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54. Mantle Structure beneath the Japan Sea as Revealed by Surface Waves.

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Abstract

Group velocities of long-period Rayleigh and Love waves are measured, by band-pass filtering and group-delay time methods, to study regional differences in a deep island arc structure. The measurements are made, over a period range 20 to 80 sec, for propagation paths across the Japan Sea. At longer periods, the observed group velocities of Rayleigh and Love waves are lower by as much as 0.1 km/sec than those for normal oceanic paths. It is found that the ARC-1 model, which was previously introduced to explain the low group velocities of long-period surface waves travelling across the Philippine Sea, can also explain these low group velocities. The major feature of this model is a reduction of mantle shear-velocity by 0.3 to 0.4 km/sec, or 8%, over a depth range 30 to 60 km as compared with that for normal oceanic models. This low mantle velocity and the high heat flow which was previously reported for this region suggest common causes such as high temperature and partial melting. The velocity contrast found here can be explained in terms of a 500°C temperature excess coupled with a 4% partial melting.

1. Introduction

The Japan Sea is a marginal sea lying between the Eurasia continent and the western Pacific Ocean. The Japan Sea is located just on the continental side of the Japan Arc where active volcanoes, deep earthquakes and deep trenches are concentrated. Because of these distinct tectonic features the Japan Sea, though small, plays an important role in discussions of island arc tectonics. Comprehensive summaries of the Japan Arc may be found in *Rikitake et al.* (1968), *Kanamori* (1970), and *Sugimura and Uyeda* (1971). The significance of the Japan Sea as a marginal sea is discussed by *Menard* (1967).

The regional difference of deep mantle structure is a key element

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in the elucidation of geophysical and geological phenomena associated with island arcs. The present paper is concerned with the determination of the deep mantle structure beneath the Japan Sea by a surface-wave approach. This approach is particularly useful for the study of deep structure under oceans where no seismographs can be installed. We employed digital methods to obtain the group velocity data. With these methods we can extend the period range to as long a period as possible for relatively short propagation paths. Data on long-period surface waves are indispensable for studying regional characteristics.

2. Data

Table 1 lists the data of earthquakes studied. Since these earthquakes were located on the basis of P times at as many as 200 stations,

Table 1. List of Earthquakes

No.	Date	Origin Time (GMT)	Latitude	Longitude	Depth (km)	Magnitude m	Bulletin	Region	l_o	l_c
1	1964 Aug. 04	$17^h 24^m 28.6^s$	46.57°N	151.36°E	86	5.7	ISC	Kurile Is.	0.84	0.16
2	1963 Oct. 14	13 21 37.0	44.79°N	151.13°E	0	5.9	ISS	Kurile Is.	0.68	0.32
3	1964 Nov. 06	09 53 20.5	44.44°N	149.09°E	42	5.7	ISC	Kurile Is.	0.67	0.33
4	1963 May 17	12 09 09.0	41.76°N	141.99°E	75	6.2	ISS	Japan	0.85	0.15
5	1968 May 16	19 16 47.2	41.30°N	142.38°E	42	5.6	EDR	Japan	0.78	0.22

the hypocenter parameters are believed to be accurate enough for the present purpose. We used long-period waves recorded by a standard Press-Ewing seismograph at Seoul (36.57°N, 126.97°E) which belongs to the world-wide standardized station network (WWSSN) of the United States Coast and Geodetic Survey. Figure 1 shows the propagation paths from the epicenters to Seoul. In order to make a precise digital analysis, enlarged copies of seismograms were digitized at a 2 sec interval. To separate Rayleigh and Love waves, the radial and transverse components were synthesized from the N-S and E-W components. For the measurements of group velocities we mostly used the band-pass filtering method, and always cross-checked the results against the group-delay times. In both cases, the instrumental group-delay time was corrected for. The effect of the finiteness of the source and the group-delay time at the source were ignored. The detailed description on these methods is given in *Kanamori and Abe* (1968*a*).

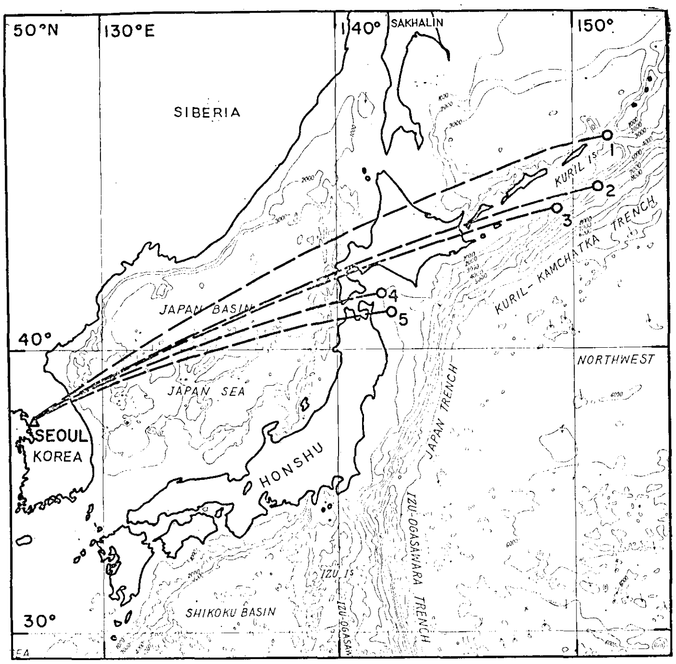

Fig. 1. Epicenters and the great-circle paths to Seoul (SEO) station.

3. Results and Interpretation

Figure 2 shows the group velocities of Rayleigh and Love waves for five propagation paths across the Japan Sea. This figure includes theoretical dispersion curves for two typical oceanic models, 8099 and ARC–1. The 8099 model (*Dorman et al.*, 1960) fits the experimental group velocities of Rayleigh and Love waves for normal oceans, such as the central Pacific basins. In contrast, the ARC–1 model (*Kanamori and Abe*, 1968*a*, *b*; *Abe and Kanamori*, 1970) fits the low oceanic group velocities of Rayleigh and Love waves travelling across the Philippine Sea. All the group velocities obtained in the present study are definitely lower than those for the 8099 model, and are much closer to those of the ARC–1 model.

The propagation paths used here consist of oceanic and continental parts; the average fractional path length of the continental part is 24% of the entire path length. In order to make the discussion more specific, we derive the group velocity for "pure-oceanic" part from the observed composite group velocities as follows. We let U, U_o and U_c be the group velocities for the mixed, oceanic and continental paths respectively. Assuming that the ocean-continent boundary does not greatly affect the group velocity measurement, we obtain

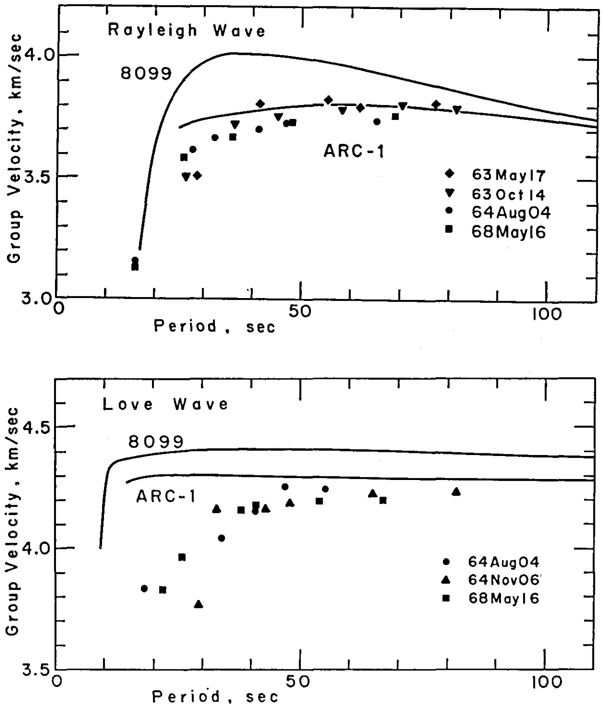

Fig. 2. Group velocities of Rayleigh and Love waves for mixed propagation paths. The dispersion curve of 8099 model fits the normal oceanic data well. The shear-velocity distribution for the two models is given in Fig. 5.

$$\frac{1}{U}=\frac{l_o}{U_o}+\frac{l_c}{U_c} \tag{1}$$

where l_o and l_c are fractional path lengths over ocean and continent. It can be shown, on the basis of *Boore*'s (1970) recent results of numerical experiments, that the above assumption is reasonable. The parameters l_o and l_c for each path are listed in Table 1. The continental region includes Hokkaido, Korea and their continental shelves. The values of l_c may be uncertain to several per cent owing to the ambiguity in defining the ocean-continent boundary. For U_c, we use the dispersion curve for the Jeffreys model, since no data are available for these regions. A slightly different choice of the model, however, would not cause a major difference in the final results.

The effective group velocities for the "pure-oceanic" region are calculated for each propagation path with the formula (1). All the data are interpolated at common periods and averaged (Fig. 3). The standard deviation for the data are shown in the figures. Difference of the group

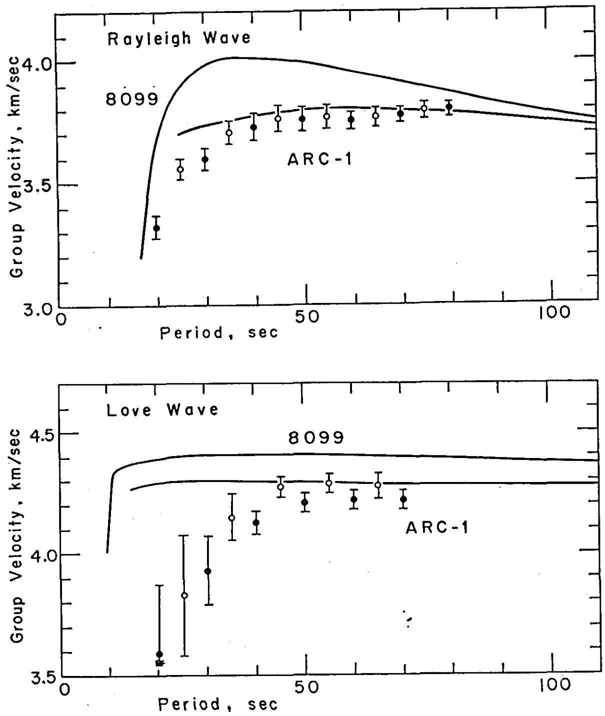

Fig. 3. Average group velocities of Rayleigh and Love waves. Filled circles indicate the group velocities for mixed propagation paths. Open circles indicate the group velocities calculated for "pure-oceanic" paths across the major portion of the Japan Sea.

velocity between the mixed and the oceanic paths is slightly larger for Love waves than for Rayleigh waves. Figure 3 shows that the ARC-1 model fits the "pure-oceanic" group velocities reasonably well at periods longer than 40 sec.

The effect of shallow structures such as water layer, sedimentary layer and the crust on group velocities is examined. According to seismic refraction studies, the Japan Basin has a typical oceanic crust; the Basin has a water layer about 3 km thick, a sedimentary layer 2 to 3 km thick, a lower crust 8 to 12 km thick, and a P_n velocity of 8.1 to 8.3 km/sec (*Andreyeva and Udintsev*, 1958; *Kovylin and Neprochnov*, 1965; *Kovylin*, 1966; *Murauchi et al.* (see *Rikitake et al.*, 1968)). We constructed, starting from the ARC-1 model, two models, A and B, incorporating these results (Table 2). The difference of the group velocities between each of the two models and the ARC-1 model is shown in Fig. 4. The group velocities are affected only at short periods. Therefore an appropriate modification of shallow structures of the ARC-1 model would improve the fit between the calculated and the "pure-oceanic"

Table 2. Layer parameters for four models, 8099, ARC-1, A, and B models.

	Shear Velocity (km/sec)	8099	ARC-1	A	B
Water	0.0	5	5	3	3
Sediment	1.0	1	1	3	3
Crust	3.7	5	5	5	8
	4.6125	49	19	19	16
Mantle	4.23	0	50	50	50
	4.30	160	140	140	140

Layer thickness is given in km.

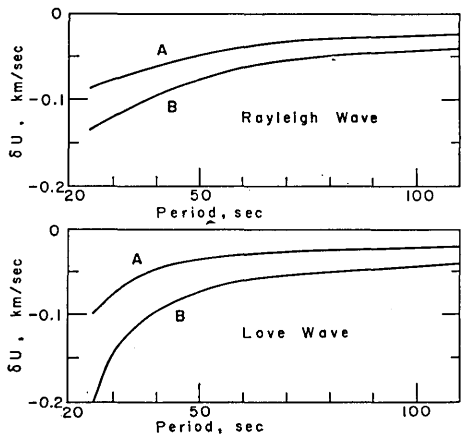

Fig. 4. The effect of shallow structures, such as water, sediment and crust on group velocity. The ARC-1 model is taken as a standard. Layer parameters of A and B models are listed in Table 2.

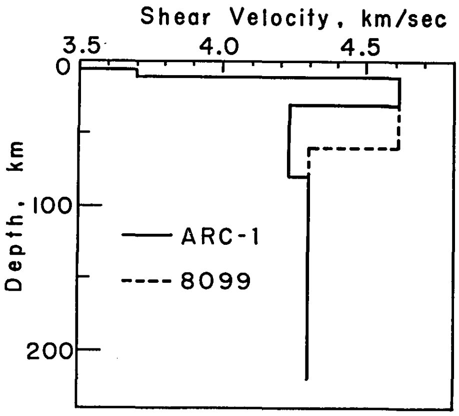

Fig. 5. Shear-velocity model, ARC-1. The oceanic model 8099 which is a starting model in constructing the ARC-1 model is shown for comparison.

group velocities in the short period range ($T \leq 30$ sec); such modification does not affect the fit at long period range. Thus we conclude that the mantle beneath the Japan Sea can be approximated by the mantle as employed in the ARC-1 model.

Because of the limited period range ($T \leq 80$ sec), the mantle structure below 100 km cannot be resolved. Figure 5 shows the difference between the shear-velocity distribution of the ARC-1 model and the 8099 model. The ARC-1 model is characterized by very low shear-velocities in a depth range 30 to 60 km; over this depth range, the shear velocity is lower by 0.3 to 0.4 km/sec or 8% for the ARC-1 model than for the 8099 model, the normal oceanic model. Although the group velocity method is not very straightforward, we believe that an overall reduction of shear velocity of this magnitude is required. It should be noted that the thickness of the high-velocity lid is thinner by as much as 50 km than that of the normal oceanic lithosphere which is about 70 km (*Kanamori and Press*, 1970).

Figure 6 shows a vertical cross section taken along 41°N latitude. The earthquake foci for the year 1967 ($d \geq 60$ km) are taken from *Ishida* (1970). Note the location of the propagation paths across the Japan Sea

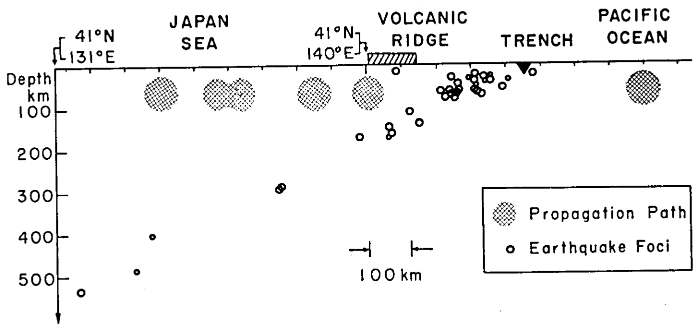

Fig. 6. Vertical cross section showing the location of the paths relative to trench, volcanic ridge, and deep seismic plane. Section is taken along 41°N. The cross hatched part indicates an approximate area sampled by the surface waves. Note that all the propagation paths across the Japan Sea lie above the deep seismic plane, while the path from the Aleutian Is. to Dodaira station (see *Kanamori and Abe*, 1968 *a*, *b* and *Abe and Kanamori*, 1970) lies on the oceanic side of the deep seismic plane.

with respect to various tectonic features. A major portion of the paths lies on the continental side of the deep seismic plane, volcanic ridge, and trench. *Kanamori and Abe* (1968*a*, *b*) and *Abe and Kanamori* (1970) found that the path from the Aleutian to Dodaira station which is on the oceanic side of the arc shows the normal dispersion characters. Thus, we conclude that a large structural heterogenity in the mantle exists across the deep seismic plane.

4. Discussion

The heat flow distribution shows a regionality similar to that found for the group velocity; it is high on the continental side and low on the oceanic side of the deep seismic plane (*Vacquier et al.*, 1966). *Utsu* (1966, 1967) found that Q is significantly lower on the continental side than on the oceanic side. A partial melting of the mantle provides a favorable explanation for the low seismic velocity, high heat flow, and low Q.

The seismic wave velocity V varies with temperature T as

$$\delta V_P \sim \left(\frac{\partial V_P}{\partial T}\right)_P \delta T \tag{2}$$

$$\delta V_S \sim \left(\frac{\partial V_S}{\partial T}\right)_P \delta T \tag{3}$$

The pressure effect is insignificant as compared with the temperature effect. A high temperature may cause a partial melting which also lowers the velocity (*Mizutani and Kanamori*, 1964; *Spetzler* and *Anderson*, 1968). According to *Hashin* (1962), the velocity in a solid with scattered spherical liquid inclusions decreases as

$$\delta V_P \sim -0.58\, c\, V_P \tag{4}$$

$$\delta V_S \sim -0.98\, c\, V_S \tag{5}$$

where the parameter c is the fractional volume concentration of the liquid inclusion. In formulas (4) and (5), it is assumed that $\lambda=\mu$ (λ: Lamé constant, μ: rigidity) in the solid and that λ is the same for the solid and liquid. Thus, the velocity decrease is given by a linear combination of the parameters c and δT. Figure 7 shows the relation between the temperature difference and melt concentration for a given P- and S-velocity decrease. We used laboratory data $(\partial V_P/\partial T)_P=-6\times10^{-4}$ and $(\partial V_S/\partial T)_P=-4\times10^{-4}$ km/sec·deg (*Soga et al.*, 1966; *O. L. Anderson et al.*, 1968).

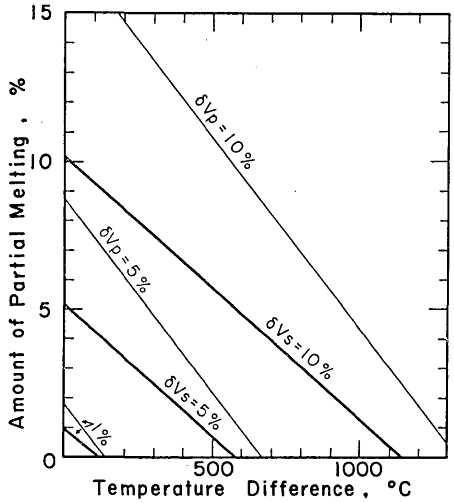

Fig. 7. Relation between the temperature contrast and melt concentration for a given P- and S-velocity contrast. The lines for 1, 5, 10% of P- and S-velocity contrast are given for reference.

The temperature beneath the Japan Islands has been estimated, though with large uncertainty, from heat flows. *Watanabe* (1968) explained the high and low heat flows observed in the Japan region in terms of a temperature contrast in the mantle; a temperature difference of 500°C between the high and low heat flow regions is suggested. In an attempt to simulate thermal processes beneath the Japan Arc, *Hasebe et al.* (1970) made a numerical experiment in which a frictional heating is assumed on the surface of the sinking lithosphere beneath Japan; a thermal process which accounts for the heat flow distribution in the Japan region results in a temperature excess of about 250°C in the mantle beneath the Japan Sea. From these results it seems reasonable to consider that the temperature beneath the Japan Sea is higher by 200 to 500°C than that in the normal mantle at comparable depths. If we take the value of 500°C, we see from Fig. 7 that a partial melting of 4% is required to account for the observed velocity contrast of 8%. For a 200°C temperature contrast, a partial melting of 6% is required.

Kanamori (1968) obtained a 4% *P*-velocity contrast in the mantle beneath Japan from the travel-time anomalies of the Longshot underground explosion, and explained it in terms of a 2% partial melting coupled with a 500°C temperature difference. Considering the difference in the method, the present result is in general agreement with Kanamori's result.

A temperature excess and the resultant partial melting may not necessarily be a unique interpretation for the velocity contrast. An alternate explanation may be provided by considering a concentration of water at grain boundaries or a dehydration of hydrated minerals. If these effects are superimposed on the temperature effect, the proposed amount of melt concentration is correspondingly reduced.

The regional difference in the mantle beneath island arcs around Japan has been studied by many investigators. By using body waves, *Fedotov and Slavina* (1968) studied the Kamchatka—Kurile Arc, and *Utsu* (1967), *Kanamori* (1968) and *Ishida* (1970) studied the Japan Arc. By using surface waves, *Kanamori and Abe* (1968*a*, *b*) and *Abe and Kanamori* (1970) determined the deep structure beneath the Izu-Mariana Arc. A common result obtained in these studies is that the mantle above the inclined deep seismic zone is characterized by an extremely low seismic velocity. Thus, we conclude, on the basis of the present and the previously obtained results, that this low-velocity mantle extends all along the chain of the Kamchatka-Kurile-Japan-Izu-Mariana Arcs.

5. Conclusion

By using long-period surface waves, the deep mantle structure beneath the Japan Sea is determined; the mantle shear-velocity over the depth range 30 to 60 km is found to be lower by 0.3 to 0.4 km/sec than that for normal oceanic models. Combining the present result with those previously obtained, we conclude that, all along the Kamchatka to Mariana Arc, a pronounced low-velocity layer extends to a much shallower depth on the inward (continental) side of the island arc than on the outward (oceanic) side. This prominent feature can be explained in terms of a 500°C temperature contrast coupled with a 4% partial melting.

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54. 表面波による日本海のマントル構造の研究

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長周期表面波の群速度をもちいて，弧状列島の縁海である日本海のマントル構造を調べた．日本北部及び千島列島の5つの地震についてソウルにおける長周期地震計の記録から，バンド・パス・フィルターとグループ・ディレイ・タイム法を利用して周期20秒から80秒までの群速度を求めた．日本海を横切る表面波の群速度は標準的な海のものにくらべ長周期のところでレイレー波ラブ波ともに0.1 km/sec ほど遅い．この遅い群速度は以前にフィリッピン海を横切る表面波の遅い群速度を説明するためにもちいた ARC-1 モデルで同じように良く説明される．このモデルの重要な特徴は標準的な海のモデルにくらべてマントルの横波の速度が深さ 30～60 km にわたって 0.3～0.4 km/sec または8% ほど遅くなっていることである．この浅い所における低速度層の存在と日本海での高熱流量とを考えあわせると，日本海の下のマントル内では他の地域にくらべて温度が高く，またそれによって部分溶融が生じていると考えられる．この考えにしたがうと 8% の横波の速度差は 4% 程度の部分溶融をともなった 500°C の温度差で説明される．
