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P-wave Velocity in the Lower-Lithosphere in the Western Northwest Pacific Basin Observed by an Ocean-bottom Seismometer Long Range Array

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Abstract

Using natural earthquakes as sources in the seismic refraction method for studying the upper mantle structure, an ocean-bottom seismometer array observation was performed in the western Northwest Pacific Basin in the summer of 1981. This observation revealed that the apparent surface velocity of P-waves refracted from the lower-lithosphere was observed as 8.4 km/sec in the epicentral distances of 7°–9°. The true velocities at their turning points (depth level 60–100 km) were about 8.3 km/sec. The existence of 8.4–8.5 km/sec (apparent velocity) layers at the top of the lower-lithosphere appears to be a general feature not only beneath the continental shield regions but also beneath the old ocean basins. Such a P-wave velocity supports the garnet-pyrolite model for the mineralogical composition of the lower-lithosphere.

1. Introduction

This paper reports that the apparent surface velocity of P-waves refracted from the lower-lithosphere beneath the western Northwest Pacific Basin was observed as 8.4 km/sec in the epicentral distances of 7°–9°, and also presents a discussion on the petrological model of the upper mantle. The existence of layered structures in the subcrustal lithosphere has been found in many geological regions in the world since the Lake Superior seismic explosion experiment in the 1960s (for example, HALES, 1969, 1972, 1981, HALES and RYNN, 1978, HALES *et al.* 1980). These findings advanced the view that the existence of layered structures in the subcrustal lithosphere is a general feature in the world but has some regional variations among continental shield regions, tectonically active regions and oceanic regions. Beneath the continental shield regions, the uppermost mantle layer directly below the Moho-discontinuity is underlain by a lower-lithosphere. The apparent surface velocities of P-waves refracted from the uppermost mantle layer below the Moho are 8.0–8/2 km/sec and those from the lower-lithosphere are 8.4–8.5 km/sec in the distance ranges of 600–1500 km (GREEN and HALES, 1968; MEREU and HUNTER, 1969; MASSÉ, 1973; HALES and RYNN, 1978; HALES *et al.*, 1980; DRUMOND *et al.*, 1982). In the tectonically active regions such as the Western United State and the Japanese island-arc, however, the lower-lithosphere is absent and the uppermost mantle is anomalous forming a thick low-velocity layer with or without a higher-velocity lid at the top (ARCHAMBEAU *et al.*, 1969; MASSÉ *et al.*, 1972; BURDICK and HELMBERGER, 1978; KANAMORI, 1967; KISHIMOTO, 1956; MIZOUE and TSUJIURA, 1974; FUKAO, 1977; INATANI and KURITA, 1980; HIRAHARA, 1977; HIRAHARA and MIKUMO, 1980).

Beneath the old oceanic basins, layered structures which are similar to the continental shield regions have been found by long range marine seismic explosion experiments in the Gulf of Mexico (HALES *et al.*, 1970) the Northwest Pacific (ASADA and SHIMAMURA, 1976, 1983), the East Mariana Basin (NAGUMO *et al.*, 1981), the East Pacific Ocean (ORCUTT and DORMAN, 1977), western North Atlantic Ocean (The LADLE STUDY GROUP, 1983), and the West Philippine Sea (BIBEE *et al.*, 1985). The values of P-wave velocities in the lower-lithosphere, however, have shown wide variations in different regions. Very high-velocities, higher than 8.77 km/sec (apparent) at distance ranges 360–800 km, were reported from the Gulf of Mexico. Similar features are also reported from the Northwest Pacific and the western North Atlantic Ocean. While the normal velocities of 8.3–8.4 km/sec (apparent) at a top of lower-lithosphere have been reported from the East Mariana Basin and the East Pacific Ocean. Since the values of P-wave velocities are essential constraints for modeling the petrological composition as well as for clarifying the nature of the discontinuity within the upper mantle, accurate measurements of P-wave velocities beneath ocean basins have been desired.

2. Data and Results

When an ocean-bottom seismometer array observation was performed in the western Northwest Pacific Basin in June-July, 1981, many natural earthquakes whose magnitudes (M) larger than 4.0 were observed in the distance ranges between 6° and 18° (Fig. 1). The first arrivals in the epicentral distances from 6° and 10° show that the apparent surface velocity is 8.4 km/sec. Some examples of the travel-time record sections

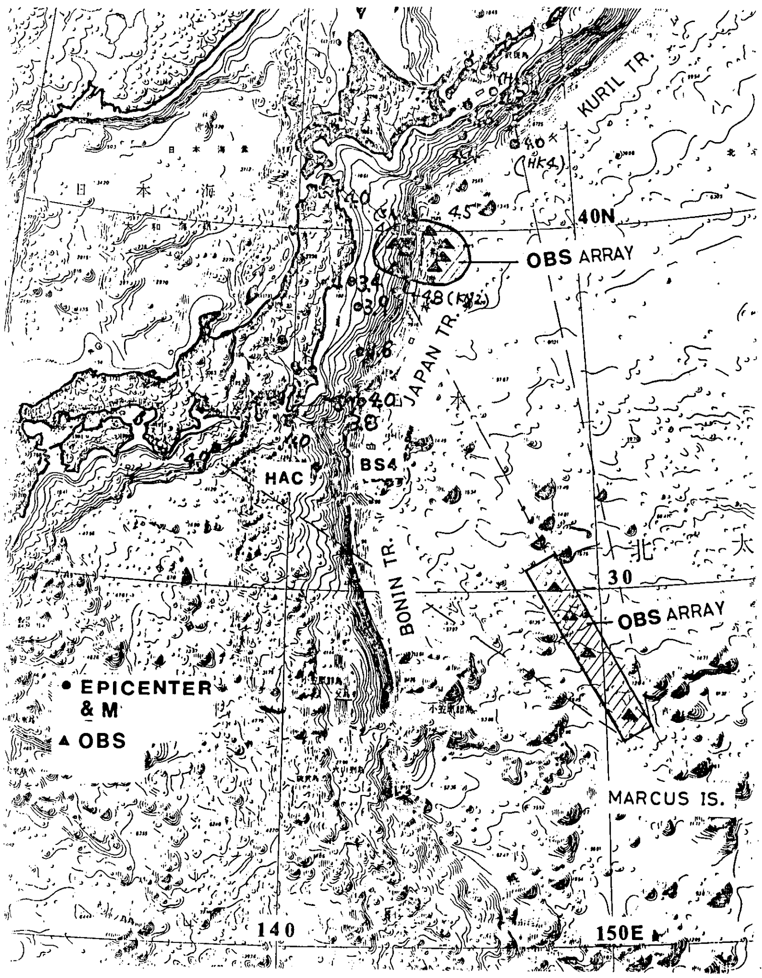


Fig. 1. Location of OBS (Ocean-Bottom Seismometer) array (solid triangles) and epicenters of natural earthquakes (solid circles). The one array deployed far off Northeast Japan is for increasing the accuracy of the earthquake source data, and the other array deployed southeasterly towards the Marcus Island is for covering long range observations. The record sections are made for the earthquakes HAC and BS4.

are presented in Fig. 2. The data of the ocean-bottom seismometer stations and these earthquakes are listed in the Tables 1 and 2.

The ocean-bottom seismometers are pop-up and acoustic release type (KASAHARA *et al.*, 1979; NAGUMO *et al.*, 1982). The sensors are one vertical and one horizontal geophone (f = 2.0 Hz) and one hydrophone. The recording is a continuous direct recording on a 4-track cassette tape recorder which runs about 900 hours. The over-all frequency responce,

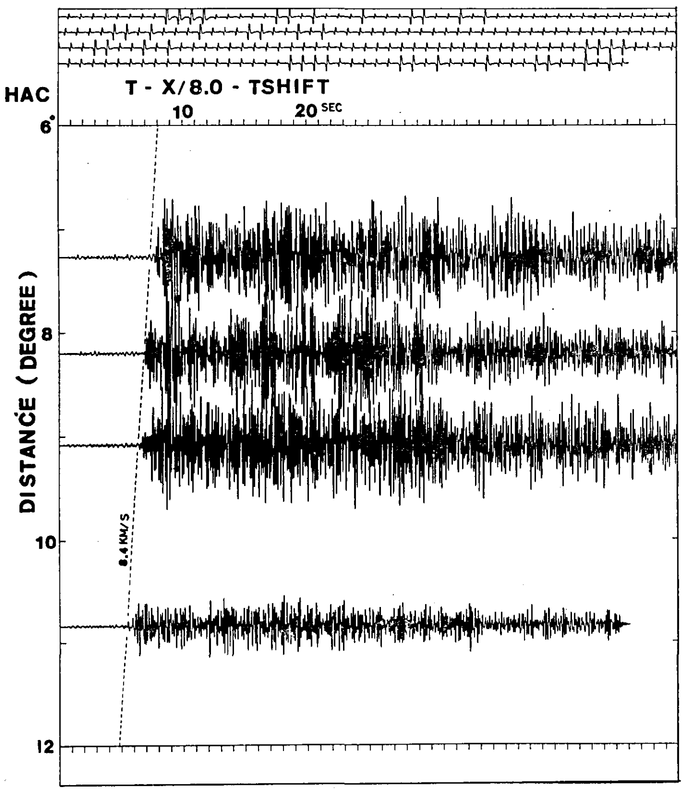


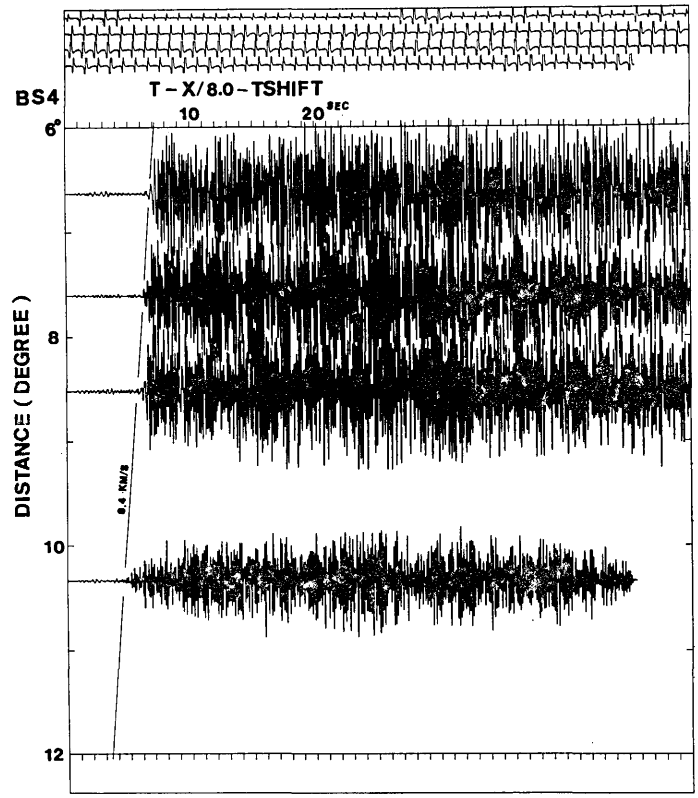
Fig. 2. (A)

Table 1. Data of the Ocean-Bottom Seismometer (OBS) stations.

Station Number	Position		Water Depth	Deployment	Recovery
	D M	D M	M	H M	H M
NY12	30 05.03N	148 27.27E	6160	1981 JUN 11 20:05	JUL 11 03:45
NY13	29 09.64	149 03.05	6040	JUN 12 06:12	JUL 14 02:35
NY14	28 17.42	149 34.61	6100	JUN 12 14:23	JUL 12 02:54
NY15	26 26.07	150 24.10	5760	JUN 15 08:19	JUL 12 18:35
EOF..					

including playback, is flat (−3 dB) in the frequency ranges from 1 to 15 Hz for the geophone channels and from 6 to 15 Hz for the hydrophone channel. The over-all signal-to-noise ratio is about 30 dB.

The travel-time record sections cover the epicentral distances from 7° to 11° for the earthquake HAC (Fig. 2A), and from 6° to 10° for the earthquake BS4 (Fig. 2B). The apparent surface velocities of these first arrivals are 8.4 km/sec in both cases. As seen on these record sections,



(B)

Fig. 2. Travel-time (T) distance record sections (vertical component) for the earthquakes (A) HAC and (B) BS4. The travel times are reduced by 8.0 km/sec. Unit for the epicentral distance is degree. TSHIFT is a constant for the display starting time.

Table 2. Data of the earthquakes (from the Seismological Bulletin of the Japan Meteorological Agency).

Earthq. Name	Epicenter		Focal Depth	Origin Time	Magnitude
	D M	D M	KM	H M S	M
HAC	33 34N	140 57E	70	1981 JUL 01 04 58 21.2	
BS 4	33 47	141 58	30	JUN 29 14 34 11.5	4.3

the first arrivals are of sufficient amplitudes and result in high accuracy (less than 0.05 km/sec of the velocity determination). Although there was a question whether these first arrivals are the mantle refracted P-waves or the HF-Pn (high-frequency Pn) phases (WALKER, 1981), it was clarified that these first arrivals are the refracted P-waves from the upper mantle, which arrive a little earlier than the HF-Pn phases (OUCHI *et al.*, 1983).

The true velocity v_t at the depth of the turning point of the refracted ray is lower than the apparent surface velocity v_{app} by the curvature effect of the earth's surface in the relation of $v_t=v_{app}(r_t/r_0)$, where $r_0=$ 6371 km: radius of the earth, r_t: radial distance from the center of the earth to the turning point of the refracted ray (MEREU, 1967). Although the exact depth of the turning point depends upon the velocity distribution, a preliminary estimation was made by using travel-time tables (for example, ICHIKAWA and MOCHIZUKI, 1971). The true velocity at the depth of the turning point for the apparent surface velocity 8.4 km/sec in a distance range from 7° to 9° is about 8.3 km/sec at a depth level 60–100 km. The continuation of the P-wave travel times beyond the epicentral distance 11° is presented in the accompanying paper (NAGUMO *et al.*, 1986).

3. Discussion

3.1 Worldwide feature

The observation of the P-wave apparent surface velocity of 8.4 km/sec in the epicentral distances of 7°–9° in the western Northwest Pacific Basin leads us to think that the existence of a layer of apparent surface velocity about 8.4 km/sec at the transition from the uppermost layer to the lower-lithosphere could be of a worldwide nature, not only common in the continental shield regions as remarked by MUIRHEAD *et al.* (1977), but also common in the regions of old ocean basins. The travel-time record sections and associated P-wave velocity models hitherto reported, however, show wide variations in different regions. Some of these variations might be caused by the lateral heterogeneity of P-wave velocity distributions and/or sedimentary layers. However, there should be some general features among these regions. In the following, we will review some of the data (record sections) and interpreted P-wave velocity models.

In the continental shield regions, the apparent surface velocities of refracted P-waves are 8.0–8.2 km/sec at the uppermost mantle layer (the layer below the Moho-discontinuity), and they increase to 8.4–8.5 km/sec (apparent surface velocity) at the top of the lower-lithosphere.

Such a rapid increase of P-wave velocity from the uppermost mantle to the lower-lithosphere has been observed in Central North America (GREEN and HALES, 1968), the Canadian shield (MEREU and HUNTER, 1969), Fennoscandia and western Russia (MASSÉ and ALEXANDER, 1974; KING and CALCAGNILE, 1976), the East European platform (VINNIK and RYABOY, 1981), France (HIRN *et al.*, 1973), North Australia (HALES and RYNN, 1978), South Australia (MUIRHEAD *et al.*, 1977), Northwest Australia (DRUMOND *et al.*, 1982), and in the North Caspian region (VINNIK and RYABOY, 1981). Although there are lateral heterogeneities in the upper mantle structures, as shown by YEGORKIN and PAVLENKOVA (1981) in the Eurasian continent, the existence of a rapid increase from the uppermost mantle to the lower-lithosphere appears to be a general feature of the upper mantle beneath the continental shield regions, and its associated velocity change is from 8.0–8.2 km/sec to 8.3–8.4 km/sec at depths of about 70–100 km.

Beneath the regions of ocean basins, the whole data hitherto reported also show the existence of layered structure in the subcrustal lithosphere. However, there is a wide variety in the values of the P-wave velocities. In the western Northwest Pacific Basin (this study), the apparent surface velocity was obtained as 8.4 km/sec (corresponding true velocity 8.3 km/sec at depth 60–100 km) in the distance ranges 7°–9°. In the East Pacific Ocean (ORCUTT and DORMAN, 1977), the high apparent velocity from the lower-lithosphere was observed in the distance ranges 300–600 km, and the corresponding true velocity was estimated as being less than 8.4 km/sec at depth 60 km. In the East Mariana Basin (NAGUMO *et al.*, 1981), the apparent velocities of the uppermost mantle were observed as 8.1–8.2 km/sec in the distance ranges 300–700 km, and the apparent velocity from a thin lower-lithosphere was observed as 8.4 km/sec in the distance ranges of 300–800 km. A corresponding true velocity was 8.33 km/sec at a depth of 46 km. Another high velocity layer of an apparent velocity of about 8.6 km/sec was observed from the base of the thick low-velocity layer in the ranges of 400–1100 km. The corresponding depth was 86 km. In the North Atlantic Ocean (LADLE STUDY GROUP, 1983), the apparent velocities were 8.24 km/sec in the distance ranges of 30–500 km and 8.65 km/sec in the distance ranges of 310–700 km. The corresponding jump of velocity was from 8.2 km/sec to 8.55 km/sec at a depth of 47 km. In the Gulf of Mexico (HALES *et al.*, 1970), the apparent velocity was 8.77 km/sec in the distance ranges of 360–800 km, the corresponding velocity jump being from 8.0 km/sec to 8.62–8.67 km/sec at a depth of 57 km. The velocity (8.6 km/sec at a depth of about 66 km) reported in the Northwest Pacific by ASADA and SHIMAMURA (1976) seems to be an over-estimation.

As seen above, the P-wave refractions from the lower-lithosphere arrive as first breaks beyond the epicentral distance of 300–600 km in the oceanic regions hitherto studied. However there are significant differences in their apparent velocities. The apparent velocities of refracted waves in the western Northwest Pacific, the East Pacific, and the East Mariana Basin were 8.4–8.5 km/sec and their true (in-situ) velocities were about 8.3–8.4 km/sec at depths of about 50–100 km, while those in the western North Atlantic Ocean and the Gulf of Mexico were 8.5–8.6 km/sec at depths of about 50–70 km. If we take the reservation made by HALES *et al.* (1970) into consideration, the high velocity of 8.6 km/sec beneath the Gulf of Mexico could be an apparent one which is caused by the lateral heterogeneity along the shooting line, which transects the Gulf and the Florida Peninsula. Thus, except for the case in the western North Atlantic Ocean, we think that the apparent surface velocity of P-waves refracted from the top of the lower-lithosphere beneath the old ocean basin is about 8.4 km/sec. Also, we think that the P-wave velocities at the top of the lower-lithosphere could be almost the same both beneath the continental shield regions and beneath the old ocean basins.

3.2 Petrological significances

Accurate knowledge about the seismic wave velocity distribution in the upper mantle is a very important constraint for considering the mineralogical composition and the state of the upper mantle rocks. As is well known, the mineralogical composition of the upper mantle rocks has been considered as those of either peridotite or eclogite, or pyrolites (WYLLIE, 1971; RINGWOOD, 1975; HARRISON and BONATTI, 1981). Which of these rocks or what combination of these rocks are the most appropriate for the upper mantle will be examined by seismic velocities.

HALES (1969) and HALES *et al.* (1970) presented the view that the velocity discontinuity from the uppermost mantle layer to the lower-lithosphere, that is from 8.05 km/sec to 8.3–8.4 km/sec at depths of 80–90 km, arises from the transition from spinel to garnet-peridotite. ITO (1974) has shown that the sub-Moho velocity discontinuity can be explained by a chemical boundary from peridotite composition (3 parts dunite, 1 part quartz eclogite) in the uppermost mantle to olivine eclogite composition (1 part dunite, 3 parts quartz eclogite) in the lower-lithosphere. HALES *et al.* (1980) recently made model calculations of seismic wave velocity distribution with depth using continental geotherm for upper mantle minerals (olivine, pyroxine, garnet) and their assemblages (pyroxene-pyrolite, garnet-pyrolite), and have shown that the seismic velocity distribution in the upper mantle can be fitted by the pyroxene-pyrolite composition in the uppermost mantle layer and by the garnet-pyrolite composition (57% olivine, 29% pyroxene, 14% garnet) in the lower-lithosphere. The values of the velocities which they calculated for the lower-lithosphere of garnet-pyrolite at a depth of 90–130 km are 8.30–8.37 km/sec (apparent velocities 8.42–8.54 km/sec) and they satisfy the velocities in the lower-lithosphere in the continental shield regions. Even though these values are calculated for the continental geotherm, they well agree with the results (about 8.3 km/sec at depths of 60–100 km) beneath the western Northwest Pacific Basin. Therefore, in the western Northwest Pacific Basin the P-wave velocities favor the view that the mineralogical composition at the top of the lower-lithosphere could be garnet-pyrolite instead of eclogite.

The velocities at the top of the lower-lithosphere in the West North Atlantic Ocean obtained by the LADLE GROUP (1983) were 8.55–8.62 km/sec at depths of 48–80 km, which are higher than those of the garnet-pyrolite in HALES *et al.* (1980). They interpreted them to be eclogite depleted from asthenosphere.

In the western Northwest Pacific Basin, the aspect of travel times beyond the epicentral distance of 12 degrees contains some complexities probably indicating fine structures associated with a lithosphere-asthenosphere transition. The details are reported in the accompanying paper.

4. Conclusions

The apparent surface velocity of P-waves refracted from the lower-lithosphere was observed as 8.4 km/sec in the distance ranges of 7°–9° in the western Northwest Pacific Basin. The corresponding true velocity is about 8.3 km/sec at a depth level of 60–100 km.

The presence of 8.4 km/sec layer at the transition from the uppermost layer to the lower-lithosphere appears to be a general feature beneath both the continental shield regions and old ocean basins.

The P-wave velocity 8.3–8.4 km/sec at a depth level of about 100 km supports the garnet-pyrolite model as a petrological composition in the lower-lithosphere. The transition from the uppermost mantle layer to the lower-lithosphere could be a chemical boundary from pyroxene-pyrolite to garnet-pyrolite.

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北西太平洋海盆西部における下部海洋リソスフィヤのP波速度

——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地震波速度を正確に知ることは，その岩石学的構成を知る上に重要なことである．1981年6月～7月，三陸沖日本海溝域からマーカス島北西海域にわたり海底地震計長距離群列観測を行った．人工地震では火薬量の制約があり，リソスフィヤ深部まで調べることが困難であるので，自然地震の大きなエネルギーを屈折法地震探査の震源として利用した．約1ヶ月の観測期間に$M \geq 4.0$の地震が数多く良いS/N比で記録された．震央距離6°—16°間のP波，S波の走時について良いデータが得られた．この論文では先づ6°—9°のP波走時について報告する．データ解析は各観測点で得られた地震記録をA/D変換して先づ計算機のディスクファイルに入れ，次に，任意の地震について各観測点の記録を読み出し走時記録断面を作るという手順によった．

震央距離7°—9°においてリソスフィヤ下部からの屈折P波の走時が明瞭に認められ，その表面見掛け速度が8.4 km/secと求められた．これに対応する真の速度は，地球表面の曲率効果のため地震波経路の最深点の深度に依存するが，深度60 km—100 kmに対して約8.3 km/secとなる．この値は従来この海域で報告されていたものより小さい．この速度は，下部リソスフィヤの岩石学的構成として，ガーネット・パイロライトモデル(57% オリビン，29% パイロキシン，19% ガーネット)を支持する．