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15 Degree Shadow Zone of the P-wave Travel-times in the Western Northwest Pacific Basin Observed by an Ocean-bottom Seismometer Long Range Array

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Abstract

A long range ocean-bottom seismometer array observation in the western Northwest Pacific Basin revealed a P-wave shadow zone beyond the epicentral distance of 15°. The apparent surface velocity of the P-wave in the distance ranges from 12° to 15° is about 8.6 km/sec, which seems to be a continuation of the 8.4 km/sec (apparent surface velocity) travel-times in the range from 6° to 12°. The off-set of travel-times at the shadow zone is about 1.7-2.0 seconds. The low-velocity zone which corresponds to this shadow zone could be a major transition from lithosphere to asthenosphere. A review of the regional differences of shadow zone gives such an estimate that the depth of the transition is deep beneath the western Northwest Pacific Basin, roughly in a depth range of 100-200 km. The detailed structural analysis will be reported in the next paper.

1. Introduction

This paper reports the data which would indicate the lithosphere-asthenosphere transition beneath the western Northwest Pacific Basin. The depth of the transition from lithosphere to asthenosphere is an important parameter for defining the thickness of lithosphere, and the nature of the transition is essential for clarifying the mechanism of plate motion in the global scale.

Use of the inversion technique in the surface-wave studies revealed multi-layered solutions for the velocity distribution showing the complex nature of the transition from the lithosphere to the asthenosphere (FORTHYS, 1975 and 1977; WEIDNER, 1974; YU and MITCHELL, 1979; MITCHELL and YU, 1980). These results have shown that the definition of the thickness of the lithosphere is ambiguous. Use of body waves is a direct method to detect the detailed structure of the lithosphere-asthenosphere transition. Recent travel-time studies in the continental shield regions (HALES *et al.*, 1980; DRUMOND *et al.*, 1982) have found that the base of the lower-lithosphere is very deep extending to a depth of about 200 km and is bounded by the Lehmann discontinuity (ANDERSON, 1979; HALES *et al.* 1980). In the tectonically active regions, such as Japan and the Western United States, the subcrustal lithosphere is generally thin or absent and is underlain by a thick low velocity layer (JOHNSON, 1967; KANAMORI, 1976; ARCHAMBEAU *et al.*, 1969; MASSÉ *et al.*, 1972; BURDICK and HELMBERGER, 1978).

In the oceanic regions, even though a thick low velocity layer has been delineated below the lithosphere by the surface-wave studies, their detailed structures have not yet been fully detected by the body wave studies (HALES *et al.*, 1970; ASADA and SHIMAMURA, 1976, 1983; ORCUTT and DORMAN, 1977; NAGUMO *et al.*, 1981; LADLE STUDY GROUP, 1983; BIBEE *et al.*, 1985). The amount of the explosives used in these marine long range seismic explosion experiments was not sufficient enough for detecting refracted P-waves which cover the transitional zone from lithosphere to asthenosphere.

We attempted to utilize the large energy of natural earthquakes as sources for marine long range seismic refraction study for the upper mantle and performed an ocean-bottom seismometer long range array observation in the summer of 1981 in the westean Northwest Pacific Basin. This paper is a preliminary report on what we observed on the record sections about the transition from lithosphere to asthenosphere. The detailed study of the velocity-depth structure will be reported in the next paper.

2. Data and Results

In order to utilize natural earthquakes for the study of the upper mantle structures, we deployed two ocean-bottom seismometer arrays; one in the source region, the Japan Trench region in far-off Northeast Japan (see Fig. 1), for increasing the accuracy of the source data (origin time, depth and location of hypocenter), and the other array at long range from the source region for detecting the deep part of the lithosphere. The former is a network array of 7 stations covering an area about 100 km×200 km, enclosing the Japan trench axis in the middle (KASAHARA *et al*, 1981). The latter is a long line array of 4 stations extending southeasterly towards the Marcus island from the array in the Japan Trench region (Fig. 1). The ocean-bottom seimometer station data are listed in the accompaying paper (NAGUMO *et al.*, 1986). The obser-

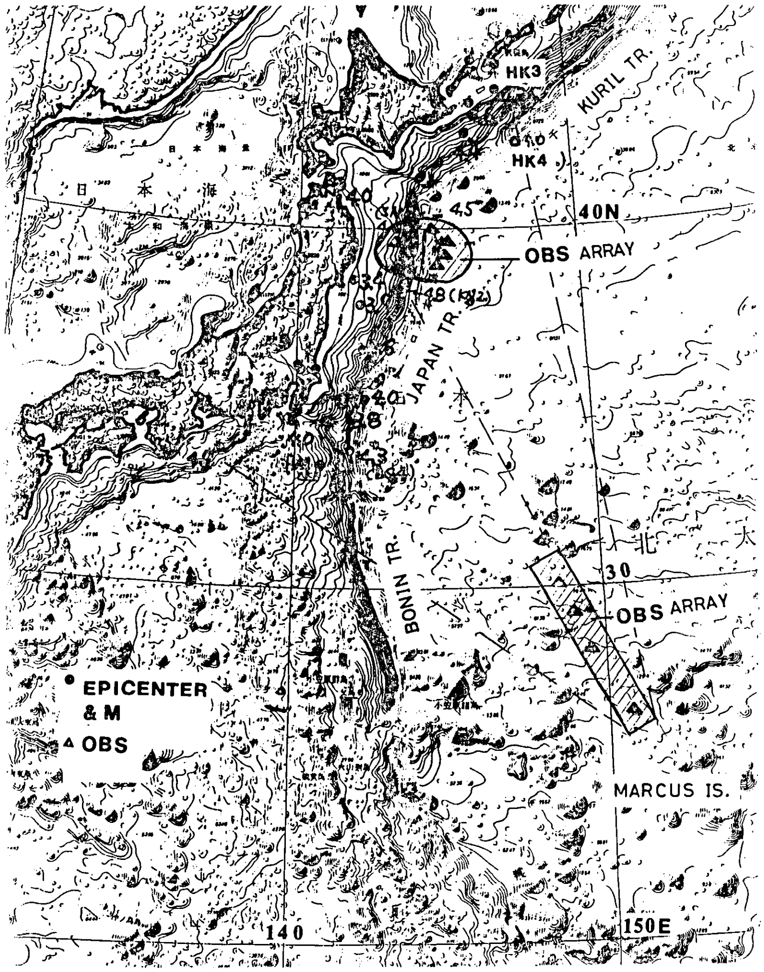

Fig. 1. Location of OBS (Ocean-Bottom Seismometer) array (solid triangles) and epicenters of natural earthquakes (solid circles). The one array deployed far off Northeast Japan is for increasing the accuracy of the earthquake source data, and the other array deployed southeasterly towards the Marcus Island is for covering long range observations.

vation period lasted about one month, from June 13 to July 11, 1981.

During the observation period, many earthquakes, whose magnitudes (M) were larger than 4.0 occurred in both the Japan Trench and the Kuril Trench regions. Their P-wave first arrivals were successfully detected in the long line array, the maximum epicentral distances being up to about 18°. Using the two earthquakes (HK 3 and HK 4, see Fig. 1) which occurred in the Kuril Trench region, a composite travel-time record section was constructed covering the epicentral distances from 12° to 18°

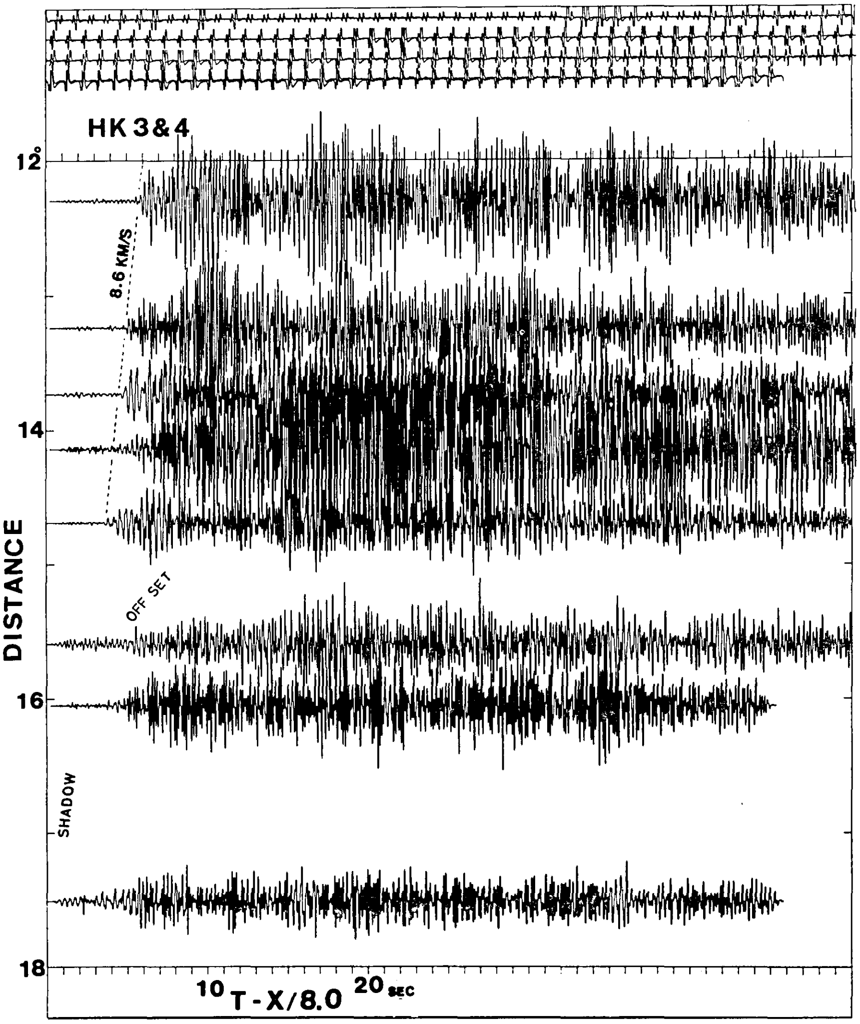

Fig. 2. Composit record section (vertical component) for the earthquakes HK 3 and HK 4. The travel times are reduced by a velocity of 8.0 km/sec. The unit of the epicentral distance is in degrees. A shadow zone of the 8.6 km/sec P-wave refraction is seen beyond 15 degree with an off-set of travel-times.

Table 1. Data of the earthquakes (from the Seismological Bulletin of the Japan Meteorological Agency).

Earthq. Name	Epicenter				Depth Focal	Origin Time						Magnitude
	D	M	D	M	KM				H	M	S	M
HK 3	43	49	147	25	00	1981	Jun.	29	14	50	26.2	4.3
HK 4	42	24	147	58	10		Jul.	05	19	22	48.9	4.0

(Fig. 2). The source data of these earthquakes, HK 3 and HK 4, are shown in the Table 1.

For composing a record section from several earthquakes, we need careful handling of the origin times. Usually, the origin times reported by the seismological bulletins include errors of a few seconds for the earthquakes which occur in this region. Therefore, it is necessary to correct these origin times properly for composing two or more earthquakes. Since the two record sections for HK 3 and HK 4 interlace one another, the amount of correction would be properly obtained by aligning the P-wave line-ups, namely by a method of base-line fitting. In Fig. 3 is shown the record sections for the earthquakes HK 3 and HK 4 separately. When there are neither discontinuity nor off-set in the travel-times, this procedure is satisfactory. However, when some discontinuity or off-set are present in the travel time curve, this procedure often includes some ambiguities. In such cases the amount of the correction should be examined by the other array deployed near the source region, where the travel-times of P-wave refraction from the uppermost mantle are generally uniform, and the interlaced record sections give reliable alignment. In this experiment, the array deployed in far off NE Japan played this role. In the case of the above two earthquakes, we did such an examination because there was a discontinuity in the travel-times and we found that the amounts of the origin time corrections obtained by the two arrays were almost the same, within an accuracy of less than 0.05 seconds, and assurred the base-line fitting to be almost satisfactory. As seen in Fig. 2, there is a remarkable discontinuity and off-set of travel-time line-up at the epicentral distances of about 15°. The apparent surface velocity in the distance range from 12° to 15° is about 8.6 km/sec. Beyond 14°, the amplitudes of the initial phases gradually diminish and disappear beyond 15°. This is a shadow zone. The arrivals of the first breaks which are seen beyond 15° show a travel-time off-set of about 1.7–2.0 seconds whose apparent velocity is, however, uncertain. This uncertainity would probable be due to mixing of the upper mantle refraction from the high-velocity zone below the low-volocity layer and the High-Frequency Pn phases which propagate through the upper part of the lithosphere as wave-guides. In this distance range, the High-Frequency Pn phases arrive a few seconds later than the mantle refracted P-phases (OUCHI *et al.*, 1983). The phases of large amplitudes appearing a few seconds after the initial P-phases in the distance range 12°–13° would include cusps of reflected waves from the underlying high-velocity layers. However their identifications are obscure. The travel-time curve of 8.6 km/sec (apparent velocity) in the distance ranges from 12° to 15° would be a continuation of the 8.4 km/s (apparent velocity) in the distance ranges

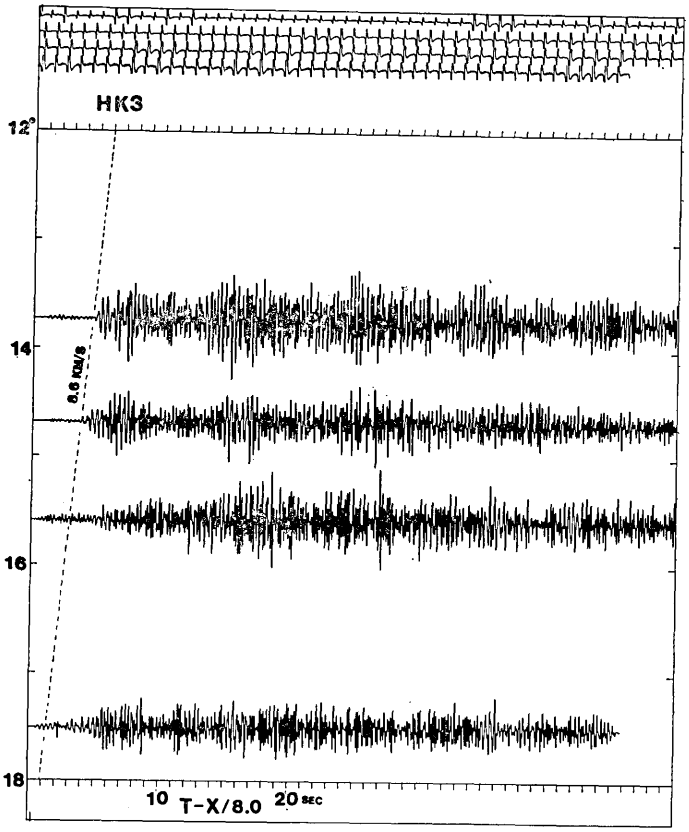

Fig. 3. (A)

from 6° to 11°, which was reported in the accompanying paper (NAGUMO *et al.*, 1986). In spite of a slight diminishing of the amplitudes in the distance ranges from 11° to 12°, there is no off-set of travel-times there. Thus, if we can assume laterally homogeneous layered earth in this region, the continuation of the refracted P-waves in the whole distance ranges from 6° to 15° would imply that the shadow zone beyond 15° would be a major transition from the lithosphere to the asthenosphere.

3. Discussion

Since one can get much important information about the seismic velocity structure only from the travel-time record sections without getting into detailed calculations, we will discuss in this section that the shadow zone of P-wave refraction from the lithosphere beyond the distance of about 15° would imply a great depth of the lithosphere-asthenosphere transition if we can assume lateral homogeneity of the seismic velocity structure in this region.

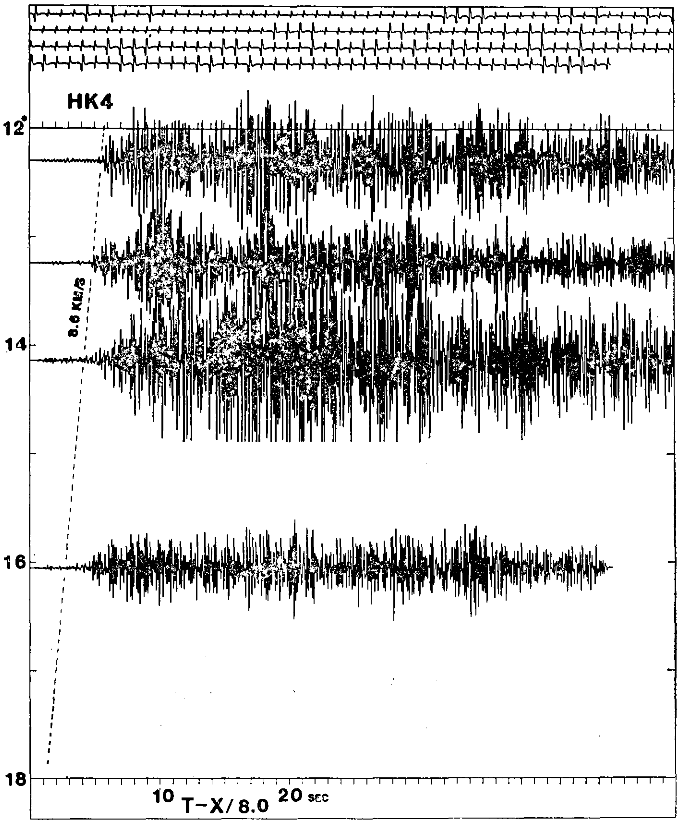

Fig. 3. (B)

Fig. 3. Travel-time (T) distance record sections (vertical component) for the earthquakes (A) HK 3 and (B) HK 4. The travel times are reduced by 8.0 km/sec. Unit of the epicentral distance is in degrees. TSHIFT is a constant for display starting time.

3.1. Shadow zone versus depth of low-velocity layer

As is well known, in the laterally homogeneous earth, the epicentral distance of a refracted ray corresponds to the depth of its turning point, and the apparent velocity along the surface, when corrected for the curvature effect, gives the true velocity at the depth of the turning point. Also a rapid decrease of the amplitude of the refracted waves indicates the presence of a negative gradient at the corresponding depth. Therefore, the epicentral distance of the shadow zone is an important data which constrains depth of the low-velocity layer.

However, the estimation of the depth at the deepest point of the ray from the distance of the shadow zone depends upon the velocity distribution in the crust and the upper mantle, especially upon the velocity gradient. Therefore, for such an estimation we need detailed data of travel-times which cover the whole range from the near source region to the shadow zone. Before going into such detailed analyses, however, we can get an approximate idea about the depth of the transition from the data itself based on present knowledge. The standard travel-time tables will be a referene of such an estimation. For example, the table by ICHIKAWA and MOCHIZUKI (1971), which has been used in the Japan Meteorological Agency for locating earthquakes in and near Japan, gives a depth of 220 km for the epicentral distance of about 15° for a surface focus earthquake. The thickness of lithosphere given by this value is deeper than those reported in many regions in the world. Another reference will be the data of the range of shadow zones themselves, which are used to analyze the base of the lithosphere.

3.2. Regional difference of the range of shadow zone

Firstly, we will review the data on the range of the shadow zone in the continental shield regions, and, secondly, in the tectonically active regions. In many continental shield regions, the P-wave refraction from the lower-lithosphere extends beyond the epicentral distance of 15° and the shadow zone does not appear up to 20°. In the Central United States, the apparent surface velocity of 8.5 km/sec continues to appear up to the epicentral distance of 2300 km (Fig. 7 in GREEN and HALES, 1968). In the Canadian shield region, the apparent surface velocity of 8.43 km/sec continues to appear up to 1500 km (Fig. 10 in MEREU and HUNTER, 1969) where the observation line was terminated. In Western Russia and Fennoscandia, the P-wave refractions from the lower lithosphere appear as the first arrivals in the ranges from 11° to 21° and as later arrivals farther up to 33° (Fig. 2 in KING and CALCAGNILE, 1976). In Northwest Australia, the apparent surface velocity of 8.4 km/sec continues to appear up to 1700 km (DRUMOND *et al.*, 1982). The velocity-depth structures in the upper mantle analyzed from the above observations show that the lower-lithosphere extends to the 400 km discontinuity without low-velocity layer. In Central North America, the P-wave velocity rapidly increases to 8.32 km/sec at a depth of 89 km and then gradually increases up to 8.58 km/sec at a depth of 362 km (Table 4 in GREEN and HALES, 1968). In Western Russia and Fennoscandia it is 8.2 km/sec at a depth of 100 km and it increases to 8.66 km/sec at a depth of 420 km. These features of the lower-lithosphere seem to be generally seen in the continental shield regions as remarked by HALES and RYNN (1978). Within such a framework, the existence of the Lehmann discontinuity (ANDERSON, 1979) has been detected in Northwest Australia as a basal high-velocity "knee" of lithosphere at a depth of about 200 km (DRUMOND *et al.*, 1982).

Even though the studies cited above show the absence of low-velocity layer in the upper mantle, there are many studies reporting the presence of low-velocity layers in the continental shield regions. In the Canadian shield region, MEREU and HUNTER (1969) reported the presence of a weak shadow zone at epicentral distances between 10° to 12.5°, which is indicated by a diminishing of the P-wave amplitudes but has no travel-time off-set. In Central North America, the Early Rise Model 2 of GREEN and HALES (1968) allowed the existence of a low-velocity zone which was indicated on the composite travel-time curves for Wichita and Little Rock profiles by a small travel-time off-set which appeared at an epicentral distance of about 1500 km. MASSÉ (1973) included a thin low-velocity layer at depths of 94–104 km in the average model for the upper mantle structure in Central and Eastern North America. In Western Russia and Fennoscandia, even though the Model KCA of KING and CANCAGNILE (1976) does not include any low-velocity layer, the Model K8 of GIVEN and HELMBERGER (1980) noted the existence of a small low-velocity zone at the base of the lithosphere at a depth of 150–200 km. This finding was derived from the wave from analyses using synthetic seismograms even though there is no shadow zone. From these studies the existence of low-velocity layer beneath the lithosphere in the continental shield region seems to be weak and thin even it exists. The regional variations of this feature are great. For example, in France (HIRN *et al.*, 1973; KIND, 1974), the Russian plateau and Eurasia (RYABOY, 1977; ALESEEV *et al.*, 1973; VINNIK and RYABOY, 1981; YEGORKIN and PAVLENKOVA, 1981, and an review by FUCHS and VINNIK, 1982; SACKS and SNOKE, 1984), the existence of low-velocity zones has been reported even within the lithosphere. They are evident from the shadow zones and off-sets of travel-times.

From the above review, we think that the thick layered structure of the lithosphere without low-velocity layer could be a feature of an end member of the evolution of lithosphere, where the evolution has matured. The presence of a thin or weak low-velocity layer in the continental shield regions could be regarded as a variation of maturity. Comparing the western Northwest Pacific Basin with the continental shield regions, we think that the lithosphere structure in the western Northwest Pacific Basin is similar to those in the matured continental shield regions except for the presence of low-velocity layer at its base.

In the continental tectonically active regions, the shadow zone of the P-wave refraction appears in the epicentral distance of 10°–13° (KISHIMOTO, 1956; KANAMORI, 1967; JOHNSON, 1967). This feature is quite different from those in the western Northwest Pacific Basin. The apparent surface velocities are generally less than 8.0 km/sec. In these regions, the upper mantle structures are characterized by a thick low-velocity zone with or without a thin high-velocity lid at the top. Beneath the Basin and Range region (MASSÉ *et al.*, 1972), the velocity of the uppermost mantle layer is about 7.7–7.8 km/sec, and it extends to a depth of about 150 km where the velocity rapidly increases to 8.3 km/sec. Beneath the Japanese island arc, the velocity of the upper mantle is anomalous, about 7.5 km/sec, below the Moho-discontinuity (HIRAHARA, 1977; HIRAHARA and MIKUMO, 1980). The upper mantle structure in these tectonically active regions may be regarded as the other end member of the evolution of lithosphere. They could be an early state or rejuvenated state of evolution.

As seen in the above review, a comparison of the shadow zones of the lithosphere refraction in several regions indicates that the lithosphere-asthenosphere structure beneath the Northwest Pacific Basin is quite different from the tectonically active regions, and it is similar to the matured continental shield region except for the basal low-velocity layer. Thus, the depth estimation of the diving rays which appear at the surface beyond the epicentral distance 15° in the continental shield regions will be another reference for the thickness of the lithosphere. It can be shown by ray tracing that the depth of the turning rays which appear at the epicentral distance of 15° are about 100–120 km in the model of Central North America (Early Rise Model 1 of GREEN and HALES, 1968) and in the model KCA of Western Russia and Fennoscandia (KING and CALCAGNILE, 1976). These are shallower than those given by the travel-time table of ICHIKAWA and MOCHIZUKI (1971). Thus the approximate depth of the transition in the western Northwest Pacific Basin seems to be in the range of 100–220 km. A more detailed study about the transition will be reported in the next paper.

4. Coclusions

In the western Northwest Pacific Basin a shadow zone of the P-wave refraction from the lower-lithosphere was observed beyond the epicentral distance of 15°. This feature would imply that the lower-lithosphere is underlain by a low-velocity layer which could be a major transition from lithosphere to asthenosphere.

The layered structure of the lithosphere in the western Northwest Pacific Basin appears to be similar to those in the continental shield regions except for the presence of the low-velocity layer underneath. The epicentral distance 15° of the shadow zone indicates that the depth of the lithosphere-asthenosphere transition is very deep.

The lithosphere structure in the western Northwest Pacific Basin is quite different from those in the tectonically active regions which are characterized by a thick low-velocity layer with or without a high-velocity lid at top.

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北西太平洋海盆西部における P 波走時の 15° 以遠の影領域

──海底地震計長距離群列観測──

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東京大学地震研究所　笠原順三
東京大学地震研究所　是澤定之

海洋リソスフィヤの深部構造を調べるために 1981 年夏北西太平洋海盆西域において海底地震計の長距離群列観測を行った．リソスフィヤからアセノスフィヤへの遷移を調べるためには人工地震の薬量では不充分なので，自然地震の大きなエネルギーを震源に利用した．自然地震を地震探査の震源に用いる時の難点は震源要素（発震時，震源位置）の精度にある．この精度を上げるために震源域に当る三陸沖・日本海溝域に 7 点の群列観測網を設けた．深部構造を検出するために，もう 1 つの直線的群列（4 観測点，測線長約 500 km）を小笠原はるか東方，マーカス島北西海域に展開した．

1981 年 6 月 13 日から 7 月 12 日まで約 1 ヶ月間の観測データが得られた．この期間中 $M \geq 4.0$ の地震が，南千島・日本海溝域に数多く起り，良好の S/N 比で記録された．一番遠い震央距離を覆う 2 つの地震（南千島の HK 3 と NK 4，第 1 図参照）について合成走時記録断面を作った（第 2 図）．この図に見られるように，震央距離 15° 以遠において P 波初動の振巾は急激に小さくなり，いわゆる影領域（Shadow zone）が現れている．この影領域には約 1.7～2.0 秒の走時オフセットを伴っており，低速度層の介在を示している．

震央距離（Δ）$12^\circ < \Delta < 15^\circ$ の P 波見掛け速度は 8.6 km/sec で，これは前報の $6^\circ < \Delta < 12^\circ$ の見掛け速度 8.4 km/sec の続きとみられる．従って，$\Delta > 15^\circ$ の影領域はリソスフィヤからアセノスフィヤへの主な遷移を示す低速度層に対応するものと考えられる．

影領域の現れる震央距離は低速度層の深さに対応する大切な観測量なので，その深さの大凡の目やすを得るため，影領域の地域性を調べてみた．中部北米大陸やフェノスカンディアなどの大陸シールド帯ではリソスフィヤからの P 屈折波が 20° 以遠まで続き，影領域は表れていない．日本弧や西部アメリカなどの活動的造構帯では震央距離 10°～13° に影領域が表われている．低速度層の深さの大凡の値を知るために，屈折波の最深点の深さを波線追跡法で当ってみた．シールド帯の構造において震央距離 15° に対応する波の最深点の深さは，波線追跡法で約 100～120 km と求まる．一方市川・望月の走時表では約 220 km という値が得られる．これから北西太平洋海盆西域のリソスフィヤ－アセノスフィヤ遷移の深さは大凡 100 km～200 km という目安を得る．次報に詳しい構造解析を記す．