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Velocities of Pn-Waves in the Taiwan Strait and Its Surrounding Area From Regional Earthquakes

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ABSTRACT

P-wave velocities of the uppermost mantle beneath the Taiwan Strait, based on the travel-time observations at Kinman, are determined from Pn arrivals of regional earthquakes. Based on the accurate locations and origin times of shallow earthquakes beneath Taiwan and its eastern offshore region, the uppermost mantle velocities of the Taiwan Strait are determined using seismic waves recorded by stations in the Strait. This study indicates that the average Pn velocities beneath the Taiwan Strait, the island of Taiwan and its eastern offshore region are 8.2±0.2 km/sec, 7.9±0.1 km/sec and 8.0±0.1 km/sec, respectively. The uppermost mantle velocity determined for the Taiwan Strait improves the epicentral determination of earthquakes on the Strait. The Moho depth beneath the western side of the Taiwan Strait is estimated to be shallower than those beneath both the eastern side of the Strait and Taiwan Island. From this data set, the Pn velocities beneath the Strait regions are slightly greater than those of the island area, and the Moho dips slightly from west to east. The crust of the Taiwan Strait area could be considered as a part of the Eurasian continent and as having been slightly deformed due to the arc-continental collision in the Taiwan region.

(Key words: Taiwan Strait, Pn velocities, Uppermost mantle velocity, Kinman island)

1. INTRODUCTION

Travel times of Pn-waves are of great importance for studying the earths interior. These times are the main source of data for the determination of earthquake foci for regional events (Umino and Hasegawa, 1994). Furthermore, the accuracy of the measurement of these times contributes to the knowledge of the crust and uppermost mantle structures of the study area.

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Pn-waves refer to short-period impulse compressional waves that propagate over distances of up to about 40 degrees with velocities in the range of 7.6 to 8.8 km/sec (Christensen and Mooney, 1995). Pn is considered the head wave of a P phase propagated on the uppermost mantle (Stephens and Isacks, 1977; Aki and Richards, 1980). Variations in Pn velocities can be used to determine regional differences in the physical properties of the uppermost mantle (Chen *et al.*, 1980; Ni and Barazangi, 1983).

With an average water depth of less than 100 m, the Taiwan Strait is situated on the continental shelf off the southeast China coast between the East China Sea and the South China Sea. Its dimensions are 380 km and 190 km in the north-south and east-west directions, respectively. From a tectonic perspective, it connects two tectonic regions of the arc-continental collision zone of the island of Taiwan and the stable Eurasian continental regions. Geological and geophysical investigations in this region may provide strong constraints for the geotectonic evolution processes of the Taiwan Strait and the arc-continental collision evolution of the island. On the basis of local seismic network observations, many workers have reported the velocity structure of the crust and the uppermost mantle beneath Taiwan (Roecker et al., 1987; Rau and Wu, 1995; Ma *et al.*, 1996). However, for the deep velocity structure of the Strait region, using explosion experiments, only a few data sets have reported (Chen and Nakamura, 1992). Earthquake observations of the Strait area have been reported less often because of the lower seismicity in the Strait and the limited number of stations in the western offshore region of Taiwan, all of which have been recently installed (Figure 1). In 1991, station KNM on Kinman, a small island near the eastern coast of Fujian Province, and station PNG in the Peng-Hu Islands, were set up by the Central Weather Bureau (CWB). In 1994, on the small island of Tung-Chi to the southeast of PNG, station WDG was installed (Figure 1). Each station was equipped with a three-component short-period seismometer (Teledyne-Geotech S-13) with a natural period of 1 sec. These stations clearly recorded the Pn phases of the major events occurring in Taiwan and its eastern offshore region. Because the events could be accurately located by the Central Weather Bureau Seismic Network (CWBSN), these seismic records provided an opportunity to study the uppermost mantle velocities of the Taiwan Strait for the long ray paths propagated in the Strait region.

The primary data for this study were three-component short-period seismograms recorded by the three seismic stations in the Strait. The shallow seismicity from Taiwan and the surrounding regions provided effective propagation paths for the Pn-waves. The aim of this study was to analyse those regional phases to determine the deep structure of the Taiwan Strait and Taiwan Island. Results of this study estimated the averaged Pn velocities beneath the Strait and Taiwan regions to be 8.2±0.2 km/sec and 7.9±0.1 km/sec, respectively. Additionally, there was some evidence for the Moho dipping from west to east.

2. DATA

The Seismological Center of the Central Weather Bureau maintains a permanent seismograph network (CWBSN) in Taiwan to study local seismicity as well as the crust and upper mantle structures. The errors of the earthquake foci located by the CWBSN have been reported as less than 5 km for events beneath Taiwan and its eastern near offshore region (CWB,

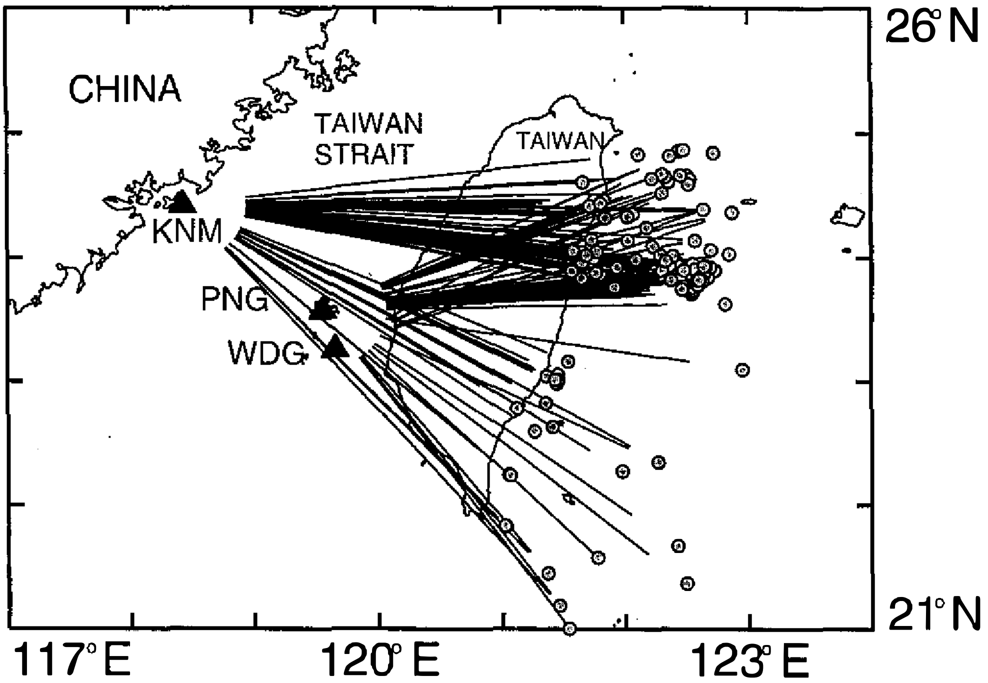

Fig. 1. Map of the epicenters of earthquakes (circles), CWBSN stations (triangles) and the Pn ray paths used in this study. These selected events have source depths of 10 to 30 km. WDG is a more recently installed station and only a few data used in this study.

personal communication). The Strait stations in this study of the CWBSN located in the western offshore region of Taiwan have the same timing system as other stations. Similarity in the recording eliminated any systemic errors in determining earthquake travel times. Such errors are frequently found for stations equipped with individual clocks or for data collected from different seismic networks. KNM is the only CWBSN station on the west side of the Taiwan Strait and is also far away from Taiwan Island. Usually, seismic wave readings from KNM carry less weight in locating earthquakes beneath the Taiwan area. However, they do provide a unique opportunity to determine regional structure. In the regional epicenter distance range (of 150 km to 1000 km), station KNM-recorded first arrivals are always Pn-waves from crustal events in Taiwan and its eastern offshore region. These Pn waves are propagated beneath Taiwan and the Strait (Figure 1). The first arrivals recorded by stations PNG and WDG from the same crustal events (Figure 1) observed by KNM are also Pn phases, but unlike the KNM case, the Pn waves recorded by these stations are mostly propagated beneath Taiwan alone (Figure 1). Therefore, the regional phases observed at KNM, PNG and WDG provide information very useful in determining the velocity structure of the Taiwan Strait area.

In this study, crustal events in Taiwan and its eastern offshore region, with depths of 10 to 30 km and magnitudes greater than 4.0 (M_L) were sorted from the CWBSN catalogue as candidates for Pn-wave analysis. Then, 125 events recorded by KNM, PNG and WDG were selected according to their impulse Pn arrivals. Most of the events were recorded by KNM and PNG with only a few been selected from WDG due to its recent installation. The epicenters of the selected events are shown in Figure 1. Although the crossover distance of Pn-waves beneath Taiwan was found to be near 150 km (Ma and Song, 1997), the data analysed in this study consisted of short-period vertical component seismograms collected from the CWBSN waveform database with epicentral distances greater than 300 km between August 1992 and July 1996. In this study, the horizontal seismograms were used to comprehensively pick the Pn arrivals. The choice of a minimum epicenter distance of 300 km for Pn-wave analysis was based on the attempt to separate the Pn phases from other later phases (e. g.Pg and PmP) which arrived at approximately the same time at shorter distances and to minimize errors coming from the uncertainty of the crust models beneath Taiwan and the Strait regions. All of the selected events had long Pn ray paths in the Taiwan Strait and partly beneath Taiwan (Figure 1). The travel times of the Pn-waves were computed using the locations and origin times reported by the CWBSN for events near Taiwan and by the U.S. Geological Survey Preliminary Determination of Epicenters (PDE) for events occurring far to the east of Taiwan. The arrival times were carefully repicked from each seismogram by the authors.

3. ANALYSIS AND RESULTS

Usually, the raw data showed high signal to noise ratios; however, some records were superposed by high frequency noise which may have been induced by telemetered transfer problems (CWB, personal communication, 1998) as shown in Figure 2. Fortunately, these high frequency noises were easily removed with a 2.0-Hz low pass filter. The filtered seismograms kept high seismic S/N ratios and the Pn arrivals could be accurately picked out (Figure 2). To construct the travel-time curve of the Pn-waves, all events were corrected as surface sources on the assumption of epicentral distance (D_0) and travel time (T_0) as shown in Figure 3. Both correction terms were determined by seismic wave propagation from source (solid star) with source depth (H) to surface (open star) based on its ray parameters. In this study, corrections were based on the crust model of Yeh and Tsai (1981) which was frequently referred to the central region of Taiwan.

The seismogram profiles corrected for source depth for station KNM are shown in Figure 4. The seismic profiles were plotted in terms of group velocity and epicentral distance. The original time axis t was replaced by a group velocity axis $v = d/t$ (where d was the corrected epicentral distance) so that the Pn phases lined up on this plot and were limited with respect to offset. The seismic phases in Figure 4 mostly lined up, which indicated reasonable source depth corrections. The solid lines from left to right in Figure 4 are the predicted Pn travel time curves with the crust model from Yeh and Tsai (1981) and the uppermost mantle velocities of 8.1, 8.0 and 7.9 km/sec, respectively. The Pn arrival for each seismogram in Figure 4 could be clearly picked out (Figure 2).

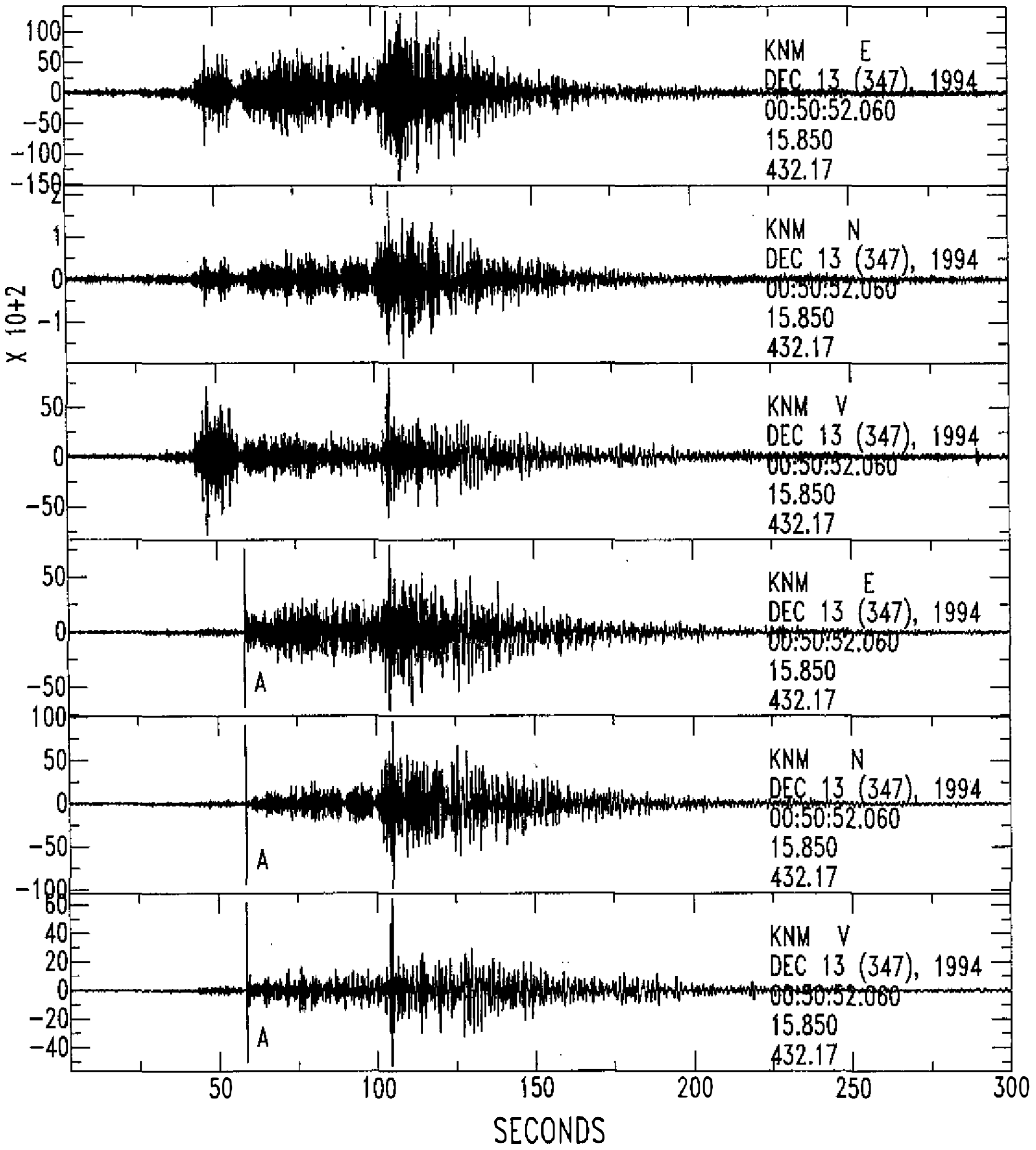

Fig. 2. Example of short-period three-component seismograms recorded at station KNM. The first three traces are the raw data, while the other three are the low pass filtered seismograms with corner frequency 2.0 Hz. The vertical bar with character A on each filtered seismogram indicates the picked Pn arrival time.

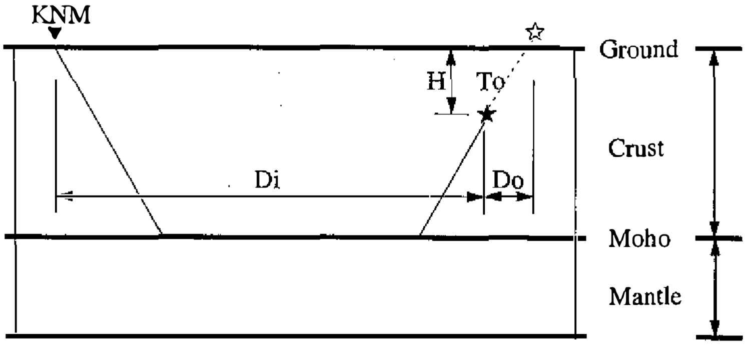

Fig. 3. Schematic diagram of the travel time and epicenter distance of an earthquake (solid star) with depth (H) corrected as a surface event (open star). Di, Do and To represent the epicentral distance, distance and time corrections, respectively. In text, the corrected epicentral distance (Δ) equals to Di + Do.

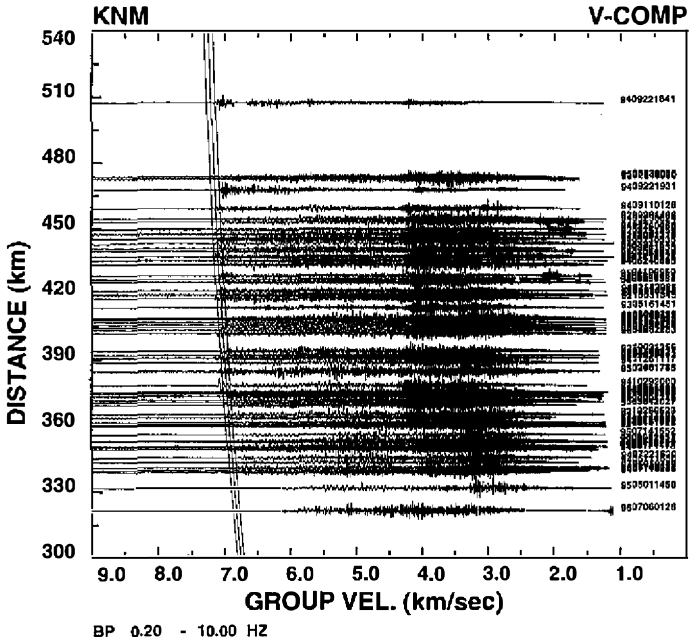

Fig. 4. Vertical seismograms recorded by station KNM as a function of group velocity to allow for a direct comparison of the traces. The vertical axis represents the source depth corrected epicenter distance. Amplitudes were normalized using individual amplitude maximum of trace. The solid lines represent travel time curves with Pn velocities of 8.1, 8.0 and 7.9 km/sec from left to right. More details are provided in the text.

The same process was used to analyse those seismograms recorded by stations PNG and WDG. If the earth model of the study area is considered one-dimensional (1-D) and if azimuthal variations are ignored, then these Pn arrivals could be used to accurately determine the Pn velocity of the source area beneath eastern Taiwan and its offshore region. The Pn velocity was calculated using a least-squares method to fit the selected data as a travel-time curve and obtain both the slope and the intercept time on the distance travel-time plots. The travel-time curve fit for the selected Pn-waves at KNM is shown in Figure 5. The data points fit the following equation very well.

$$T = \frac{\Delta}{V} + I \qquad (1)$$

where T is the travel time of the Pn-waves, V is the velocity of these waves immediately under the crust, Δ is the epicentral distance and I is the intercept time. Both T and Δ used the depth-corrected values presented in Figure 3. The mean velocity and mean intercept time for the Pn-waves recorded at station KNM are:

$$V = 8.0 \pm 0.1 \text{ km/sec and } I = 6.7 \pm 0.7 \text{ sec} \qquad (2)$$

where 0.1 and 0.7 are the corresponding standard deviations. Due to the similarity of the ray paths of PNG and WDG for the selected events (Figure 1), the selected Pn phases of both stations fit the travel-time curve based on Equation (1) as shown in Figure 6. The mean velocity and mean intercept time for the Pn-waves of the events recorded at PNG and WDG are:

$$V = 8.0 \pm 0.4 \text{ km/sec and } I = 7.7 \pm 0.8 \text{ sec.} \qquad (3)$$

From Equations (2) and (3), the estimated Pn velocities, *i.e.*the averaged uppermost mantle velocities beneath the source region, were consistently near 8.0 km/sec. However, the intercept time from KNM was nearly one second less than that from PNG and WDG. This difference could be considered a result of the variation in the Pn velocities beneath the island and the strait regions, because the ray paths from source to station KNM included both the island and strait paths, where those from PNG and WDG included only island paths (Figure 1). The higher intercept time for stations PNG and WDG compared to that of station KNM implies relatively slow Pn velocities beneath the island area. To deduce the average Pn velocity ($\overline{V}$) along the ray paths:

$$\overline{V} = \frac{\Delta}{(T - I)} \qquad (4)$$

where the definitions of Δ, T and I are as for Equation (1). I is assumed to be 6.93 sec as estimated from a surface source using the model from Yeh and Tsai (1981). The estimation of the Pn velocities were determined by the small standard variations (±0.1 km/sec) in the long Pn ray paths and the accurate selections. The estimated average Pn velocity from station KNM was 8.0 ±0.1 km/sec (Figure 7), while that for stations PNG and WDG was 7.9 ±0.1 km/sec (Figure 8). From Figure 1, it can be seen that the Pn legs of the ray paths from sources to PNG and WDG were mostly beneath the island, suggesting the average value of Pn velocity there.

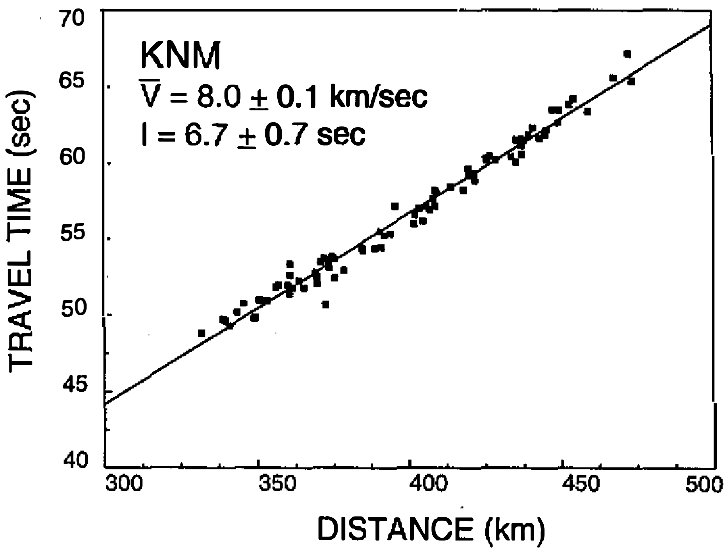

Fig. 5. Plot of source depth corrected travel times vs. distance for station KNM. $\bar{V}$ and I represent the estimated Pn velocity and intercept time, respectively. The error range was estimated by one standard deviation of data and was the same as other figures in this study.

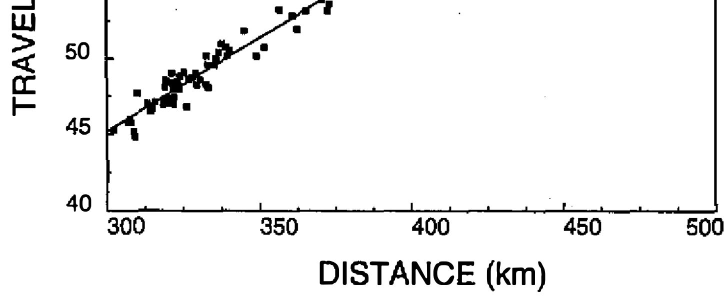

Fig. 6. Plots of source depth corrected travel times vs. distance for stations PNG and WDG. $\bar{V}$ and I represent the estimated Pn velocity and intercept time, respectively.

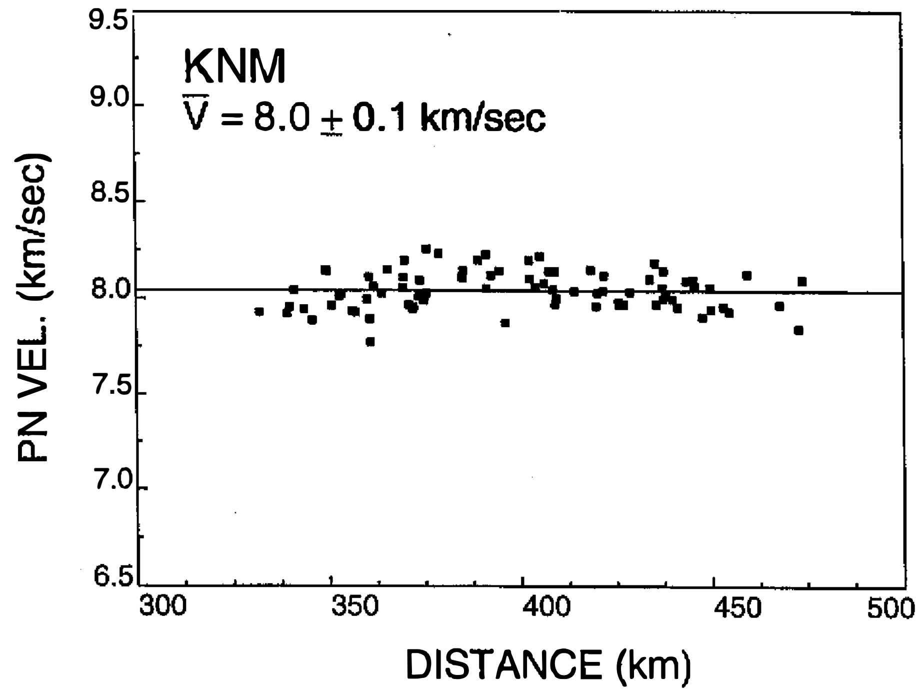

Fig. 7. Plot of the depth corrected average Pn velocities from sources to station KNM vs. distance. $\bar{V}$ represents the estimated Pn velocity.

This indicated that the Pn velocities beneath the island and strait area of Taiwan were potentially different. To verify this difference, Equation (4) was revised to yield:

$$\bar{V} = \frac{\Delta_1}{\left(T - I - \frac{\Delta_2}{7.9}\right)} \tag{5}$$

where the ray path Δ of equation (1) was separated as Δ_1 and Δ_2. Both represented the ray paths from KNM to the coast line of western Taiwan and from the same coast line to the epicenter, respectively. $\bar{V}$ represents the average Pn velocity beneath the Taiwan Strait, while the Pn velocities beneath the island are taken as 7.9 km/sec as estimated from PNG and WDG in Figure 8. I is assumed to be 6.93 sec as estimated from a surface source using the model from Yeh and Tsai (1981). The estimation of the mean Pn velocities from Equation (5) and the data from KNM was $\bar{V}$ = 8.2±0.2 km/sec (Figure 9). The average Pn velocities ($\bar{V}$) estimated from Equation (5) had pure paths beneath the strait region; hence, the estimated Pn value of 8.2 km/sec could be considered to represent the Pn velocity beneath the Taiwan Strait. The above analysis implies that the velocities of the Pn-waves beneath the strait area are slightly higher than those in the Taiwan area.

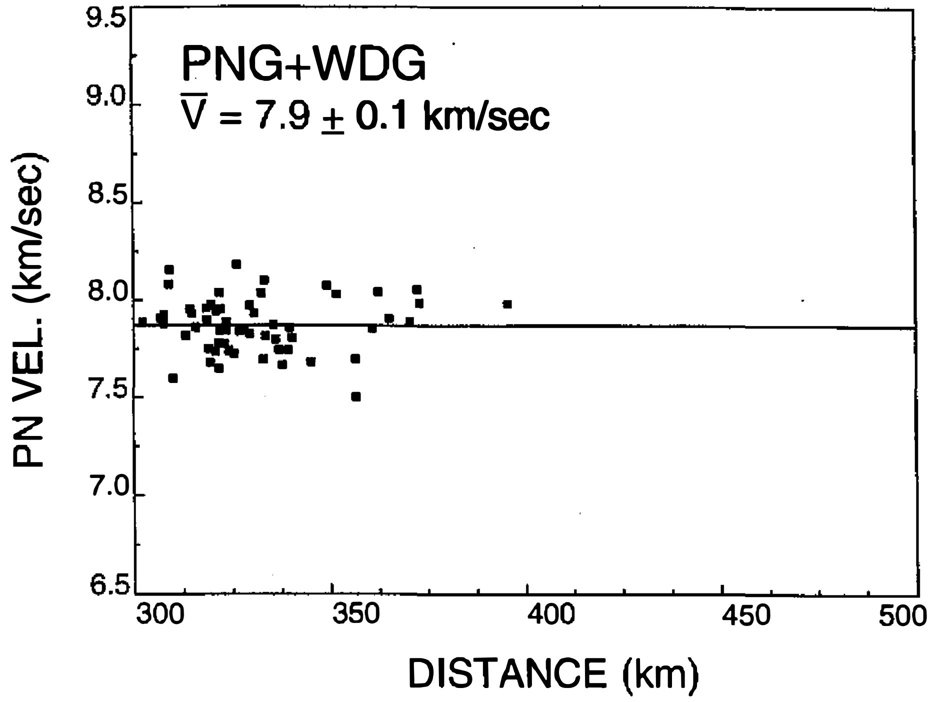

Fig. 8. Plot of the depth corrected average Pn velocities from sources to stations PNG and WDG vs. distance. $\overline{V}$ represents the estimated Pn velocity.

4. DISCUSSION

The Pn velocity beneath Taiwan Island was determined to be 7.9 km/sec, which is similar to the uppermost mantle velocity (7.8 km/sec) obtained by Yeh and Tsai (1981). In contrast, the Pn velocity beneath the Taiwan Strait was 8.2 km/sec, which is higher than that in the Taiwan Island region. Pn travel times are normally sensitive to uppermost mantle P-wave velocities; consequently, variations there are presumably related to temperature and/or compositional structure. A global average for Pn velocity is 8.09 ±0.20 km/sec (Christensen and Mooney, 1995) with shields and platforms being slightly faster (8.1 to 8.2 km/sec) and continental orogens and rifts being slightly slower (7.9 to 8.0 km/sec). It is assumed that the Pn velocity difference between the Taiwan Island and Strait regions can be considered as tectonic in origin with the arc-continental collision and continental shield environments. In general, the island region has a thicker crust relative to the strait area.

The Pn velocity difference is of great significance for the CWBSN in locating earthquakes in the strait region because the earth models routinely used by the CWBSN referred to the models of Yeh and Tsai (1981) and Ho (1994). However, both of these models are related to the central and southwestern Taiwan regions which have slower uppermost mantle velocities than the strait region. Thus, they are not suitable for the determination of hypocenters in

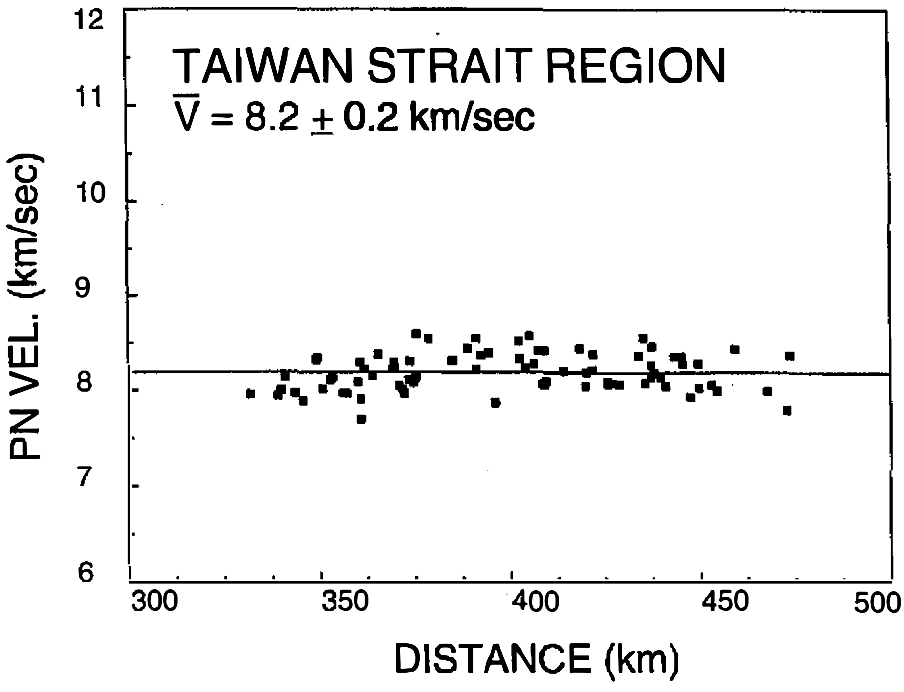

Fig. 9. Plot of the average Pn velocities from the western coast of Taiwan to station KNM vs. distance. $\overline{V}$ represents the estimated Pn velocity.

strait events. Because most strait events are far away from any of the CWBSN stations and include long Pn paths, the use of a model which underestimates uppermost mantle velocity must mislocate the hypocenters. From this point of view, the accurate Pn velocity as determined in this study possibly improve the hypocentral determination of strait events. After available strait events reported by the CWBSN catalogue were relocated, the seismicity, earthquake focal mechanisms and stress patterns of the Taiwan Strait region could be improved perhaps.

The correction and accuracy of this information is most important for any comprehensive discussion of regional tectonic evolution. Although further details on the crustal velocities and thickness are still limited for the analysis of the crustal phases (*e.g.*Pg, PmP, Sn, Sg and SmS), the detailed 1-D crustal structure can indeed be determined and will be extended upon in further research.

In this study, the 1-D crustal model from Yeh and Tsai (1981) was used to correct the source depths and intercept times. However, the Moho depth beneath KNM may have been different from that in the source area. The crust beneath station KNM can be referred to that given by the seismic refraction survey (Liao et al., 1987) of the southeast China coast with crust thickness 31 km. If the strait region was considered to be slightly disturbed by the arc-continental collision in the Taiwan region and the Moho beneath the Strait was relatively flat, the Moho should have dipped from west to east. The dipping Moho structure deduced by this study is consistent with that from the geochemistry interpretations by Chung *et al.*(1994). They analysed the spatial chemical and isotopic variation in the basalts and indicated that the center for the lithosphere thinning and asthenoshpere upwelling occurred on the western side of the Taiwan Strait.

The Pn velocity in the Taiwan Strait region was estimated with a standard deviation of 0. 2 km/sec from Equation (5) and Figure 9. There was nearly a 2.4 % velocity variation in the study area, which came from several different factors, such as hypocenter uncertainty, waveform picking errors, lateral velocity variations in the study area and mantle velocity gradient, none of which was considered in this study. The picking errors were estimated to be less than 0.1 sec for events used in this study with magnitude (M_L) greater than 4 and seismograms with a 100 Hz sampling rate. The Pn velocity variation could be excluded from the picking errors since only those events with epicenters at a distance greater than 300 km were selected. Considering the possible earthquake location errors of 10 km and the distance range of Pn-arrival reading used in this study (300 to 500 km), the estimated error for the mean Pn velocity is near the 0.2 km/sec (Figure 9). Because the Pn velocity errors estimated in this study must have included other origins, this simple test can be said to have verified that the errors of the earthquake foci located by the CWBSN have been less than 10 km for events near the eastern offshore region of Taiwan. In keeping with the basic assumptions of this study, only regional 1-D models were included. Although the sub-regions of offshore eastern Taiwan, Taiwan Island and the strait region were all originally separated in this study, the lateral variations within each sub-region may have induced some Pn velocity estimation errors. However, science at present only one CWBSN station, KNM, has been installed on the western side of the strait, the limitation of the data, presented an obstacle to further analysis of the lateral velocity variations in the strait. In this study, another error with regard to the Pn velocity estimation must be noted-the mantle velocity gradient. It is also possible that the existence of the mantle velocity gradient overestimates the Pn velocities at large epicentral distances using crustal events. However, the mantle velocity gradient should have been estimated using other constraints but were not considered in this study. Hence, this should also be considered in any further interpretations of the results of this study.

5. CONCLUSIONS

Based on the seismograms of stations KNM, PNG and WDG in the CWBSN obtained from shallow events beneath Taiwan and its eastern offshore region, the P-wave velocities of the uppermost mantle beneath the Taiwan Strait were estimated as 8.2±0.2 km/sec. The Pn velocity beneath Taiwan Island was demonstrated to be 7.9±0.1 km/sec, and thus conformed with the model from Yeh and Tsai (1981). The Pn velocity beneath the eastern Taiwan offshore region was calculated as 8.0±0.1 km/sec. It was deduced that the Moho depth was shallower beneath the western side of the Taiwan Strait than on the eastern side of the strait. The Pn velocity analysis used in this study potentially improved the epicentral determination of strait events.

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