Present-day deformation across the southwest Japan arc: Oblique subduction of the Philippine Sea plate and lateral slip of the Nankai forearc

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We estimate long-term/permanent crustal deformation in the Nankai forearc, southwest Japan, that accumulated over one earthquake deformation cycle in the Nankai subduction zone. A short-term deformation due to an oblique subduction of the Philippine Sea plate is modeled based on coseismic fault slips associated with interplate thrust earthquakes at the Nankai Trough, and subtracted from the interseismic crustal velocity field observed by GPS. The long-term/permanent deformation left in the data shows arc-parallel movement of the forearc at a rate of 5–10 mm/yr. We interpret that the forearc movement, driven by the oblique plate convergence, is accommodated by steady aseismic slip on the deep portion of the fault plane of the Median Tectonic Line (MTL) on the rear boundary of the Nankai forearc. The rate of the forearc movement is consistent with the geological slip rate of the MTL in the late Quaternary, and also with that expected from deflection of the slip vector of the 1946 Nankai earthquake from the current plate convergence vector.

Key words: Nankai Trough, oblique plate convergence, Global Positioning System, Median Tectonic Line.

1. Introduction

The Nankai Trough region of southwest Japan (Fig. 1) provides one of the best-studied examples of an earthquake deformation cycle at the plate subduction zone. The Philippine Sea plate subducts beneath southwest Japan, causing megathrust earthquakes every 100–200 years. Repeated geodetic surveys and tide-gauge records since the late 19th century have revealed deformation history of nearly all of the last cycle (e.g. Sagiya and Thatcher, 1999). Recent site displacements and velocities from the Global Positioning System (GPS) observations are direct indicators of plate motion and internal deformation arising from plate interaction.

The southwest Japan arc is divided into the Nankai forearc and the rest of the overriding plate by the Median Tectonic Line (MTL), the longest arc-parallel strike-slip fault system in the late Quaternary in southwest Japan whose right-lateral slip motion originates from oblique convergence of the plate. In contrast to the geological features, however, there is little evidence to show that there was contemporary activity along the MTL. Current seismicity is relatively low so that no linear distribution of microearthquakes could be found. Moreover, geodetic constraint to fault kinematics is poor because no creep motion has been detected across the fault trace (Onoue *et al.*, 2002). Strain perturbation around MTL is also difficult to determine because arc-normal contraction due to the plate subduction is so dominant (Fig. 1).

Miyazaki and Heki (2001) found westward block movement of the Nankai forearc by subtracting plate subduction effects from GPS velocities. Adding velocity data from dense GPS campaign measurements across the MTL, Tabei *et al.* (2002) showed that the forearc movement could be modeled by the steady aseismic slip at the depth of the MTL. McCaffrey (1996) showed that about half of modern subduction zones in the world have mobile forearc blocks, and the above studies indicate the Nankai Trough is one of them. However, it should be noted that the movement of the Nankai forearc estimated in those studies is purely contemporary, reflecting only the deformation field during the past five years.

In this paper we propose a new approach to extracting the permanent movement that would be left after one earthquake deformation cycle. Ongoing interseismic deformation in the Nankai forearc may be a mixture of short-term crustal shortening in the direction of plate convergence and long-term/permanent lateral block movement along the MTL, irrespective of their magnitudes. In contrast, coseismic deformation associated with a great interplate earthquake is equivalent to the accumulated short-term deformation over one cycle, which does not include any permanent components. Combining interseismic and coseismic deformations enables us to decompose the deformation field into short-term and permanent components.

2. Oblique Plate Convergence and Earthquake Slip Vectors

Figure 2 shows the relationship between plate convergence vectors and earthquake slip vectors at the Nankai Trough. Focal mechanisms of the last great interplate earthquakes, the 1944 Tonankai ($M = 7.9$) and the 1946 Nankai ($M = 8.0$), which have been determined by Kanamori

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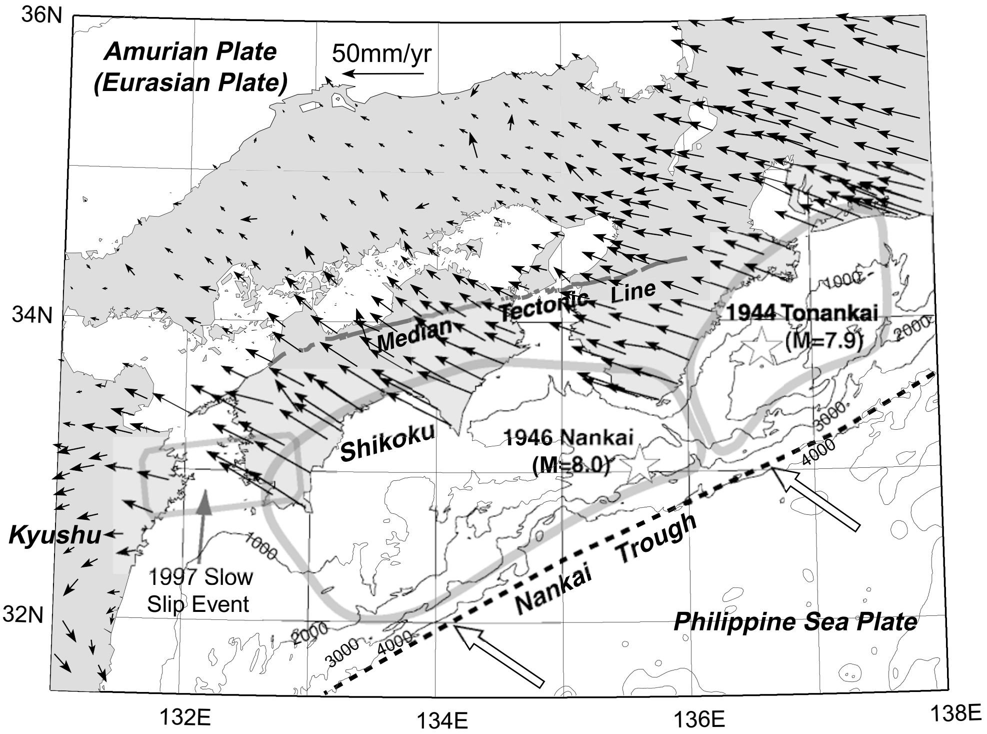

Fig. 1. Oblique convergence of the Philippine Sea plate and interseismic horizontal velocity field of southwest Japan. Velocities are determined from continuous data from March 1996 to December 1999 obtained by the nationwide GPS array (Hatanaka *et al.*, 2003), and all are plotted with respect to the Amurian plate. Star symbols show the epicenters of the 1944 Tonankai ($M = 7.9$) and 1946 Nankai ($M = 8.0$) earthquakes. Areas surrounded by a thick shaded line coincide with the source regions of the next earthquakes supposed by the Headquarters for Earthquake Research Promotion (http://www.jisin.go.jp/main/index-e.html). Also shown is the source region of the slow thrust event in 1997 (Ozawa *et al.*, 2001), although GPS data affected by this event are excluded from velocity estimations.

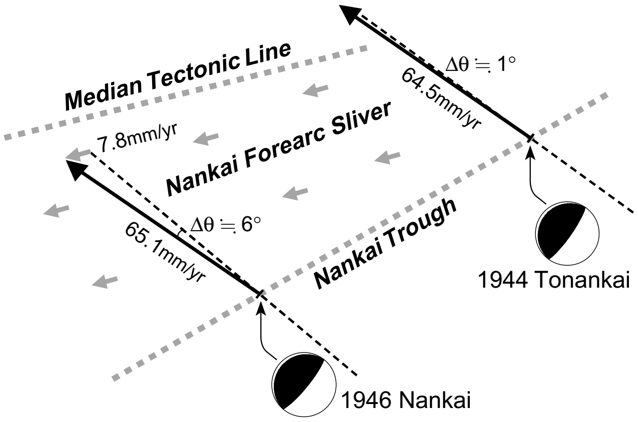

Fig. 2. Schematic illustration showing a relation between plate convergence vectors and earthquake slip vectors. Thin dashed lines indicate directions parallel to the slip vectors of the 1944 Tonankai and 1946 Nankai earthquakes (after Kanamori, 1972), while solid arrows indicate the convergence vectors of the Philippine Sea plate at the epicenters (after Miyazaki and Heki, 2001). The slip vector of the Tonankai earthquake is nearly parallel to the plate convergence vector, whereas that of the Nankai earthquake is deflected by about 6 degrees. The resultant residual component of the convergence vector may be taken up by the permanent lateral slip movement of the Nankai forearc in the interseismic period.

(1972), represent very similar low-angle thrustings. The convergence vector of the Philippine Sea plate has been reestimated by Miyazaki and Heki (2001) by using GPS velocities distributed over the plate. The Euler vector with respect to the Amurian plate predicts a convergence rate of 64.5 mm/yr in an azimuth of 305 degrees at the epicenter of the Tonankai earthquake, and a rate of 65.1 mm/yr in 304 degrees' direction at the Nankai earthquake.

The slip vector of the Tonankai earthquake is nearly parallel to the plate convergence direction, probably indicating a simple mechanism of interseismic strain accumulation and coseismic rebound. On the other hand, there is a deflection of about 6 degrees between the horizontal trend of the slip vector and the plate convergence direction in the case of the Nankai earthquake. If the next great Nankai earthquake releases interseismic strain accumulated in a direction parallel to the slip vector, the above deflection would produce a residual component of velocity as large as 7–8 mm/yr. However, this estimation may be insignificant when spatial variation of slip distribution exists or the observational error exceeds the deflection. Here we simply point out that the residual velocity could reflect permanent lateral movement of the Nankai forearc. In the following, we will test the possibility by using different kinds of data.

3. Interseismic Velocities and Coseismic Displacements

Tabei *et al.* (2002) have conducted GPS campaign measurements along a 200 km-long traverse line across the MTL since 1998. Figure 3(a) shows horizontal velocities at 23 sites together with those at 42 stations of the nationwide continuous array based on campaign-mode analyses. They calculated elastic deformations caused by plate subduction using a multisegment plate interface (Sagiya and Thatcher,

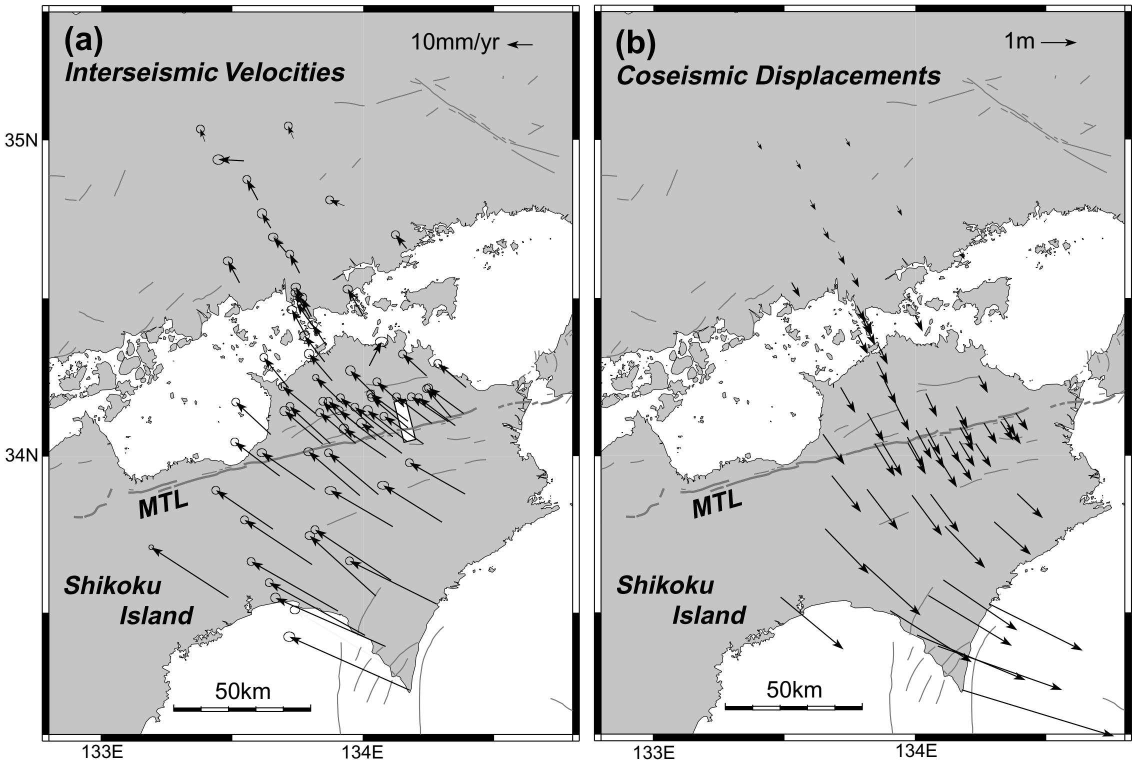

Fig. 3. (a) Observed crustal velocities in the interseismic period in the Amurian plate reference frame with 3σ (99%) error ellipses (after Tabei *et al.*, 2002). An open rectangle embedded in the figure represents the area of seismic reflection study by Ito *et al.* (1996). (b) Coseismic displacements produced by the 1944 Tonankai and 1946 Nankai earthquakes. Displacements at the same positions as the GPS observation sites are reproduced using the slip distribution on the multirectangular fault model of Sagiya and Thatcher (1999).

1999) and plate convergence vector from GPS observations (Miyazaki and Heki, 2001). By subtracting them from the observed velocities, they found that the forearc region south of the MTL moves westward with respect to the inner zone of southwest Japan at a rate of about 5 mm/yr, probably driven by the oblique subduction of the Philippine Sea plate.

Here we try another approach to extract permanent movement. First, we estimate coseismic displacement due to the 1944 Tonankai and 1946 Nankai earthquakes as being equivalent to the accumulated short-term deformation over one earthquake deformation cycle. Figure 3(b) shows the results where displacements at the same positions as the current GPS sites are calculated by using the slip distribution on multisegment plate interface proposed by Sagiya and Thatcher (1999). Superiority of the model adopted here to the previous ones may be the inversion of integrated geodetic data and the correction for postseismic transient movements.

Next, we calculate the ratio of the arc-normal component of the inverted coseismic displacement to that of the interseismic GPS velocity at each individual site. The ratio averaged over all sites can be interpreted as an earthquake recurrence time because there is little evidence to show that there is permanent contraction in a direction perpendicular to the Nankai forearc. There is no significant reverse fault in the region, and the vertical slip rate of the MTL is much smaller than the right-lateral one, about one-tenth of the latter (Research Group for Active Faults of Japan, 1991). Although arc-normal crustal shortening is dominant in the interseismic period, as shown in Fig. 3(a), most of the accumulated strain will be released at the time of the next interplate earthquake. As pointed out by Wang (2000), the long-term strain regime in the forearc is far from arc-normal contraction.

The arc-normal direction applied in our analysis is ambiguous. We use three possible directions to calculate a recurrence time: (1) parallel to the slip vector of the 1946 Nankai earthquake, (2) perpendicular to the strike of the Nankai Trough, and (3) perpendicular to the strike of the MTL. Despite this ambiguity, the results are very similar, yielding recurrence times of 77.9, 76.6, and 76.0 years for the directions (1)–(3), respectively.

Finally, we obtain a residual velocity at each site, which is a vector difference between the observed interseismic velocity and the inverted coseismic displacement divided by the average recurrence time. The residual velocities are thus free of effects due to the 1946 earthquake deformation cycle and show only movements due to forearc migration and MTL deformation. Figure 4(a) shows residual velocity field when the “arc-normal” indicates a direction parallel to the earthquake slip vector. Stations located south of the MTL show a westward motion at a rate of 5–10 mm/yr except at the southernmost part of the network. Similar westward motion is seen also at stations densely distributed near the MTL. In contrast, stations located further north show no systematic motion. There is a high velocity gradient zone 20–30 km north of the MTL, while no velocity discontinuity is detected across the surface trace of MTL.

4. Discussion

The estimated recurrence time of about 76–78 years seems rather small compared with the average 130 yr recurrence

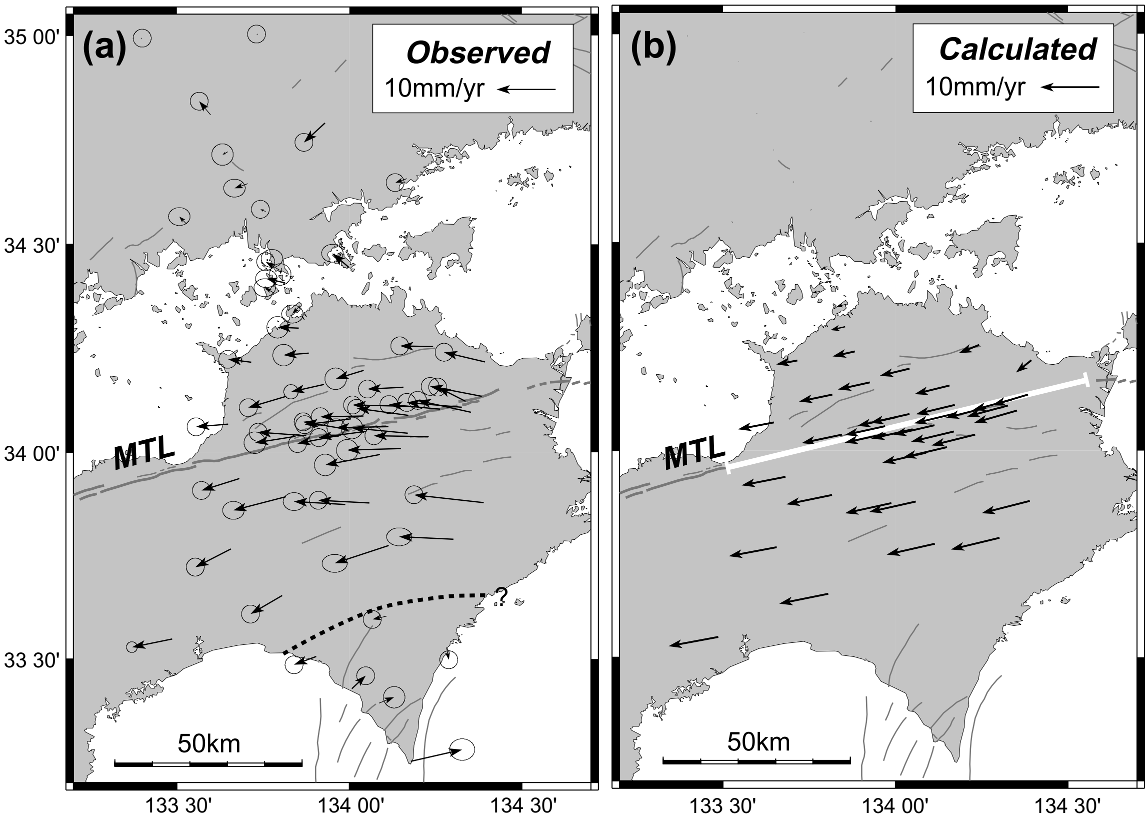

Fig. 4. (a) Residual velocities remaining after one earthquake deformation cycle at the Nankai Trough. Crustal velocity calculated from coseismic displacement and average recurrence time of the earthquake is subtracted from the observation at each site. (b) Velocities calculated from the best-fit forward model of the MTL. Location of the upper margin of the model fault is shown by a thick white line ($L = 100$ km). Parameters giving the best-fit model are a dip angle of 35 degrees (northward), a locking depth of 15 km, and a rate of the relative block motion of 9 mm/yr.

time of the Nankai earthquake during the past 1300 years. Two interpretations are possible: small coseismic displacements at the 1946 event or large interseismic GPS velocities. According to Kumagai (1996), the time sequence of 10 Nankai earthquakes fits well with a time-predictable recurrence model and the magnitude of the 1946 event ($M = 8.0$) was the second smallest among those 10 events. These facts support the first interpretation because the time-predictable model predicts that smaller events are followed by shorter recurrence times which is consistent with the relation between the 1946 event and the calculated recurrence time. On the other hand, Hyodo and Hirahara (2003) have shown that interseismic velocity on the overriding plate in the direction of plate convergence gradually increases with the elapsed time after the subduction earthquake when the viscoelasticity of the upper mantle is considered. Since we are now at the intermediate-later stage of the earthquake deformation cycle of the Nankai Trough, we may observe large interseismic velocities that lead to the underestimate of a recurrence time.

We model the residual velocity field in Fig. 4(a) according to the same procedures employed by Tabei *et al.* (2002). First, we assume that the fault plane of the MTL dips to the north at a shallow dip angle based on the seismic reflection survey results of Ito *et al.* (1996). Second, the upper zone of the fault plane is assumed to be fully locked to a certain depth and steady aseismic right-lateral slip occurs below it, since no velocity discontinuity is detected across the surface trace, whereas a high velocity gradient zone exists north of it. Fault length is fixed at 100 km throughout the calculation because the most likely rupture length of the MTL is 100–120 km (Tsutsumi and Okada, 1996). Then we search for the best-fit model varying dip angle, locking depth, and rate of steady aseismic slip with steps of 5 degrees, 2.5 km, and 1 mm/yr, respectively. The southernmost part of the network, which shows systematic deviation from the westward block motion, is excluded from the modeling. The best-fit model has a dip angle of 35 degrees, a locking depth of 15 km, and a rate of steady aseismic slip of 9 mm/yr. Surface deformation calculated from the model is shown in Fig. 4(b), and model that fits the observation is shown for a profile perpendicular to the MTL in Fig. 5.

Though the estimation of recurrence time and therefore the derivation of residual velocities are dependent on a specific coseismic fault model, we point out that the estimated rate of steady aseismic slip along the MTL is consistent with those derived from other kinds of data. We have already shown that the deflection of the plate convergence direction from the horizontal trend of the 1946 earthquake slip vector may produce a residual component of a velocity as large as 7–8 mm/yr. Moreover, geological surface observations have revealed that the average right-lateral slip rate along the MTL in the Quaternary is about 5–10 mm/yr (Research Group for Active Faults of Japan, 1991). Consistency among the estimations from different data sets suggests a small but permanent lateral movement of the Nankai forearc bounded on the north by the MTL.

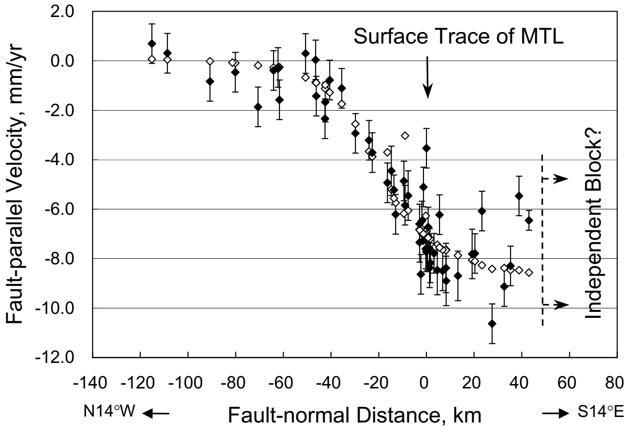

Fig. 5. Plots of velocity components parallel to the strike of the MTL as a function of the normal distance from the MTL. A solid diamond with an error bar represents the fault-parallel component of the residual velocity. An open diamond represents the velocity component predicted from the best-fit MTL model.

The estimated rate of the steady aseismic slip along the MTL is a little larger than the 5 mm/yr that was derived in the previous study by Tabei *et al.* (2002) although the same GPS velocity data have been used and the estimated dip angle and locking depth of the fault plane are identical in the two studies. The difference of the estimated slip rates may reflect a difference in analysis methods, especially a difference in the time span of the deformation. The previous study dealt with the deformation during the past few years that were covered by the GPS observations, not taking into consideration the earthquake deformation cycle at the Nankai Trough. In contrast, this study has addressed the permanent forearc movement that would be left after one earthquake deformation cycle. However, the difference of the estimated slip rates is too small to exactly identify its origin. It is a very interesting problem whether or not the aseismic slip rate along the MTL shows spatial and temporal variation.

How far the forearc lateral movement extends and where and how it terminates are interesting problems to be resolved in the future. As shown in Fig. 1, the GPS velocity field shows drastic changes from Shikoku to eastern Kyushu. Off the east coast of Kyushu, the Nankai Trough changes to a more southward strike, making a plate convergence direction more normal to the plate boundary. Furthermore, the earthquake distribution in the upper plane of the subducting plate shows a much steeper subduction angle, about 40–50 degrees, beneath Kyushu. These conditions make it unlikely that there are lateral forearc movements in Kyushu and further south. However, Nishimura (2003) has shown that right-lateral block movement is also occurring in eastern Kyushu based on the simultaneous estimation of rigid block rotation and elastic deformation, using observed GPS velocities. In 2002, we constructed another GPS campaign network across the MTL in western Shikoku, nearly parallel to and about 120 km west of the net discussed here. This network will provide valuable data to better understand lateral variations of fault geometry and forearc movement.

It is not clear why GPS velocities in the southernmost part of the network systematically deviate from the westward block motion. One interpretation is that this region belongs to another tectonic block that has been detached from the Nankai forearc and behaved independently at the time of the earthquake. It may be significant that this region is comprised of Cretaceous-Tertiary accretionary sequences called the Shimanto belt. However, it is still unknown whether or not it shows peculiar kinematic behavior through the earthquake deformation cycle. We are planning to improve station coverage around the northern boundary of this region (shown by a dotted line in Fig. 4(a)) to better understand block-to-block transition such as the high velocity gradient zone north of the MTL.

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