence of slow slips after the earthquake are explained by the subduction acceleration

Supporting Information:
- Supporting Information S1

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Acceleration of regional plate subduction beneath Kanto, Japan, after the 2011 Tohoku-oki earthquake

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Abstract Two oceanic plates (the Pacific (PA) and Philippine Sea (PH)) subduct beneath the land plate, and they forms deeper (PH-PA) and shallower (land-PH) plate boundaries beneath Kanto. Remarkably enhanced seismicity was observed in the densely populated area after the 2011 Tohoku-oki earthquake, which cannot simply be explained by the southern expansion of the postseismic slip of the earthquake. We examine interplate repeating earthquakes to constrain the relative plate motion across aseismically slipping faults. The repeater slip rates show creep rates in the deeper and shallower boundaries, respectively, increased to 2.4–6.6 times and 1.3–6.2 times the pre-Tohoku-oki rates. In addition, the repeater slip directions show no change larger than 4° in the deeper boundary. The interplate creep rates and slip directions suggest that regional movements of both the two plates had accelerated. They probably caused the seismicity increase, frequent slow slips on the shallower boundary, and enhanced probability of larger earthquakes.

1. Introduction

The plate motion is usually thought to be a steady process that does not change over a geological time scale [*Sella et al.*, 2002]. However, great megathrust earthquakes such as magnitude 9 Tohoku-oki earthquake may temporally change its rate in a regional scale [*Heki and Mitsui*, 2013; *Hu et al.*, 2016; *Sun and Wang*, 2015]. The Tokyo (Kanto) metropolitan area is located to the south of the slip area for the Tohoku-oki earthquake. The area is characterized by subductions of two oceanic plates beneath a continental plate (Figure 1). There exists Okhotsk (OH), Philippine Sea (PH), and Pacific (PA) plates from top to bottom, and they are contacting with each other [*Hasegawa et al.*, 2007; *Ishida*, 1992; *Uchida et al.*, 2010]. Therefore, the interactions between the three plates are important for understanding seismotectonics in this region. The shallower plate boundary hosts the 1923 *M*7.9 Kanto earthquake [*Wald and Somerville*, 1995] and Boso slow-slip events [*Hirose et al.*, 2012; *Kato et al.*, 2014; *Ozawa*, 2014], whereas the deeper plate boundary hosts moderate to small earthquakes and the interplate locking there was estimated to be relatively weak [*Uchida et al.*, 2009]. *Toda et al.* [2008] regards the PH under Tokyo as the Kanto fragment that is a different body from PH, but our results are not affected by the assumption of the plate. The remarkable increase of small-to-moderate earthquakes in the Tokyo metropolitan area after the Tohoku-oki earthquake (Figure 1c) was interpreted to have increased the probability of anticipated $M \sim 7$ earthquakes [*Gardonio et al.*, 2015; *Ishibe et al.*, 2015; *Stein and Toda*, 2013; *Toda and Stein*, 2013] based on the relationship between earthquake magnitude and frequency (Gutenberg-Richter law [*Gutenberg and Richter*, 1944], a linear relationship between magnitude (M) and the logarithm of the number of earthquakes with magnitude larger than M). The postseismic seismicity increase and shortening of recurrence intervals of Boso slow slip events on the plate boundary fault between PH and OH (shallower boundary) in the vicinity of Tokyo (Kanto) are probably related to the Tohoku-oki earthquake that occurred to the north of Tokyo (Figure 1) [*Gardonio et al.*, 2015; *Hirose et al.*, 2012; *Ishibe et al.*, 2015; *Kato et al.*, 2014; *Ozawa*, 2014; *Toda and Stein*, 2013]. However, the mechanism for this remarkable seismicity change is not confirmed yet.

2. Creep Rate Estimation From the Cumulative Slip of Repeating Earthquakes

The plate motions cause relative displacement across the plate-boundary faults. Repeating earthquakes (repeaters) on the plate-boundary faults are thought to be occurring on a locked patch surrounded by creeping area [*Igarashi et al.*, 2003; *Kimura et al.*, 2006; *Nadeau and Johnson*, 1998; *Uchida and Matsuzawa*, 2013]. Since the total slip should be the same in the long term, the cumulative slip of repeaters represents the total amount of aseismic displacement (creep) on surrounding area of the plate boundary [*Igarashi et al.*, 2003;

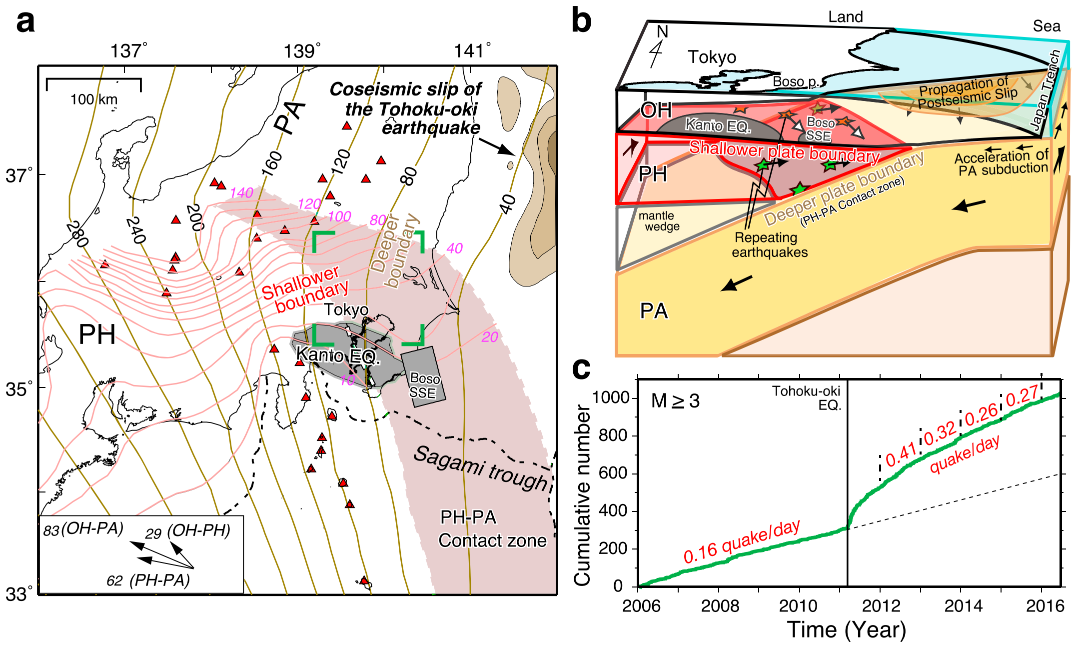

Figure 1. Tectonic setting of Kanto and Tokyo metropolitan area and seismicity change after the Tohoku-oki earthquake. (a) Map view of plate configuration based on *Nakajima and Hasegawa* [2010]. The ocher contours show the depth of the upper boundary of Pacific (PA) and the PA contacts with Philippine Sea (PH) plate in the gray shaded area that corresponds to deeper plate boundary under Tokyo. The pink contours show the depth of the upper boundary of PH plate that corresponds to the shallower plate boundary under Tokyo. The slip distribution of the 2011 Tohoku-oki earthquake is shown by contours with 5 m interval [*Iinuma et al.*, 2012], the slip area for the 1923 Kanto earthquake is shown by gray line [*Wald and Somerville*, 1995], and the fault model for the 2011 Boso slow-slip event is shown by rectangle [*Hirose et al.*, 2012]. (b) Schematic figure showing the plate configuration and interplate slip beneath the Tokyo metropolitan area. The Okhotsk (OH), PH, and PA plates exist from shallow to deep part. On the OH-PH (shallower) boundary, slip areas of the 1923 Kanto earthquake and Boso slow slip events exist in shallow part (areas closer to the trough). On the PA-OH boundary, postseismic slip of the 2011 Tohoku-oki earthquake propagated from the north. Repeaters exist on both shallower (blue stars) and deeper (green stars) boundaries. (c) Cumulative number of earthquakes with $M \geq 3$ and focal depth < 90 km in the green rectangle in Figure 1a. The vertical line shows the occurrence time of the Tohoku-oki earthquake. The red numerals are earthquake rate for all period before the Tohoku-oki earthquake and each year after the Tohoku-oki earthquake.

Nadeau and Johnson, 1998; *Uchida and Matsuzawa*, 2013]. Another tool to estimate interplate displacement is geodetic data. However, the existence of multiple plates at shallow and deep depths in this region makes it difficult to uniquely estimate interplate slip from surface geodetic data. The estimation of displacement from repeating earthquakes can precisely specify the location of the slip, because the repeater locations can be accurately determined by their hypocenter location. Previous studies clearly show the alignment of repeating earthquakes along the shallower (PH-PA) and deeper (PA-OH) plate boundaries [*Kimura et al.*, 2006; *Uchida et al.*, 2010].

Here we estimate interplate slip rate from the repeating earthquakes, which are selected based on their seismic waveform similarity. We extended the data analysis period of *Uchida and Matsuzawa* [2013] to the period from 1993 to the end of 2013 to select repeating earthquakes. The original analysis period for this region was from 1993 to the end of 2011. The repeating earthquakes are identified from waveform coherence of 40 s long records that is observed at seismic stations operated by Hokkaido University, Hirosaki University, Tohoku University, and the University of Tokyo. The slip of each repeating earthquake was then estimated by using an empirical relationship between moment and slip [*Nadeau and Johnson*, 1998]. The cumulative slip is averaged for multiple (3 to 84) repeating sequences in regions A-D (Figure 2) to estimate robust slip (creep) history in each area. The areas are positioned to separate different cluster of repeating earthquakes. They are located at the same horizontal position on both deeper (PH-PA) and shallower (OH-PH) boundaries to compare the slip history. The details of the repeating earthquake slip amount analysis are provided in the supporting information [*Hanks and Kanamori*, 1979; *Uchida et al.*, 2012].

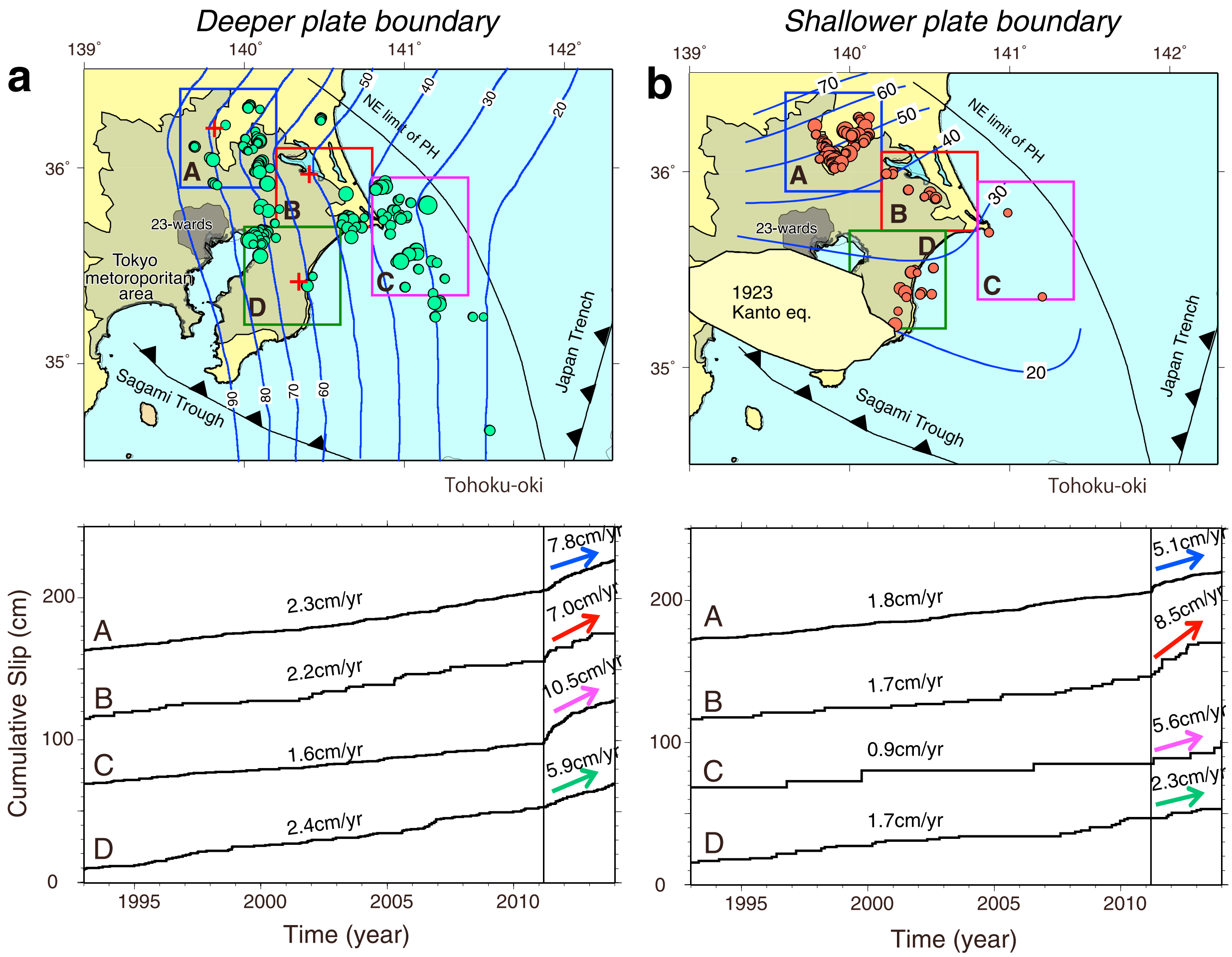

Figure 2. Repeater activity on the (a) deeper and (b) shallower plate boundaries. (top row) The distribution of repeater sequences (circles) and (bottom row) the averaged cumulative slip for sequences in areas A–D. The blue lines in the top row show the depth to the Pacific plate (Figure 2a) and the Philippine Sea plate (Figure 2b) [*Uchida et al*., 2010]. The dark and light gray areas show the central area of Tokyo (23-ward) and the Tokyo metropolitan area, respectively. The red crosses in Figure 2a is the locations of GPS stations shown in Figure S3. The vertical lines in the bottom figure show the occurrence time of the Tohoku-oki earthquake. The black line indicates the northeastern limit of the Philippine Sea plate [*Uchida et al*., 2009].

The results show that slip rates significantly increased after the Tohoku-oki earthquake for both the shallower and deeper boundaries (Figure 2). The slip rate increased by 2.4–6.6 times on the deeper (PH-PA) boundary and by 1.3–6.2 times on the shallower (PA-OH) boundary (Table S1 in the supporting information). Since newly found repeater sequences after the Tohoku-oki earthquake are only 14% of all the repeater sequences, most of the rate increase is due to shortening of the recurrence interval of the repeaters. The repeaters indicate that relatively large accelerations of slip on both plate boundaries occurred in northern areas closer to the Tohoku-oki rupture zone (Figure 1a and areas B and C of Figure 2). The acceleration patterns of the deeper and shallower boundaries appear to be correlated: regions having larger (smaller) accelerations on the deeper boundary also have larger (smaller) accelerations on the shallower boundary (Figure 3). This feature of the correlated acceleration patterns is similarly obtained even if we use different selection of the regions (Figures S1 and S2 in the supporting information). We also note that GPS time series at stations above these regions show similar pattern in the amount of cosiesmic and postseismic displacement (region B > region A > region D) although they do not directly show the slip on the deeper and shallower boundaries (Figure S3).

3. Creep Direction Estimation From the Slip Vector of Repeating Earthquakes

The slip direction of interplate repeating earthquakes from their focal mechanisms provides additional constraints of the relative plate motion. We used waveform modeling of 0.02–0.05 Hz waveform to estimate

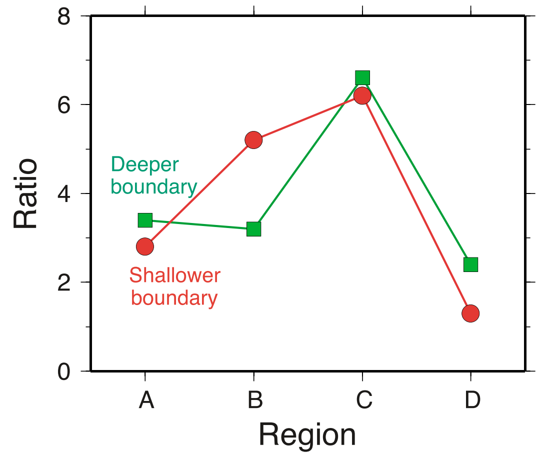

Figure 3. The ratio of slip rate for the period after the Tohoku-oki earthquake (11 March 2011 to 31 December 2013) to the period before the earthquake (1 January 1993 to 10 March 2011). The green line and squares show the ratios for the regions on the deeper (PH-PA) boundary, and the red line and circles show the ratios for the regions on the shallower boundary (OH-PH).

the slip direction of repeater sequence. We developed a new method that utilizes the same station set and faulting plane (i.e., strike, dip, and centroid location) in the waveform modeling analysis that improved the accuracy of relative slip directions. In this analysis, we used Full Range Seismograph Network of Japan (F-net) and High-sensitivity Seismograph Network (Hi-net) tilt data observed by National Research Institute for Earth Science and Disaster Resilience (Figure S4). We first performed centroid moment tensor analysis [*Dreger and Helmberger*, 1993] for each earthquake (Figure S5). Then we fixed the seismic stations for the analysis, the location of the centroid, and the strike and dip of the fault plane for each repeater sequence and grid searched the fault rake and centroid time to obtain reliable relative rake angles for each member of a repeating earthquake sequence. Finally, the rake angles are converted into slip directions. The details of the repeating earthquake slip direction analysis are provided in the supporting information [*Fukao*, 1977; *Saikia*, 1994; *Shiomi et al*., 2003; *Ukawa et al*., 1984].

We examined the rotation of slip direction for eight repeater sequences on the PH-PA boundary (Figures 4a and S6a and Table S2). We also examined four repeater sequences on the OH-PH boundary for reference (Figures 4b and S6b and Table S2). The final rotation angle uncertainty for each sequence is less than 5°. Since the slip direction of individual repeaters may be affected by local ambient stress and heterogeneous coseismic and postseismic stress perturbations, we estimate regional rotation from the average rotation angle of all sequences. The average rotation angle relative to the last event before the Tohoku-oki event is $-0.07 \pm 1.57°$ (Figure 4). If we generate synthetic waveforms representing a 4° clockwise rotation with random error (Figure S7) and perform a synthetic test (Figure S8c), the average and inferred uncertainty of the obtained slip direction is 3.87 ± 1.55. This range of direction does not overlap observed range of rotation angle (Figure 4a). Therefore, our result shows that there is no regional slip direction change larger than 4° on the deeper boundary after the Tohoku-oki earthquake (Figure 4a). The shallower boundary also does not show rotation although the number of available data is small (Figure 4b).

The slip direction of individual sequences also shows that there is no systematic change in slip direction on both plate boundaries, although relatively large clockwise rotation was estimated for a sequence located on deeper boundary beneath the edge of the 1923 Kanto earthquake on the shallower boundary (Figure 4a, orange circle).

4. Discussion

Relatively large postseismic slip was observed in the area adjacent to the study area, suggesting the local PA subduction has accelerated after the earthquake [*Hu et al*., 2016; *Ozawa et al*., 2011; *Sun and Wang*, 2015]. Even if the direction of local plate motion does not change, when the local velocity for PA or PH increased, the direction of interplate slip changes since the slip direction is relative motion of the two plates (Figure S9). The robustness of the PA subduction direction under Kanto can be justified because the cause of the postseismic slip on PA is due to the delayed compensation of slip deficit in the area surrounding the slip area of the Tohoku-oki earthquake. If the local PA subduction speed doubled and PH speed did not change, 4.1° clockwise rotation of interplate slip is expected from the relative vector of the movements (Figure S10). Therefore, when the local acceleration of PA occurred, the acceleration of PH is necessary to observe no rotation of interplate slip

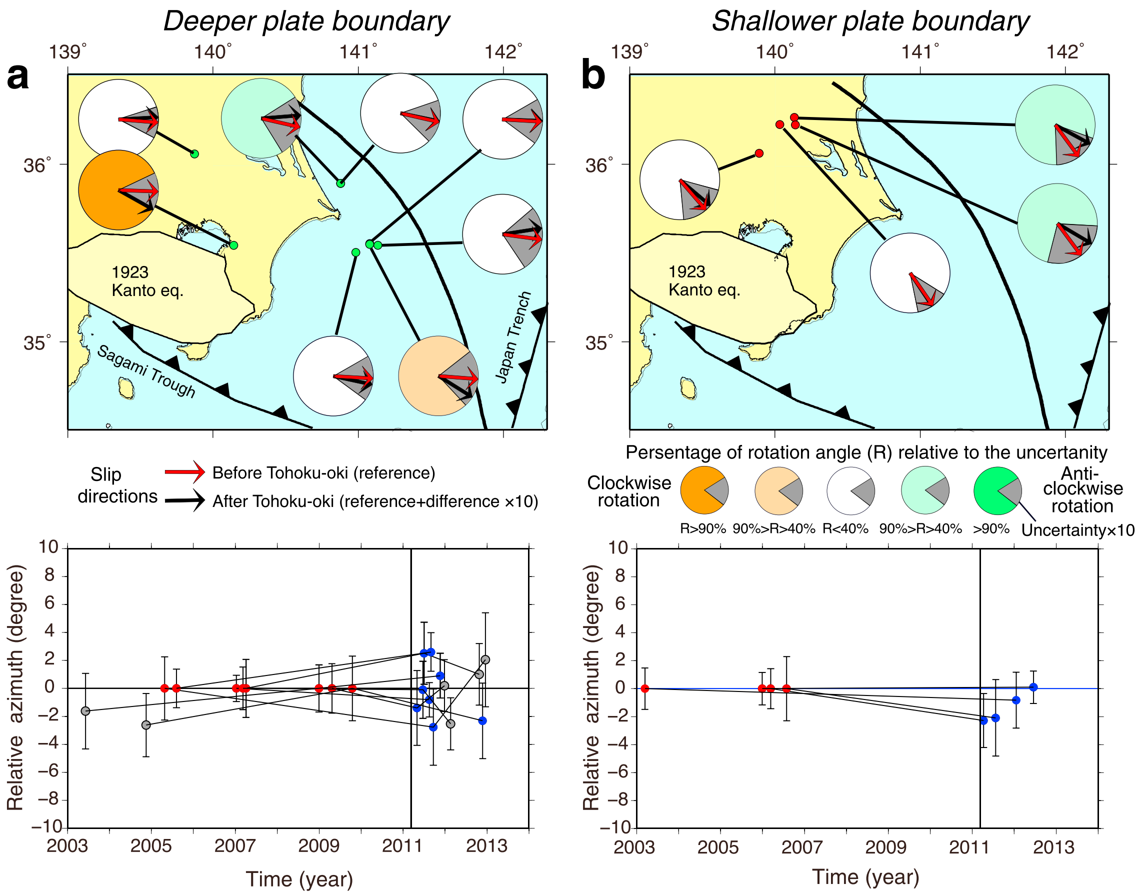

Figure 4. Rotation angle of interplate repeating earthquakes before and after the Tohoku-oki earthquake on the (a) top and (b) bottom of the PH. The top figures show the spatial distribution of the rotation by color and arrows for events just before and after the Tohoku-oki earthquake. The slip direction of the last event just before the Tohoku-oki earthquake (red arrows) is true, but the direction for event after the Tohoku-oki earthquake (black arrows) is plotted at directions that exaggerate the differences from pre-Tohoku events by 10 times. The uncertainty ranges (gray areas) are also exaggerated 10 times. The bottom figures show the temporal change of slip direction for each repeater sequence. In the bottom figures, the slip directions are shown relative to the event just before the Tohoku-oki earthquake that is shown by red points. The events just after the Tohoku-oki earthquake are shown by blue points.

direction in the deeper boundary. The no-rotation of slip direction for many sequences suggests not only the regional PA subduction but also the regional PH subduction accelerated after the Tohoku-oki earthquake (Figures S10 and S11). They probably caused the seismicity increase in broad depth range and frequent slow slip events on the shallower boundary in the Kanto area. Note the difference in slip rate in a relatively small distance (areas A–D), and we do not say that the whole plate motion changed.

As discussed above, the large postseismic slip around the Tohoku-oki earthquake suggests increased movement of subducted PA near the plate interface after the earthquake. However, the subduction rate increase of PH slab under Tokyo is not self-evident. Although we cannot specify the cause of the PH speed increase, the structure under Tokyo suggests that more subduction of PH, which is subducting in between PA and OH, was allowed due to the postseismic movement of PA. Other possibilities include basal drag of the PH by PA due to a partial coupling along the boundary of the PH-PA boundary, stress triggering of aseismic slip on the shallower boundary due to coseismic and postseismic stress change of the Tohoku-oki earthquake, and widespread postseismic deformation due to viscoelastic relaxation following the Tohoku-oki earthquake.

The shallow part of the PH-OH boundary includes the source area of the 1923 *M*7.9 Kanto earthquake (Figures 1 and 4), which has been accumulating stress since the earthquake. The rotation angle for the repeater sequence on the PA located just to the north of the source area shows clockwise rotation (Figure 4a), although the amount of the rotation angle is close to the uncertainty range. When the direction of plate motion does not change, quantitative relationship between the slip-rate change and slip direction (Figure S9a) suggests that PA velocity increase results in clockwise slip rotation on the deeper boundary. This clockwise rotation may reflect the locking of the updip part of the shallower boundary (OH-PH) where the slip area for the 1923 *M*7.9 Kanto earthquake exists (Figures 1 and 4). About 100 years has passed since the Kanto earthquake. The recurrence interval of Kanto earthquake is thought to be 200–400 years from geodetic, geomorphological, geological, and historical data [*Headquarters of Earthquake Research Promotion*, 2004]. Although the accelerated movement of the PH (Figure 2) seems to be decaying in the later period of the analysis, the additional subduction may have impacted the source area of the Kanto earthquake. Previous earthquake simulation studies by rate-and-state fault model suggest that the effect of perturbation in various stages of the seismic cycle results in complex behavior on the timing of the subsequent event [*Gallovič*, 2008]. However, if we simply consider that the earthquake timing is advanced by the amount of that additional slip divided by pre-Tohoku-oki slip rate, it corresponds to 5–15 years.

5. Conclusions

The estimation of interplate displacement in this study suggests that the speed up of the subduction of both PH and PA in regional scale, which was induced by Tohoku-oki earthquake, broadly enhanced the seismicity in Kanto area. The shortened recurrence interval of the Boso slow-slip events resulted also from the speed-up of the PH in the area. The accelerated movements of subducted plates in this area can cause temporally enhanced probability of larger earthquakes and advancement of the next recurrence of the Kanto earthquake.

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