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The Upper Boundary of the Philippine Sea Plate beneath the Western Kanto Region Estimated from S–P and P–S Converted Waves

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Abstract

Although the subduction of the Philippine Sea plate has generally been investigated by using microearthquake seismicity and determining the three-dimensional seismic wave velocity structure, the configuration of the slab in the western Kanto region is not well known because of low seismic activity.

To detect the plate boundary, we placed five seismic stations in the western Kanto region. Clear later phases (X_1 and X_2-phases) were observed between the P and S arrivals. The seismograms of earthquakes occurring in eastern Yamanashi prefecture show a clear later phase (X_1) on the vertical component. The X_1-phase, identified as the S to P converted wave at the upper boundary of the descending Philippine Sea plate, constitutes seismological evidence for the existence of the Philippine Sea slab to 20 km depth beneath the western Kanto region. The S–P converted points are located in a restricted region along the depth direction, however, necessitating analyses of other phases for slab geometry delineation.

The seismograms from earthquakes occurring beneath the east coast of the Izu Peninsula showed a clear later phase (X_2-phase) dominant on the horizontal components. The observed values of the X_2–P time and locations of known velocity discontinuities are consistent with the later phase being a P to S converted wave at the upper boundary of the subducting Philippine Sea plate. The upper boundary estimated from travel time data of the converted wave is located at depths of 28–35 km.

Seismological evidence for the existence of the subducting Philippine Sea plate beneath the western Kanto region is shown in this study. The subducting Philippine Sea plate was found to exist at depths shallower than 20 km and deeper than 25 km from the S–P and P–S converted wave data in the aseismic western Kanto region,

respectively. The location of the boundary is estimated to be at depths from 10 km to 35 km.

1. Introduction

The geological structure beneath the Kanto and Tokai regions is considered to be complex due to the existence of two subducting slabs. In this area, the Philippine Sea and Pacific plates descend northwestward and westward, respectively, beneath the Eurasian plate.

Configurations of subduction of the Pacific and Philippine Sea plates have been investigated using the distributions of microearthquakes, and by inverting for three-dimensional velocity structure (NAKAMURA and SHIMAZAKI, 1981; HORIE and AKI, 1982; SHIMAZAKI *et al.*, 1982; ISHIDA, 1984; KASAHARA, 1985; NOGUCHI, 1985; YAMAZAKI and OOIDA, 1985: ISHIDA, 1986; HASEMI and ISHIDA, 1987; ISHIDA and HASEMI, 1988; ISHIDA, 1991). In the western Kanto region, however, the configuration of the subducting Philippine Sea plate has not yet been unambiguously delineated, because shallow earthquakes are virtually absent in this region. This has resulted a number of papers discussing the existence of the Philippine Sea plate in this area (e.g. NAKAMURA and SHIMAZAKI, 1981; SHIMAZAKI *et al.*, 1982).

Recently, reflected and converted phases from the upper boundary of the subducting plates have been studied (MIZOUE *et al.*, 1981; KANJO, 1987; OBARA and SATO, 1988; IIDAKA *et al.*, 1989; OBARA, 1989; IIDAKA *et al.*, 1990). The existence of the Philippine Sea slab was shown from seismological observation of converted waves at the upper plate boundary in the aseismic western Kanto region (IIDAKA *et al.*, 1990). Seismograms

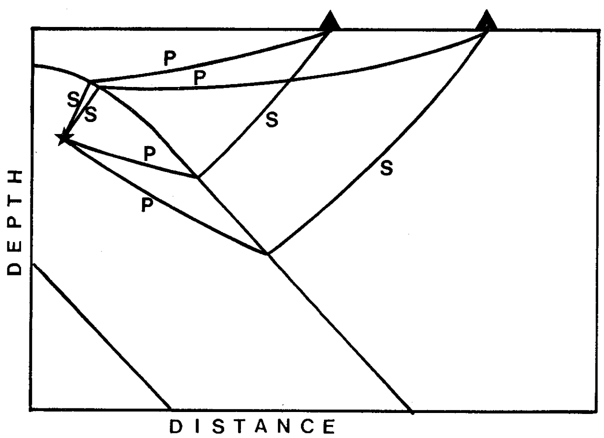


Fig. 1. Differences in the ray paths of S to P and P to S converted waves are shown schematically.

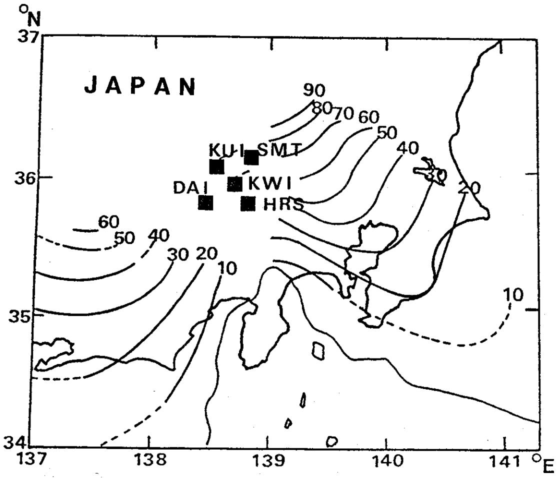


Fig. 2. Map of five seismic stations (squares) located in the western Kanto region. Iso-depth lines of the upper boundary of the Philippine Sea plate inferred from the seismicity after ISHIDA (1991) are shown in km.

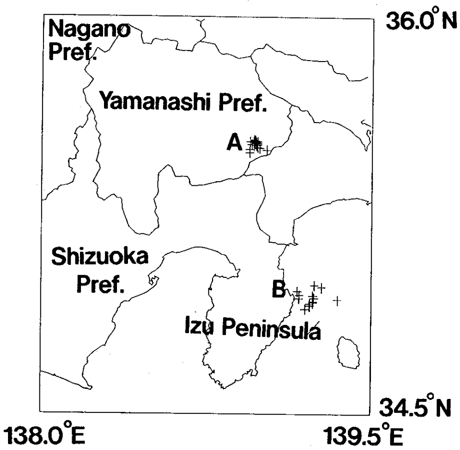


Fig. 3. Epicenter map of the earthquakes used in this study. The location of earthquakes which occurred in eastern Yamanashi prefecture (A) and the east coast of Izu Peninsula (B) are shown by crosses.

from temporary seismological stations show clear later arrival on the vertical component at several stations. This later phase was identified as the S-to-P converted wave at the upper boundary of the subducting Philippine Sea plate.

In this paper, we compare the ray paths of the S-P converted and P-S converted waves at the upper boundary of the subducting slab (Fig. 1). While the conversion points of the S-P converted waves are located in a narrow depth range, conversion points of the P-S converted waves occur over a broad depth range. As a result, observations of P-S converted waves over wide epicentral distances can yield conversion points traceable down to deep levels. Converted phases have been shown to be practical and highly-promising indicators for detection of the plate boundary (MIZOUE *et al.*, 1981). The P-S converted phase is suitable for estimation of the geometry of the subducting

Philippine Sea slab.

Seismograms from earthquakes occurring beneath the east coast of the Izu Peninsula from 1988 to 1989 showed a clear later phase on the horizontal components between the P and S arrivals at seismic stations located in the western Kanto region (Figs. 2, 3). Using information from this later phase, we estimated the location of the upper boundary of the subducting Philippine Sea plate.

2. Analysis

2.1. S-P converted phase

Microearthquake seismograms from earthquakes occurring in eastern Yamanashi prefecture (Fig. 3) have unusual wave form characteristics at four stations (DAI, HRS, KUI, and KWI) (Fig. 2). A sharp impul-

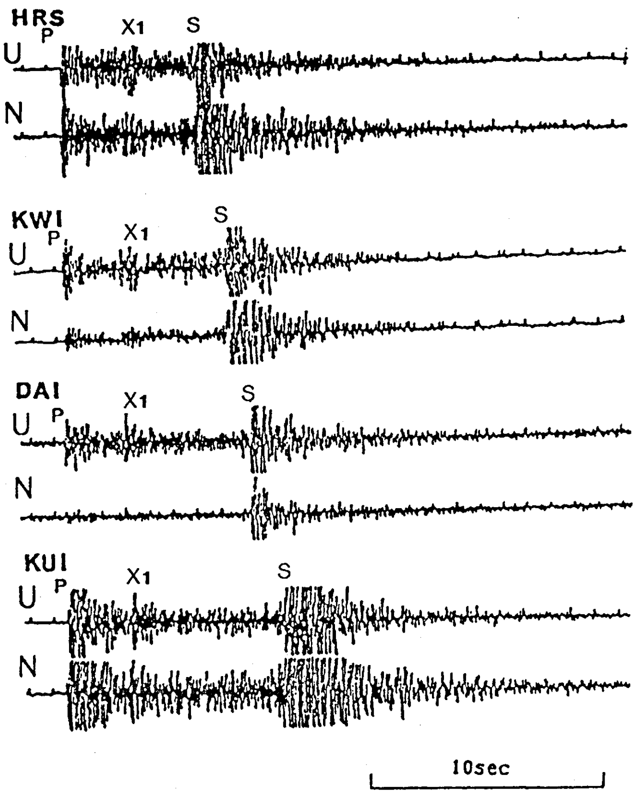


Fig. 4. Examples of the later phase X_1. This phase is prominent on the vertical component. The X_1-phase was investigated in detail by IIDAKA *et al.* (1990). U is the vertical component and N is the horizontal component in the north-south direction.

sive phase (X_1-phase) is observed preceding the direct S wave on vertical component seismograms (Fig. 4). Features of this X_1-phase are:

(1) Amplitudes are largest on the vertical component.

(2) The X_1-phase is observed when the ray path crosses the plate boundary between the Philippine Sea and Eurasian plates.

(3) The maximum amplitude of the X_1-phase is equal to, or larger than, that of the direct P wave.

(4) The X_1-P times are not sensitive to epicentral distance (Fig. 5).

Five interpretations for the later phase, investigated in detail by IIDAKA *et al.* (1990), have been proposed: (a) S-converted P at the upper boundary of the subducting Philippine Sea plate; (b) P-reflected

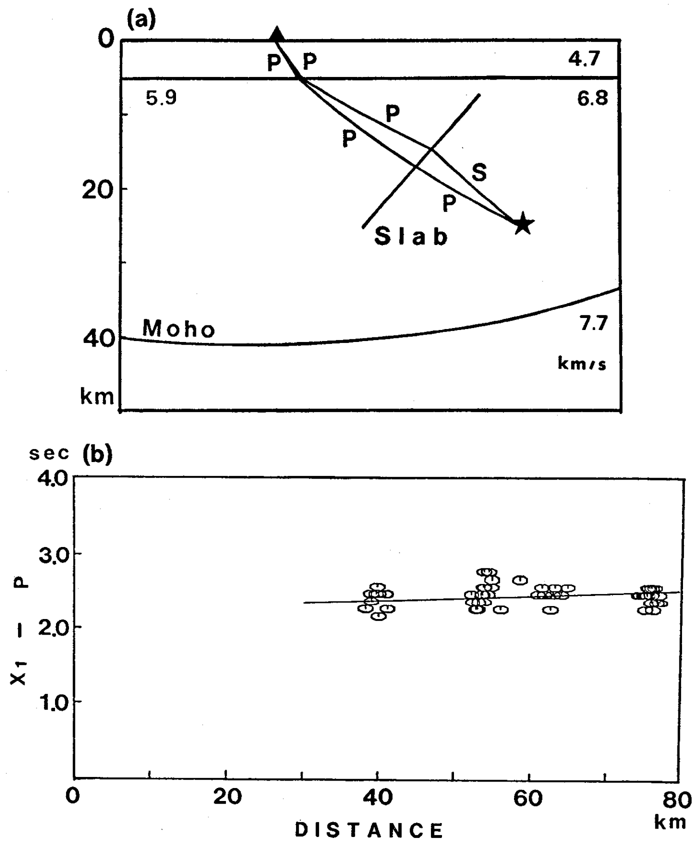


Fig. 5. (a), Schematic representation for the ray paths of direct P- and S-converted P waves. The star and triangle denote the hypocenter and station, respectively; (b), Calculated times (solid line) for an S-converted P wave at the upper boundary of the subducting Philippine Sea plate versus epicentral distance when the depth of the hypocenter is 25 km. Observed X_1-P times are shown by open circles.

P at the Moho boundary; (c) S-converted P at the Conrad boundary; (d) S-converted P at the bottom of the sedimentary layer; and (e) multiple reflections within the shallowmost layers just beneath the station. Probable paths in the study were based on the observed value of the X_1-P time and the locations of known velocity boundaries.

Comparison of calculated X_1-P time from a two-dimensional ray-tracing scheme (ČERVENÝ and PŠENČÍK, 1983) with the observations revealed that cases (b), (c), and (d) were not consistent with the observed data. Velocity structure models with different depths for the Conrad and Moho boundaries were also examined, but produced apparent velocities which were different from the observations. In addition, case (e), which predicts that the X_1-phase can be observed along ray paths that do not cross the plate boundary, cannot be considered correct, because the X_1-phase is only observed where the ray path crosses a plate boundary.

Based on the results of the analyses, the X_1-phase was concluded to correspond to the S to P converted wave at the upper boundary of the subducting Philippine Sea slab, demonstrating the existence of a slab in the western Kanto region. The configuration of the plate boundary that was obtained is shown in Fig. 12 (IIDAKA *et al.*, 1990). The iso-depth lines indicated a high dip angle of about 50°, and the boundary was suggested to be located at a depth shallower than 20 km. Because the S-P conversion points are located within a restricted region along the depth direction (Fig. 1), however, the dip angle that was obtained using the S-P converted wave cannot be considered reliable. Consequently, the analysis of S-P converted phases is not a useful method for tracing the slab boundary deep levels in this region. Instead, we consider the P-S converted phase, which is more suitable for determination of the plate boundary.

2.2. X_2-phase on seismograms of earthquakes beneath eastern Izu Peninsula

A clear phase (X_2-phase) preceding the direct S wave on horizontal component seismograms is observed from earthquakes occurring beneath the east coast of Izu Peninsula (Fig. 6). The X_2-phase has the following characteristics:

(1) Amplitudes of the X_2-phase are most dominant on the horizontal components.

(2) The phase is only observed when its ray path crosses the plate boundary between the Philippine Sea and the Eurasian plates.

(3) The apparent velocity of the X_2-phase is higher than that of the S wave and lower than that of the P wave.

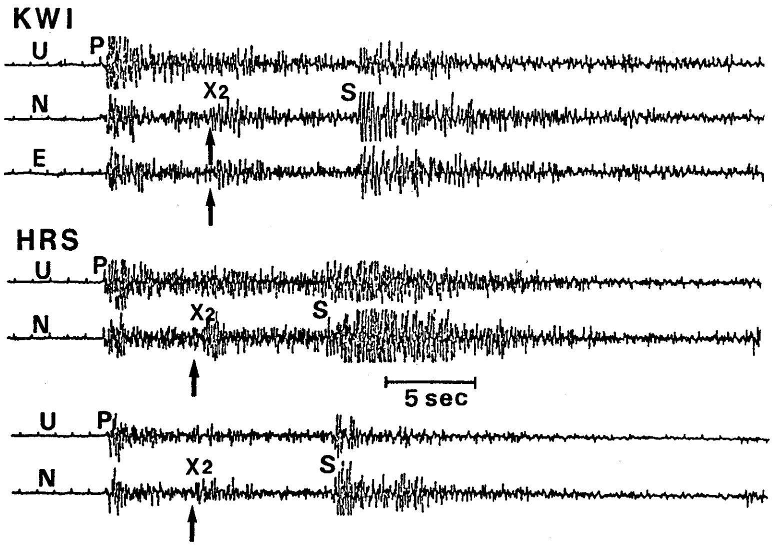


Fig. 6. Examples of the later phase X_2. This phase is prominent on the horizontal components. N and E are horizontal components in the north-south and east-west directions, respectively, and U is the vertical component.

Feature (1) implies that the X_2-phase corresponds to an S wave. Possible interpretations for the X_2-phase are (Fig. 7);

(a) P-converted S wave at the Conrad boundary.

(b) P-converted S wave at the Moho boundary.

(c) P-converted S wave at the bottom of the sedimentary layer.

(d) Multiple reflections at the boundaries of shallow layers just beneath the station.

(e) P-converted S wave at the upper boundary of the subducting Philippine Sea plate.

Possible interpretations are examined using a two dimensional ray-tracing scheme (ČERVENÝ and PŠENČÍK, 1983), which can adequately model the expected heterogeneity. In this area, the velocity heterogeneity is thought to occur in the northwest direction, because the dip direction of the subducting Philippine Sea slab is considered to be northwest (IIDAKA *et al.*, 1990) and the depths of the Conrad and Moho boundaries increase to the northwest from the Izu Peninsula (ASHIYA *et al.*, 1987). Furthermore, based on the hypocenter-station geometry, ray paths are also expected to be in the northwest direction. The velocity structure in this area can thus be modeled by the two-dimensional scheme. In the theoretical calculation, $V_p/V_s=1.73$ is assumed. Three theoretical hypocenters at depths of 10, 15 and 20 km are used for the calculation.

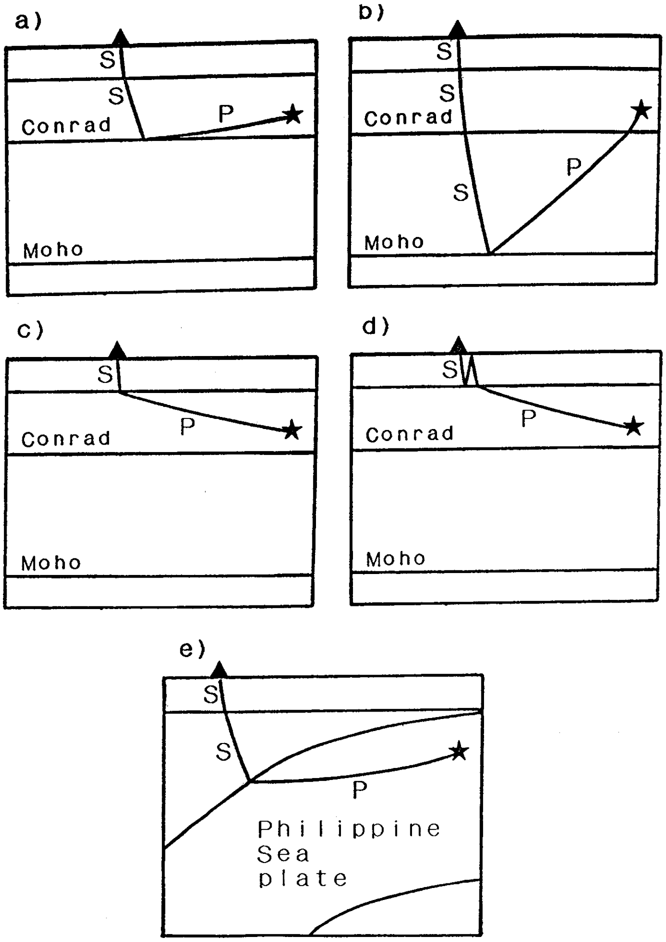
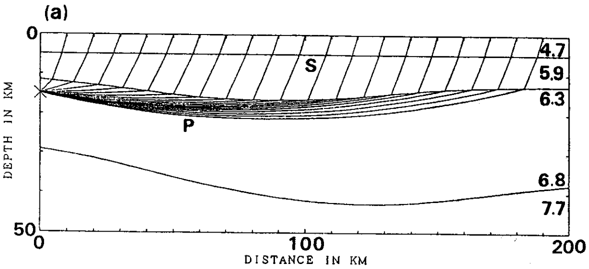


Fig. 7. Various interpretations for the X_2 -phase. Triangles and stars denote stations and hypocenters, respectively.

First, we examine cases (a) and (b). In the theoretical calculation, the configurations of the Conrad and Moho boundaries are modeled after ASHIYA *et al.* (1987). The theoretical X–P times for cases (a) and (b) do not fit the observed data (Fig. 8, and 9). In case (a), the X–P times of the three theoretical curves are smaller than the observations. Variation in the depth of the Conrad boundary by 5 km results in a base line shift as depth is changed. However, because the apparent velocity of the converted phase at the Conrad boundary is different from the observations, case (a) can be rejected even though the depth of the Conrad boundary is not well known. In case (b), the X–P times at three hypocentral depths are much larger than the observations. Shoaling of the depth of the Moho boundary by up to 10 km still can-



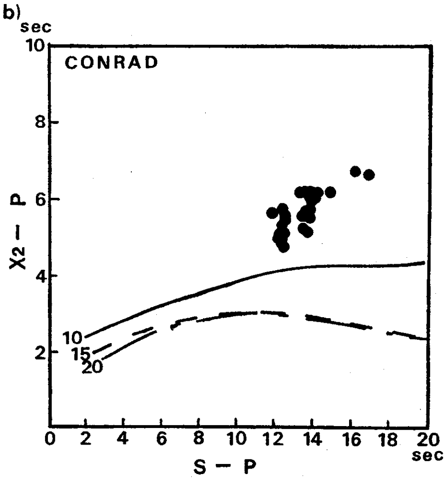


Fig. 8. (a), Ray paths of P to S converted waves at the Conrad boundary. P-wave velocity in each layer is given in km/s; (b), The X-P time graph. The observed X_2-P data are denoted by solid circles. Theoretical X-P time data for a P-S converted wave at the Conrad boundary are shown by lines. Three theoretical lines of the focal depths of 10, 15, and 20 km are shown by solid, broken, and dash-dotted lines, respectively.

not match the theoretical to the observed data. If the depth of the Moho boundary shoals by 13 km, the theoretical curve matches the observed data which have S-P times less than 15 seconds, but do not match the observed data which have S-P times greater than 15 seconds. We conclude that it is difficult to explain the observations as converted waves at the Conrad or Moho boundaries.

Examination of the theoretical times of case (c) shows that the predicted X_2-P time data are almost constant as the S-P time increases, and that the value is less than 2 sec. The mismatch between the observed and calculated times implies that case (c) can also be discarded (Fig. 10).

Case (d), which predicts that the X_2-phase should also be observed for ray paths that do not cross the plate boundary, can also be rejected since we have not observed the X_2-phase for such a scenario.

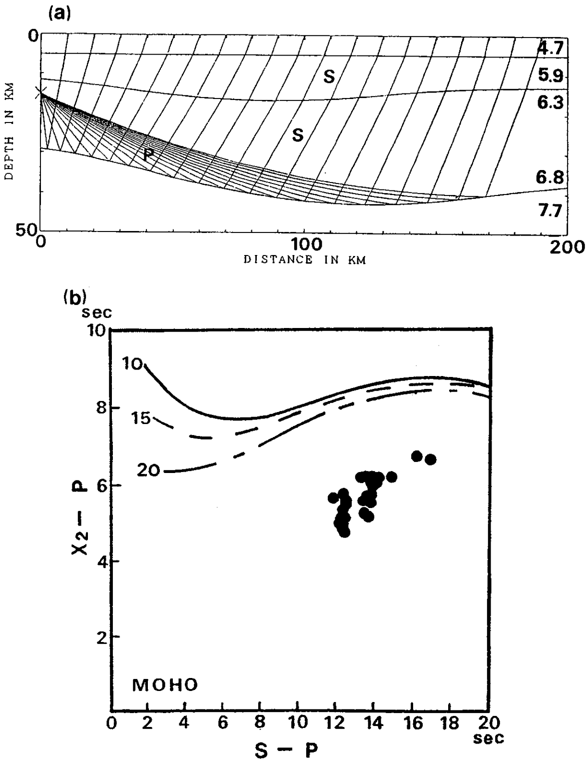


Fig. 9. (a), Ray paths of P to S converted waves at the Moho boundary are shown. Numbers indicate P-wave velocity in each layer; (b), The X-P time graph. The observed X_2-P data are denoted by solid circles. Theoretical X-P time data for a P-S converted wave at the Moho boundary are shown by lines. Three theoretical lines of the focal depths of 10, 15, and 20 km are shown by solid, broken, and dash-dotted lines, respectively.

All observed features of the X_2-phase, however, can be explained if the ray path corresponds to a P to S conversion at the upper boundary of the subducting Philipplne Sea plate (e) in Fig. 7, Fig. 11). In this case, theoretical curves for the three hypocentral depths are similar, and the curves match the observed data very well.

2.3. Location of the upper boundary of the Philippine Sea slab

The location of the plate boundary between the Philippine Sea and Eurasian plates was constrained using travel time data from the X_2-phase recorded by seismic stations run by the Earthquake Research Institute of the University of Tokyo (ERI). The seismograms of the five seismic stations are 1 Hz velocity types. Fourteen earthquakes that occurred beneath the east coast of the Izu Peninsula from 1988 to 1989 are used (Fig. 3). The parameters of the hypocenter deter-

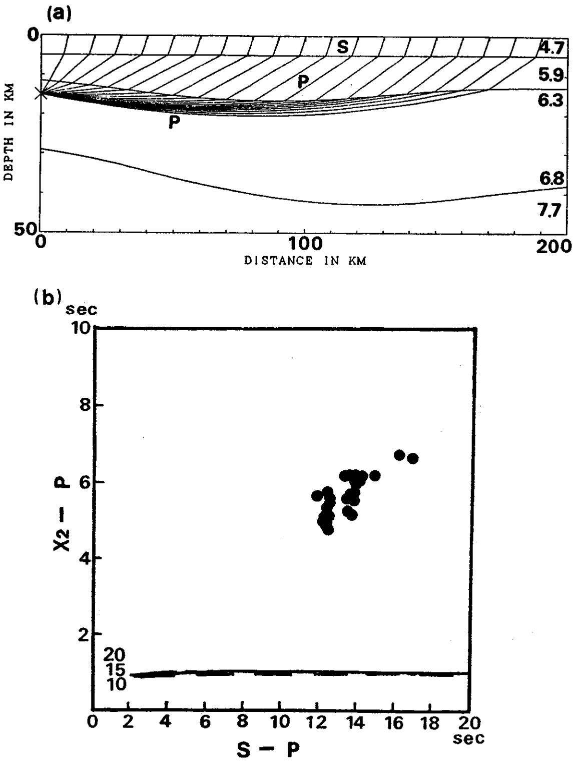


Fig. 10. (a), Ray paths of P to S converted waves at the sedimentary layers are shown. Numbers indicate P-wave velocity in each layer; (b), The X–P time graph. The observed X_2–P data are denoted by solid circles. Theoretical X–P time data for a P–S converted wave at the sedimentary layer boundary are shown by lines. Three theoretical lines of the focal depths of 10, 15, and 20 km are shown by solid, broken, and dash-dotted lines, respectively.

mined by ERI are adopted. The hypocenters ranged in depth from 10 to 30 km.

To determine the location of the plate boundary, three parameters must be resolved. These are the strike, dip, and depth of the plate boundary. The strike of the plate is assumed to cross at right angles to the hypocenter-station direction. The other two parameters (dip, depth) are determined in the study. We use a trial and error method to locate the boundary by calculating travel time residuals using two-dimensional ray tracing (ČERVENÝ and PŠENČÍK, 1983). First, the location of the boundary is assumed, and residuals (observed and calculated X–P) are calculated by changing the dip angle of the boundary. Secondly, the location of assumed plate boundary between the station and focus is varied resulting in different dip angles. In this manner, the time

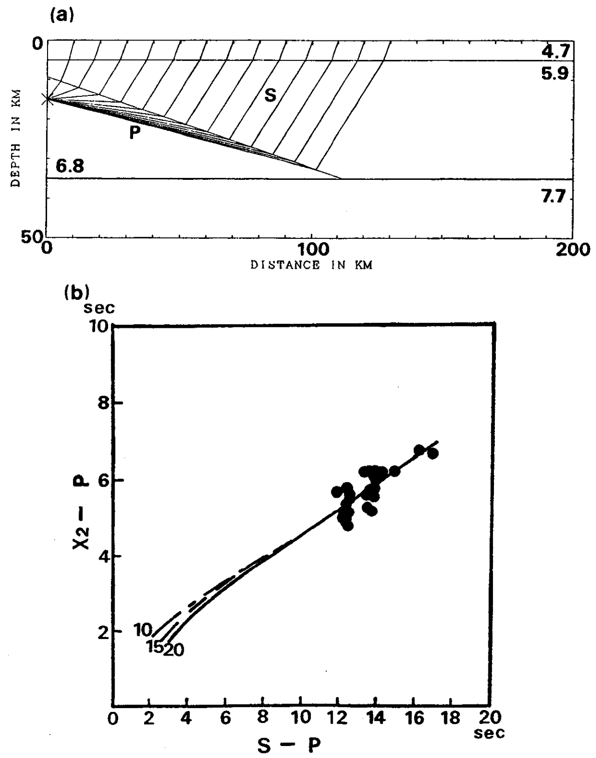


Fig. 11. (a), Ray paths of P to S converted waves at the upper boundary of the subducting Philippine Sea plate are shown. Numbers show P-wave velocity in each layer; (b), The X-P time graph. The observed X_2-P data are shown by solid circles. Theoretical X-P time data for a P-S converted wave at the upper boundary of the slab are shown by lines. Three theoretical lines of the focal depths of 20, 15, and 10 km are shown by solid, broken, and dash-dotted lines, respectively. Numerals denote the depths of theoretical foci.

residuals are calculated at a number of locations and dip angles. The best location of the plate boundary, defined by the location and dip angle, is obtained when the cumulative residual for all observations D is minimized. D is calculated according to the formula:

$$D=[\sum^{n}(O(\text{X-P})-C(\text{X-P}))^2]$$

where O(X-P) is the observed X-P time, C(X-P) is the calculated X-P time and n is the number of observed data.

The observed data are well-explained by assuming that the ray paths correspond to a P wave which is converted to an S wave at the upper boundary of the subducting plate. Calculated PS-P time data which fit the observed data are shown in Fig. 11. The observed data

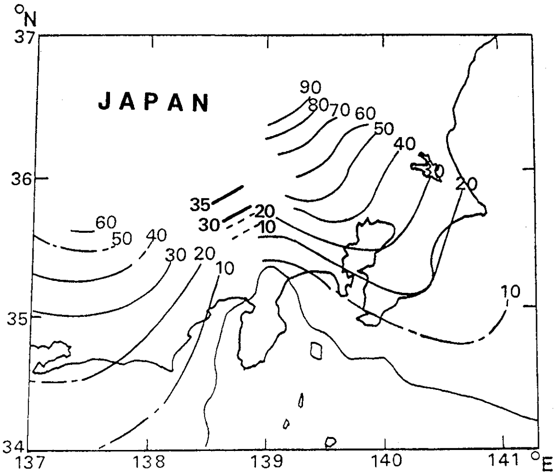


Fig. 12. Iso-depth lines of the upper boundary of the subducting Philippine Sea plate obtained using P-S converted wave data are denoted by two thick lines. The iso-depth lines obtained using S-P converted wave data (IIDAKA *et al.*, 1990) are shown by broken lines. Thin contour lines show results obtained by ISHIDA (1991).

show that the PS-P time increase as the S-P time increases, consistent with the trend of the calculated curve. The boundary obtained by minimizing the cumulative time residual is located from 28-km to 35-km depth in the western Kanto region (Fig. 12), and has a dip angle of 12.9 degrees.

3. Discussion

A previous study showed that the Philippine Sea slab exists at depths shallower than 20 km (IIDAKA *et al.*, 1990). There was no evidence for the existence of the subducting Philippine Sea slab at depths of deeper than 20 km. The iso-depth lines of the upper boundary of the Philippine Sea slab obtained by P-S and S-P converted waves are shown by solid and broken lines in Fig. 12. The results of the two studies constitute evidence for the presence of the subducting Philippine Sea plate in the aseismic western Kanto region. The location of the Philippine Sea slab is estimated to be at depths from 10 km to 35 km. Uncertainties in the location of this boundary are discussed below.

The 12.9-degree dip angle of the subducting Philippine Sea slab obtained in this study using P-S conversion data is very small compared to the 50 degrees estimated from an S to P converted wave study (IIDAKA *et al.*, 1990). However, the dip angles were estimated from data sensitive over different depth ranges, shallower than 20 km for the S to P data and deeper than 25 km for the P-to-S conversion data. In addition, the dip angle of the subducting plate estimated from the travel time data of S to P converted waves may have large uncertainty because the conversion points of S-P conversion are located within a narrow depth range of less than 5 km (IIDAKA *et al.*, 1990).

In contrast, the depth range for P to S conversion is significantly larger and located along the depth direction of the subducting slab (Fig. 1). However, in this case the reading error for the P-S converted phase is expected to be large because the phases are not impulsive, i.e., the observed X_2-P time data for a given S-P time have a scatter of about 1 second (Fig. 11).

The uncertainty of the location and dip angle of the obtained boundary was estimated by first calculating the standard deviation of the observed data at each S-P time, and then determining the maximum and minimum values of the dip angle and locations that are within one standard deviation of the observational data. The obtained range of dip angles varies between 8.0 and 15.4 degrees, and locations of the boundary shift by ± 10 km along the hypocenter-station direction.

Location errors were examined by calculating the effects using a different assumed velocity structure and different hypocentral depths. The use of an other velocity model proposed by MIKUMO (1966) resulted in shifts of less than 5 km in the north-west direction. It is concluded that the boundary location obtained from converted phase data is insensitive to the velocity structure used in the model calculation. The theoretical curves calculated for three cases of 10, 20 and 30 km depths were found to be similar. Depth errors in the hypocenter thus do not appear to shift the location of the plate boundary.

On two of the five seismic stations (DAI and SMT), the expected P-S converted wave was not observed, due to higher noise levels and possible local structural heterogeneity. At station DAI, the noise level was higher than at other stations, making it difficult to detect the converted phase. At station SMT, several later phases thought to be caused by local structure around the SMT station were observed. The presence of these phases, which were not observed at other seismic stations, masked identification of the P-S phase.

Lack of spatially-dense data precludes more detailed analysis in this study. To further delineate the configuration of the slab in the western Kanto region, a spatially dense seismic network and three-dimensional analyses are necessary. In addition, the amplitudes of the converted waves can give important information about the velocity contrast at the boundary.

4. Conclusions

Clear later seismic phases (X_1- and X_2-phases) can be observed at seismic stations located in the western Kanto region from earthquakes that occurred in eastern Yamanashi prefecture and the east coast of the Izu Peninsula. Using two-dimensional ray-tracing, possible interpretations are examined which could explain the characteristics of the phases and satisfy the X-P time data. The later phases cannot be explained by converted phases at the Conrad and Moho discontinuities. Instead, the X_1- and X_2-phases are identified as S to P and P to S converted phases, respectively, at the upper boundary of the subducting Philippine Sea plate.

Seismological evidence for the existence of the subducting Philippine Sea plate beneath the western Kanto region is shown in this study. The use of the converted phase constitutes a useful technique for estimating the location of the conversion boundary. The upper boundary of the slab is determined using the travel time data of the later phases. Residuals between the observed and calculated data are minimized to estimate the best location of the boundary. The subducting Philipplne Sea plate was found to exist at depths shallower than 20 km and deeper than 25 km from the S-P and P-S converted wave data, respectively, in the aseismic western Kanto region. The location of the boundary is estimated to be at depths from 10 km to 30 km.

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S-P および P-S 変換波から推定された関東地方の西側地域のフィリピン海プレートの上面について

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これまでに，フィリピン海プレートの形状は，震源分布や3次元速度構造のインバージョン等の手法を用いて求められてきた．しかしながら，関東地方の西側地域は地震活動がきわめて低く，その形状を求めることは困難であった．

この地域においてプレート境界を検出するために5点の観測点を設置し観測をおこなった．これらの観測点においてP波とS波の間に2つの明瞭な後続波 (X 1, X 2 相) が検出された．これらのうち，山梨県東部の地震に対して上下動に卓越する明瞭な後続波 (X 1 相) が観測され，この後続波は沈み込むフィリピン海プレートの上面でのS波からP波への変換波であることがわかった．このことによって関東地方の西側地域において沈み込むフィリピン海プレートの存在が示された．しかし，観測点と震源との関係から変換点は限られた深さでしか求めることができなかった．

その後，伊豆半島東方沖の地震に対して，これらの観測点の地震記録に水平動に卓越する明瞭な後続波 (X 2 相) が確認された．この後続波の成因について解析を行ったところ，沈み込むフィリピン海プレート上面でのP波からS波の変換波であることがわかった．この後続波の走時を調べることによってプレート上面が推定され，深さ 28～35 km に求められた．

この研究によって，この地域では S-P 変換波と P-S 変換波の観測から沈み込むフィリピン海プレートの存在が示され，その境界面を深さ 10 km から 35 km まで確認することができた．