Lateral Variations in Upper Mantle Structure of the Philippine Sea Basin

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ABSTRACT

The group velocities of Rayleigh waves along twenty-three paths, which pass through most major physiographic features of the Philippine Sea, are determined using the phase-matched filter technique. These paths are grouped into five different areas in each of which a major physiographic feature is present. Shear velocity structures of the upper mantle beneath the Philippine Sea are derived by inversion of the averaged dispersion data for each path group. The results suggest a substantially thinner lithosphere (about 30 *km* thick) and a much softer asthenosphere (with shear velocity as low as 3.8 *km/sec*) for this basin compared to typical oceanic structures. The derived models show that in the eastern volcanic islands, the softer layer is just underneath the lithosphere and its depth increases gradually to the west throughout the basin. This feature would not only reflect the high values of heat flow observations in the eastern area, but a gradually cooling and solidifying feature towards the west may also proposed in the upper asthenosphere. However, variation of structures between the northern and southern portions of the West Philippine Basin is not easily distinguished in this current study.

1. INTRODUCTION

Structural heterogeneities of the Earth have already been recognized by many past studies. Among these without doubt, surface wave analyses have played important roles because group velocities, phase velocities, and amplitude attenuation of surface waves have been useful in delineating structures of the crust and upper mantle in various regions of the Earth.

The Philippine Sea is one of the largest marginal seas in the world and is considered to be a good site for surface wave studies because of abundant seismic data suitable for surface wave analysis on the border around the sea. Based on the group velocity dispersion characteristics of Rayleigh waves for periods less than 50 seconds, Santo (1963) classified almost all areas of the

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Philippine Sea as type 3 (intermediate). However, according to a seismic refraction study of Murauchi *et al* (1968), the basins of the Philippine Sea have a fairly oceanic structure. When comparing the dispersion characteristics of long-period Love and Rayleigh waves for two paths passing through the Philippine Sea with normal oceanic paths, Kanamori and Abe (1968) presented a regional average structure with a very thin lithosphere (model ARC1), and that the asthenosphere at a depth of 30 *km* rather than the usual oceanic 70 *km*.

Previous studies on lateral structural variations of the crust and upper mantle beneath the Philippine Sea (Seekins and Teng, 1977; Yu, 1982), have given different results for highly regionalized velocity areas. This inconsistency between various studies is probably because of inappropriate regionalization in wave paths. For example, in their studies, the Ridge subdivision including most portions of the western Philippine basin may not be appropriate, because the topographical features in the central part of the basin are quite different from those at the northern end. Moreover, if we check again the averaged dispersion curves of different paths, we may find that most portions of the path from the Kyushu (the path with higher velocities) should be through the Shikoku and Parece Vela basins rather than along the ridges (ref. Figures 1 and 3 of Seekins and Teng (1977)). Of course, other reasons for the different data sets or data errors may also be suggested to explain this inconsistency.

To avoid the ambiguity of arbitrary regionalization, we shall again study lateral variations of the upper mantle structure beneath the Philippine Sea by directly examining the dispersion characteristics of Rayleigh-wave group velocities along a few path groups. These path groups are selected as possibly representing the distinguishable structural province. Meanwhile, structures in regions of the Shikoku basin and most parts of the eastern volcanic island chain will be carefully derived in this study.

2. PHYSIOGRAPHIC FEATURES OF THE PHILIPPINE SEA BASIN

Geographically, the Philippine Sea lies approximately, between 5° to 35° N latitude and 121° to 148° E longitude. It consists of a series of deep-water basins and shallow ridges, and is surrounded by an almost unbroken system of deep-sea trenches and island arcs which separate it from the adjacent seas. A description of major physiographic features and bathymetry of the Philippine Sea is already given by Mammerickx *et al.* (1976) (see Figure 1).

The eastern Philippine Sea has long linear features roughly parallel to the eastern trench systems extending from Izu-Bonin, Mariana, Yap, to Palau. These include the eastern volcanic islands where the Bonin and Mariana troughs are covered, the Shikoku and Parece Vela basins, and the Palau-Kyushu ridge.

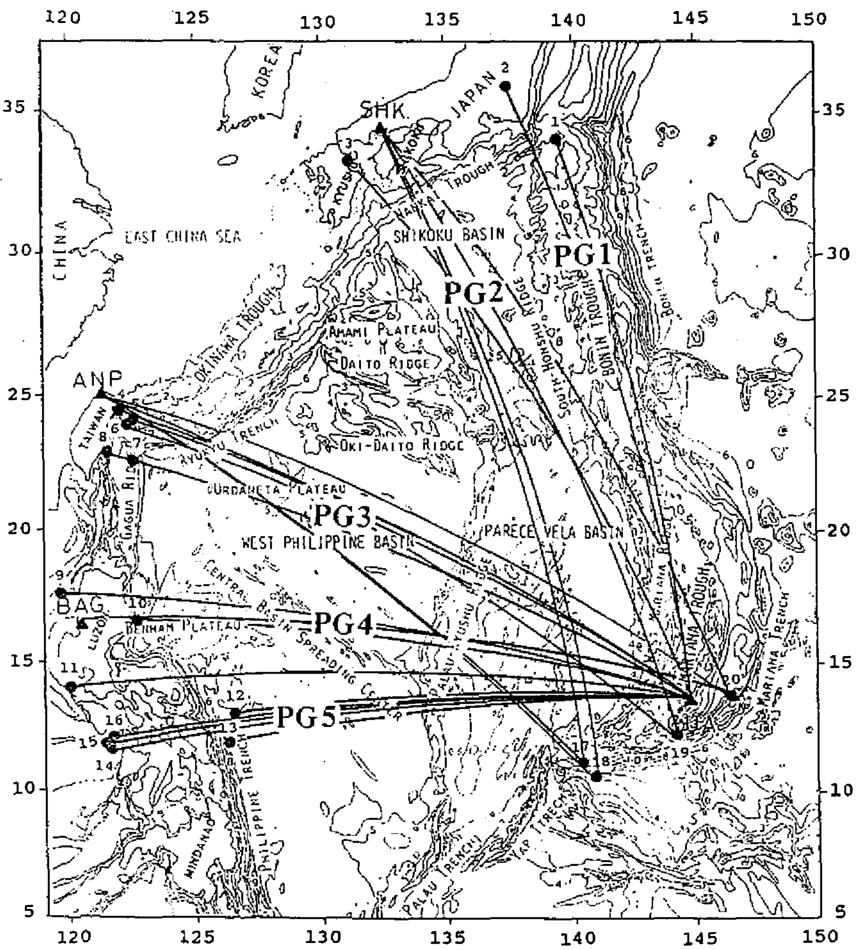

Fig. 1. **Map of major structural features of the Philippine Sea (from Mammerickx *et al.*, 1976). Contour interval = 1000 *m*. The approximate Rayleigh wave paths are also shown on the map. Symbols of PG1 through PG5 indicate the five different path groups concerned in the study.**

These parallel topographic features have been used as evidence for the extensional or back-arc spreading origin interpretation of the Philippine Sea (Karig, 1971). Moreover, recent geological and geophysical surveys indicate that the Mariana trough is the youngest basin with active back-arc spreading in the Philippine Sea (Karig *et al.*, 1978; Bibee *et al.*, 1980).

The western Philippine Sea contains a series of ridge complexes in the north, the Daito and Oki-Daito ridges and the Amami plateau. These ridges trend nearly to east-west and terminate on the west by the Ryukyu trench and on the east by the Palau-Kyushu ridge. The Daito Ridge Complex has been interpreted as remnant arcs (Murauchi *et al.*, 1968; Mizuno *et al.*, 1978) and as continental fragments (Nur and Ben-Avraham, 1982). In the southern

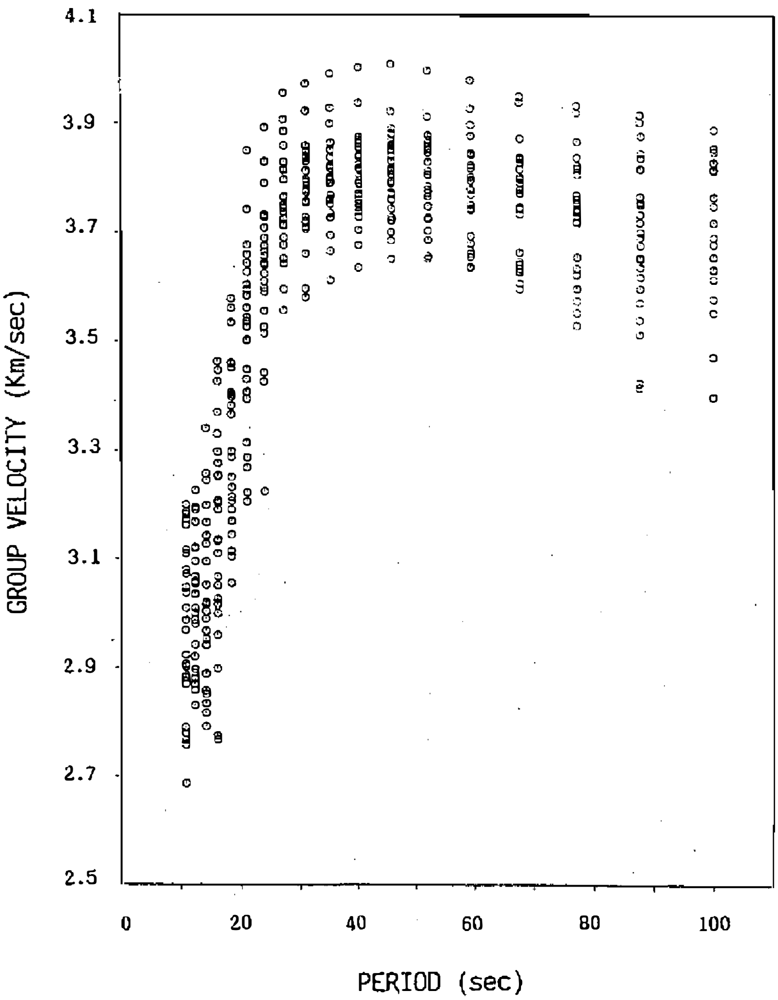

Fig. 2. **Group velocity distributions of the twenty-three Rayleigh wave paths.**

portion, Ben-Avraham *et al.* (1972) described a ridge (the so-called Central Basin Ridge) as a linear zone of rough, irregular topography that bisects the basin, extending northwest from the Palau-Kyushu ridge to the vicinity of either Taiwan or Luzon (see Figure 1). This ridge was assumed to be an inactive inter-arc spreading system (Karig, 1973) and a portion of the mid-ocean speading center trapped behind a subduction zone initiated along Palau-Kyushu at 42-45 Ma (Uyeda and Ben-Avraham, 1972; Hilde *et al.*, 1977). Based on a long-term study of the magnetic lineations and bathymetric data, Hilde and Lee (1984) suggested that this ridge should be interpreted as the Central Basin Spreading Center.

According to the studies of Kobayashi and Nakada (1978), Mrozowski and Hayes (1979), Hussog and Uyeda (1981), and Mrozowski *et al.* (1982),

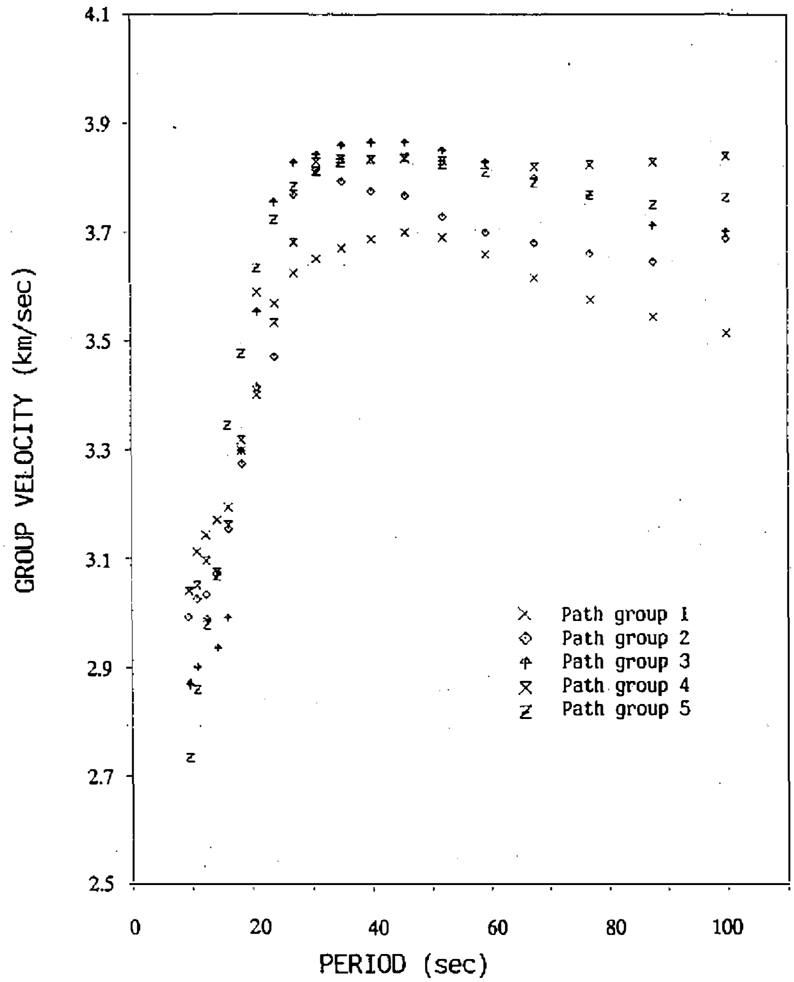

Fig. 3. The dispersion variation of the five different path groups.

the Mariana trough, the Shikoku and Parece Vela basins, and the west Philippine basin were formed by spreading between 6-0 Ma, 30-17 Ma, and 48-40 Ma ago, respectively (ref. Seno and Maruyama, 1984). Based on the identification of magnetic anomalies and data synthesis from the Deep Sea Drilling Project with other marine geophysical and geological observations, Seno and Maruyama (1984) made a paleogeographic reconstruction of the Philippine Sea. They suggested that the Philippine Sea was formed by two distinct episodes of back-arc spreading. In the first episode, the Proto-Izu-Bonin trench retreated northward and the west Philippine basin formed behind the north half of the Palau-Kyushu ridge. In the second episode, the Izu- Mariana trench retreated eastward and the Shikoku and Parece Vela basins formed behind it. If this reconstruction is really the case for the origin of the Philippine Sea, then the structure of the western Philippine Sea must be different than that of the eastern basin.

Thus, detailed study of lateral variations in the upper mantle structure of the Philippine Sea would be helpful to provide evidence supporting this evolution postulation.

3. DATA SELECTION AND ANALYSIS

In this study, the vertical components of long-period seismograms from the World-Wide Standard Seismograph Network (WWSSN) stations, ANP (Anpu, Taiwan), BAG (Baguio, Luzon), GUA (Guam, Mariana), and SHK (Shiraki, Honshu), generated by twenty shallow-depth, moderate-size earthquakes located at or near the perimeter of Philippine Sea (Table 1), have been used to determine the group velocities of the Rayleigh waves. The selected seismograms have been digitized at variable interval points including every major break in the slope so that the shape of the curve can be reproduced in the output. The digitized record length was chosen to include all waves arriving at velocities between 1.5 and 4.5 *km/sec*. Noise levels on all of the selected seismograms are very low.

All useful digitized data are processed by the FTAN (frequency-time analysis) technique. Generally, there are four different Gaussian filters being proposed for FTAN : 1) the constant relative bandwidth filter (CRBF) (Dziewonski *et al.*, 1969) is the most commonly used, which keeps the Gaussian parameter

Table 1. Source parameters of the events used in the study.

Event No.	Date			Origin Time *hr*	*min*	*sec*	Location Lat.(*N*)	Long.(*E*)	Depth (*km*)	Magnitude (*MS*)
1	3	Oct.	1983	13	33	35.0	33.941	139.513	12	6.0
2	13	Sept.	1984	23	48	49.9	35.789	137.488	10	6.1
3	20	Apr.	1975	17	35	50.4	33.200	131.300	7	6.1
4	20	Mar.	1976	1	6	58.7	24.284	121.800	40	5.7
5	8	Feb.	1978	0	15	38.9	24.146	122.663	40	5.7
6	15	July	1977	2	12	54.4	24.051	122.214	33	5.7
7	23	May	1975	16	1	49.2	22.697	122.574	6	6.2
8	23	Feb.	1976	9	2	31.6	23.019	121.687	33	5.8
9	29	Aug.	1977	14	23	40.5	17.441	119.869	12	6.2
10	19	Mar.	1977	19	35	8.0	16.814	122.354	39	5.8
11	13	Feb.	1976	10	33	42.7	13.916	120.123	29	5.8
12	15	Feb.	1976	1	54	23.1	13.000	125.788	33	6.1
13	27	Nov.	1977	2	19	52.3	11.800	125.472	33	5.7
14	22	Oct.	1975	15	59	48.6	11.647	121.672	33	5.8
15	21	Oct.	1975	23	6	22.8	11.661	121.646	33	6.3
16	21	Oct.	1975	17	12	23.7	11.707	121.750	33	6.1
17	11	Aug.	1985	0	19	1.5	11.156	140.217	24	6.0
18	14	Feb.	1983	0	23	19.4	10.504	140.924	39	5.7
19	31	May	1985	7	24	34.1	12.246	144.280	32	6.0
20	3	Aug.	1983	6	4	39.6	12.741	146.340	47	5.9

α at a constant value throughout all periods; 2) the display-equalized filter (DEF) (Nyman and Landisman, 1977) averages the signal in a more natural way. The "averaging region" of this filter is approximately a circle of varying size throughout the frequency-time domain; 3) the optimum bandwidth filter (OBF) (Inston *et al.*, 1971) is the most complicated, which is designed to maximize the temporal resolution in the application of the FTAN. In using this filter, approximate dispersion properties of the signal are required; 4) the phase-matched filter (PMF) (Dziewonski *et al.*, 1972) measures the residual signal, which is the cross correlation of the observed seismograms with a theoretical signal whose dispersion approximates the observed dispersion. As the residual signal is less dispersive when compared to the observed seismogram, the determination of this dispersion is more precise, with smaller systematic errors.

A detailed study of the temporal resolution and accuracy among these four Gaussian filters, as applied to surface wave dispersion analysis over a broad period range, has been given by Feng and Teng (1983). An important conclusion of their study is that the optimum bandwidth filter gives a better performance for relatively short-period (less than 50 *sec*) dispersion measurements. Moreover, the phase-matched filter can improve dispersion measurement resolution over a broader period range with reduced systematic errors. For most periods between 10 and 200 seconds, the errors in group velocity are about 0.01 *km/sec* and relative errors in amplitude are about 5 percent. Thus, group velocities obtained from the phase-matched filter are used to further interpretation in the study.

Group velocities of the selected twenty-three Rayleigh-wave paths (Figure 1), are determined at period range between 10 and 100 seconds and plotted in Figure 2. From this Figure, we can easily see that distribution of these group velocities is quite scattered, indicating that lateral variations in structure should be considered. For this consideration, the twenty-three Rayleigh-wave paths are grouped into five different path groups, in each of which a major physiographic feature is present. Specifically, path group 1 passes only through the eastern volcanic island chain; path group 2 covers most portions of the Shikoku and Parece Vela basins; path groups 3, 4, and 5 are not so simple, however, each of them travels along more than one major physiographic features. For each path group, the dispersions of two or more paths are averaged to get a more reasonable dispersion curve. These averaged dispersion data are shown in Figure 3 and will be used to derive shear velocity models of the upper mantle in the next section.

The dispersion data for the eastern volcanic island region are carefully examined in the study, because the wave paths lie very close to the Izu-Bonin and Mariana trenches. A study of Seekins and Teng (1977) found that waves traveling through the entire length of the region were generally unusable. They considered that the unusable dispersion is propably due to severe interference from the downgoing Pacific plate. However, according to the studies of Katsumata and Sykes (1969) and Eguchi (1984), the Pacific plate is subducted at a high angle (nearly vertical) underneath the Philippine Sea plate beyond the frontal arc. Thus, the explanation of Seekins and Teng (1977) might be insufficient, because interference from multi-pathing is also important in the case of a path close to the plate boundary. However, the degree of interference from multi-pathing can also be reduced by processing the seismograms in which the waveform patterns look good (see Figure 4), and rejecting all paths within 15° in azimuth of a node in the amplitude radiation pattern. In this study, we present two fairly good dispersion curves for paths passing through the entire length of the region (path group 1) (see Figure 5). The dispersion curve obtained by Seekins and Teng (1977) for the AMB (active marginal basin) region is also shown in this Figure. From Figure 5, we can easily see that the dispersion data of the two paths are all higher than the values of Seekins and Teng (1977). Upon this result, a lower heat flow in the Bonin trough is suggested as compared to the value for the Mariana trough.

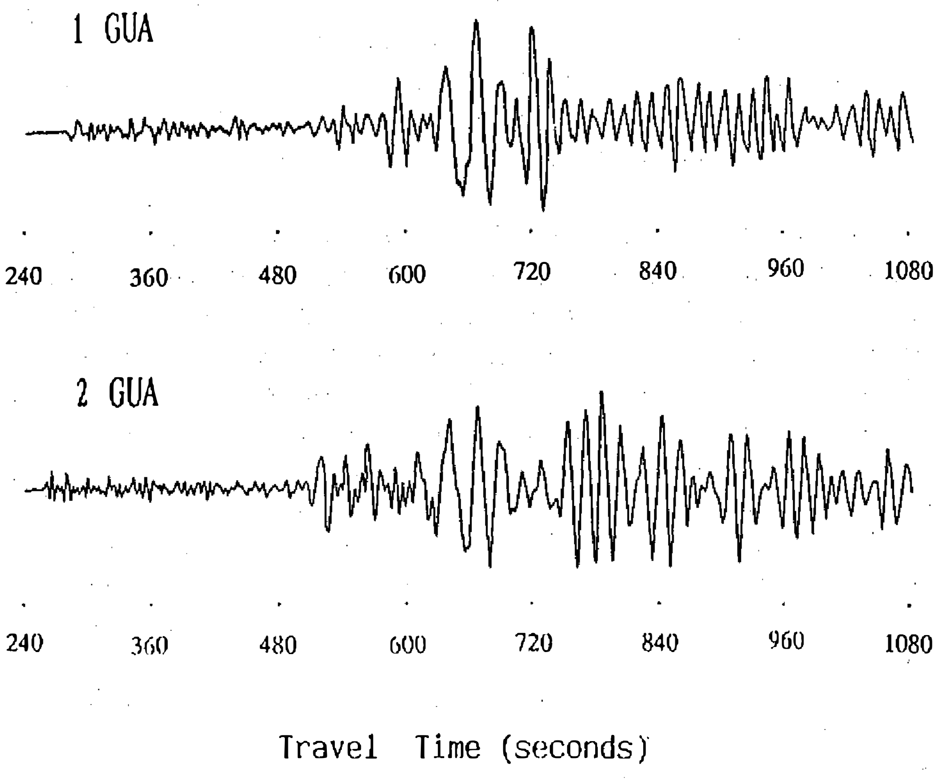

Fig. 4. **Two good quality original seismograms used in the study.**

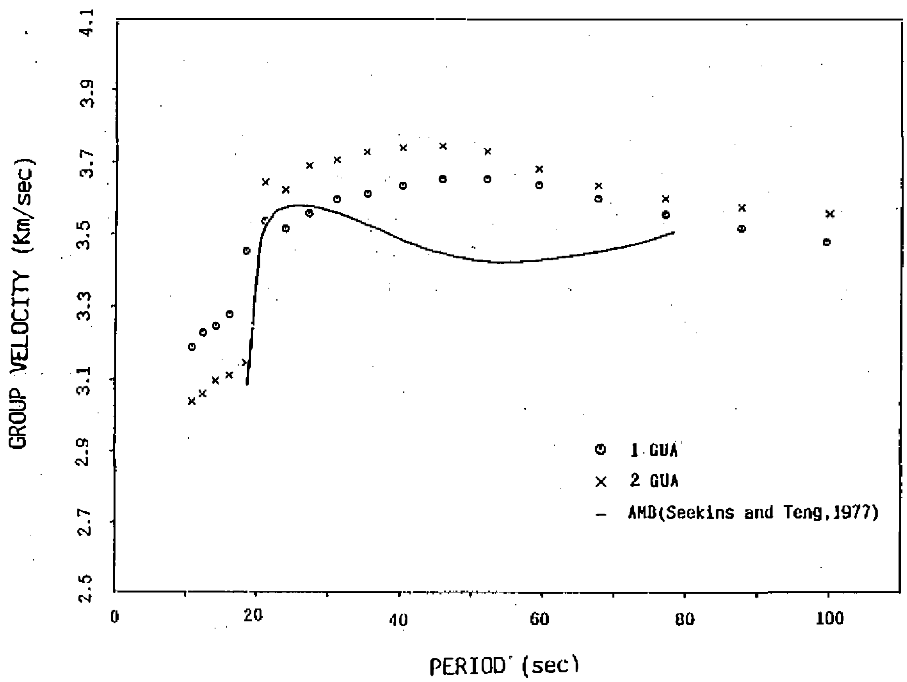

Fig. 5. The dispersion data of the two paths shown in Figure 4. The results of Seekins and Teng (1977) for the active marginal basin region is also shown for comparison.

4. UPPER MANTLE STRUCTURES

The dispersion curves of Figure 3 show that the averaged group velocities are lower for path group 1, intermediate for path group 2 and higher for path groups 3, 4, and 5. The velocity difference between path group 1 and path group 2, or between path group 2 and path group 3 is greater than 0.1 *km/sec*. The fact that velocities vary with the paths can be explained by either lateral changes in structure, azimuthal anisotropy, or both. However, Con's (1985) study has shown that the azimuthal anisotropy of the Philippine Sea is less than 0.5% if a uniform anisotropy is assumed for the whole Philippine Sea. The direction of maximum velocity is at approximately $340^{\circ} \pm 5^{\circ}$ from the north. So, the anisotropy is not the major factor with which we are concerned. On the other hand, lateral structural variation would play an important role in the basin. As the total path length in each subdivision of the major structural features is not evenly distributed, the pure-path method will not be used to derive the regionalized velocities in the study.

Shear velocity structure of the upper mantle beneath the Philippine Sea is derived by inversion of the dispersion data for each path group as shown in Figure 3. In doing this inversion, a crustal thickness of 11 *km* including the water layer is assumed for most portions of the basin except the eastern volcanic islands (path group 1, where a thickness of 14 *km* is assumed). Vertical distributions of the P velocities are taken from the studies of Murauchi *et al.* (1968) and Seekins and Teng (1977). The P velocity and density are fixed for all iterations of the inversion. The S velocities of Seekins and Teng (1977) are taken as the initial values for the inversion. After a few iterations, an acceptable shear velocity model for each path group was obtained. The acceptable shear velocity and its variance (1 σ) for each depth range derived by inversion of the dispersion data for the five different path groups is listed in Table 2. A comparison of variations among these models is also shown in Figure 6. Variation of the structure at depths greater than 165 *km* may not be well resolved because the period of the data is not long enough.

Table 2. The shear velocity and its variance (1 σ) of each depth range derived by inversion of the dispersion data for the five different path groups.

Depth Range (*km*)	Path Group 1 (*km/sec*)	Path Group 2 (*km/sec*)	Path Group 3 (*km/sec*)	Path Group 4 (*km/sec*)	Path Group 5 (*km/sec*)
‖11 ~ 30	4.41±0.04	4.49±0.03	4.61±0.05	4.57±0.03	4.59±0.03
30 ~ 65	3.78±0.03	4.12±0.05	4.35±0.04	4.30±0.02	4.31±0.03
65 ~ 105	4.00±0.03	3.86±0.03	4.24±0.04	4.23±0.03	4.25±0.02
105 ~ 165	4.18±0.03	4.19±0.02	4.03±0.06	4.01±0.03	4.05±0.03
165 ~	4.39±0.01	4.38±0.02	4.38±0.01	4.39±0.01	4.35±0.02

‖ The depth of 11 *km*, which represents the crustal thickness, will be replaced by 14 *km* for the model of path group 1.

From the inversion results, a substantially thinner lithosphere and a much softer asthenosphere are obtained when compared to Pacific structures. In the Pacific, the thickness of the lithosphere gradually thickens from about 30 *km* to greater than 150 *km* as the age of the ocean-floor increases (Yoshii, 1975; Schlue and Knopoff, 1977; Yu and Mitchell, 1979). A profile of the upper mantle structure in the approximate east-west direction is shown in Figure 7. In this Figure, the structure of the western Philippine Sea is probably not correct because path groups 3 through 5 have only about half portions of the paths which lie within the western Philippine Sea. However, if we can take the same area, the Parece Vela basin, off, then the differences of dispersion characteristics among path groups 2 through 5 will roughly represent the structural features of the Shikoku basin, the northwestern and southwestern Philippine Sea, respectively. In Figure 7, we find that shear velocities in the asthenosphere vary from about 3.8 *km/sec* to about 4.0 *km/sec*, which are much lower than the values obtained in the Pacific (the values are 4.1 ~ 4.2 *km/sec*). The softer asthenosphere can be explained by a higher degree of partial melting for minerals in

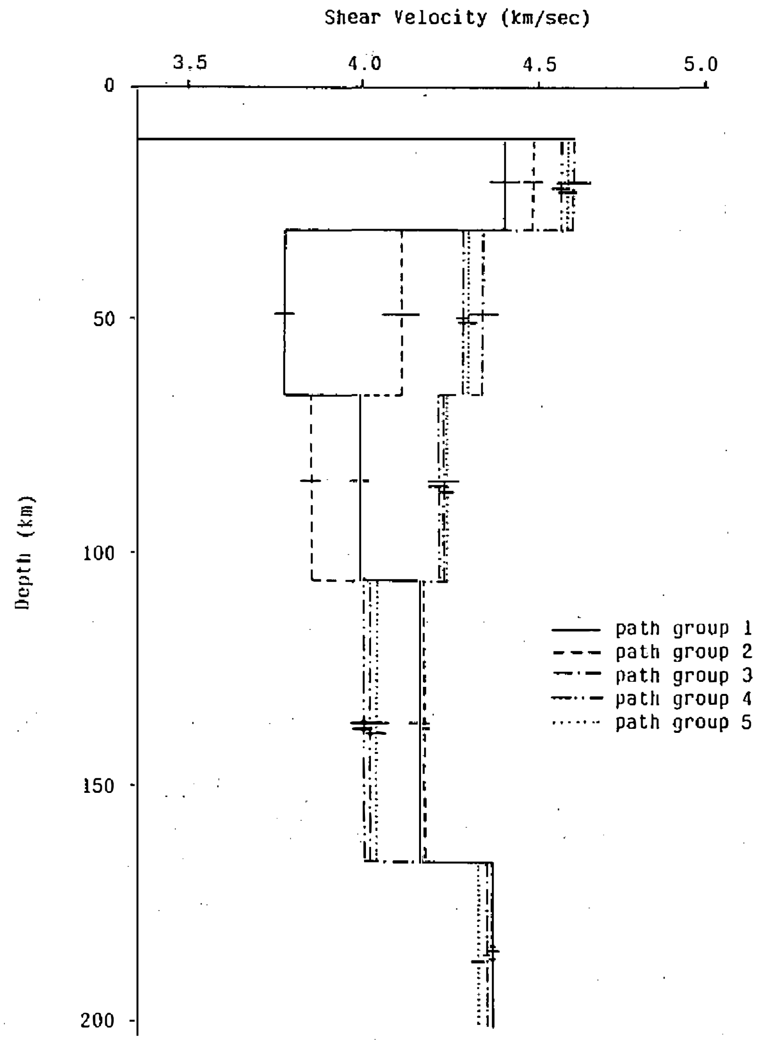

Fig. 6. Variation in shear velocity structures of the upper mantle beneath the Philippine Sea derived by inversion of the dispersion data in Figure 3. The variance of ±1 σ for velocity in each depth range is also shown in the figure.

the upper mantle and is consistent with high heat flow observations (Anderson, 1975; Sclater *et al.*, 1976). Depth to the top of the asthenosphere increases gradually from 30 km in the east to about 105 *km* in the west, suggesting that the upper asthenosphere is gradually cooling and solidifying from east to west throughout the whole basin. Similar dispersions for path groups 3 through 5 indicate that variations in the structure between the northern and southern portions of the west Philippine basin cannot be distinguished in this study.

Using the depth versus age data from DSDP holes in the Pacific Ocean and Philippine Sea, Louden (1980) concluded that the depth and heat flow values in the Philippine Sea are consistent with thermal models in which the

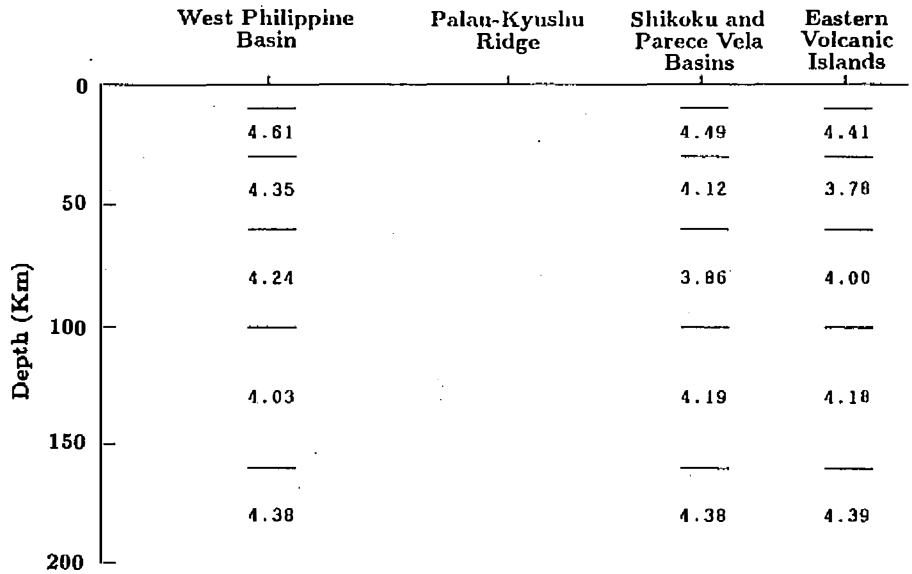

Fig. 7. A shear velocity structure profile of the upper mantle beneath the Philippine Sea in an approximate east-west direction.

lithosphere may remain thinner than it is in the Pacific, but still must reach a minimum thickness of at least 50 $\sim$ 75 km. However, there may be an as yet unexplained discrepancy between seismic and thermal plate thickness in the Philippine Sea. Thus, the gradually thickening transition layers between lithosphere and asthenosphere in regions of the Shikoku basin and the west Philippine basin may be referred to as the thermal structure model in this case.

5. CONCLUSIONS

In this study, group velocities of Rayleigh waves along twenty-three paths, which pass through most major physiographic features of the Philippine Sea, have been determined by using the phase-matched filter technique. These wave paths have been grouped into five different path groups, in each of which a major physiographic feature is present. Variations in dispersion data of the five path groups show that lateral changes in structure of the upper mantle beneath the Philippine Sea should be considered. The unusually low velocities in the eastern volcanic islands probably reflect high heat flow observations in that region (McKenzie and Sclater, 1968; Sclater, 1972; Anderson, 1975). Shear velocity structures of the upper mantle have been derived by inversion of the averaged dispersion data for each path group. The inversion results show that a substantially thinner lithosphere and a much softer asthenosphere, as compared to typical oceanic structures, were obtained. Although these results have already been suggested by previous studies (Kanamori and Abe, 1968; Seekins and Teng, 1977), the shear velocity distributions differ considerably from their studies for every similar region. For example, in the eastern volcanic islands, the result indicating a softer layer just underneath the lithosphere would be better than the result of Seekins and Teng (1977) in order to reflect the high heat flow observations in the area. Furthermore, variations of the derived upper mantle structures in the eastern volcanic island region, the Shikoku and Parece Vela basins, and the west Philippine basin would definitely support the evolution postulation of Seno and Maruyama (1984).

Another proposed conclusion of this study will be that a westward gradually cooling and solidifying feature in the upper asthenosphere is indicated, because the depth of the softer layer increases from east to west throughout the basin (Figure 7). However, structural variations between the northern and southern portions of the West Philippine Basin are not easily distinguished. Further studies on 3-D structures of the basin will be given in forthcoming papers.

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菲律賓海盆上部地函構造之側向變化

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摘要

本研究利用相位匹配濾波法分析23條穿越菲律賓海盆主要構造的雷利波群速資料，並藉以推研海盆上部地函構造之側向變化。這些波徑被歸類成五個波徑群，每個波徑群僅可能表現一個構造區的特性或可用來呈現某部分構造區的特性爲主。利用各波徑群的平均頻散資料推求各區之剪力波速度構造，結果顯示，相對於一般典型的海洋構造，菲律賓海盆存在著一個相當薄的岩石圈（僅約30公里厚）和一個甚軟的軟流圈（剪力波速度低至3.8公里／秒），且此甚軟的軟層在海盆東側的火山島地區立即出現在岩石圈下，並由東向西逐漸變深，這種特性不僅反應海盆東區所呈現的高熱流測值，也顯示軟流圈的上部由東向西有逐漸冷卻並固化的現象。再者，由本研究的資料尚無法分辨西菲律賓海盆北半部和南半部在構造上有否差異。