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Short Note

P-Wave Velocity of the Uppermost Mantle off the Japan Sea Coast

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Abstract: An analysis is made of the Pn-velocity in the region just off the Japan Sea coast of the Tohoku District. The data used here are arrival times of Pn-waves from shallow earthquakes occurring at the northern and southern parts of the region obtained at twelve seismic stations near the coast. In order to reduce the effect of the hypocenter errors, we determine Pn-velocity from apparent velocities of Pn-waves for a number of earthquakes which are located close to each other. The Pn-velocity is obtained to be 7.9 km/s with a standard error less than 0.03 km/s. This result is confirmed by the arrival time data of Pn-waves from an earthquake in Yamaguchi Prefecture. Our result is not reconciled with the anisotropic model proposed by a previous study. Taking the results of the present study and several previous studies into account, we suggest a model as follows: Pn-velocity, which is 7.5 km/s beneath the land area, changes sharply to 7.9 km/s across a transition zone near the coast and increases gradually up to 8.0-8.2 km/s as leaving from the coast.

P-wave velocity structure of the uppermost mantle beneath the Japan Sea has been studied by several researchers. By using data from the seismic explosion experiment along the Oga-Kesennuma profile in northeastern Honshu, Yoshii and Asano (1972) suggested Pn-velocity of 8.2 km/s beneath the Japan Sea; the value is quite higher than that of 7.5 km/s beneath the land area. Analyzing travel time data from two large explosions named SEIHA 4 and SEIHA 5 in the Japan Sea, Okada *et al.* (1978) proposed that there exists a large azimuthal anisotropy of Pn-velocity. According to their result, the Pn-velocity varies by approximately 0.4 km/s (*i.e.*, 5%) around average velocity of 7.94 km/s, and the direction of the maximum velocity is N141°E. Hirata *et al.* (1987) investigated the velocity structure of the crust and the uppermost mantle beneath the Yamato Basin in the Japan Sea, and obtained the Pn-velocity of 8.0-8.1 km/s. Sato and Kosuga (1987) estimated the Pn-velocity to be 8.20-8.27 km/s just beneath the source area of the 1983 Japan Sea Earthquake by using arrival time data of Pn-waves from its aftershocks observed at two stations Matsushiro (MAT) and Okushiri (OKS). The above two studies concerned Pn-velocities beneath regions leaving from the Japan Sea coast farther than about 100 km. Sato and Kosuga (1987) did not detect the azimuthal anisotropy of Pn-velocity beneath the Japan Sea as proposed by Okada *et al.* (1978).

It is necessary to determine Pn-velocity off the Japan Sea coast accurately in order to locate hypocenters of the earthquakes beneath the sea reliably and to understand the property of the transition zone between the land and the Japan Sea. In this study, we used arrival time data of Pn-waves from two groups of shallow earthquakes, which occurred around the Japan Sea coast, observed at nine stations of the seismic network of Tohoku University, two stations (MMA and IWS) of Hirosaki University and one station (NOU) of the University of Tokyo (see Fig. 1). These earthquakes occurred in a period from May, 1986 to September, 1987. The northern group contains 24 earthquakes, all of which are aftershocks of the 1983 Japan Sea Earthquake. They are located in a small region off Iwasaki. The 17 earthquakes of the southern group are located in a narrow zone along the Japan Sea coast, south of the Sado Island. Hypocenters determined by the seismic network of Tohoku University were relocated by using arrival time data read directly from the seismograms and applying the crustal velocity model of Zhao *et al.* (1990). The model takes account of the differences of the Pn-velocities and the depths of the Conrad and the Moho discontinuities between beneath the land area and beneath the Japan Sea. The relocated focal depths are all shallower than 20 km. The standard deviations of the travel time residuals for the relocated hypocenters are considerably reduced. The calculated standard errors of the relocated hypocenters are less than 3 km. The relocated epicenters are shown by solid circles in Fig. 1.

In order to estimate the Pn-velocity off the Japan Sea coast, we used only the first arrival times obtained at stations with epicentral distances larger than 140 km, because the first arrivals are considered to be Pn-arrivals there according to the result of Zhao *et al.* (1990). The waveform data of the selected earthquakes were reproduced on a graphic display from the magnetic tapes, and clear first arrivals (Pn-waves) were read from the hard copies of the display. The uncertainties of the arrival time readings are estimated to be less than 0.1 s. The numbers of Pn-wave readings are 96 and 59 for the northern and the southern groups, respectively.

For each event we chose, as reference, one station which has the nearest epicentral

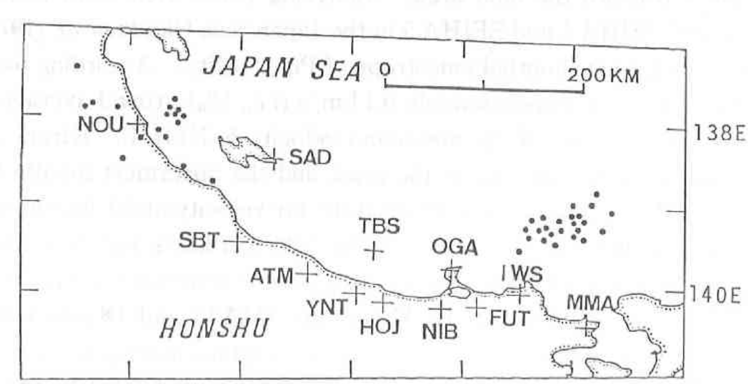

Fig. 1 Locations of seismic stations (crosses) and epicenters of earthquakes (solid circles) used in the present study.

distance and whose Pn arrival time is considered to have the best accuracy among all available data. The observed Pn arrival times at the reference station (T_0) and the other station (T_i, $i=1, 2, 3, \cdots$), can be expressed as

$$T_0 = t_0 + A_s + A_0 + D_0/V \quad (1)$$

$$T_i = t_0 + A_s + A_i + D_i/V \quad (2)$$

where t_0 is the origin time of the event, A_s the Moho time term at the source, V the average Pn-velocity. A_0 and A_i are Moho time terms at 0-th (reference) and i-th ($i=1, 2, 3, \cdots$) stations; D_0 and D_i are epicentral distances at 0-th and i-th stations, respectively. Taking the difference between eqs. (1) and (2), we obtain

$$T_i - T_0 = (A_i - A_0) + (D_i - D_0)/V. \quad (3)$$

For one earthquake, $n-1$ equations such as (3) can be written if n data are available. The Moho time term A_i is mainly dependent on the Moho depth beneath i-th station. A variation of the Moho depth by 1 km causes a change of A_i of about 0.07 sec. According to Zhao *et al*. (1990), the Moho depth contours around the Japan Sea coast run approximately in parallel to the coastline, and the variation of the Moho depth is about 1-2 km beneath the stations used in this study (Fig. 1). Thus, the variation of A_i is considered to be only about 0.1 sec, which is comparable to the reading error of the arrival time data T_i. If the 0-th and the i-th stations are located in almost the same

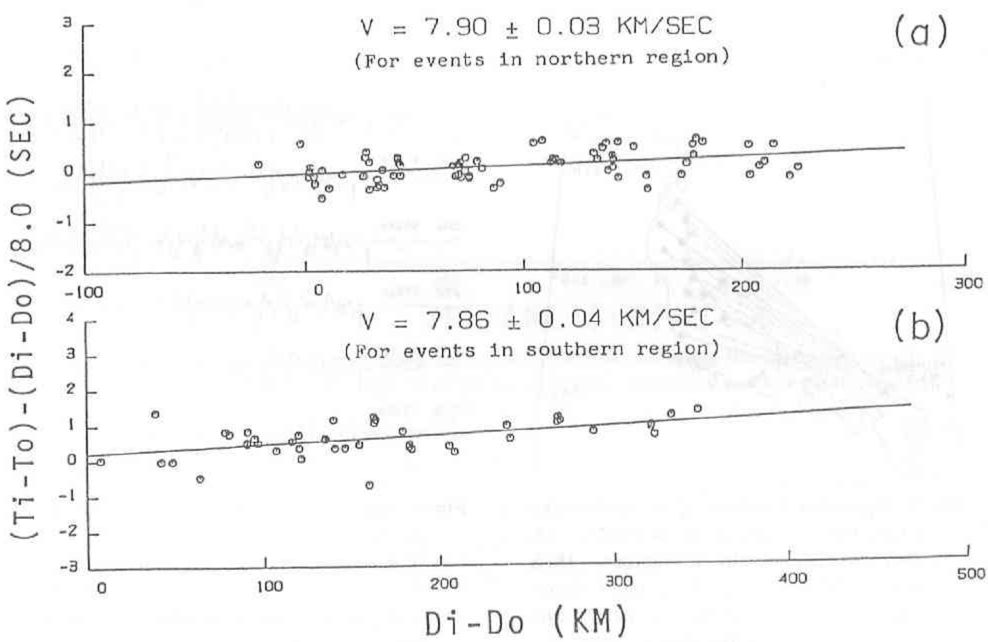

Fig. 2 Differential arrival times ($T_i - T_0$) of Pn-waves plotted against differential epicentral distances ($D_i - D_0$) for (a) the northern and (b) the southern group earthquakes as shown in Fig. 1. The reduction velocity is 8.0 km/s.

direction from a source, the differential epicentral distance $(D_i - D_0)$ is hardly affected by the mislocation of the hypocenter. Plotting the differential arrival times $(T_i - T_0)$ against the differential epicentral distances $(D_i - D_0)$ for many events, we can estimate the Pn-velocity V from the slope of a straight line which best fits the data in the least squares sense.

Figure 2 shows differential arrival times $(T_i - T_0)$ of Pn-waves from the earthquakes of (a) the northern and (b) the southern groups plotted against corresponding differential epicentral distances $(D_i - D_0)$. The reduction velocity is 8.0 km/s. The best fitting straight lines in the least squares sense in (a) and (b) give a value of Pn-velocity of 7.90 km/s with the standard error of only 0.03 km/s and a slightly smaller value of 7.86 ± 0.04 km/s, respectively. The two values are consistent within the error range.

On November 18, 1987, a shallow earthquake with magnitude 5.6 occurred in Yamaguchi Prefecture. The epicenter determined by Japan Meteorological Agency (JMA) is shown in Fig. 3. Ray paths from this earthquake to some stations in northeastern Japan are also shown schematically. Clear first arrivals (Pn-waves) were observed at most of the stations. Figure 4 shows seismograms of Pn-waves from this earthquake

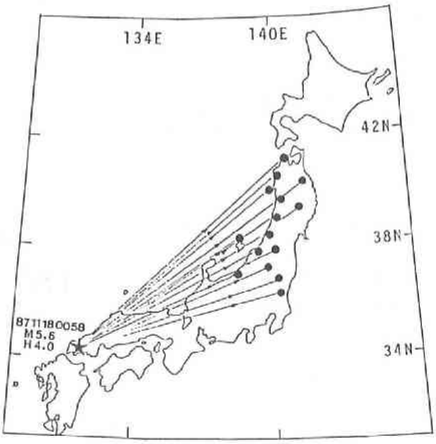

Fig. 3 Epicenter location of an earthquake (star) that occurred on November 18, 1987 in Yamaguchi Prefecture. JMA (Japan Meteorological Agency) determined the focal depth to be 4.0 km. Rays from this earthquake to some stations in northeastern Japan (solid circles) are schematically shown by straight lines.

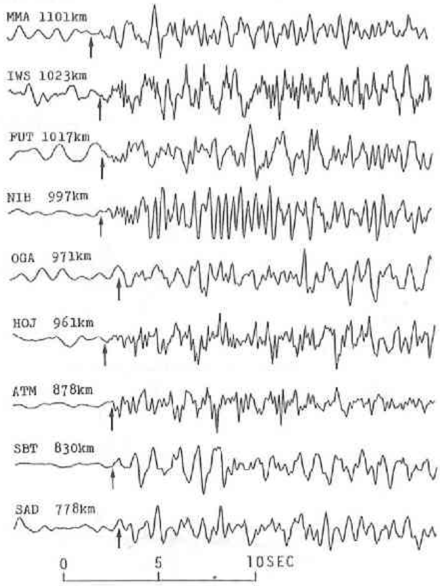

Fig. 4 Seismograms of Pn-waves from the earthquake in Yamaguchi Prefecture (Fig. 3) observed by nine stations along the Japan Sea coast (Fig. 1). Station code and epicentral distance are shown for each seismogram.

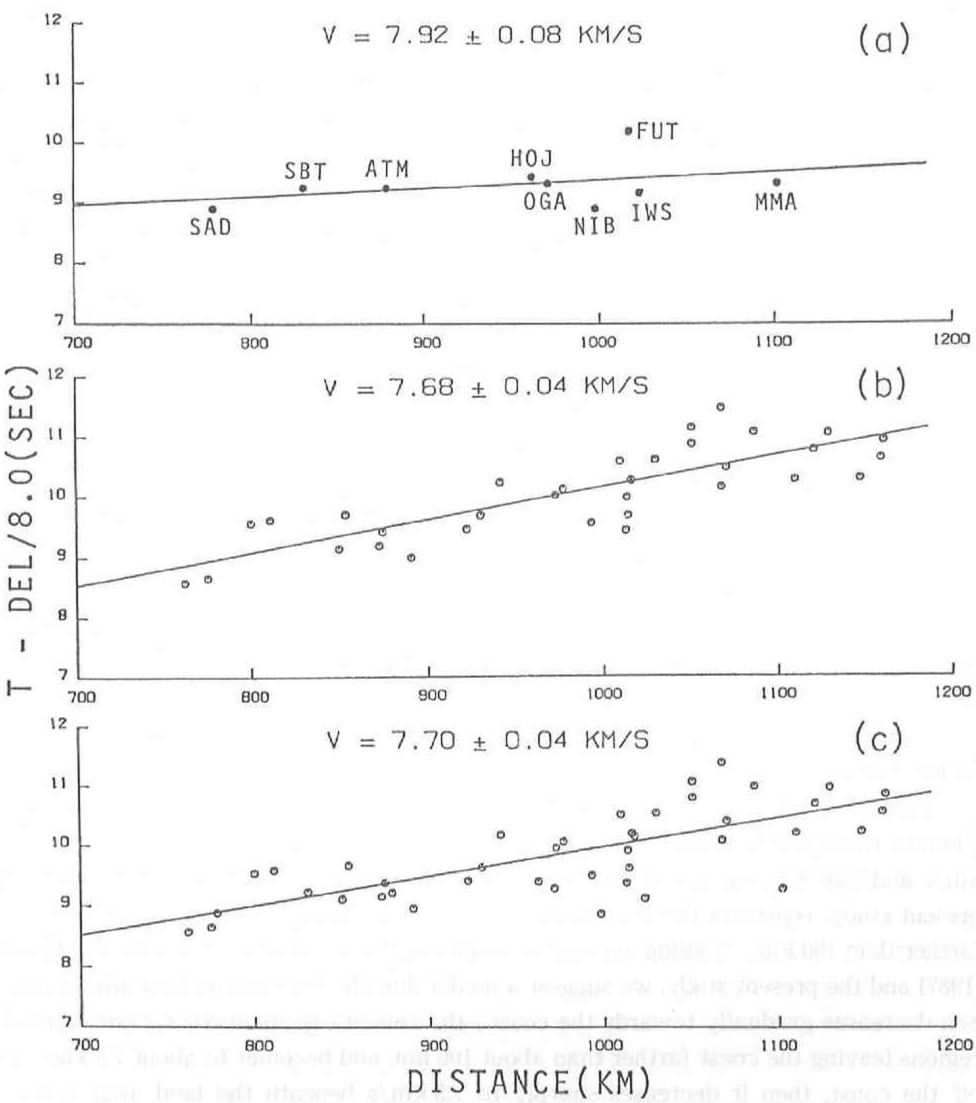

Fig. 5 Travel times of Pn-waves observed by (a) nine stations along the Japan Sea coast, (b) all the available stations except those along the Japan Sea coast and (c) all the available stations plotted against epicentral distances. The reduction velocity is 8.0 km/s.

observed at nine stations along the Japan Sea coast. Travel times of Pn-waves reduced by 8.0 km/s are plotted against epicentral distances and are shown in Fig. 5(a). The Pn-wave data at stations NOU, YNT and TBS are not plotted because a large part of the ray path to NOU passed through the land area, and because the Pn arrivals at YNT and TBS were not so clear. Apparent velocity of Pn-wave is estimated to be 7.92±0.08 km/s which is quite close to the result obtained in Fig. 2. Figure 5(b) is the result from the data recorded by all the available stations except those along the Japan Sea coast. This gives a value of 7.68 ± 0.04 km/s, which is slightly larger than the Pn-velocity of 7.5 km/s beneath the land area obtained with good accuracy by Yoshii and Asano (1972). It is considered that the discrepancy is caused by the fact that the Pn-waves to the northern stations pass through mainly beneath the Japan Sea, while the waves to the southern stations pass through the land area. The result from all the available data (Fig. 5(c)) gives a value of 7.70 ± 0.04 km/s which is close to the Pn-velocity of 7.73 km/s in the velocity model used in the routine hypocenter determination of the seismic network of Tohoku University.

The azimuthal anisotropy model by Okada *et al.* (1978) predicts a low Pn-velocity, about 7.5-7.6 km/s, in the direction along the Japan Sea coast. The predicted value is significantly smaller than the value of 7.90 km/s obtained with good accuracy in this study. The anisotropy model by Okada *et al.* (1978) seems implausible at least for the region off the Japan sea coast. As pointed by Sato and Kosuga (1987), a re-examination is necessary for the prevailing idea of Pn-velocity anisotropy beneath the Japan Sea. It should be noted, however, that the average Pn-velocity of 7.94 km/s obtained by Okada *et al.* (1978) is close to the values of 7.90 km/s in Fig. 2(a) and 7.92 km/s in Fig. 5(a) of the present study.

Yoshii and Asano (1972) assumed the Pn-velocity off the Japan sea coast around the Oga Peninsula to be 8.2 km/s, which is considerably larger than that obtained by this study. It is necessary to re-examine the Pn-velocity they assumed, together with the Conrad and the Moho depths along the Oga-Kesennuma profile they obtained, as suggested by Horiuchi *et al.* (1982) and Zhao *et al.* (1990).

Hirata *et al.* (1987) and Sato and Kosuga (1987) obtained the Pn-velocity beneath the Yamato Basin and beneath the source area of the 1983 Japan Sea Earthquake of 8.0-8.1 km/s and 8.20-8.27 km/s, respectively. These values, larger than that obtained by the present study, represent the Pn-velocities beneath regions leaving the Japan Sea coast farther than 100 km. Taking account of results of Hirata *et al.* (1987), Sato and Kosuga (1987) and the present study, we suggest a model that the Pn-velocity beneath the Japan Sea decreases gradually towards the coast; the velocity is about 8.0-8.2 km/s beneath regions leaving the coast farther than about 100 km, and becomes to about 7.9 km/s just off the coast, then it decreases sharply to 7.5 km/s beneath the land area across a transition zone nearly along the coastline of the Japan Sea (Zhao *et al.*, 1990).

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