Strain partitioning and interplate coupling along the northern margin of the Philippine Sea plate, estimated from Global Navigation Satellite System and Global Positioning System-Acoustic data

Takuya Nishimura1*, Yusuke Yokota2*, Keiichi Tadokoro3*, and Tadafumi Ochi4*

1Disaster Prevention Research Institute, Kyoto University, Gokasho, Uji, Kyoto 611-0011, Japan
2Hydrographic and Oceanographic Department, Japan Coast Guard, 3-1-1, Kasumigaseki, Chiyoda-ku, Tokyo 100-8932, Japan
3Graduate School of Environmental Studies, Nagoya University, D2-1510, Furo-cho, Chikusa-ku, Nagoya 464-8601, Japan
4Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology, 1-1-1 Umezono, Tsukuba, Ibaraki 305-8560, Japan

ABSTRACT

Southwest Japan is located in the subduction margin between the continental Amurian and oceanic Philippine Sea plates. Recent land GNSS (Global Navigation Satellite System) and offshore Global Positioning System-Acoustic geodetic measurements were used to clarify the deformation in and around these plate margins. We examined strain partitioning and interplate coupling using a block modeling approach on the observed velocities. Although the main plate boundaries are the Nankai Trough and Sagami trough, our results suggest that one-third of the relative plate motion between the two plates is accommodated by several block boundaries in the southeastern margin of the Amurian plate. The most active boundaries, with a slip rate of 28 mm/yr, cross southwest Japan from the Okinawa Trough through the Median Tectonic Line and Niigata Kobe tectonic zone, to the eastern margin of the Japan Sea. A subparallel boundary with a slip rate of 4–5 mm/yr is along the coastline of Japan. These two boundaries have a right-lateral shear motion that accommodates part of the interplate motion, with a boundary across the Korean Peninsula and Japan Sea. The slip partitioning results in an eastward decrease of relative block motion from 78 to 4 mm/yr along the Nankai Trough and Suruga trough. Interplate coupling is moderate to strong at 10–25 km depth along the Nankai Trough, but it is lower at ~132°E, ~136°E, and ~137°E than in the surrounding regions, corresponding to the segment boundaries of past megathrust earthquakes, suggesting that regions of insufficient strain accumulation act as a barrier for earthquake rupture.

INTRODUCTION

Southwest Japan is situated in a subduction zone, where the northern margin of the Philippine Sea plate subducts beneath the southeastern margin of the continental Amurian plate. Large M ≥ 8 megathrust earthquakes have ruptured shallow parts of the plate interface with a recurrence interval of 100–200 yr along the Nankai Trough. The main boundary between these plates (Ando, 1975; Ishibashi, 2004). Many slow earthquakes, including slow slip events (SSEs), low-frequency tremors, and very low frequency earthquakes (VLFs) also occur around the rupture area of the megathrust earthquakes on the plate interface (cf. Obara, 2010). However, previous studies suggest that the relative plate motion between the Amurian and Philippine Sea plates is not accommodated by a single boundary. Numerous active faults and high seismicity, including M ~7 earthquakes on the islands of Japan, indicate strain partitioning in the continental margin (e.g., Shen-Tu et al., 1995). The most famous feature of the strain partitioning is the fault system of the Median Tectonic Line (MTL), which accommodates part of the margin-parallel component of the oblique relative motion between the Amurian and Philippine Sea plates (i.e., Fitch, 1972). Its right-lateral strike-slip motion was proposed based on geological studies (Kanaori, 1990; Tsutsuzumi et al., 1991), and has been confirmed by geodetic observations (Miyazaki and Heki, 2001; Tabei et al., 2003). Another dextral strike-slip fault system subparallel to the MTL has been proposed 400 km from the Nankai Trough (Gutscher and Lallemmand, 1999; Gutscher, 2001). Contemporary deformation in southwest Japan has been monitored by dense, continuous GNSS (Global Navigation Satellite System) networks since the mid-1990s. The largest network is the GEONET (GNSS Earth Observation Network System), operated by the Geospatial Information Authority of Japan (Sagiya, 2004). The GEONET showed that high strain rates are found not only...
in areas close to the main subduction margin along the Nankai Trough and the Sagami trough, but also the middle of the island arc and backarc. One such area is the Niigata-Kobe tectonic zone (NKTZ, Fig. 1) (Sagiya et al., 2000). In recent years, the geodetic network has been expanded offshore, and more than 20 GPS-A (Global Positioning System-Acoustic) seafloor stations have been deployed along the northern margin of the Philippine Sea plate (e.g., Yokota et al., 2015; Tadokoro et al., 2012; Nishimura et al., 2014).

Using these dense geodetic data, many previous studies have focused on interplate coupling along the Nankai Trough (i.e., Liu et al., 2010; Yoshioka and Matsuoka, 2013). Yokota et al. (2016) first used GPS-A data to estimate interplate coupling; their result suggests heterogeneous interplate coupling along the Nankai Trough, which cannot be resolved only by land GNSS data. However, most previous studies have attributed deformation in the overriding plate only to interplate coupling on the megathrust interface, and their estimated coupling may be biased because they ignore the strain partitioning, as pointed out by Nishimura and Hashimoto (2006). In order to overcome this problem, several studies have modeled GNSS velocities in southwest Japan using the block model approach, incorporating strain partitioning in the plates as well as elastic deformation. Hashimoto et al. (2000) first used the block model for GNSS velocity data in the islands of Japan; they did not estimate a detailed distribution on the plate interface because their model approximated the plate interface as several rectangular faults. Nishimura and Hashimoto (2006) and Wallace et al. (2009) divided southwest Japan into three and five blocks, respectively, but they both only modeled the region west of 135°E. Loveless and Meade (2010) modeled all the islands of Japan, and their result is often referred to as the standard result of block motion and interplate coupling. However, none of these studies used offshore GPS-A data or GNSS data from after 2002.

We also model crustal velocities in southwest and central Japan using the block model approach. Our study is distinct because we use all available geodetic data, including GPS-A data. We use data from GEONET stations con-
constructed after 2002, as well as GNSS stations operated by several institutions, so that the average density of GNSS stations used is almost double that of previous studies. Using GNSS stations in the Korean Peninsula that belong to the stable Amurian plate allows us to clarify strain partitioning in the continental margin. We obtain a high-resolution estimate of the coupling distribution along the entire Nankai Trough and Sagami trough owing to the use of offshore geodetic data. We then discuss the estimated interplate coupling and block rotation from the viewpoint of seismotectonics in Japan.

DATA AND METHOD

GNSS Velocity Data

We estimated site velocities at permanent GNSS stations in Japan and South Korea for a stable interseismic period, free of earthquakes and transient events during 2005–2009. Daily coordinates at GNSS stations in Japan are estimated from raw RINEX (Receiver Independent Exchange Format) data provided by the Geospatial Information Authority of Japan, Japan Coast Guard, National Institute of Advanced Industrial Science and Technology, Kyoto University, Nagoya University, and International GNSS Service. The coordinates were estimated by precise point positioning with ambiguity resolution (Bertiger et al., 2010) using the GIPSY-OASIS ver. 6.2 software (https://gipsy-oasis.jpl.nasa.gov/), and were transformed into the IGB08 reference frame (http://acc.iigs.org/igs-frames.html) using the transformation parameters provided by the National Aeronautics and Space Administration Jet Propulsion Laboratory. Daily coordinates for stations on the Korean Peninsula were downloaded from the website of the Nevada Geodetic Laboratory (http://geodesy.unr.edu/). The strategy and procedure for estimating daily coordinates at the Nevada Geodetic Laboratory is almost the same as ours. Therefore, we regarded all daily coordinates used in this study as being in the ITRF2008 (International Terrestrial Reference System) reference frame (Altamimi et al., 2011). We estimated site velocities at all the GNSS stations by fitting a function with linear, annual, and semiannual terms for the period from April 2005 to December 2009; we chose this period because it spans only a few tectonic events, including the 2006 earthquake swarm off the eastern coast of the Izu Peninsula, and the 2007 moment magnitude, Mw 6.6 Noto Peninsula (Ozawa et al., 2008) and Mw 6.6 Niigataken Chuetsu-oki (Nishimura et al., 2010) earthquakes. We removed their coseismic displacements by adding a step term in the function for stations in the affected area. The velocities shown in Figure 1 were transformed to the Eurasian plate reference frame using the Euler vectors of the ITRF2008 plate motion model (Altamimi et al., 2012).

The primary feature of the velocity vectors (Fig. 1) is the west-northwestward movement along the Nankai Trough. The velocity in most regions is almost parallel to the motion of the subducting Philippine Sea plate, which suggests strong interplate coupling at the Nankai subduction zone (Liu et al., 2010; Yoshioka and Matsuoka, 2013). However, the velocity direction in some areas deviates systematically from that of the Philippine Sea plate. For example, the southern part of Kyushu and the northernmost part of the Izu Islands move southward and westward, respectively.

Although the GNSS velocity vectors (Fig. 1) are intuitively easy to understand in terms of the tectonic deformation, their direction and magnitude depend on the reference frame. In contrast, the strain rate distribution is independent of the reference frame, and useful for identifying where high strain rates are concentrated in the subduction margin. We calculated the distribution of strain rates in southwest Japan using the method of Shen et al. (1996) and Sagiya et al. (2000). The distribution of areal strain rates and maximum shear strain rates is plotted in Figures 2A and 2B, respectively; both plots show high strain rates along the Pacific coast, particularly in Shikoku. The direction of contraction there is consistent with that of the Philippine Sea plate, and consistent with the interplate coupling along the Nankai Trough and Sagami trough shown by previous studies (e.g., Nishimura et al., 2007; Liu et al., 2010; Yoshioka and Matsuoka, 2013). However, the principal strain in central Kyushu and central Honshu around (136°E, 35°N) shows east-west contraction, which deviates from the direction of plate convergence. We also note that the strain rate distribution in the inland regions is very heterogeneous. Several zones of strain concentration, including the NKTZ (Sagiya et al., 2000), are clearly recognized in both the areal (region a in Fig. 2A) and maximum shear (region a in Fig. 2B) strain rates. Although most zones of high strain rates correspond to surface traces of major active faults, we note zones of high shear strain rates in southern Kyushu (region b in Fig. 2B) and along the northern coast of western Honshu (region c in Fig. 2B), where there are no major active faults. These zones have been identified geodetically by previous GNSS studies in Kyushu (e.g., Takayama and Yoshida, 2007; Wallace et al., 2009) and western Honshu (Nishimura and Takada, 2017). Some zones of strain concentration are far from the main plate boundary (the Nankai Trough and Sagami trough) and cannot be explained by simple elastic deformation due to interplate coupling on the plate boundary, because elastic strain decreases with cubic distance from the source in a homogeneous medium. Therefore, using a block model, we suggest that the inland strain concentration zones provide evidence of strain partitioning in the overriding continental plate. Figure 2A shows inflation around some volcanoes, including Mount Fuji and Sakurajima, Oshima, and Miyake-jima. In the block model, we correct these inflations using the velocity data and point inflation sources, which we explain in detail herein. (For a detailed discussion on strain rates and inland earthquakes, see Nishimura, 2017.)

GPS-A Velocity Data

We used velocity data from 23 offshore GPS-A stations operated by the Japan Coast Guard and Nagoya University along the northern margin of the Philippine Sea plate (e.g., Nishimura et al., 2014). The start of measurement at these stations varies from 2004 to 2012. Campaign GPS-A measurements are usually conducted a few times per year. Although the 2011 Mw 9.0 Tohoku-oki earthquake caused significant coseismic and postseismic deformation at the offshore stations, we need a long period to estimate the stable velocity
Figure 2. Strain rate distribution estimated from GNSS (Global Navigation Satellite System) velocities from April 2005 to December 2009. Brown lines and red triangles represent surface traces of major active faults (Headquarters for Earthquake Research Promotion, 2011) and active volcanoes (Japan Meteorological Agency, 2011). (A) Areal strain rates; arrows represent principal strain rates. Ext—extension; Cont—contraction. (B) Maximum shear strain rates.
because of the temporal sparseness and precision of GPS-A measurements. The velocity from 2004 to 2016 was estimated at 19 stations along the Nankai Trough after removing the coseismic and postseismic displacement using the model. These velocities were updated using those published in Yokota et al. (2016) and Tadokoro et al. (2012) to include coordinates observed by recent campaigns conducted to 2016. The procedure for correcting for the displacement caused by the Tohoku-oki earthquake and estimating the secular velocities were explained in detail in Yokota et al. (2016) and Graduate School of Environmental studies, Nagoya University (2016). We also used the published velocity for two stations in the easternmost part of the Nankai Trough (Yasuda et al., 2014) and at two stations along the Sagami trough (Watanabe et al., 2015 before the Tohoku-oki earthquake. After transforming the secular velocities with the MORVEL (mid-ocean ridge velocity) Euler vectors (DeMets et al., 2015), as shown in Figure 3. We adjusted the block geometry to reduce the misfit of velocities near the block boundaries by trial and error. Most block boundaries are derived from a simplified geometry of major active faults (Fig. 3A). Boundaries between the Setouchi (SE) and Shikoku (SH) blocks, and between the Chubu (CH) and Kanto (KA) blocks, correspond to the fault systems of the MTL and the Itoigawa-Shizuoka tectonic line, regarded as the most active onshore fault system in Japan. The boundary around the Osaka (OS) block corresponds to the Rokko-Awaji, Arima-Takatsuki, Ikoma, and MTL fault systems. The boundary around the Biwako (BI) block corresponds to the Biwako-Seigun, Hanaore, Nobi, Kizugawa, and Ise Bay fault systems. Most part of the boundary between the Hokuriku (HO) and Chubu (CH) blocks is identified by the Atotsugawa fault system. The northern and southeastern boundaries of the Central Kyushu (CK) block correspond to the northern rim of the Saga Plain–Mizunawa–Beppu Haneyama and Futagawa-Hinagu fault systems, respectively. Part of the latter fault system was ruptured by the 16 April 2016 M_w7.0 Kumamoto earthquake (Figs. 3A, 3B; Fukahata and Hashimoto, 2016). The boundary between the Amurian (AM) plate and Japan Sea block (US) approximates the Honam shear zone (Jin and Park, 2007) in the Korean Peninsula.

Shallow seismicity in the crust (Fig. 3B) also gives clues as to the block structures. Seismicity lineaments often, but do not always, correspond to active faults. A distinctive lineament without major active faults exists along the northern coast of western Honshu between 131°E and 135°E, and was identified as a seismic belt by Kawanishi et al. (2009). The eastern part of this seismic belt and the proposed Sari-in shear zone (Nishimura and Takada, 2017) overlap the zone of concentrated maximum shear strain rates (Fig. 2B). We therefore decided to model this zone approximately by the Osaka block.

### Block Modeling

In the block model, that surface deformation is expressed as a sum of rigid block rotations and interseismic elastic deformation due to locked faults on block boundaries (Matsu’ura et al., 1986). We used the inversion program DEFNODE (McCaffrey, 2002) to model the observed velocities with this approach. Elastic deformation is calculated as nominal slip opposite to the relative block motion, that is, back slip (Savage, 1983) or more generally, slip deficit on the fault in an elastic half-space (Okada, 1985). The slip-deficit rates are estimated at nodes on the boundary faults under the constraint of a rate ranging between zero and that of the relative block motion, but we did not apply a spatial constraint to the slip-deficit distribution. Slip-deficit rates between nodes are linearly interpolated on the faults. We also estimated internal permanent strain in most continental blocks.

We used horizontal and vertical velocities at 840 GNSS stations and horizontal velocities at 23 GPS-A stations in the inversion analysis (Supplemental File 1). The data weight in the inversion is the reciprocal square of the product of the velocity uncertainties and data type constants. Data type constants are introduced to weight the vertical and horizontal velocities, although their uncertainties are larger than those of the horizontal GNSS velocities. The vertical deformation is important for distinguishing between rigid rotation and elastic deformation due to fault locking because only elastic deformation causes vertical deformation in the block model we used. Offshore GPS-A data are also important for resolving offshore interplate coupling near the Nankai Trough and Sagami trough. Data near the region of interplate coupling have the most resolving power for coupling distribution, which is our main objective, and are less sensitive to various model assumptions including block geometries. We therefore used 1, 1/5, and 1/10 as data type constants for horizontal GNSS, vertical GNSS, and GPS-A velocities, respectively. The velocities were corrected for volcanic deformation around the Izu Oshima, Miyakejima, Fuji, and Sakurajima volcanoes by removing the synthetic velocities due to point inflation (Mogi) sources beneath the volcanoes. The parameters for the inflation sources (Table 1) were estimated from the velocities at stations within 50 km of the volcanoes by fixing the source locations estimated in previous studies (Nishimura, 2011; Hotta et al., 2016).

### Block Geometry

We constructed the block geometry mainly based on surface traces of major active faults (Headquarters for Earthquake Research Promotion, 2017), shallow seismicity, the strain rate distribution from the geodetic data, previous block models (Wallace et al., 2009; Loveless and Meade, 2010; Nishimura, 2011), and previous regional seismotectonic studies (Matsumoto et al., 2015), as shown in Figure 3. We adjusted the block geometry to reduce the misfit of velocities near the block boundaries by trial and error.

Most block boundaries are derived from a simplified geometry of major active faults (Fig. 3A). Boundaries between the Setouchi (SE) and Shikoku (SH) blocks, and between the Chubu (CH) and Kanto (KA) blocks, correspond to the fault systems of the MTL and the Itoigawa-Shizuoka tectonic line, regarded as the most active onshore fault system in Japan. The boundary around the Osaka (OS) block corresponds to the Rokko-Awaji, Arima-Takatsuki, Ikoma, and MTL fault systems. The boundary around the Biwako (BI) block corresponds to the Biwako-Seigun, Hanaore, Nobi, Kizugawa, and Ise Bay fault systems. Most part of the boundary between the Hokuriku (HO) and Chubu (CH) blocks is identified by the Atotsugawa fault system. The northern and southeastern boundaries of the Central Kyushu (CK) block correspond to the northern rim of the Saga Plain–Mizunawa–Beppu Haneyama and Futagawa-Hinagu fault systems, respectively. Part of the latter fault system was ruptured by the 16 April 2016 M_w7.0 Kumamoto earthquake (Figs. 3A, 3B; Fukahata and Hashimoto, 2016). The boundary between the Amurian (AM) plate and Japan Sea block (US) approximates the Honam shear zone (Jin and Park, 2007) in the Korean Peninsula.

Shallow seismicity in the crust (Fig. 3B) also gives clues as to the block structures. Seismicity lineaments often, but do not always, correspond to active faults. A distinctive lineament without major active faults exists along the northern coast of western Honshu between 131°E and 135°E, and was identified as a seismic belt by Kawanishi et al. (2009). The eastern part of this seismic belt and the proposed Sari-in shear zone (Nishimura and Takada, 2017) overlap the zone of concentrated maximum shear strain rates (Fig. 2B). We therefore decided to model this zone approximately by the Osaka block.

### Table 1. Parameters of Volcanic Inflation Sources

<table>
<thead>
<tr>
<th>Volcano</th>
<th>Depth (km)</th>
<th>Volume change rate (10^6 m^3/yr)</th>
<th>Latitude (°N)</th>
<th>Longitude (°E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuji</td>
<td>15.0</td>
<td>5.16</td>
<td>34.536</td>
<td>138.733</td>
</tr>
<tr>
<td>Oshima</td>
<td>6.0</td>
<td>2.47</td>
<td>34.736</td>
<td>139.399</td>
</tr>
<tr>
<td>Miyakejima</td>
<td>9.5</td>
<td>5.99</td>
<td>34.067</td>
<td>139.503</td>
</tr>
<tr>
<td>Sakurajima</td>
<td>8.5</td>
<td>4.46</td>
<td>31.649</td>
<td>139.689</td>
</tr>
</tbody>
</table>

*Supplemental File. Velocity data at GNSS and GPS-A stations used in this study. Please visit [http://doi.org/10.1130/GES01529.1](http://doi.org/10.1130/GES01529.1) or the full text article on [www.gsapubs.org](http://www.gsapubs.org) to view the Supplemental File.*
assumed a block boundary between the Japan Sea (JS) and Setouchi (SE) blocks on the eastern part of the seismic belt. The assumed block boundary goes offshore west of 132.5°E, while the seismic belt continues inland along the coast in order to reduce residuals after trial and error. The boundary between the Shikoku (SH) and southern Kyushu (SK) blocks was proposed as an active shear zone by previous GNSS studies (e.g., Wallace et al., 2009) and is assumed to be in an active seismic zone where $M_w$ 6.1 and 6.0 earthquakes occurred in 1997 (e.g., Toda and Stein, 2003).

The locations of the block boundaries offshore are mostly speculative, because there is no clear supporting evidence, and they cannot be constrained by our geodetic data because of the sparse distribution of stations. However, the offshore block boundaries do not significantly affect our inversion results for

---

Figure 3. Block geometry used in this study. Abbreviations of the tectonic blocks: IF—Izu forearc block, IM—Izu microplate, PS—Philippine Sea plate, KA—Kanto block, HO—Hokuriku block, CH—Chubu block, BI—Bivako block, OS—Osaka block, SE—Setouchi block, SH—Shikoku block, JS—Japan Sea block, SK—southern Kyushu block, CK—central Kyushu block, AM—Amurian plate. (A) Active faults (Headquarters for Earthquake Research Promotion, 2017) in the shaded relief topographic map. (B) Shallow seismicity at depth $\leq$ 20 km and magnitude $\geq$ 2, 1923-2016 ($M_s$ is moment magnitude). Stars with occurrence year and magnitude indicate epicenters of selected large earthquakes. The orange triangles indicate active volcanoes.
block rotations and slip-deficit rates. For example, separation of the Shikoku (SH) and Chubu (CH) blocks reduces misfits in the model, but the misfits are not highly dependent on the location of their boundary if it is located in the Kii Channel (~135°E) between Shikoku and Honshu. We divide the continental part of the analyzed region into 11 blocks. The subducting plate, which is conventionally regarded as the single Philippine Sea plate, is divided into three blocks, the (stable) Philippine Sea (PS) plate, Izu forearc (IF) block, and Izu microplate (IM), following the model of Nishimura (2011). In total, 14 tectonic blocks are assumed in the block model and their rigid rotational movements are estimated (Figs. 3A, 3B). Internal permanent strain rates, which are uniform in each block, are also estimated for most continental blocks, i.e., HO, CH, BI, OS, SE, SH, JS, CK, and SK.

The three-dimensional fault geometry of the block boundaries is mainly based on previous studies of seismic tomography and active source seismic surveys, and seismicity. The shape of the plate interfaces between the subducting and continental plates along the Nankai Trough is approximated to the isodepth contours of Baba et al. (2002) and Hirose et al. (2008a). The plate interface along the Sagami trough is derived from Takeda et al. (2007) and Hirose et al. (2008b). Because GPS-A stations are located on the seafloor at depths of 800–2900 m below sea level, the surface displacement would be biased if we calculated surface displacement due to slip below the stations using an elastic half-space dislocation model (Okada, 1985). In order to reduce this effect, we made the subsurface PS-SK, PS-SH, PS-CH, and IM-CH interfaces at depths of 5–15 km shallower by as much as 2 km along the Nankai Trough. We also made the subsurface PS-SH interface shallower by several kilometers near 33°N, 133°E, between Shikoku and Kyushu, because a northward systematic misfit was found with the original model derived from Hirose et al. (2008a).

The node intervals for estimating slip-deficit rates vary from ~5 to 70 km and ~20 to 80 km along the dip and strike directions for subduction faults along the Nankai Trough and Sagami trough, respectively. The uniform depth interval of the nodes along the dip direction is 5 km. The maximum depth of the nodes is 50 km and 40 km for the Nankai Trough and Sagami trough, respectively. The node intervals for crustal faults are 8 km and ~10–90 km along the dip and strike directions, respectively. Most of the updip and downdip nodes are assigned to depths of 0.5 and 24.5 km, respectively. We assumed a subsurface fault geometry only for boundaries with slip rates that are expected to be high and can be sufficiently constrained by neighboring geodetic stations. Block boundaries for which subsurface fault geometries are not assigned indicate creeping faults slipping at the rate of the relative block motion in our model.

Resolution Tests

Geodetic inversion generally has a limited resolving power for slip deep and offshore faults (e.g., Sagiya and Thacher, 1999; Nishimura et al., 2004). Yokota et al. (2016) showed that offshore geodetic data improve resolving power near the Nankai Trough. We made assumptions about the fault geometry and demonstrated how much slip is resolved with our data set. We calculated synthetic displacements predicted from the assumed stripe distribution along the strike and dip directions (Figs. 4A, 4D). The synthetic displacements were added; random Gaussian noises correspond to three times the data uncertainties assigned in the inversion, because data misfits in our inversion result suggest that the assigned data uncertainties are underestimated (as discussed in RESULTS). The synthetic displacements are inverted to estimate slip-deficit rates only on the subduction interfaces along the Nankai Trough and Sagami trough. The other parameters, i.e., slip-deficit rates on crustal faults, block rotation, and internal strain of the blocks, are fixed in these resolution tests.

The stripes along the strike are reproduced at an intermediate depth (Fig. 4B). Those along the dip are reasonably reproduced, except for a region near the trough (Fig. 4E). The southwestern region with a depth of ≤20 km east of Kyushu is poorly resolved. Figure 4 suggests that the unresolved area for the assigned stripes approximately corresponds to the area with estimated uncertainties of ≥20 mm (shaded regions in Fig. 4). Comparisons between Figures 4B and 4C and 4E and 4F suggest that offshore GPS-A data are useful to resolve the offshore slip, although the slip near the trough axis cannot be resolved despite using the existing GPS-A data.

RESULTS

One interesting aspect of the block model is the separation of the observed velocities into the estimated block rotation and elastic deformation components because of fault locking, and the internal uniform deformation component of each block. We plot the first two components in Figure 5. Except for the offshore regions along the troughs and southern Shikoku, the block rotation component is greater than the elastic deformation. Because the directions of both components are similar in most areas, ignoring the block rotation in the continental plates results in larger estimates of interplate coupling. The Euler poles and rotational rates of the rigid blocks are listed in Table 2. Except for the Izu microplate, the Euler poles are far from the studied region, which means that block motion can be approximated by translation. The block motions of the KA, CH, BI, OS, and SH blocks are similar and westward. However, those of the HO, SE, CK, and JS blocks are similarly westward to northwestward with a rate of ≤10 mm/yr. Therefore, the boundary between these two groups, as well as the Nankai Trough and Sagami trough, are the most important in southwest Japan from the viewpoint of contemporary kinematics. This characteristic is apparent in the relative block motion along the boundaries of the tectonic blocks (Fig. 6), as discussed herein. Estimated internal strain rates (Table 3) show that except for the SK block, compressional strain in the continental blocks dominates in a direction of relative plate convergence north of the Nankai Trough (Fig. 6). The internal extension in the east-west direction may be related with extensive volcanic activities of Sakurajima and several calderas in SK, which is apparent on areal strain rates shown in Figure 2A. The OK and BI blocks in the NKTZ show the largest internal strain rates, to ~9 x 10^-8 yr^-1. These large internal strain rates may be attributed to the numerous active faults in our simplified tectonic block (Fig. 3A).
Slip-deficit rates on the subduction interfaces and crustal faults are shown in Figures 7 and 8, respectively. The shaded regions represent large uncertainties in the estimated slip-deficit rates. Along the Nankai Trough, the distribution of slip-deficit rates is heterogeneous in both the strike and dip directions, and regions of high slip-deficit rates are found in offshore Shikoku, offshore Kii Peninsula, the Bungo Channel, and the southernmost region east of Kyushu. Although we are not confident of the results for this last region because of the large uncertainties there, results for the other three regions are robust based on our trial and error method for the block geometries. The regions of high slip-deficit rates off Shikoku and the Kii Peninsula are located at 10–20 km depths, but the region in the Bungo Channel is located at 20–40 km depth. Regions of large uncertainties are located near the updip and downdip edges of the assigned fault area. Although the offshore data contribute to decreasing the width of the updip uncertain region by ~50 km, slip near the trough axis is still not constrained by the geodetic data. It is notable that the uncertainties in the slip-deficit rates are large in the most southwestern part of the Nankai Trough east off Kyushu and the eastern half of the Sagami trough. Slip-deficit rates in these regions are important for assessing the size of the source region of future megathrust earthquakes, but the
geodetic data cannot constrain them. Slip-deficit rates for inland faults (Fig. 8) are estimated to be mostly similar to their interblock velocities, but they are also mostly within their uncertainties. Slip-deficit rates of ≥10 mm/yr are estimated on the SH-SK, BI-SE, BI-HO, and CH-HO boundaries. The latter three boundaries correspond to the Biwako-Seigan, Hanaore, and Atotsugawa faults, and they are accumulating elastic strain that may be released by future earthquakes.

The observed velocities are reasonably reproduced by our model (Fig. 9). Along the Nankai Trough and Sagami trough, the observed vertical velocities show subsidence around the southern tips of the capes and peninsulas, and uplift in the more northern region. This systematic pattern is explained by the model (Fig. 9B). The normalized root mean squares (nrms) for horizontal onshore, horizontal offshore, and vertical onshore velocities for the preferred

<table>
<thead>
<tr>
<th>Block</th>
<th>Latitude (°N)</th>
<th>Longitude (°E)</th>
<th>Rotation rate (°/Ma)</th>
<th>$\varepsilon_{\text{max}}$ (°)</th>
<th>$\varepsilon_{\text{min}}$ (°)</th>
<th>Azimuth (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Philippine Sea plate</td>
<td>54.38</td>
<td>157.28</td>
<td>−1.255 ± 0.014</td>
<td>0.55</td>
<td>0.09</td>
<td>220</td>
</tr>
<tr>
<td>Izu forearc block (IF)</td>
<td>46.64</td>
<td>156.95</td>
<td>−1.331 ± 0.116</td>
<td>2.28</td>
<td>0.14</td>
<td>233</td>
</tr>
<tr>
<td>Izu microplate (IM)</td>
<td>36.77</td>
<td>138.91</td>
<td>−8.778 ± 0.311</td>
<td>0.09</td>
<td>0.02</td>
<td>193</td>
</tr>
<tr>
<td>Kanto block (KA)</td>
<td>75.61</td>
<td>169.77</td>
<td>−0.321 ± 0.070</td>
<td>15.69</td>
<td>0.39</td>
<td>218</td>
</tr>
<tr>
<td>Chubu block (CH)</td>
<td>82.38</td>
<td>194.39</td>
<td>−0.250 ± 0.043</td>
<td>16.87</td>
<td>0.45</td>
<td>241</td>
</tr>
<tr>
<td>Hokuriku block (HO)</td>
<td>−5.07</td>
<td>112.38</td>
<td>0.083 ± 0.080</td>
<td>66.50</td>
<td>1.12</td>
<td>26</td>
</tr>
<tr>
<td>Biwako block (BI)</td>
<td>69.16</td>
<td>137.65</td>
<td>−0.277 ± 0.181</td>
<td>33.75</td>
<td>0.75</td>
<td>182</td>
</tr>
<tr>
<td>Osaka block (OS)</td>
<td>67.04</td>
<td>153.16</td>
<td>−0.243 ± 0.272</td>
<td>52.52</td>
<td>0.74</td>
<td>207</td>
</tr>
<tr>
<td>Setouchi block (SE)</td>
<td>−22.24</td>
<td>95.58</td>
<td>0.082 ± 0.017</td>
<td>38.32</td>
<td>1.11</td>
<td>32</td>
</tr>
<tr>
<td>Shikoku block (SH)</td>
<td>24.30</td>
<td>130.29</td>
<td>0.972 ± 0.093</td>
<td>1.35</td>
<td>0.20</td>
<td>12</td>
</tr>
<tr>
<td>Southern Kyushu block (SK)</td>
<td>30.23</td>
<td>120.98</td>
<td>−0.570 ± 0.237</td>
<td>5.36</td>
<td>1.54</td>
<td>257</td>
</tr>
<tr>
<td>Central Kyushu block (CK)</td>
<td>67.79</td>
<td>131.17</td>
<td>−0.076 ± 0.101</td>
<td>60.28</td>
<td>5.82</td>
<td>195</td>
</tr>
<tr>
<td>Japan Sea block (JS)</td>
<td>37.36</td>
<td>173.67</td>
<td>−0.052 ± 0.018</td>
<td>17.65</td>
<td>1.92</td>
<td>99</td>
</tr>
<tr>
<td>Amurian plate (AM)</td>
<td>74.98</td>
<td>243.43</td>
<td>0.015 ± 0.010</td>
<td>71.12</td>
<td>5.35</td>
<td>303</td>
</tr>
</tbody>
</table>

Note: The rotation rate is indicated with one standard error. $\varepsilon_{\text{max}}$, $\varepsilon_{\text{min}}$, and azimuth represent the maximum and the minimum axes of the 68% confidence error ellipse and azimuth of the major axis, respectively.
model are 4.76, 15.64, and 7.75, respectively. These statistics suggest that our block model does not explain the data within the assigned data uncertainties, which are generally <0.5 mm/yr (as shown in the Supplemental File [footnote 1]). We attribute these large misfits to the underestimated velocity uncertainties assigned in the inversion analysis. Another major source of the large misfits is anomalous GNSS sites affected by nontectonic disturbances such as landslides, monument instability, and local multipath interferences. Because the nrmss are ~3 for the horizontal onshore GNSS data of most continental blocks, we increased the uncertainties used for the resolution test by three times, and demonstrated that the quality of our data is sufficient to resolve the coupling distribution on a major part of the subducting plate interface along the Nankai Trough and Sagami trough. The residual (i.e., observed – calculated) horizontal velocities appear to be almost random, but there are some systematic patterns near the block edges and along the Nankai Trough and Sagami trough (Fig. 10). This can probably be attributed to our simplified geometry of blocks and boundary faults. The largest residuals are found southeast off Kii Peninsula, near 137°E. This may be caused by postseismic deformation of the Mw 7.2 and Mw 7.4 earthquakes off Kii Peninsula on 26 September 2004, which was an intraslab event in the subducting plates (Nakano et al., 2015) (Fig. 3B). Systematic southward residuals are also found at nearby on-land GNSS stations, similar to the observed coseismic displacements and predicted postseismic displacements due to viscoelastic relaxation (Suito and Ozawa, 2009). Therefore, heterogeneous slip-deficit rates along the Nankai Trough near 137°E may be affected by the postseismic deformation due to the 2004 earthquakes.

### DISCUSSION

#### Strain Partitioning of Interplate Motions in and around Southwest Japan

Our results show that rigid block motions on the continental plate, except for the SK block, have a west to northwest direction, and that they serve as intermediate motions between those of the subducting Philippine Sea plate and the stable Amurian plate (Fig. 5). Oblique subduction along the Nankai Trough causes strain partitioning, as represented by the MTL (e.g., Fitch, 1972; Fitch and Kanamori, 1975). We attribute these large misfits to the underestimated velocity uncertainties assigned in the inversion analysis. Another major source of the large misfits is anomalous GNSS sites affected by nontectonic disturbances such as landslides, monument instability, and local multipath interferences. Because the nrmss are ~3 for the horizontal onshore GNSS data of most continental blocks, we increased the uncertainties used for the resolution test by three times, and demonstrated that the quality of our data is sufficient to resolve the coupling distribution on a major part of the subducting plate interface along the Nankai Trough and Sagami trough. The residual (i.e., observed – calculated) horizontal velocities appear to be almost random, but there are some systematic patterns near the block edges and along the Nankai Trough and Sagami trough (Fig. 10). This can probably be attributed to our simplified geometry of blocks and boundary faults. The largest residuals are found southeast off Kii Peninsula, near 137°E. This may be caused by postseismic deformation of the Mw 7.2 and Mw 7.4 earthquakes off Kii Peninsula on 26 September 2004, which was an intraslab event in the subducting plates (Nakano et al., 2015) (Fig. 3B). Systematic southward residuals are also found at nearby on-land GNSS stations, similar to the observed coseismic displacements and predicted postseismic displacements due to viscoelastic relaxation (Suito and Ozawa, 2009). Therefore, heterogeneous slip-deficit rates along the Nankai Trough near 137°E may be affected by the postseismic deformation due to the 2004 earthquakes.
Figure 7. Estimated slip-deficit rates on subduction interfaces along the Nankai Trough and Sagami trough. Shaded region represents standard errors ≥20 mm/yr. Contours on subduction interfaces are isodepths at 10 km intervals. Black dots represent nodes used in estimating slip-deficit rates.

Figure 8. Estimated slip-deficit rates on crustal faults. Shaded region represents standard errors ≥5 mm/yr. Tectonic block abbreviations as in Figure 3. Other symbols are the same as in Figure 6. Note that crustal faults without the plotted slip-deficit rates are assumed to creep.
The motions of our continental blocks can be interpreted as those of forearc slivers. Gutscher and Lallemand (1999) proposed two major right-lateral shear zones in Shikoku and western Honshu (i.e., the MTL and North Chugoku shear zone, NCSZ), and that part of the transcurrent motion is being transferred from the MTL to the NCSZ based on recent and historical seismicity. Nishimura and Takada (2017) identified a high strain rate in an eastern part of the NCSZ using the GNSS data and proposed to call it the San-in shear zone; they suggested that the 2000 Mw 6.7 western Tottori (Fig. 3B) and 2016 Mw 6.2 central Tottori earthquakes occurred in the San-in shear zone. However, Loveless and Meade (2010) concluded, from GNSS data, that movement across the NCSZ was negligible. Our model suggests that the boundary between the JS and SE blocks, corresponding to the NCSZ, has a significant slip rate (~5 mm/yr), which is half of that between the SE and SH blocks, corresponding to the MTL (9–10 mm/yr). This discrepancy is explained by an insufficient number of stations near the NCSZ (used in Loveless and Meade, 2010) providing velocity data for 1996–1999. Five GNSS stations were added along the Japan Sea coast north of the NSCZ between 132.5°E and 135°E in 2002 and 2004. We found a considerable velocity gradient, as well as high rates of maximum shear strain (Fig. 2B), across the eastern part of the NCSZ in 2005–2009 using these new stations. Another possibility to explain the discrepancy is the location of the shear zone. Because we found no significant velocity gradients across the western part of the NCSZ, we assumed a block boundary in the offshore region west of 132.5°E, not at the NCSZ, that is identical to the seismicity lineament. Our model further predicts significant relative block motion between the JS and AM blocks on the Korean Peninsula at a rate of 1–3 mm/yr.

Movements of the forearc blocks along the Nankai Trough demonstrate the total partitioning ratio within the continental plate. The block motion velocities at (33°N, 133°E) in the SH block and at (33.5°N, 137°E) in the CH block are 18 and 24 mm/yr with respect to the (stable) Amurian plate, respectively. Their components that are parallel to the Philippine Sea plate motion reach ~26% and ~36%, respectively, of the Philippine Sea plate motion. Along the easternmost part of the Nankai Trough, called the Suruga Trough, partitioning within the subducting oceanic plate also appears, as in the Izu microplate (e.g., Sagiya, 1999; Nishimura et al., 2007). A significant part of the plate motion between the subducting Philippine Sea and stable Amurian plates is accommodated by several block boundaries along the margin of both plates. This strain partitioning along the plate margins causes a dramatic decrease in the relative block velocity along the Ryukyu-Nankai-Suruga trench system, from 78 to 4 mm/yr eastward in the studied area. One interesting point is that the block boundaries along the plate margins accommodate not only margin-parallel motion but also margin-normal motion, which may be attributed to crustal shortening across the plate margins.

From the viewpoint of movements relative to the Okhotsk (or North America) plate, which northeast Japan belongs to, many previous studies using GNSS (e.g., Sagiya et al., 2000; Heki and Miyazaki, 2001) suggest that the NKTZ is a major tectonic boundary between the Okhotsk and Amurian plates (Fig. 1). Our model predicts a high rate of interblock motion (~3–14 mm/yr) along the
Ho-CH, SE-BI, and SE-OS boundaries, consistent with previous studies (Fig. 6). The boundary of high interblock velocities extends to the SE-SH and CK-SH boundaries. This suggests that these boundaries corresponding to the NKTZ, MTL, and Futagawa-Hinagu fault zones are major tectonic boundaries between the Okhotsk and Amurian plates that transect the islands of Japan. Therefore, the KA, CH, BI, OS, and SH tectonic blocks can be interpreted as either a forearc sliver south of the MTL related to oblique subduction of the Philippine Sea plate or part of the Okhotsk plate. Although it is difficult to distinguish between the motions using the observed crustal deformation, the similarities of the KA motion to those of CH, BI, OS, and SH favor the latter interpretation, because most previous studies showed that KA is a part of the Okhotsk plate and plate convergence to the south of KA (i.e., Sagami trough) is much less oblique.

Comparison between Geodetic and Geological Slip Rates along Major Fault Zones

The estimated relative motion along the block boundaries (Fig. 6) is almost consistent with the slip sense of the corresponding faults in a compilation of many geological studies (Headquarters for Earthquake Research Promotion, 2017). For example, right-lateral strike-slip motion with a small convergent component between the SE and SH blocks is consistent with the slip sense of the MTL. The motion between the SE and BI blocks has both convergent and right-lateral strike-slip components. Two parallel faults, i.e., a right-lateral strike-slip fault (the Mikata-Hanaore fault system) and a reverse fault (the Biwako-seigan fault system), correspond to this boundary, and the estimated relative motion is the sum of the slip senses on these faults. Boundaries with our slip rates similar to geological ones within twice the ratio are the CH-KA, SE-SH, and BI-CH boundaries, which correspond to the major fault systems, i.e., the Itoigawa-Shizuoka tectonic line, Nobi, and MTL fault systems; slip rates for these boundaries are estimated to be 1–5, 1–2, and 3–9 mm/yr in this study, respectively. They are approximately equal to ~1–9, ~2, and ~5–9 mm/yr from the geological studies. However, the slip rates estimated in this study are several times to an order of magnitude larger than the geological rates along several boundary faults. For example, the CK-SH, HO-CH, and CK-SE boundaries were estimated to have slip rates of 6–9, 13–14, and 5 mm/yr, respectively. The geological slip rates for the corresponding fault systems (i.e., the Beppu Hanyama–Futagawa–Hinagu, Atotsugawa, and Mizunawa fault systems) are <4, 2–3, and 0.2 mm/yr, respectively. Possible causes of this apparent discrepancy between geodetic and geological slip rates are insufficient assumptions...
in the block-fault model, and fluctuations and evolution of fault slip rates at different time scales.

We included internal permanent deformation in the crustal blocks, as there are numerous active faults in some of the blocks (Fig. 3A). Microseismicity (Fig. 3B) is located not only on the block boundaries, but also within many of the blocks. Using a 13 yr catalogue of microseismicity in Kyushu, Matsumoto et al. (2016) showed that accumulation of small earthquakes can cause detectable inelastic deformation; this is evidence of permanent internal deformation in the blocks. Incorporating internal permanent deformation in the block model decreases the relative block motion rates along some block boundaries; this reduces the discrepancy between the geodetic and geological slip rates. Johnson (2013) showed that the discrepancy can be solved by incorporating internal deformation into a block model for California; our study demonstrates that this is also the case in southwest Japan.

Geological studies have shown that fault slip rates can vary temporally on a scale of 1 k.y. (e.g., Knuepfer, 1992; Friedrich et al., 2003). The discrepancy between geodetic and geological slip rates on some faults in California is explained by changes in the activity at fault systems at difference time scales (e.g., Meade and Hager, 2005). The SH-SK, HI-SK, and JS-SE block boundaries in southern Kyushu and western Honshu do not correspond to the major active faults. However, these block boundaries are required in order to explain the observed velocities. We speculate that these boundaries are relatively young geologically, and evolved in the recent past. Therefore, geomorphological features caused by subsurface fault movements have not been well developed.

**Relationship between Interplate Coupling, Past Large Earthquakes, SSEs, and Shallow VLFEs**

The heterogeneous distribution of slip-deficit rates at depths of 5–25 km along the Nankai Trough is one of the most distinctive findings of this study (Fig. 7). Previous studies using only on-land GNSS data (e.g., Wallace et al., 2009; Liu et al., 2010; Yoshioka and Matsuoka, 2013) showed more uniform distributions in this depth range, which is suggested to be due to a thermally controlled transition from brittle to ductile behavior (Hyndman et al., 1995). A peak of slip-deficit rates off Shikoku and an overall decrease eastward (Fig. 7), while an increase in the degree of asesismic creep is thought to occur on the plate boundary offshore Kyushu. Yokota et al. (2016) used offshore GPS-A data to estimate slip-deficit rates, and found a heterogeneous distribution along the offshore Nankai Trough. Their results and ours are similar in pattern, but our rates are generally smaller than theirs. We suspect that ignoring the contribution of inland block motions biased the slip-deficit rates and caused the larger rates reported by Yokota et al. (2016). A deep-slip peak around (136.5°E, 35°N) estimated by Yoshioka and Matsuoka (2013) and Yokota et al. (2016) was not resolved in our study. This slip deficit may also be an artifact of ignoring inland block motions. We plotted the distribution of coupling ratios, which is the ratio between the slip-deficit rate and interblock velocity, and source areas of large earthquakes and SSEs in Figure 11. The coupling ratios at 10–25 km depth along the Nankai Trough are mostly >0.5, and the past and anticipated source areas of large earthquakes along the Nankai Trough are mostly locked and are accumulating strain that may be released by future large earthquakes (Fig. 11). We found three areas of low coupling ratio (<0.5) at ~132°E, ~136°E, and ~137°E for this depth range. These areas may correspond to the segment boundaries of megathrust earthquakes along the Nankai Trough. We speculate that insufficient strain accumulation due to low coupling may prevent a fault rupture from propagating over these areas. No historical Nankai earthquakes have ruptured west of 132°E (Ishibashi, 2004). The eastern edge of the source area for the 1944 Mw 8.1 Tonankai earthquake is located near 137°E (Sagiy as and Thatcher, 1999); ~136°E bounds the source areas of the 1944 Tonankai and 1946 Nankai earthquakes. The epicenters of these earthquakes were also located near 136°E (Fig. 11). On 1 April 2016, an Mw 6.0 interplate earthquake occurred there, and significant afterslip was observed by offshore borehole observatories (Wallace et al., 2016). This is also a region of episodic shallow SSEs recently observed by the same borehole observatories (Araki et al., 2017). These phenomena support low coupling near 136°E, and it may cause stress concentration to promote the initiation of seismic rupture in the surrounding region. In addition to these low coupled regions, we find a locally less coupled region near 135°E, 33°N (Figs. 7 and 11). This region corresponds to a subducted seamount and was proposed to act as a barrier to prevent a rupture during the 1946 Nankai earthquake (Kodaia et al., 2002). These observations support the inference of Wang and Bilek (2011, 2014), i.e., that the subducted rough surface on a megathrust interface promotes creeping on the interface, thus stopping earthquake rupture propagation.

Most long-term SSEs along the Nankai Trough occur downdip of the source region of megathrust earthquakes, and short-term SSEs occur further down-dip (Fig. 11) (e.g., Obara, 2010; Kobayashi, 2014). Source areas of the long-term SSEs, except those around Kyushu near 131.8°E, have high coupling ratios (>0.5), similar to those of the megathrust earthquakes. Because long-term SSEs have occurred only near 131.8°E in the period of the used GNSS data (Yarai and Ozawa, 2013), high coupling is common in the source areas of the Nankai long-term SSEs during inter-SSE periods. However, many short-term SSEs occurred in the period spanned by the GNSS data (e.g., Obara, 2010; Nishimura et al., 2013). The coupling ratio in their source areas is low (<0.5) east of 135°E and moderate to high (≥0.5) west of 135°E, although slip accommodated by short-term SSEs west of 135°E is larger than that east of 135°E. These suggest that there is no relationship between the interevent coupling ratio and the slip mode (i.e., fast or slow slip) during an event releasing accumulated strain. VLFEs occur both downdip and updip of the source areas of megathrust earthquakes along the Nankai Trough (Ito et al., 2009a, 2009b). Shallow VLFEs occur in a limited region close to the trough (Fig. 11). The coupling ratio is small in the VLFE region, except east of Kyushu. The estimated high slip-deficit rates east of Kyushu are not well resolved by the observations and may be ghosts due to
inland deformation related with large calderas and unmodeled block rotation in and around southern Kyushu (cf. Wallace et al., 2009). Offshore geodetic observations are necessary to clarify the coupling in this region. A low coupling ratio in the other VLFE regions is concordant with a recent finding that shallow SSEs, releasing tectonic strain, sometimes occur in the VLFE region at the offshore Nankai Trough (Araki et al., 2017).

Along the Sagami trough, the shallow plate interface from the trough axis to a depth of 15 km is almost fully coupled, not only in the source area of the 1923 Kanto earthquake (Wald and Somerville, 1995) but also in the source area of the repeating Mw ~6.6 Boso SSEs (Ozawa, 2014). Large uncertainties east of the 1923 source region (Fig. 7) indicate that our model cannot constrain the strain accumulation there. However, 20 yr of GNSS data in southeastern Kanto show a contraction in the direction of interblock motion in spite of the occurrence of 5 large SSEs. Offshore GPS-A stations on the eastern part of the Sagami trough are required in order to assess the earthquake potential in the Tokyo metropolitan area.

### CONCLUSIONS

We combined onshore GNSS and offshore GPS-A data to estimate a secular velocity in and around southwestern Japan, where the Philippine Sea plate is subducting beneath the Amurian plate along the Nankai Trough and Sagami trough. The strain rate distribution from a dense GNSS network, current seismicity, and many active faults support strain partitioning in both the overriding continental plates and the subducting oceanic plate. We modeled the contemporary deformation using a block model approach and estimated the rigid rotations of 12 crustal blocks, as well as the coupling distribution on faults bounding the blocks. Our results suggest that approximately one-third of the relative plate motion between the Amurian and Philippine Sea plates is accommodated in the southeastern margin of the Amurian plate, causing a rapid eastward decrease in the convergence rate along the Nankai Trough, from 78 to 4 mm/yr. Offshore geodetic data revealed a heterogeneous coupling distribution at seismogenic depth, between 10 and 25 km. Weak coupling was found at ~132°E, ~136°E, and ~137°E, corresponding to the segmentation boundaries of past megathrust earthquakes along the Nankai Trough. This suggests that dynamic rupture during an earthquake might not propagate over low coupled regions because of insufficient accumulated strain.

### ACKNOWLEDGMENTS

We thank Takeshi Sagiya and Yuichiro Takada for helping with Global Navigation Satellite System (GNSS) data collection. We are grateful to the Geospatial Information Authority of Japan, Nevada Geodetic Laboratory, Japan Meteorological Agency, and Global Earthquake Model for providing GNSS and earthquake catalogue data. We also appreciate constructive comments by Laura Wallace and Jack Loveless and an anonymous reviewer that improved the quality of the paper. This study was supported by the Japan Society of the Promotion of Science (JSPS) Grants-in-Aid for Scientific Research (KAKENHI; grant JP16H06007), the MEXT (Ministry of Education, Culture, Sports, Science and Technology of Japan) Earthquake and Volcano Hazards Observation and Research Program, and the MEXT “New Disaster Mitigation Research Project on Mega Thrust Earthquakes Around the Nankai/Ryukyu Subduction Zones.”
REFERENCES CITED

Altamimi, Z., Collilieux, X., and Métivier, L., 2011, ITRF2008: An improved solution of the interna-


Matsumoto, S., Nishimura et al. | Strain partitioning and interplate coupling along the northern margin of the Philippine Sea plate


Nishimura et al. | Strain partitioning and interplate coupling along the northern margin of the Philippine Sea plate


Nishimura et al. | Strain partitioning and interplate coupling along the northern margin of the Philippine Sea plate


Nishimura et al. | Strain partitioning and interplate coupling along the northern margin of the Philippine Sea plate


Nishimura et al. | Strain partitioning and interplate coupling along the northern margin of the Philippine Sea plate


