

Subduction of a wedge-shaped Philippine Sea plate beneath Kanto, central Japan, estimated from converted waves and small repeating earthquakes

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[1] We estimate the configuration of the Philippine Sea plate (PHS) subducted beneath Kanto to understand the seismotectonics in the Tokyo metropolitan area. In addition to small repeating earthquakes that delineate both the upper and lower boundaries of the PHS, previously unrecognized converted waves at its upper boundary from lower-boundary repeater sources provide a new constraint on the position of the boundary. The results from 794 S-to-P and 212 P-to-S converted waves together with ~ 200 repeater locations show that (1) the PHS has a wedge-like shape, decreasing in thickness from 50 km beneath Tokyo to zero at its northeastern limit, and (2) the PHS is relatively flat in the eastern part of Kanto and bends upward near its northeastern limit. From the fact that the PHS in the Izu-Bonin forearc also has a similar wedge-like shape, we infer that its shape was formed before its subduction. On the other hand, the relatively flat PHS at its northeastern limit and its upward bend are probably a consequence of ongoing deformation from an interaction with the underlying thick Pacific plate (PAC). The history of the PHS as a forearc before subduction and its contact with the PAC after subduction suggests that the temperature of this part of the PHS is colder than other regions, which probably causes anomalously deep seismicity on the PHS in Kanto. Colder PHS temperatures imply that the source regions of large earthquakes may extend deeper than expected, an important fact when assessing the locations of disastrous earthquakes for Tokyo.

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1. Introduction

[2] In the Kanto area, near a trench-trench-trench triple junction, the forearc part of the Philippine Sea plate (PHS), is subducting northwestward from the Sagami trough, and the Pacific plate (PAC) is subducting westward beneath the PHS from the Japan and Izu-Bonin trenches (Figure 1a). The Kanto area, including Tokyo, has a number of distinctive seismological features compared with southwest Japan and northeast Japan.

[3] The plate geometry and interplate seismicity along the Honshu arc in map view and cross section are summarized in Figure 1. Along the upper boundary of the Philippine Sea plate (red contours [*Hirose et al.*, 2007; *Nakajima et al.*, 2009a], hereafter referred to as the UBPHS), the inferred source areas for the Tokai (T) (see http://www.bousai.go.jp/jishin/chubou/20011218/siryou2-2.pdf), Tonankai (TN), and Nankai (N) earthquakes (see http://www.jishin.go.jp/main/chousa/01sep nankai/index.htm) are located at depths of 10–

25 km (green areas). The source area for the 1923 Kanto earthquake (K) [*Wald and Somerville*, 1995] estimated from geodetic and seismic body wave data also falls at depths of 10–25 km (Figure 1b). Deep low-frequency earthquakes (blue dots and circles) together with nonvolcanic deep tremors [*Obara*, 2002], which are also considered interplate events [*Shelly et al.*, 2006; *Ito et al.*, 2007; *Ide et al.*, 2007], are distributed at depths of 30–40 km, along the downdip extension of the inferred source areas for the T, TN, and N (M ~ 8 earthquakes) (Figures 1a and 1b).

[4] However, deep low-frequency earthquakes and tremors are absent along the PHS in Kanto. Instead, anomalously deep (~55 km) interplate seismicity (red beach balls in Figure 1a and red circles in Figure 1b) exists at the UBPHS beneath Kanto at the downdip extension of the 1923 Kanto earthquake (Figure 1a). Here, we plotted earthquakes occurring along the UBPHS by selecting those with nodal planes shallower than 30° and slip directions consistent with the relative plate motion at the UBPHS ($135^{\circ}-155^{\circ}$ clockwise from north). The low-angle thrust-fault-type earthquakes, including small repeating earthquakes at the UBPHS beneath Kanto (red symbols in Figure 1b), are located at depths considerably deeper than the downdip limit of M ~ 8 interplate earthquakes (25-30 km) and the deep low-frequency earthquakes (30-40 km) in southwest Japan (Figure 1).

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Figure 1



Figure 2. Schematic showing the configuration of three plates in Kanto. Not to scale. The Pacific plate (PAC) is subducting from the east beneath the North American (NA) plate. Between these two plates, the Philippine Sea plate (PHS) subducts from the southeast. Interplate earthquakes including small repeating earthquakes occur on the plate boundaries between the three plates. Gray, white (pink), and red stars indicate the earthquakes on the PAC-NA, PHS-PAC, and NA-PHS boundaries, respectively. The shaded area on the UBPAC shows the PHS-PAC contact zone. Black lines from white stars (contact zone earthquakes) to reverse triangles (stations) show the raypaths of converted waves at the UBPHS.

[5] Along the upper boundary of the Pacific plate (UBPAC), shown by black contours [*Nakajima and Hasegawa*, 2006], aftershock areas for $M \sim 7$ earthquakes (pink areas [*Hasegawa et al.*, 1985; *Uchida et al.*, 2009]) are distributed only to the north of the NE limit of the PHS (bold line) [*Uchida et al.*, 2009], along the Japan trench. Low-angle thrust-fault-type earthquakes whose nodal planes are shallower than 30° and slip directions are consistent with the relative plate motion at the UBPAC (80°–125° clockwise from north) (green beach balls in Figure 1a and diamonds in Figure 1b) indicate

that many interplate earthquakes occur along the UBPAC, and their depth limit in Kanto is deeper than those in NE Japan to the north of the NE limit of the PHS (Figure 1b). Thus, beneath Kanto, interplate events occur at depths deeper than the other areas both along the UBPHS and UBPAC in Japan. The cause of the deepening of the interplate events may be a key to understanding seismotectonics in Kanto.

[6] The plate configuration in Kanto is presented schematically in Figure 2. The shallowest plate of NE Japan including Kanto is treated as the North American plate

Figure 1. Plate geometry and interplate seismicity along Honshu, Japan. (a) Map view. (b) Cross-sectional view along line X-Y in Figure 1a. Red and black contours in Figure 1a denote the upper boundary of the PHS [*Hirose et al.*, 2007, 2008; Nakajima et al., 2009a] and PAC [Nakajima and Hasegawa, 2006], respectively. Green areas along the Nankai trough show the inferred source areas for the Tokai (see http://www.bousai.go.jp/jishin/chubou/20011218/siryou2-2.pdf) (T), Tonankai (see http://www.jishin.go.jp/main/chousa/01sep nankai/index.htm) (TN), and Nankai (see http://www.jishin.go.jp/main/ chousa/01sep nankai/index.htm) (N) earthquakes. The green area in Kanto shows the estimated slip area for the 1923 Kanto earthquake (K) [Wald and Somerville, 1995]. Pink areas along the Japan trench show the aftershock areas for $M \sim 7$ interplate earthquakes [Hasegawa et al., 1985; Uchida et al., 2009]. These depth distributions of slip areas are estimated based on the above mentioned plate models and horizontal location of the slip areas. The green focal mechanisms in Figure 1a and green diamonds in Figure 1b show low-angle thrust-fault-type earthquakes that are consistent with relative motions of PAC-NA or PAC-PHS. Red focal mechanisms in (a) and red circles in (b) show low-angle thrust-fault-type earthquakes that are consistent with the relative motion of the PHS and NA. The depth range is deeper than 25 km. See main text for the detailed selection method of these low-angle thrust-fault-type earthquakes. The data source for the focal mechanisms is F-net (see http://www. fnet.bosai.go.jp/freesia/index.html) for the period from 1997 to 2008. Blue dots in (a) and blue circles in (b) show deep lowfrequency earthquakes relocated by *Hirose et al.* [2007]. White triangles are active volcanoes. The solid line connecting the triple junction and the solid square labeled "L" shows the NE limit of the PHS [Uchida et al., 2009]. The solid squares labeled "IS," "I," and "K" along X-Y, respectively, show the locations of the Itoigawa-Shizuoka tectonic line (the boundary between NE Japan and SW Japan), Ise bay and Kii peninsula. Red and green stars in (b) are small repeating earthquakes along the upper boundary of the Philippine Sea plate and Pacific plate, respectively [Uchida et al., 2009].

(NA) in Figure 2. The plate is sometimes referred to as the Okhotsk plate (OKH) [e.g., Seno et al., 1996], but the difference between NA and OKH does not affect the result of this study. There are shallower (UBPHS) and deeper (UBPAC) plate boundaries in Kanto, and interplate events are found both along the UBPHS and UBPAC (at the PHS-PAC contact zone). The UBPHS, which lies 30-40 km beneath Tokyo, is considered as a particularly hazardous fault because it is the shallowest plate boundary within the Tokyo metropolitan area, the locus of approximately 40% of Japan's economic activities. Along the UBPHS, an area at the downdip extension of the 1923 Kanto earthquake (M7.9, Figure 1) was identified by the Japanese government as one of the potential source faults of $M \sim 7$ earthquakes in the near future. Those $M \sim 7$ earthquakes are smaller than the 1703 and 1923 Kanto earthquakes ($M \sim 8$), but they are estimated to be capable of killing more than 11,000 people (see http://www. bousai.go.jp/chubou/12/setumei-siryo4.pdf). This scenario is based on five historical $M \sim 7$ earthquakes that occurred after 1885 (see http://www.jishin.go.jp/main/chousa/04aug sagami/index.htm), but whether the earthquakes were located on the PHS is not known yet. Recently, Uchida et al. [2009] suggested from small repeating earthquake data that the seismic coupling at the deeper plate boundary (the PHS-PAC contact zone, Figure 2) is not large and Nakajima and Hasegawa [2009] suggested from velocity structure data that the internal structure of the PHS is related to the occurrence of large intraslab earthquakes. Thus, the assessment of the seismic potential at the UBPHS is of great importance.

[7] In this seismically unique and important area, several models of the PHS configuration have been proposed [e.g., Ishida, 1992; Sekiguchi, 2001; Sato et al., 2005; Hori, 2006; Kimura et al., 2006; Wu et al., 2007; Hirose et al., 2008; Toda et al., 2008; Nakajima et al., 2009a]. In addition to low-angle thrust-type earthquakes, small repeating earthquakes that occur only on faults with high deformation rates such as plate boundaries are proven to be particularly useful in delineating plate boundaries [e.g., Uchida et al., 2003; Kimura et al., 2006]. These interplate earthquakes provide direct evidence for the plate boundary position; but they are unevenly distributed on the PHS surface and it is hard to infer the plate configuration over a wide area using the earthquakes alone. Location and focal mechanisms of intraplate earthquakes and seismic velocity structure are useful in imaging the subducted slab, but neither has been proven entirely suitable for defining the plate boundary because of spatial resolution limitations and difficulty in interpreting the results.

[8] The variations in the configuration of the upper PHS boundary in the abovementioned studies are large and this diversity is partly due to complexity in the tectonic setting and earthquake distribution in this area. For example, *Toda et al.* [2008] proposed that some part above the PAC, which was usually considered to be the PHS, is a fragment of the PAC based on analysis of the seismic velocity structure. Converted waves identified in this study provide new independent data that help constrain the location of the upper boundary of the PHS without seismicity near the boundary [e.g., *Snoke et al.*, 1977; *Horiuchi et al.*, 1982; *Zhao et al.*, 1990; *Matsuzawa et al.*, 1986, 1990; *Nakajima et al.*, 2002]. To clarify the seismotectonics in Kanto, we estimate the shape of the PHS based on many *PS* and *SP* waves converted at its upper sur-

face and on small repeating earthquakes occurring on the upper and lower surfaces.

2. Small Repeating Earthquakes as Plate Boundary Events

[9] A repeating earthquake (RE) sequence is a series of earthquakes that are regularly occurring at the same patch on a fault. REs have been found, for example, at the San Andreas Fault [e.g., Ellsworth, 1995; Nadeau and McEvilly, 1997], the NE Japan subduction zone [e.g., Igarashi et al., 2003; Kimura et al., 2006; Uchida et al., 2009], and Taiwan [Chen et al., 2007]. These earthquakes are thought to be caused by repeated ruptures of small asperities on the plate boundary surrounded by a stably sliding area. In this study we use 1015 REs that were identified by Uchida et al. [2009] in and around Kanto. They are identified based on the similarity of seismograms observed for the period from 1992 to 2007 at seismic stations in the microearthquake observation networks of Tohoku University and the University of Tokyo. Here, an earthquake pair is considered to represent a repeating earthquake sequence if the average of coherences at 1, 2, 3, 4, 5, 6, 7, and 8 Hz for a 40 s window is larger than 0.95 at two or more stations [Uchida et al., 2009].

[10] There are three types of REs in Kanto in terms of their locations as shown schematically in Figure 2. Beneath the southwestern part of Kanto, the PHS exists between the NA (OKH) and the PAC, and the REs occur both on the UBPHS (red stars) and on the lower boundary of the PHS (LBPHS, white (pink) stars). Note that the REs on the LBPHS occur along the PHS-PAC contact zone, estimated from the seismic velocity structure [*Hasegawa et al.*, 2007], and the LBPHS corresponds to the upper boundary of the PAC (UBPAC) for the contact zone. In the northeastern part of Kanto, the REs occur along the boundary between the PAC and NA (the UBPAC, shaded stars). The southwestern and northeastern parts are divided by the NE limit of the PHS (Figure 2).

[11] The distribution of the three types of REs together with the NE limit of the PHS that was estimated from the slip vectors of the interplate earthquakes is shown in Figure 3. The REs located along the NA-PHS boundary (UBPHS, Figure 3a), the PHS-PAC boundary (LBPHS, Figure 3b) and the NA-PAC boundary (UBPAC, Figure 3c) are classified according to the source location as demonstrated in *Uchida et al.* [2009]. The slip vectors of the REs are consistent with the respective relative plate motions at the locations [*Sella et al.*, 2002] that are shown in the left bottom corners in Figure 3. The REs along the UBPHS (Figure 3a) are relatively sparse but there are many REs along the UBPAC including the PHS-PAC contact zone (Figures 3b and 3c).

3. Converted Waves at the Upper Boundary of the Philippine Sea Plate

[12] Seismic waves converted at the upper boundary of the subducted plate have often been detected in seismograms of local earthquakes, and their travel times are used to estimate the location of the boundary [e.g., *Matsuzawa et al.*, 1986, 1990; *Obara and Sato*, 1988; *Zhao et al.*, 1990; *Bock et al.*, 2000; *Ohmi and Hori*, 2000]. Such converted waves are proven to be useful in delineating the plate boundary, espe-



Figure 3. Distribution of small repeating earthquakes on (a) the NA-PHS boundary, (b) the PHS-PAC boundary, and (c) the NA-PAC boundary [*Uchida et al.*, 2009]. Arrows show slip vectors of the REs estimated from the F-net focal mechanism catalog (see http://www.fnet.bosai. go.jp/freesia/index.html). The big arrows at the bottom left corners indicate the relative plate motions at respective plate boundaries [*Sella et al.*, 2002]. The dashed line is the NE limit of the PHS estimated by *Uchida et al.* [2009].

cially in areas without interplate seismicity [e.g., *Matsuzawa* et al., 1990; *Iidaka et al.*, 1991].

[13] We have identified prominent converted waves emanating from the UBPHS in high-quality waveform data recorded by the dense nationwide seismic network (Hi-net) operated by National Research Institute for Earth Science and Disaster Prevention, Tsukuba, Japan (NIED) and by other seismic networks operated by the Japan Meteorological Agency (JMA), the University of Tokyo, and Tohoku University (Figure 4a). The detected waves are found to be S-to-P (SP) and P-to-S (PS) converted phases, which are ubiquitous characteristics of REs occurring within the PHS-PAC contact zone (Figures 2 and 3b). The raypaths of converted waves from the earthquakes in the contact zone to seismic stations are shown schematically in Figure 2. The upgoing P(S) waves from REs at the PHS-PAC contact zone (LBPHS) are partly converted to S(P) waves at the UBPHS (gray dots) and reach the seismic stations (reversed triangles). The REs along the LBPHS are more abundant and uniformly distributed than the REs along the UBPHS (Figure 3) and thus are useful in estimating the locations of the UBPHS in a wide area.

[14] Examples of waveforms for SP and PS converted phases are shown in Figure 5. The earthquake hypocenters and stations that correspond to the waveforms are labeled a-h and a'-h', respectively, in Figure 4a. We used threecomponent velocity waveforms to identify the phases. The sampling frequency is 100 Hz. The SP phase arrives at the stations as a compressional wave, and the PS phase arrives at the stations as a shear wave. In Figure 5, between P (hexagons) and S (squares) waves, the arrivals of SP converted waves (circles) appear in vertical components and the arrivals of PS converted waves (diamonds) appear in horizontal components. For the earthquake-station pair a-a' (Figures 4 and 5a), the particle motions both for SP and P waves show large amplitudes in the vertical component, small amplitudes in the radial component, and very small amplitudes in the transverse component (Figures 6a and 6b). This is consistent with almost identical raypaths for the two phases. The particle motions for PS and S waves show large amplitudes in the radial component and small amplitudes in the vertical and transverse components (Figures 6c and 6d). Although the PS phase for the earthquake-station pair a-a' is not used in the inversion because of its low S/N ratio, these features indicate that the phase is actually a P to S converted phase. The arrival times of SP waves are approximately 1 s after the P wave for earthquake-station pairs of Figures 5a and 5f and 1.5-3.5 s after the P wave for other pairs. In general, the SP phase arrives at stations 0.5–5 s after the P wave, and the PS phase arrives at stations 0.5–7 s before the S wave. Large amplitudes of the converted waves suggest that these waves are generated at a sharp seismic velocity boundary. These observations reveal that the phases are converted waves from the UBPHS, which lies between the hypocenters and the stations (Figure 2). Although converted waves might also be generated at the continental Moho or the Conrad discontinuity, the SP-P or S-PS times associated with these discontinuities would be larger than observed because these boundaries are far from the earthquakes' hypocenters. The use of REs on the LBPHS as sources for the converted phases also reduces the possibility of phase misidentification because there is no possibility of wave conversion or reflection at the LBPHS where the source earthquakes are located.

4. Estimation of Upper Boundary of the Philippine Sea Plate From Converted Waves

[15] We have measured *SP-P* (N = 794) and *S-PS* times (N = 212) for 102 REs in the PHS-PAC contact zone (Figure 4a), with an estimated phase-reading error of ~0.5 s. The *SP-P* and *S-PS* times for REs occurring at the contact zone (LBPHS) are useful to constrain the location of the



UBPHS and thickness of the PHS, because they are sensitive to the distance between the conversion points (UBPHS) and the hypocenters. This is because the type of wave (P or S) differs only along the paths within the PHS (see raypaths in Figure 2). The use of S-SP and PS-P times may be a straightforward way to estimate the UBPHS because they are insensitive to the earthquake locations. However, this strategy needs a precise velocity structure above conversion points because the type of wave differs along the paths above the UBPHS where the velocity structure is probably complicated. Instead, we used the SP-P and S-PS times that can constrain the thickness of the PHS well without modeling of a precise shallow velocity structure. This approach also enables us to compare the location of conversion points (UBPHS) with the earthquake hypocenters on the UBPHS because the hypocenters on the UBPHS and those used for the converted wave analysis were located using the same method and velocity structure. The phases are visually identified in threecomponent waveforms and the obtained data are divided into four grades according to their picking quality.

[16] To check the data for the converted waves, we first estimate the conversion points using each event-station pair (i.e., a separate analysis is performed for each of the 1006 SP-P or S-PS time data). Here, we assume that the UBPHS is locally flat for each analysis because we cannot estimate the inclination of conversion plane from a single datum. The depths of the conversion points are determined by a grid search that finds the smallest residual of the observed SP-P or S-PS time. The theoretical travel times are calculated using a velocity structure shown in Table 1 that is based on previous studies [Hasegawa et al., 1978; Hirose et al., 2008; Nakajima et al., 2009b]. This velocity structure is simple but sufficient for estimating the location of the UBPHS because the differential travel time (SP-P, S-PS) does not suffer from a shallow complicated velocity structure, where the waves travel in the same wave type (P or S). Because the conversion points are expected to be deeper than 20 km in the study area and shallower than the source earthquakes, the grid search is performed for UBPHS depths between 20 km and the depth of the respective earthquakes with intervals of 0.1 km.

[17] The *SP-P* and *S-PS* time data (Figure 4b) and estimated depth of the conversion points (depths to the UBPHS, Figure 4c) show the overall features of the original data. The *SP-P* time (circles) and *S-PS* time (diamonds) seem to monotonically decrease from southwest to northeast (Figure 4b). This feature is also seen in the *SP-P* time difference for the

Figure 4. (a) Earthquakes (stars) and stations (crosses) used for the converted wave analysis. Contour lines denote the upper boundary of the PAC estimated in this study. Stars labeled a–h and crosses labeled a'–h' are locations of earthquakes and stations shown in Figures 5a–5h, respectively. (b) Observed *SP-P* (circles) and *S-PS* (diamonds) times plotted at the conversion points in source-station data analyses. (c) Distribution of conversion points for PS (circles) and SP (diamonds) converted wave data. Stars and squares respectively denote the locations of REs and other low-angle thrust-fault-type earthquakes near the Tokyo bay. Black and gray dashed lines show NE and SW limit of the PHS-PAC contact zone, respectively [*Nakajima et al.*, 2009b; *Uchida et al.*, 2009].



Figure 5. Examples of seismograms that show *SP* and *PS* converted waves. Three-component velocity seismograms are shown here. Epicenters and stations for these seismograms are indicated in Figure 4a. Hexagons, circles, diamonds, and squares indicate the arrivals of *P*, *SP*, *PS*, and *S* waves, respectively. The *SP* converted waves are prominent in the vertical components and *PS* converted waves are prominent in NS or EW components. Shaded symbols indicate phases that are not prominent. The amplitude is scaled by the maximum amplitude in each trace. Horizontal bars shown in Figure 5a are the time windows for particle motion analysis (Figure 6).

waveforms shown in Figure 5 (longer *SP-P* times for e-e', g-g' pairs and shorter *SP-P* times for a-a', b-b' pairs). The short wavelength heterogeneity is relatively small (the values for nearby conversion points are similar) in the *SP-P* and *S-PS* times. The time difference distribution shows the spatial trend of the PHS's thickness (large *SP-P* and *S-PS* correspond to thick PHS and vice versa) because the time difference between *SP* and *P* (or *S* and *PS*) is roughly proportional

to the length of the raypath within the PHS where the waves travel in different types (P or S). The conversion points (circles and diamonds) are not uniformly distributed according to the inhomogeneous distribution of the RE sources along the LBPHS (Figure 4b), but they cover a wider area compared with the source distributions (Figure 4a). The depth distributions of conversion points (Figure 4c) are consistent with the source depths of REs on the UBPHS (stars in



Figure 6. Particle motion of (a) *P*, (b) *SP*, (c) *PS*, and (d) *S* phases for the waveforms shown in Figure 5a. U, R, and T are the mean vertical, radial, and transverse axis, respectively.

Figure 4c) and the low-angle thrust-fault-type earthquakes near the Tokyo bay (squares) that also indicate the position of the UBPHS independent from the converted wave data. The overall features of the conversion point depths along the UBPHS show that the depth deepens from southeast to northwest, but the conversion points with depths of 25–30 km (red and orange circles) seem to be a little elongated in the east-west direction.

[18] Next, we simultaneously estimate the depth distribution of the UBPHS by using all *SP-P* and *S-PS* time data and hypocenter data for REs and other interplate earthquakes on the UBPHS. We express the depth distribution of the UBPHS (H_p) as a polynomial of latitude (ϕ) and longitude (λ) according to *Horiuchi, et al.* [1982]:

$$H_p(\phi',\lambda') = C_0 + C_1\phi' + C_2\lambda' + C_3\phi'^2 + C_4\phi'\lambda' + C_5\lambda'^2 + \dots + C_{14}\lambda'^4,$$
(1)

where $\phi' = \phi - 35.6$ and $\lambda' = \lambda - 140.2$.

[19] The 15 unknown parameters (C_n) were determined by inversion of all the *SP-P* and *S-PS* time data. The depth to the UBPHS along the Sagami trough (Figure 1) is fixed according to the seafloor bathymetry because the PHS is subducting from the trough. Locations of events on the PHS (REs and low-angle thrust-fault-type events near Tokyo bay; squares and stars in Figure 4c) are also used to constrain the depths to the UBPHS, which are useful to estimate the depth precisely in a wide area. We incorporate these data into the inversion by treating them as SP-P time data of zero seconds (i.e., the distance between each hypocenter and the UBPHS is zero kilometers). The velocity structure is the same as that used for single earthquake-station pair analysis (Table 1). The SP-Pand S-PS data are weighted according to the grade of data quality. The hypocenter data for the earthquakes on the UBPHS are weighted 2, 4, and 8 times more than SP-Pand S-PS time data with the highest grade according to their catalog depth uncertainty.

[20] As a result, we obtained the depth distribution of the UBPHS as shown in Figure 7a. Estimated values of coefficients C_n are listed in Table 2. The depth distribution shown with contours in Figure 7a is similar to that estimated by each earthquake-station pair analysis (Figure 4c). The dip angle of the UBPHS is smaller in eastern Kanto than in western Kanto. The isodepth contours are WNW-ESE trending in the shallow (depth < 40 km) western part, but ENE-WSW trending near the northeastern limit of the PHS (dashed line). The dotted blue contour lines in Figure 7a show the UBPHS depths estimated from only the converted wave data (i.e., without the hypocenter data of the RE and low-angle thrust earthquakes on the UBPHS). The difference between the models with and without the location data of the earthquakes on the UBPHS is small, with the exception of the southwestern region where no conversion points exist. We also located the UBPHS using equal weighting (10 times more than the SP-P/S-PS data of the highest grade) for the hypocenter location data of the earthquakes on the UBPHS (dotted red contour lines), but the difference in the results was found to be very small.

[21] The colors of symbols in Figure 7a show residuals between observed and theoretical travel times. For the SP-P and S-PS times the residuals are plotted at the conversion points (circles and diamonds, respectively). For the interplate events the residuals from zero SP-P times are plotted at the epicenters (stars for REs and squares for low-angle thrust-fault-type events). The residuals show that the model fits well for most of the data including the interplate events on the UBPHS. In most cases, the residuals are less than one second and there are no regional patterns to the sign or magnitudes of the residuals.

5. Thickness of the Philippine Sea Plate

[22] The thickness of the PHS, as well as the shape of its surface, is important information for understanding the subduction morphology. In addition to the upper boundary, we estimate the geometry of the lower boundary of the PHS, which is also the upper boundary of the PAC (UBPAC) at the PHS-PAC contact area. Thin contours in Figure 4a show the depth of the UBPAC estimated from the depths of the REs on the PAC (stars in Figure 4a) as an update of the model of

 Table 1. P- and S-Wave Velocity Structure Used for the Data

 Analysis^a

Depth Range (km)	P Wave (km/s)	S Wave (km/s)	
0-27	6.30	3.64	
$27-H_p$	7.70	4.45	
$H_p - r$	8.00	4.62	

 $^{a}H_{P}$ is the depth to the UBPHS.



Figure 7. (a) Depth to the upper boundary of the PHS (contours). Blue dashed contours represent a result without the data from earthquakes on the UBPHS. Red dashed contours represent a result with equal weight (10 times more than the *SP-P/S-PS* data of the highest grade) for the data from earthquakes on the UBPHS. The conversion points for *SP* converted wave (circle), *PS* converted waves (diamonds), locations of REs at the UBPHS (stars), and low-angle thrust-fault-type earthquakes (squares [*Hirose et al.*, 2008]) are shown with color indicating residuals of travel times. (b) Comparison of the upper boundaries of the PHS estimated by several studies. Black contours are the same in Figure 7a. Green, orange, red, and blue colors show the results from *Ishida* [1992], *Hori* [2006], *Kimura et al.* [2006], and *Hirose et al.* [2008], respectively. Dashed line is the NE limit of the PHS.

 Table 2.
 Inverted Values of Unknown Parameters for the Depth to the UBPHS

Coefficient	Value	
C_0	31.10578	
C_1	1.09307	
C_2	22.72103	
C_3	-8.16767	
C_4	-33.00002	
C_5	-6.61560	
C_6	-1.78942	
C_7	4.56631	
C_8	-5.83169	
C_9	9.71801	
C_{10}	0.04703	
C_{11}	5.26643	
C_{12}	18.96968	
C_{13}	16.94813	
C_{14}	11.57799	

Nakajima and Hasegawa [2006]. Because these REs on the PAC are the sources for the converted wave analysis, the estimation from these REs is suitable when discussing the PHS thickness (the depth difference between the UBPHS and LBPHS). The depth to the UBPAC increases from east to west and there is a ridge that runs in the WNW-ESE direction (Figure 4a).

[23] The thickness of the PHS is shown by color in Figure 8 and seems to be homogeneous in the NW-SE direction, which is the subduction direction of the PHS beneath Kanto. The thickness in the SW-NE direction decreases monotonically from the western boundary of the PHS-PAC contact area (shaded dashed line [*Nakajima et al.*, 2009a]) to the NE limit of the PHS (black dashed line). The location where the thickness approaches zero coincides with the NE limit of the PHS that is estimated independently from slip vectors of interplate earthquakes [*Uchida et al.*, 2009]. The PHS is approximately 60 km thick at the thickest part near Tokyo.



Figure 8. Thickness distribution of the PHS. Black and shaded dashed lines denote the NE and SW limits of the PHS-PAC contact zone, respectively [*Nakajima et al.*, 2009b; *Uchida et al.*, 2009]. For the SW limits beneath Boso peninsula and further south, which is not well constrained in *Nakajima et al.* [2009b], we adjusted it to the position of ~60 km thickness according to the thickness in the land area. The source area of the 1923 Kanto earthquake estimated by *Wald and Somerville* [1995] is delineated by a pink line. Red stars are small repeating earthquakes on the PHS. Bold and thin contours are the same as those in Figures 7 and 4a, respectively.



Figure 9. (a) Schematic figure showing the shape of the PHS subducting beneath Kanto. (b) East-west cross sections along A–B and C–D in Figure 9a. The PHS near the NE limit of the PHS is deformed because of the interaction with the PAC and the slab dip near the NE limit of the PHS is relatively gentle.

The upward bend of the tip of the PHS occurs around a PHS thickness of 20 km (Figure 8).

[24] The thickness of the PHS to the south of the Sagami trough (south of ~34.5°N) is also estimated from the depth to the UBPAC (thin contours in Figure 8 [*Nakajima and Hasegawa* [2006]) and the seafloor bathymetry because no plate overlies the PHS there. The thickness pattern for the forearc region in the Izu-Bonin arc (to the south of ~34.5°N) and that of the area beneath Kanto (to the north of ~34.5°N) show very similar wedge-like shapes.

6. Discussion

[25] The trench-trench (TTT) type triple junction off Kanto, Japan, is the only known example of the TTT(a) type triple junction [*McKenzie and Morgan*, 1969]. Threedimensional kinematic discussions of the TTT(a) type configuration imply an interaction at depth between the three plates [e.g., *Le Pichon and Huchon*, 1987; *Huchon and Labaume*, 1989]. We observed a relatively flat subduction of the PHS in the eastern part of Kanto, in which the isodepth contours of the UBPHS (Figure 7) change from an orientation subparallel to the Sagami trough to one subparallel to the Japan trench near the NE limit of the PHS. This demonstrates that the PHS bends upward near its eastern edge (Figures 7a and 8). This feature is robust for the different weightings on the hypocenter data on the UBPHS (Figure 7a).

[26] We believe that the deformation of the PHS is due to a space problem between NA (OKH) and PAC where the PHS is intercalating [e.g., Huchon and Labaume, 1989]. The plate configuration derived in this study near the triple junction is shown schematically in Figure 9. At the area near the NE limit of the PHS and the triple junction, the PHS cannot subduct any deeper because of the existence of the PAC beneath the PHS, and it bends upward compared with the dip angle of the shallower part of the PHS (Figures 9a and 9b). Considering the fact that the PAC that contacts the underside of the PHS is thicker (~100 km in thickness [e.g., Zhao et al., 1994]) than the PHS near the edge (<20 km, see Figure 8), the larger deformation in the PHS near the edge is reasonable when the two plates interact with each other. The depth limit of the PHS subduction is smaller in the area close to the triple junction and becomes larger in the area far from the triple junction due to the curvature of the PAC (Figure 9a). This results in a small inclination of the UBPHS at the eastern part of Kanto and a large inclination at the western part (Figure 9a). We believe that the observation of relatively large deformation (bending), a flat subduction near the NE limit of the PHS close to the triple junction and a small deformation and steep subduction in the inland area, can be basically explained by this model.

On the other hand, the ridge of the PAC that runs in the WNW-ESE direction (Figure 4a) may also be a manifestation of the interaction between the PHS and PAC, although it should be carefully tested in view of the plate dynamics.

[27] Comparison of our UBPHS model with the ones proposed by previous studies as shown in Figure 7b indicates that our result is close to the result of *Hirose et al.* [2008]. The result of Kimura et al. [2006] is also similar to ours, although their estimation is limited only in the northeast part of the study area. The model proposed by Ishida [1992] shows a different dip direction in the northeastern area and *Hori*'s [2006] model shows a shallower depth in the southeastern part. Slight differences in UBPHS geometry between ours and those of Hirose et al. [2008] and Kimura et al. [2006] are seen in the easternmost area, especially near Choshi (Figure 7b). In this area we had both the repeating earthquakes and converted waves data to constrain. Compared with Toda et al. [2008], who proposed the existence of a fragment of the PAC above the PAC north of approximately 35.7°N, we did not observe any abrupt changes in the thickness of the PHS or depth of the UBPHS across ~35.7°N. Of course, the shapes of the UBPHS are not well constrained offshore and near the triple junction because of the lack of the data, but the coincidence of the NE limit of the PHS estimated from focal mechanisms [Uchida et al., 2009] with the edge of the wedge shape of the PHS that is calculated from this plate model and other characteristics discussed below support the validity of our model.

[28] The use of the same earthquakes both for the analysis of the UBPHS and for the estimation the upper boundary of the PAC enabled us to obtain a precise distribution of the thickness of the PHS in this study. Despite the complicated shape of the PHS's upper surface (UBPHS), the result shows a simple thickness pattern that decreases from 50 km beneath Tokyo to zero at its northeastern limit. There are many studies on the shape of the upper boundary of the PAC [e.g., Ishida, 1992; Obara and Sato, 1988; Ohmi and Hori, 2000] in addition to that of the UBPHS in Kanto; but the thickness distribution of the PHS has not been paid much attention, with the exception of Nakajima et al. [2009a], who estimated the thickness from seismic velocity structure based on the results of our study. We found that the thickness of the PHS is important for understanding the subduction process of the PHS. The PHS is deformed probably because of interaction with the PAC as discussed above, but it retains a simple wedge-like thickness pattern, which is almost the same as that of the PHS before subduction. We infer from this fact that the shape was formed when the PHS was located at the forearc region of the Izu-Bonin subduction zone, as a result of long-term subduction of the PAC beneath the PHS. As for the wedge-like shape beneath Kanto, we obtained a smooth pattern compared with the results of the study by Nakajima et al. [2009a]. A smoothly decreasing thickness toward the NE limit of the PHS is reasonable if the PHS material beneath Kanto was formed along the Izu-Bonin arc.

[29] The anomalously deep interplate seismicity in Kanto also seems to be closely related to the forearc wedge subduction. The downdip limit of the interplate earthquake distribution on the PHS in Kanto (55 km) is deeper than that in SW Japan (25–30 km) but similar to that of the PAC in NE Japan (55 km), as shown in Figure 1. The Philippine Sea plate subducting beneath Kanto (~50 Ma) is older than that in SW Japan (15–27 Ma) [*Seno and Maruyama*, 1984]. This difference in age for the subducting plate explains in part the deeper interplate earthquake on the PHS in Kanto compared with that in SW Japan because the older plate tends to have colder temperatures than the younger one, and temperature is an important controlling factor of the downdip limit of the interplate earthquake [e.g., *Hyndman and Wang*, 1993]. However, the age of the plate alone cannot explain the downdip limits of the interplate earthquake [e.g., *Hyndman and Wang*, 1993]. However, the age of the plate alone cannot explain the downdip limits of the interplate earthquake on the upper boundary of the PHS in Kanto similar to that on the upper boundary of the PAC in NE Japan (Figure 1) because the PAC north of Kanto is older (~130 Ma [*Nakanishi et al.*, 1989]) than the PHS in Kanto (~50 Ma).

[30] As shown by many thermal models [e.g., *Furukawa*, 1993; Hyndman and Wang, 1993], it is likely that the forearc region of the PHS subducting beneath Kanto is colder than the typical PHS because of the continuous subduction of the cold PAC below it. The motions of the PHS and PAC with respect to the NA plate are almost the same in terms of their north-south components (arrows in Figure 1a), and the PHS and PAC contacted each other over a wide area [Hasegawa et al., 2007; Nakajima et al., 2009a]. Therefore, the existence of the PAC prevents the PHS from being heated by the mantle even after it subducts from the Sagami trough. The heat flow in Kanto is very low compared with those in southwest Japan and Tohoku [Furukawa, 1993; Tanaka et al., 2004] supporting the possibility that colder material exists beneath Kanto. These facts suggest that the deep interplate seismicity in Kanto is due to the cold condition of the PHS.

[31] The absence of deep nonvolcanic low-frequency earthquakes and tremors can also be related to temperature conditions. In SW Japan, where the warm PHS is subducting, deep nonvolcanic earthquakes and tremors occur at depths \sim 30 km, near the location where the subducting plate begins to contact with the mantle part of the upper (continental) plate [Shelly et al., 2006; Ito et al., 2007]. On the other hand, in NE Japan, where the cold PAC is subducting, there are interplate earthquakes even in the region where the PAC surface contacts the mantle part of the upper plate, and no deep nonvolcanic low-frequency earthquakes are found there. The seismicity in Kanto seems similar to that in NE Japan. In NE Japan, $M \sim 7$ interplate earthquakes such as the Miyagi-oki earthquake [Umino et al., 2006] occur in the slab-mantle contact area. For Kanto, a number of observations imply the existence of a serpentinized mantle wedge at depths of 20-45 km northeast of Tokyo Bay that controls the downdip limit of seismic slip [Kamiya and Kobayash, 2000; Matsubara et al., 2005]. These observations suggest that serpentine minerals that usually exhibit velocity-strengthening frictional behavior prevent seismic slip at the UBPHS where it contacts the mantle part of the upper plate. However, a combined analysis of GPS data and leveling data reveals that the plate boundary is coupled to some extent in the 30-40 km depth range on the PHS [Sagiya, 2004; Nishimura et al., 2007] and Nakajima et al. [2009a] showed the large volume of serpentinized mantle wedge does not cover all over Kanto, but is limited to the region west of ~139.5°E. The largest interplate earthquake on the UBPHS at the downdip extension of the Kanto earthquake is M5.3, for the period from 1997 to 2007, judging from the F-net focal mechanism catalog, but we think

that careful study of the earthquake potential for M7 earthquakes along the UBPHS is important for earthquake disaster mitigation in the Tokyo metropolitan area.

7. Conclusions

[32] We estimated the depth of the upper boundary of the PHS and its thickness from converted waves and interplate earthquake data that included small repeating earthquakes. The shape of the upper boundary of the PHS shows a relatively steep subduction in western Kanto and a relatively flat subduction in eastern Kanto. Contact with the PAC below is estimated to be the cause of this deformation of the PHS. Its thickness, however, shows a simple spatial distribution that decreases monotonically from ~60 km at the SW limit of the PHS-PAC contact zone to ~0 km at the NE limit of the zone. From the observation that the Izu-Bonin forearc also has a similar wedge-like shape, we infer that the shape was formed before it was subducted. Its long history as a forearc material along the Izu-Bonin trench contacting with the cold PAC and its subduction with the PAC suggest a low temperature for the subducting PHS. The interplate seismicity at depths of up to 55 km on the PHS is probably a manifestation of cold ambient temperatures. This argument implies that the UBPHS has seismic potential deeper beneath Kanto than previously thought.

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