Crustal deformation by the Southeast-off Kii Peninsula Earthquake

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Abstract

A series of large earthquakes occurred southeast of Kii Peninsula on September 5, 2004. The apparent crustal deformation caused by these earthquakes was detected by GEONET around central Japan. The focal mechanism estimated by seismogram records is reverse fault type with north-south P-axis. The crustal deformation observed by GEONET is generally consistent with the mechanism estimated by the seismological analysis. Even though the epicenters are near the Nankai trough, these earthquakes were not the plate boundary thrust type as indicated by the dip angle of the fault, which does not coincide with that of the Philippine Sea plate. Lastly it was noted that the slowslip event in the Tokai region since the fall of 2000 is slightly affected by the postseismic effect of these earthquakes.

1. Overview of the event

A series of large earthquakes occurred offshore southeast of Kii Peninsula on September 5, 2004. A large foreshock (M6.9) occurred at 19:07(JST), and the mainshock (M7.4) occurred at 23:57 (JST) on September 5. The intensity 5- (JMA scale) was recorded at several sites in the Kii peninsula for the mainshock. The seismic ground motion of the mainshock was felt very widely around central Japan. Both earthquakes triggered tsunami. However the damage by the earthquakes and tsunami was not severe. The largest aftershock was the earthquake, whose magnitude was 6.5, occurring at 23:58 (JST) on September 8, 2004.

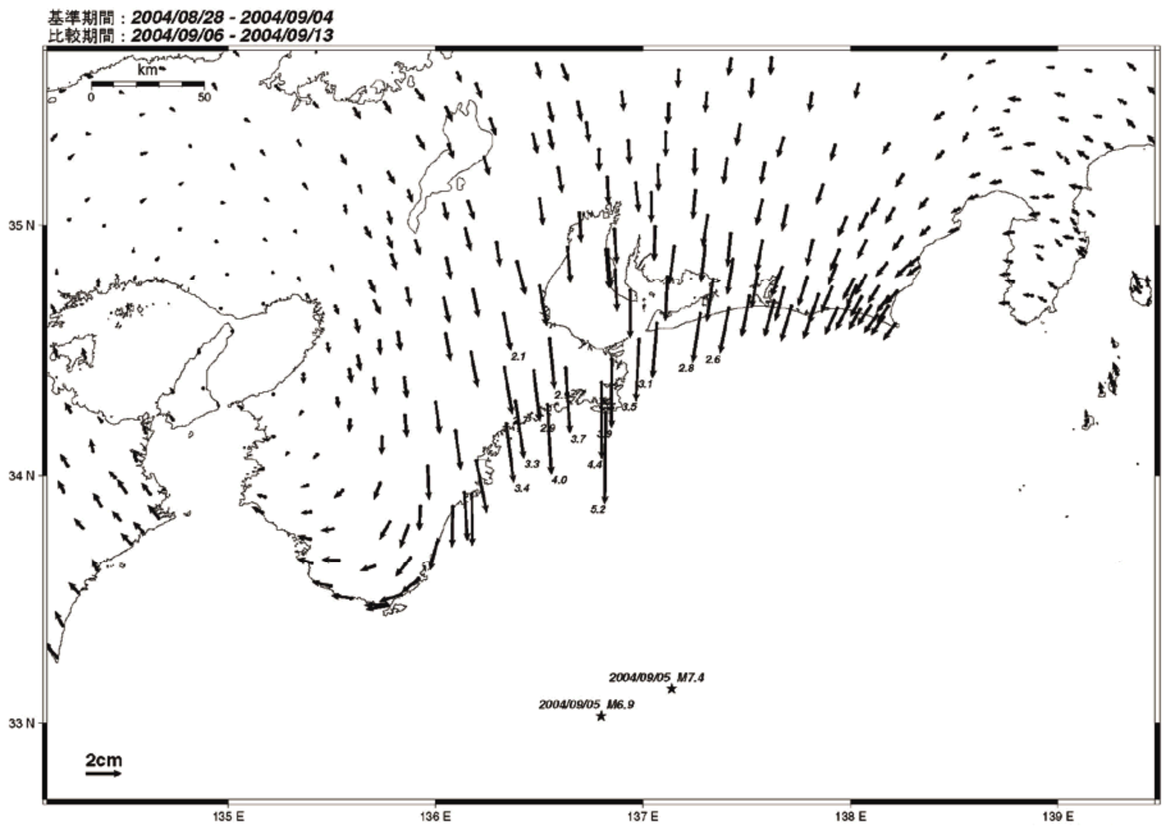

Fig. 1 Coseismic horizontal movement of GEONET stations in the Chubu and Kinki region referred to by Ohgata as the South-East off-Kii Peninsula Earthquakes on September 5, 2004 (foreshock M6.9 at 19:07, and mainshock M7.4 at 23:57)

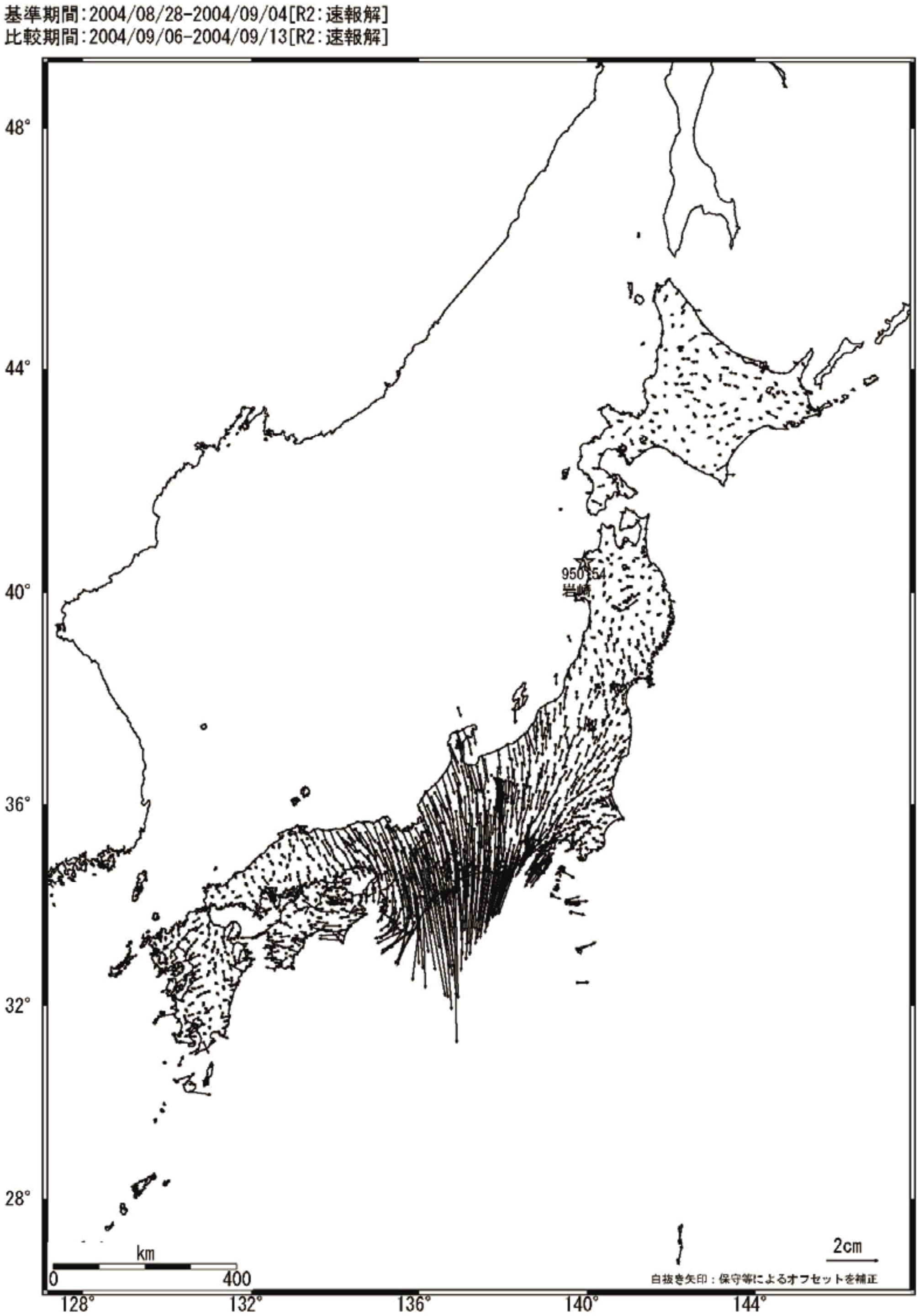

Fig. 2 Coseismic horizontal movement of GEONET stations relative to the Iwasaki site (☆) by the South-East off-Kii Peninsula Earthquakes on September 5, 2004

The epicenters of these earthquakes were close to the Nankai trough. The focal mechanism estimated from the P-wave initial motion is of the reverse fault type with a north-south compression axis. Aftershock activity was seen mainly in the area extending from east-northeast to west-southwest along the Nankai trough. Another aftershock activity was seen in the area extending toward the northwest from the epicenter of the mainshock.

As the epicenters of these earthquakes are near to the Nankai trough and the rupture zone of the Tonankai Earthquake (1944, M8.0), it was suspected that these earthquakes are related to the expected Tokai earthquake, which is expected to occur along the plate boundary zone along the Nankai trough. However, two facts contradicted these earthquakes being inter-plate ones. First, the epicenter of the mainshock was located too close to the trough, or too far south, for a plate boundary earthquake. Second, the dip angle derived from the focal mechanism does not coincide with the plate subduction dip. Therefore, these earthquakes are considered to be intraplate earthquakes occurring in the Philippine Sea plate.

2. Co-seismic crustal deformation and fault model

A notable crustal deformation was detected by GEONET (GPS Earth Observation NETwork) observation around the Kii Peninsula and Tokai region. The largest deformation was detected at sites in the Shima peninsula. Horizontal deformation relative to the Ohgata site, which is selected as the fixed point, on the coast of Niigata prefecture, is as large as 5cm toward the south (Fig. 1).

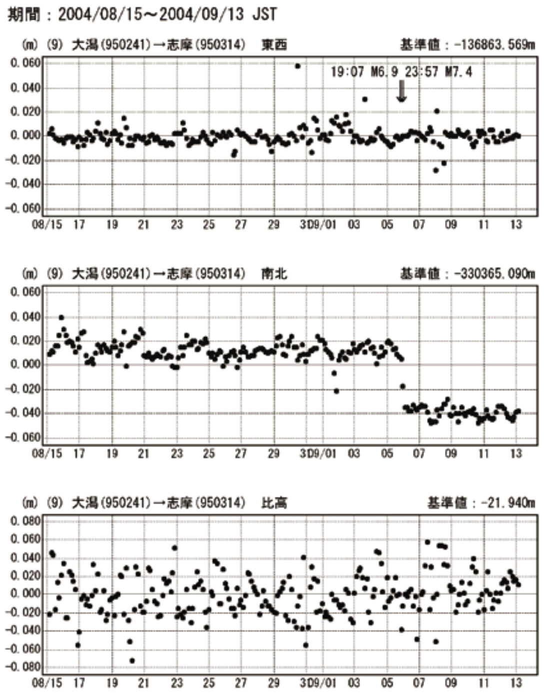

Fig. 3 Time series of three components of baselines between the GEONET sites in the Shima peninsula and the Ohgata site along the events on the South-East off-Kii Peninsula Earthquake. The relative position is calculated under the strategy of Q2 solution of GEONET using IGS Ultra-rapid ephemeris.

The detected co-seismic crustal deformation extended as far as the Tohoku region and Shikoku regions. Figure 2 shows the wider area of horizontal crustal movement pattern relative to Iwasaki station on the western coast of Aomori prefecture, which is indicated by ☆ on the figure. This figure shows that the Ohgata site, which is used as the reference site for the horizontal crustal movement, is affected by the earthquake.

A time series of horizontal and vertical positions of the Shima station is shown in Figure 3. Each plot is the result of a "Q2 solution" of GEONET, which means the analysis has been done every 3 hours using 6 hour data. It is difficult to separate the deformation by the foreshock (19:07) and that by the mainshock (23:57). A report by Nagoya University discussed the deformation by the foreshock. This shows that the possible horizontal movement would be not more than 1cm. No significant co-seismic deformation was detected for the aftershock of M6.4 on September 7th, 08:29 (JST) or M6.5 on September 8th, 23:58 (JST).

The fault models to interpret the co-seismic crustal deformation are shown in Figure 4. This model is presented by GSI, using an inversion program to estimate the parameters of the faults. It is difficult to determine a unique model solely from the crustal deformation data, as the epicenter is located far from the coast and the observation sites are limited on the northern side of the epicenter. Therefore we referred to the focal mechanism derived from seismic observation, and aftershock activity region to set the starting value for inversion computation. Moreover, we made our inversion using coseismic crustal movement including the effect of mainshock and foreshock. It is very difficult to distinguish the foreshock effect, as the mainshock occurred just about 5 hours after the foreshock.

The focal mechanism for the mainshock and the largest foreshock estimated from seismogram records seems to be a reverse fault with a P-axis of north-south direction (JMA, 2005). However, there is no decisive information to chose which nodal plane is the fault. The strike of the largest foreshock (M6.9, 19:07, Sep.5) coincides with the direction of the trough, east to west. While the epicenters of the earthquakes occurring after this foreshock and before the mainshock

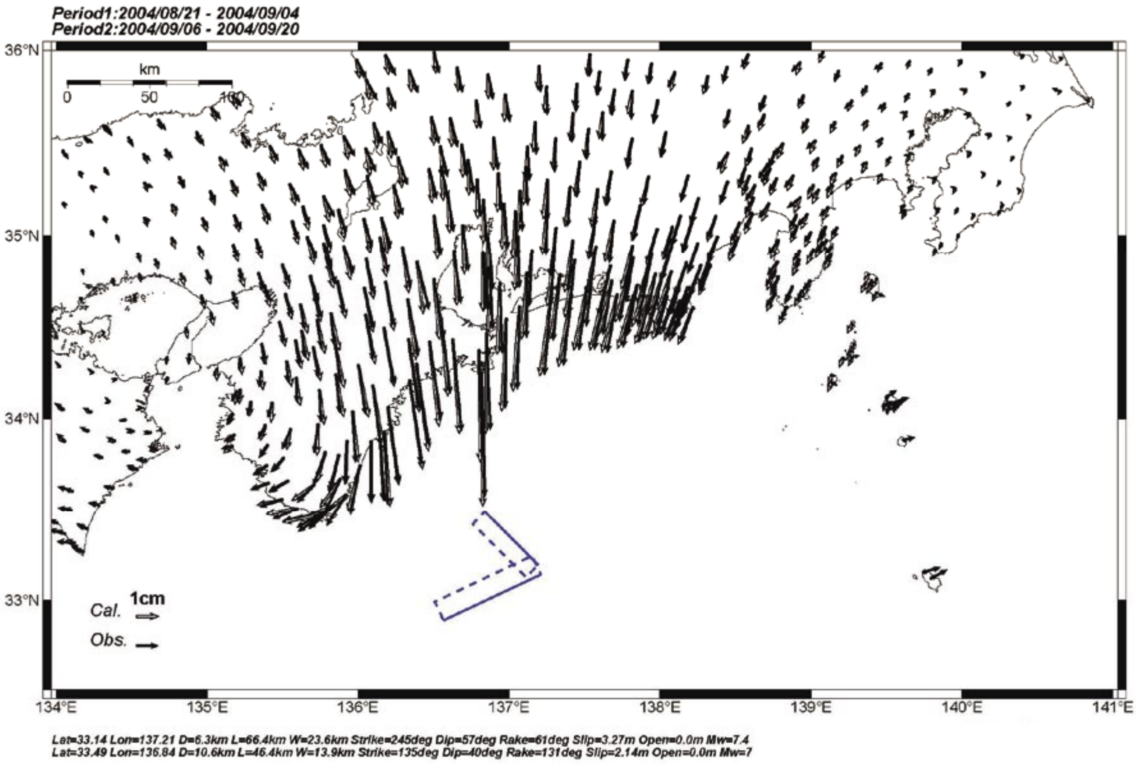

Fig. 4 Fault models for the South-East off-Kii Peninsula Earthquake estimated from crustal deformation data by GEONET, reverse fault along the Nankai Trough with a reverse fault with northwest-southeast strike for mainshock

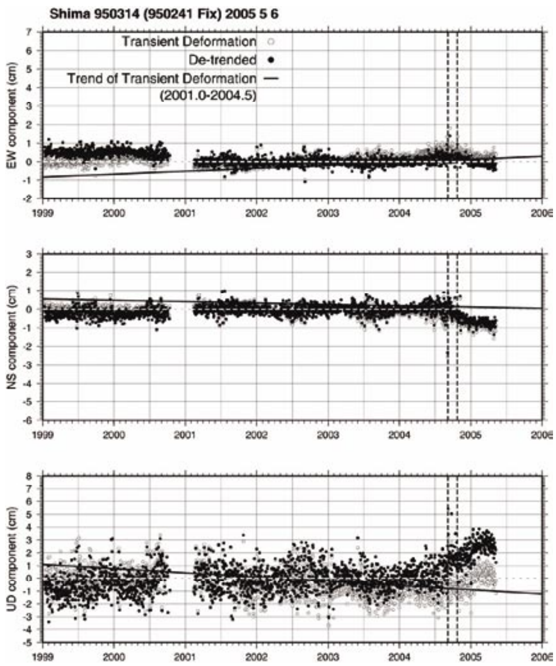

Fig. 5 Analysis of the time series of crustal deformation to detect the afterslip of the southeast off-Kii Peninsula earthquake from the Tokai slow slip

are distributed along a line parallel to the trough axis, west to east. Therefore, a seismic fault is expected to cover this aftershock zone. However, as both the nodal planes derived from the focal mechanism solution have strike matching the trough axis, it is difficult to choose which plane is the fault. As the depth of hypocenter is not reliable, we chose the north dip plane as the fault, because it gives a little smaller residual for the inversion computation.

One of the nodal planes of the focal mechanism of the mainshock (M7.4, 23:57, Sep. 5) runs from the southeast to the northwest. A group of aftershocks occurring after the mainshock is distributed along the line from southeast to northwest, too. Therefore, we set another fault along this aftershock zone. We determined the parameters for these two faults, and the results are shown in the figure.

Though the strike and dip parameter derived from our inversion coincide with those from seismic observation analysis, the moment of those faults does not match with the ones for the foreshock and mainshock computed from seismic wave analysis. The moment magnitude (Mw) 7.4 for the fault parallel to the trough is too large for the foreshock. On the other hand, the moment magnitude 7.0 for the fault running toward the northwest from the southeast is too small for the mainshock. Therefore we consider that the fault along the trough slipped partially at the foreshock event and that both faults slipped simultaneously at the mainshock event.

Other studies have also presented a combination of two or three fault models for the foreshock and mainshock event activity. For example, Yagi (2004) suggested that the main shock was caused by the combination of a reverse fault along the trough and strike slip fault, which is nearly vertical, extending from the southwest to northwest along the aftershock's distribution, from the analysis of seismic wave records. The fault for the foreshock is a south dip reverse fault along the trough in his model. Another model, presented by Yamanaka (2004), placed a reverse fault with strike slip component along the southeast to northwest line as the source fault for the mainshock and a reverse fault with a north dip along the trough as the source of the foreshock.

As shown above, analysis of seismic waves also cannot provide a conclusive model. Even combining the information on crustal deformation and seismic observation, we are not able to determine a unique solution. Additional information such as ocean bottom seismogram observation results also did not give a clear fault plane image.

The information possibly able to contribute the determination of the model is the sea floor crustal deformation monitoring observation. Sea floor crustal deformation monitoring is done by a combination of acoustic distance measurement between the sea floor and a ship on the sea surface and kinematic positioning of that ship. Japan Hydrographic and Oceanographic Department (JHOD) and Nagoya University have been carrying out the sea floor crustal deformation monitoring observation independently off Kii Peninsula. The observation site of JHOD is located northwest of the focal region. The coseismic movement, according to their observation, was about 5 cm toward the east-southeast direction (JHOD, 2004). This is not consistent with the expected crustal movement pattern by any of the models described before. The observation site of Nagoya University is located north west of the aftershock zone extending northwest from southeast. The coseismic movement by their observation was about 15cm toward the south (Nagoya University, 2004). The discussion in their report presents a northeast dip fault for the source fault along the aftershock zone extending from southeast to northeast. However, they suspend the conclusion because a slight change of the position of the end of the fault causes a large fluctuation of the calculated deformation vector from the model. At the present moment, a final conclusion for the fault model is not yet determined.

However, researchers agree on at least two facts. The earthquakes, including foreshock and mainshock, are not interplate earthquakes, and they are earthquakes occurring in the Philippine Sea plate.

3. Postseismic crustal deformation

Fig. 5 shows the time series of the relative position of the Shima site, in Mie prefecture, relative to Ohgata site. White circles are the relative daily coordinate value removing the trend or secular component, which is estimated from the data from 1997 to 1999. As the slow slip event in Tokai started in 2000, the trend in white circles means the effect of slow slip. The linear fit for the white circles, estimated from the data from the begining of 2001 to July 2004, is shown on the figure as a black line. This is, so to say, the trend of the slow slip. The black dots plotted on the figure are the residual after removing this trend. The vertical broken line in September 2004 is the time line of the Southeast-off Kii Peninsula earthquake. The coseismic step is removed at this line and another vertical line at October 2004, which is the time line for the Chuetsu earthquake. Black dot plots, in the north-south component graph and vertical component graph, depart from the zero line after the Southeast-off Kii Peninsula earthquake. This means the crustal movement pattern at the Shima site changed after the event. The postseismic movement is about 1cm toward south, which is about one fifth of the coseismic movement at the Shima site. In the graph, the black dot and white circle plot becomes nearly horizontal after the beginning of 2005. Therefore we can speculate that the postseismic movement continued about three months after the earthquake. The same pattern of postseismic effect can be seen widely around GEONET sites along the Pacific coast of western Shizuoka prefecture to Mie prefecture.

Fig. 6 shows the model that the after slip of the source fault along the trough caused the postseismic movement. As the postseismic movement is less than 1 cm, it is difficult to determine the parameters of the afterslip. Therefore only the slip value is estimated while fixing the position, size and slip direction of the fault. Total moment released by the afterslip is estimated to be equivalent to Mw=6.9.

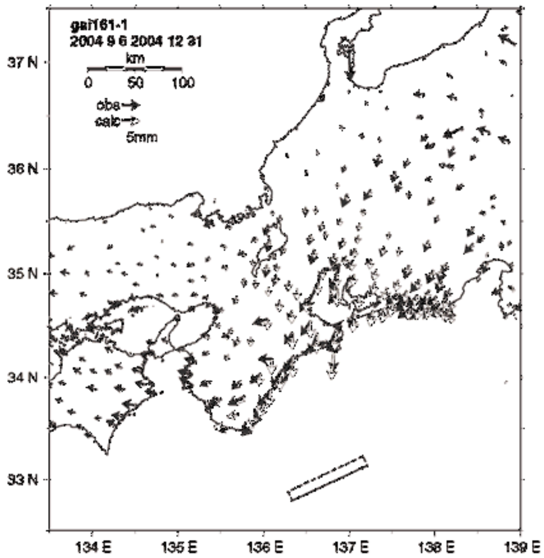

Fig. 6 Comparison of observed and estimated horizontal crustal movement by afterslip model of the South-East off-Kii peninsula Earthquake for four months after the event

After the effect of postseismic crustal movement faded out, the trend of crustal deformation returned to the pattern before the earthquake. This means that Tokai slow slip has been ongoing after the earthquake and at least until early 2005.

4. Conclusions

The Southeast-off Kii Peninsula Earthquake was a notable event which occurred near the source region of Tonankai earthquake. It is considered to be an intra-plate earthquake occuring in the Philippine Sea Plate because of its mechanism estimated from seismic data and crustal deformation data. We proposed a fault model for this event based on the crustal deformation data. However, there is not a unique consistent model which can solely interpret all facters relating to this event. Even though a small postseismic effect was seen around the Tokai area, it did not affect the slow slip continuation.

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