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28. *The Crust and Upper Mantle Structure in Japan.*

Part 2. Crustal structure in Japan from the phase velocity of Rayleigh waves.

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1. Introduction

As shown in Fig. 1, the Research Group for Explosion Seismology (R. G. E. S.) has carried out several successful observations of seismic waves generated by artifical explosion in various districts in Japan. There are several crustal and upper mantle models derived from their studies.

Aki and Kaminuma have made these models of structure into rough interpretations of their results obtained from the phase velocity of Rayleigh waves. In determing the crustal thickness from the phase velocity, they used the phase velocity curves corresponding to a model called 6EJ. This model was obtained by modifying Press' model 6E in such a way that the velocities were uniformly reduced by 5.5 per cent. The crustal thicknesses thus obtained generally agree with those which resulted from the refraction studies. The thickness of crust in Tohoku region was 25 to 30 km and in central Japan 30 to 40 km, the thickest crust in the Japanese Islands. The crustal thickness of western Japan is 25 to 30 km (see Kaminuma, 1964; Fig. 9). Kanamori (1963) made detailed study combining the results from seismic refraction with those from Rayleigh waves, gravity and laboratory experiments on velocity of rocks.

In this paper, a crustal and upper mantle model is made from the phase velocity dispersion curves of Rayleigh waves considering the results from seismic refraction studies and laboratory experiments.

2. Results from explosion studies

The regions where the crustal structure is obtained from explosion seismic observations are North-East Japan (Matuzawa; 1959), Northern

Kwantô (Usami et al.; 1958), Hokota-Kamaishi line (Matuzawa et al.; 1959), Western profiles A and B of the Miboro and Eastern profile of the Miboro (Mikumo et al.; 1961), and central Japan along longitudinal line 139°E profiles (Hotta et al.; 1964).

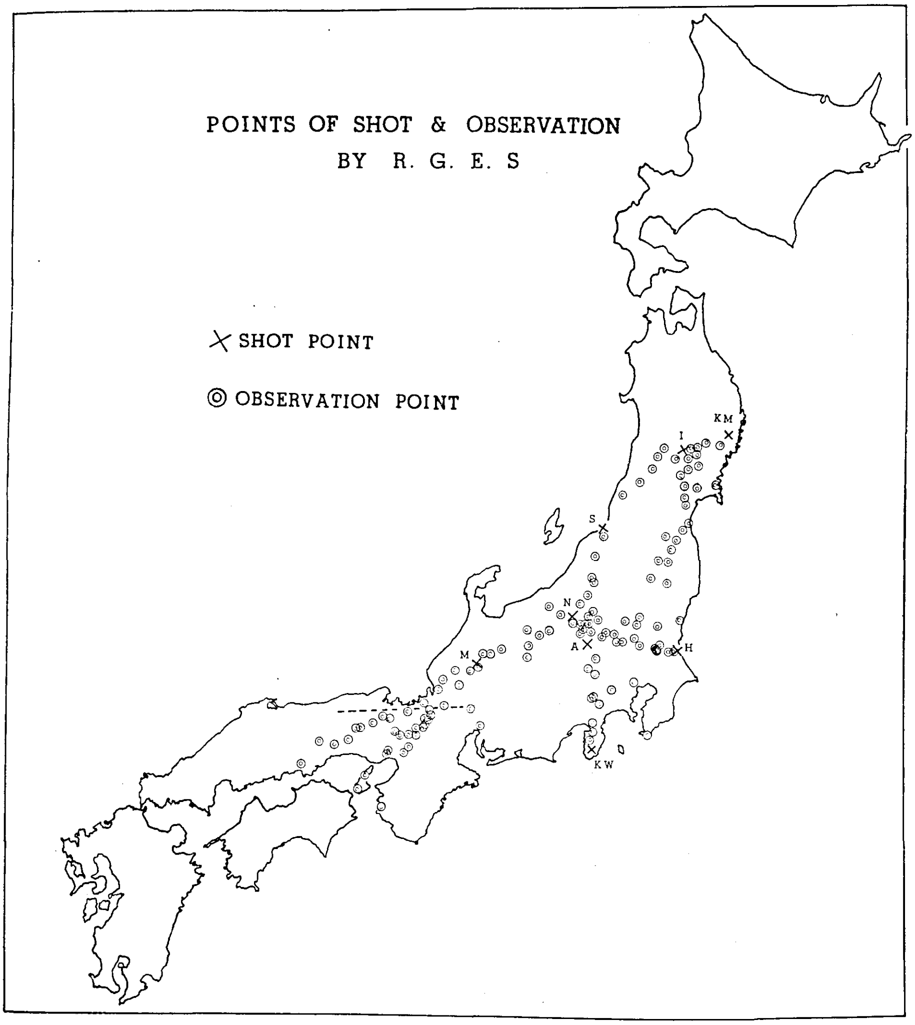

Fig. 1. The points of shots and observations for the explosion seismic observations operated by the Reserch Group for Explosion Seismology.

One or two models of crustal structure are proposed for each profile. The models are most probable ones obtained from the interpretation of the travel time curves by each explosion seismic observation along those profiles.

Although several differences exist between a structure in one district and that in another, there are fundamental features common to them all. The crusts of these models consist of two layers, but sometimes a superficial layer with low P wave velocity is on the surface layer. Some models are flat layered and others inclined. The frequency distribution of P wave velocity for all models is shown in Fig. 2. The results are as follows;

	Thickness	Velocity of P wave
1st layer	1- 3 km	2.3-2.7 km/sec
2nd	5-10	5.5-5.8
3rd	10-20	6.0-6.2
4th		6.5-6.9
——	Moho. discon.	——
5th	——	7.5-8.0

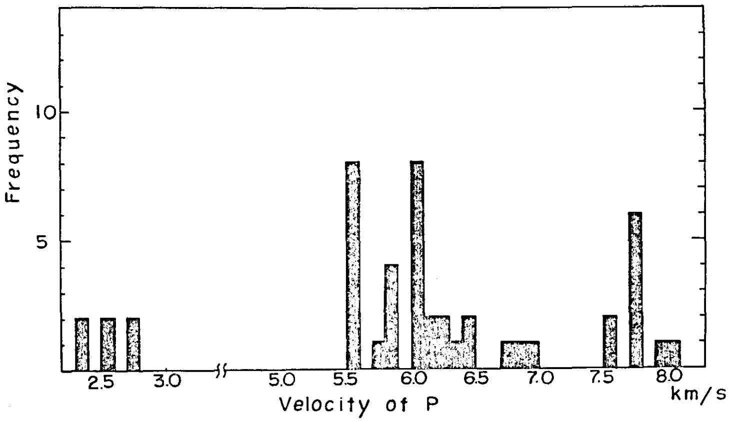

Fig. 2. The frequency of P wave velocities for all models derived by the explosion seismic observations.

The first layer is the superficial one and is not so important when the dispersion of Rayleigh waves with periods of 20 to 40 sec are discussed. As shown in Fig. 2, the 2nd and 3rd layer, in which P wave velocities are about 5.5 km/s and 6.0 km/s respectively exist throughout Japan.

The 4th layer with P wave velocity of 6.8 km/s is derived from the study of central Japan along the longitudinal line 139°E profile. In that model, this layer is considered as the 3rd layer. But the models of Miboro eastern profile and Northern Kwantô district, which cross the longitudinal line 139°E profile, do not include this layer. It is one of the purposes of this paper to verify whether this layer exists throughout the Japan Islands.

P wave velocity in the upper mantle varies from place to place, and as shown in Fig. 2, the range of variation seems to be from 7.5 km/s to 8.0 km/s, which is substantially lower than the normal mantle velocity in the continent.

The averaged thickness of the crust is about 25 km in Tohoku district, about 30 km in Kanto district, from 30 to 40 km in Chubu district and about 30 km in Kinki district.

3. Poisson's ratio and density in Japan

Kanamori and Mizutani (1965) have calculated the Poisson's ratios of many rocks from V_p and V_s measured in laboratory experiments. In the worst case, the Poisson's ratio included probable errors of about 10 per cent. But the Poisson's ratio is increasing with the pressure increasing up to about 2 kilobars and then becomes constants to increase pressure more than about 2 kilobars.

From the Poisson's ratio at 10 kilobars versus P wave velocity at 10 kilobars, Kanamori and Mizutani concluded that granitic rocks have the Poisson's ratio of about 0.26, gabbroic rocks have values around 0.30 and eclogite about 0.31. The Poisson's ratio of the rocks consisting of the upper crust is smaller than that of rocks consisting of the lower crust and upper mantle at the same pressure. From this we may concluded that the Poisson's ratio is smaller in the upper crust than in the lower crust and is larger in the upper mantle than in the crust.

Yoshiyama (1957) has concluded that the ratio of V_p and V_s is not much greater than 1.67 in the crust and is about 1.78 in the upper mantle, the corresponding Poisson's ratio being 0.22 and 0.27 respectively.

The relation between velocity and density has been discussed by Woollard (1959), Birch (1961) and Kanamori and Mizutani (1965). A simple convenient relation was given by Kanamori and Mizutani from the data of Birch and theirs which is

$$V_p=(2.8\rho-1.3)\pm0.5\,\text{km/s}\ .$$

As described in the latter section, we used this formula in determing the density in the crust and upper mantle.

4. Comparison with the results of explosion seismology

The crustal structure in central Honshu in a profile along the longitudinal line 139°E was obtained by Hotta et al. (1964), employing observed data on seismic waves from three explosion carried out by R.G.E.S..

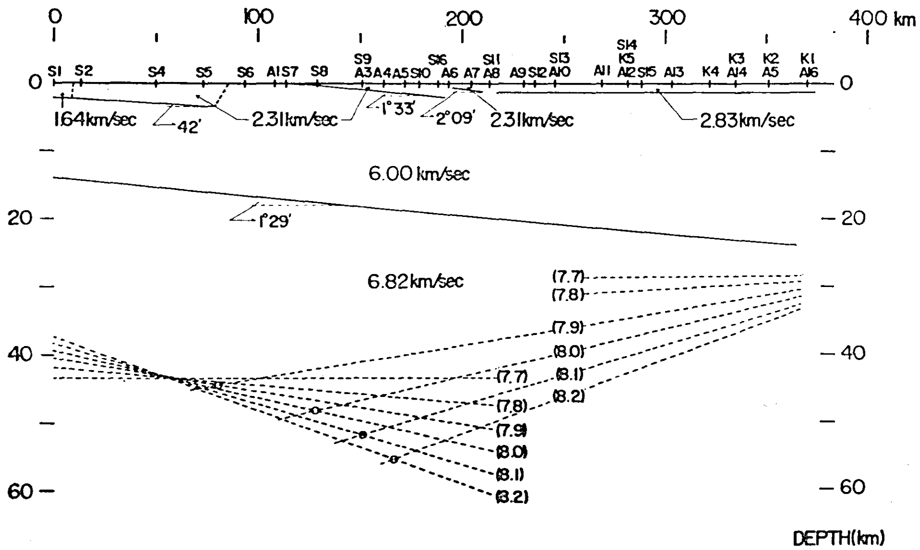

Fig. 3. A crustal structure along the longitudinal line of 139°E. Broken lines show estimated Mohorovičic discontinuity with assumed P wave velocity in upper mantle in parenthesis (Hotta et al.; 1964).

There are also several phase velocity data of Rayleigh waves along that profile obtained by Aki and Kaminuma (1961, 1963 and 1964), as shown in Figs. 4 and 5 with open circles. We shall compare the phase velocity data with the model obtained from the explosion-seismic observation. This model is shown in Fig. 3.

Fig. 4 also shows the dispersion curves of Rayleigh wave phase velocity corresponding to models based on the analysis of travel time curves from explosion-seismic observation with several different thicknesses of the crust.

P wave velocity of 6.0 km/s in the first layer of the profiile along the longitudinal line 139°E existed as the second layer in the eastern

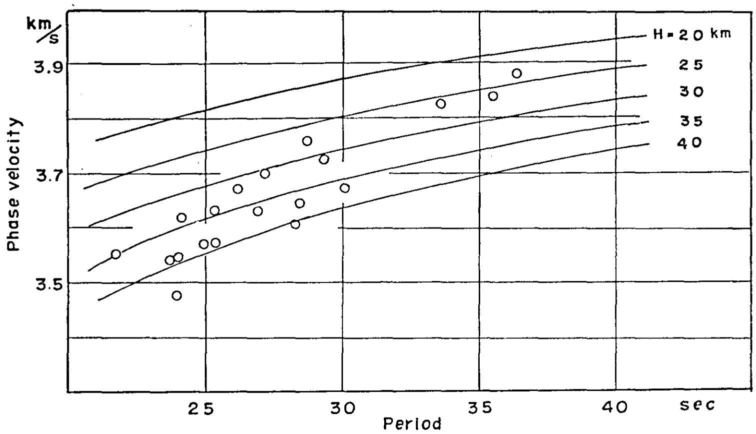

Fig. 4. The theoretical dispersion curves with various crustal structures for the model which is shown in Fig. 3. The data are phase velocities of Rayleigh waves obtained by Aki and Kaminuma.

profile, which crosses that profile of the Miboro explosion-seismic observation. But the existence of the second layer with P wave velocity of 6.82 km/s was first ascertained in Japan. The depth of the Mohorovičic discontinuty is only approximately estimated owing to the lack of information about the wave passing through the upper mantle.

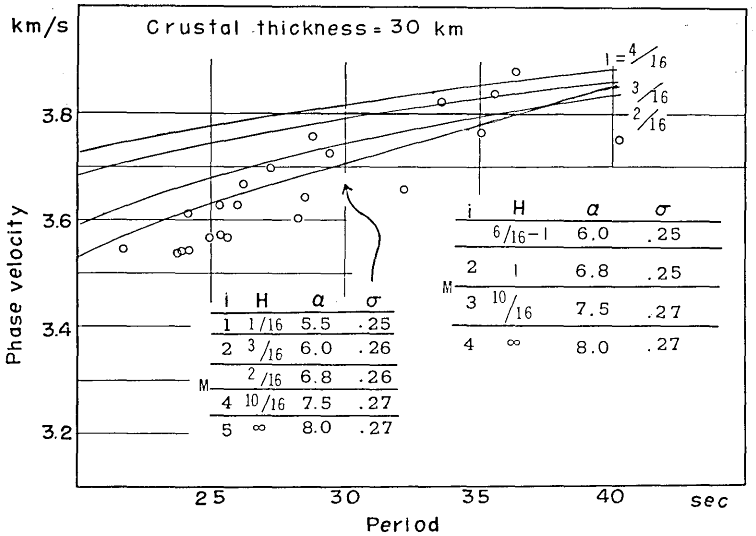

Fig. 5. The theoretical dispersion curves with different thickness ratios of the first to the second layer in the crust for the model. The data are phase velocities of Rayleigh waves obtained by Aki and Kaminuma.

The Poisson's ratio in the second layer is about 0.256 from body wave observations of aftershocks of the Niigata earthquake according to this profile (personal communication from Prof. Asada).

As far as we take 7.5 km/s as the velocity of P wave in the upper mantle and 0.26 as the Poisson's ratio in the lower crust, the Poisson's ratio is not smaller than 0.25 in the crust and larger than 0.27 in the upper mantle.

Fig. 5 shows the dispersion curves with different thickness ratios of the first to the second layer in the crust. The surface layer is not considered because of its small influence in the period concerned. As shown in Figs. 4 and 5, it is impossible to explain the phase velocity data by these models. But if we consider the layer with P wave velocity of 5.5 km/s, it will fairly well explain the phase velocity data. The dispersion curves of this model are also shown in Fig. 5.

The layer with P wave velocity of 5.5 km/s or 5.55 km/s exists in the models of most profiles. Of course, this layer exists in the eastern profile of Miboro seismic explosion which crosses the profile along the longitudinal line 139°E. This layer may be thin in the very narrow region along that profile.

As the layer with P wave velocity of 6.8 km/s does not exist in the eastern profile of Miboro seismic explosion, this layer is very thin or does not exist widely in central Japan.

5. Standard phase velocity curves in Japan

A new crustal and upper mantle model in central Japan is obtained from the results of the explosion seismology and of the phase velocity dispersion of Rayleigh waves. For the computation of theoretical phase velocity dispersion curves, we have adopted the crustal models J-S-C2 and J-S-C3 which are based on the structure given by R. G. E. S. as

Table 1. Layer parameters for models J-S-C2 and J-S-C1

J-S-C2					J-S-C3			
V_p	V_s	ρ	σ	H	V_p	V_s	ρ	σ
5.5 km/s	3.175 km/s	2.7 gr/cm	0.25	5 km	5.5 km/s	3.175 km/s	2.7 gr/cm	0.25
6.0	3.414	2.8	0.26	15	6.0	3.414	2.8	0.26
6.5	3.696	3.0	0.26	10	6.8	3.867	3.0	0.26
7.7	4.317	3.2	0.27	—	7.7	4.317	3.2	0.27

described in Section 4 and shown in Table 1.

6.5 km/s is taken as the velocity of P wave in the third layer for J-S-C2 and J-S-C3. Because if we take 6.8 km/s as the P wave velocity in the third layer, we must consider a thicker crust than the crustal thickness derived by the explosion seismology and the surface wave studies. The broken and dashed line in Fig. 6 shows the dispersion

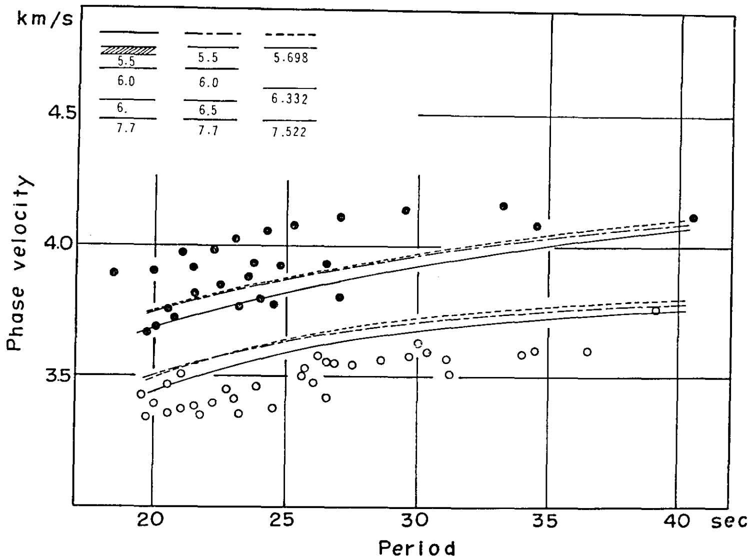

Fig. 6. The dispersion curves of Love and Rayleigh waves for various models with the crustal thickness of 30 km. The solid lines are the dispersion curves for J-S-Cl, the dashed lines for 6EJ and the doted lines for J-S-C2. The open and closed circles are the data in central Japan.

curves for J-S-C2 and 6EJ with crustal thickness of 30 km. J-S-C2 and 6EJ show nearly the same dispersion of Love and Rayleigh waves with periods of 20 to 30 sec.

If the layer with P wave velocity of 2.5 km/s is considered as the surface layer at the top, the dispersion curves of theoretical phase velocity show better agreement with the data of observations. This model is J-S-C1, the dispersion curves of the model being shown by the solid line in Fig. 6. At the period of 20 sec, the velocity for J-S-C1 with the crustal thickness of 30 km is about 0.06 km/s lower than that for J-S-C2 with the same crustal thickness and agrees with the data of observation. Finally, we have adopted J-S-C1 as the model for central Japan. The physical constants of this model are shown in Table 2 and Fig. 7. It is one of the special features of this model that the Poisson's ratios are not constant in all layers. J-VII-2 and J-VII-4 derived by Kanamori (1963) have the same Poisson's ratio in all layers and the models for the Canadian shield, the central U. S. and 6EJ are given the data of shear velocity directly.

Table 2. Layer parameters for the model J-S-C1

J-S-C1				
H	V_p	V_s	ρ	σ
1 km	2.5 km/s	1.472 km/s	2.5 gr/cm	0.25
5	5.5	3.175	2.7	0.25
16	6.0	3.414	2.8	0.26
10	6.5	3.696	3.0	0.26
	7.7	4.317	3.2	0.27

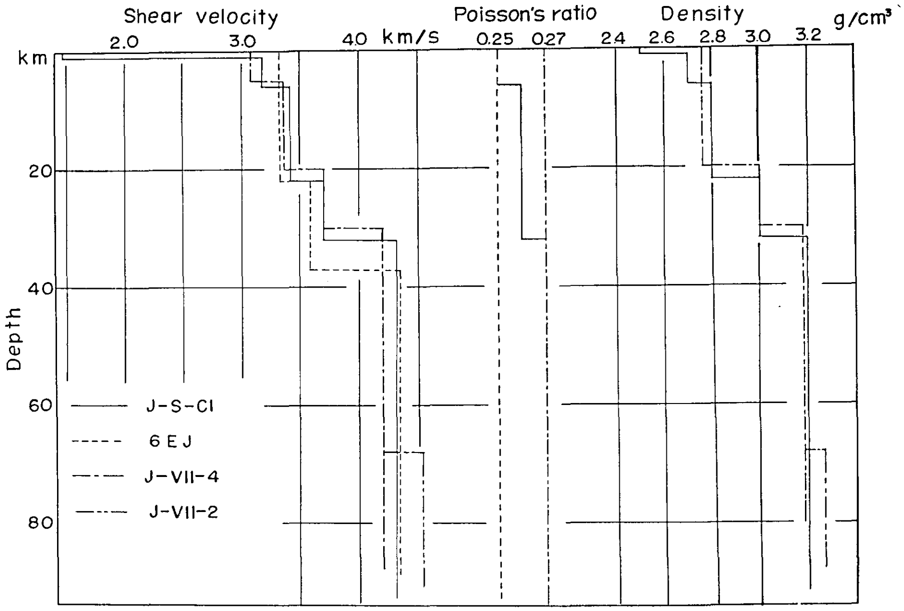

Fig. 7. The shear velocity, Poisson's ratios and density for models J-S-Cl, 6EJ, and J-VII-4.

The densities in each layer are obtained from the laboratory data derived by Kanamori (1963) and Kanamori and Mizutani (1965) as also described in the previous section.

The dispersion curves for J-S-C1 are shown in Fig. 8. The crustal thickness in central Japan is about 32 km.

6. The crustal structure in Japan

The dispersion curves of J-S-C1 do not explain the observed phase velocity of Love waves in central Japan, as shown in Fig. 8. This problem will be discussed in the next paper.

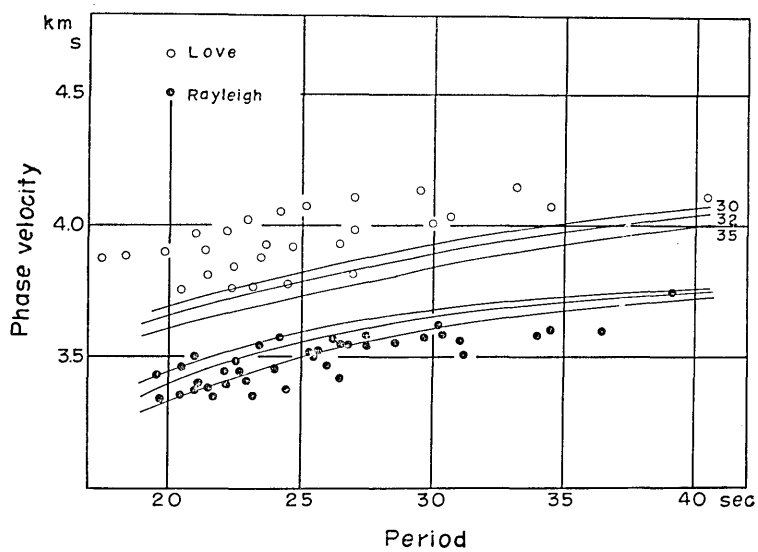

Fig. 8. The dispersion curves of Love and Rayleigh waves for J-S-Cl with the crustal thicknesses of 30, 32 and 35 km. The data are phase velocities of Love and Rayleigh waves in central Japan.

The Rayleigh wave dispersion curves of J-S-C1 are shown in Fig. 9 for several different thicknesses of the crust. The open and closed circles refer to the averaged phase velocity in Japan obtained from the Aleutian (Kaminuma and Aki; 1963) and the Mindanao shock (Kaminuma; 1964) respectively. The velocities from the Aleutian shock were averaged over all regions except the southern Hokkaido and that from the Mindanao shock averaged over central parts of Honshu, regions 4, 5, 6, 7 and 8. Since the averaged crustal thickness of these areas in the case of the Mindanao shock is thicker than that of the Aleutian shock from 6EJ, the phase velocities from the Aleutian shock are higher 0.005 to 0.01 km/s than those of the Mindanao shock.

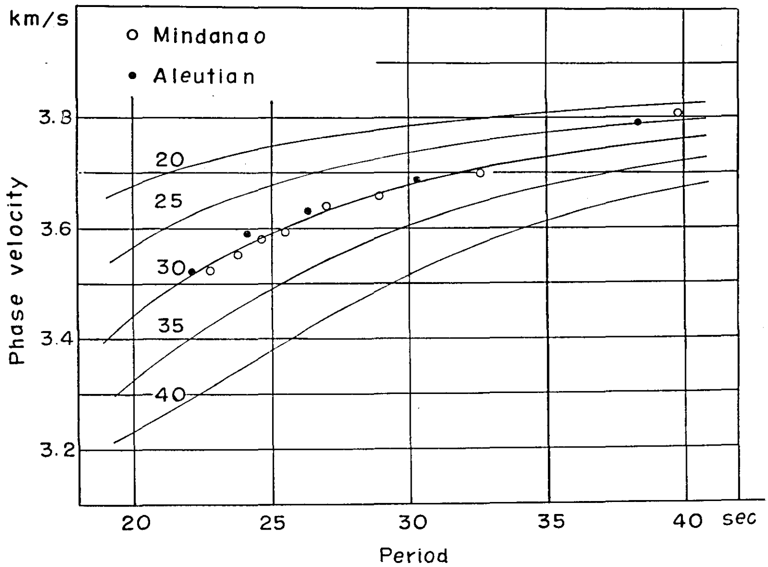

Fig. 9. The dispersion curves of Rayleigh waves for J-S-Cl with the crustal thicknesses 20, 25, 30, 35 and 40 km. The open and closed circles are the averaged phase velocities of Rayleigh waves in Japan.

At any rate, the dispersion of these averaged phase velocities show good agreement with the theoretical dispersion of the phase velocity for periods shorter than 35 sec. The averaged thickness of the area is about 30 km. J-S-C1 seems to explain the crustal and upper mantle structure in central and western Japan fairly well.

On an assumption that J-S-C1 can be applied to the crustal structure of the whole Japan Islands, the crustal thickness in Japan from phase velocity of Rayleigh waves is obtained from the dispersion curves for J-S-C1, as shown in Fig. 10. In the determination of crustal thickness, we use for each region probable errors less than about 2.5 per cent. The errors of 2.5 per cent in velocity are equal to the errors of 1 or 2 km in thickness. The thickness of each region in Fig. 10 includes errors of 1 to 3 km. But in the case of the Samoa shock, the crustal thickness of the western Tohoku with the probable error of about 10 km is also included.

The thickness from J-S-C1 is the thinner by 1 to 3 km than that from 6EJ in most regions. A map of crustal thickness in Japan is drawn from the phase velocity of Rayleigh waves as shown in Fig. 11. The Hokkaido province is excluded because there is only one set of

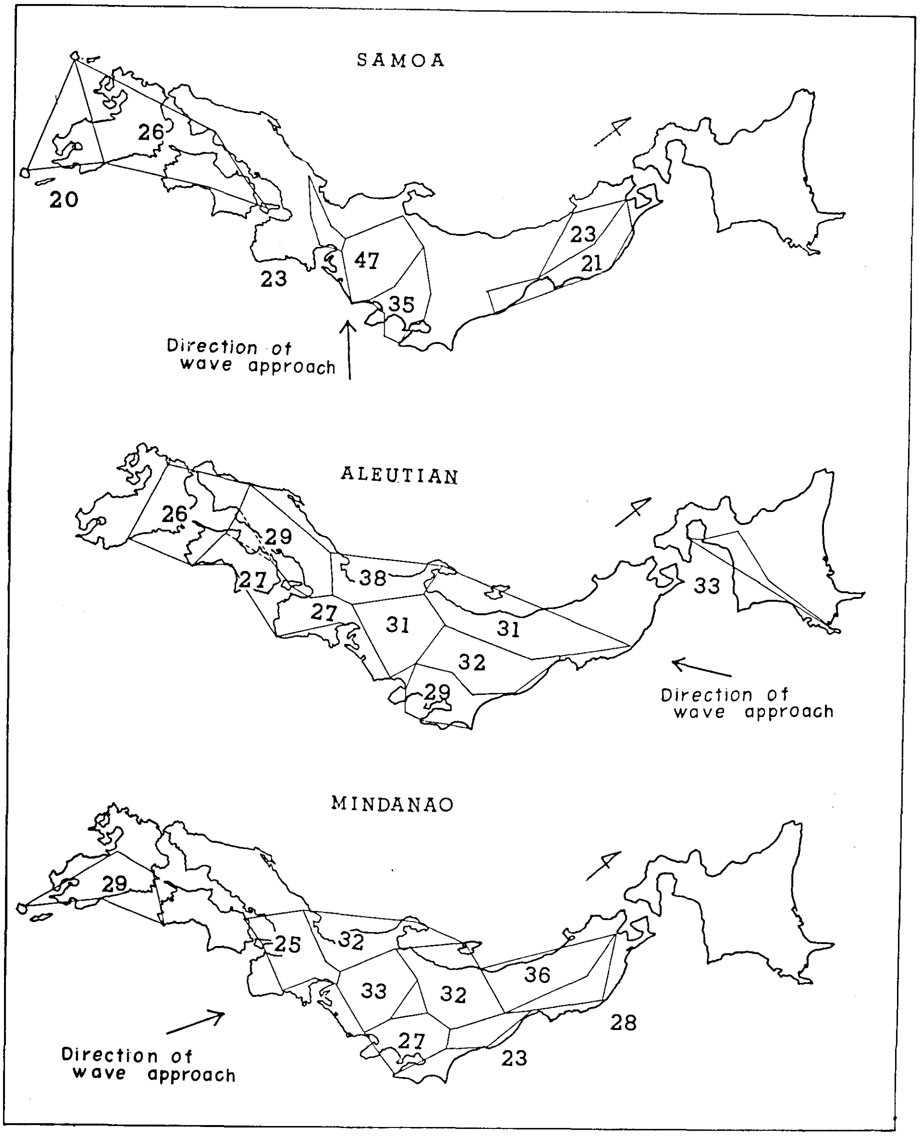

Fig. 10. Crustal thickness for each region obtained by use of phase velocity curves for J-S-Cl from the waves of the Samoa, the Aleutian and the Mindanao shock.

measurements for this area.

There is a hollow of the Mohorovičic discontinuty which is not indicated in the previous paper on the western Japan. In the Bungo region, the thickness is obtained as 29 ± 1 km from the Mindanao shock

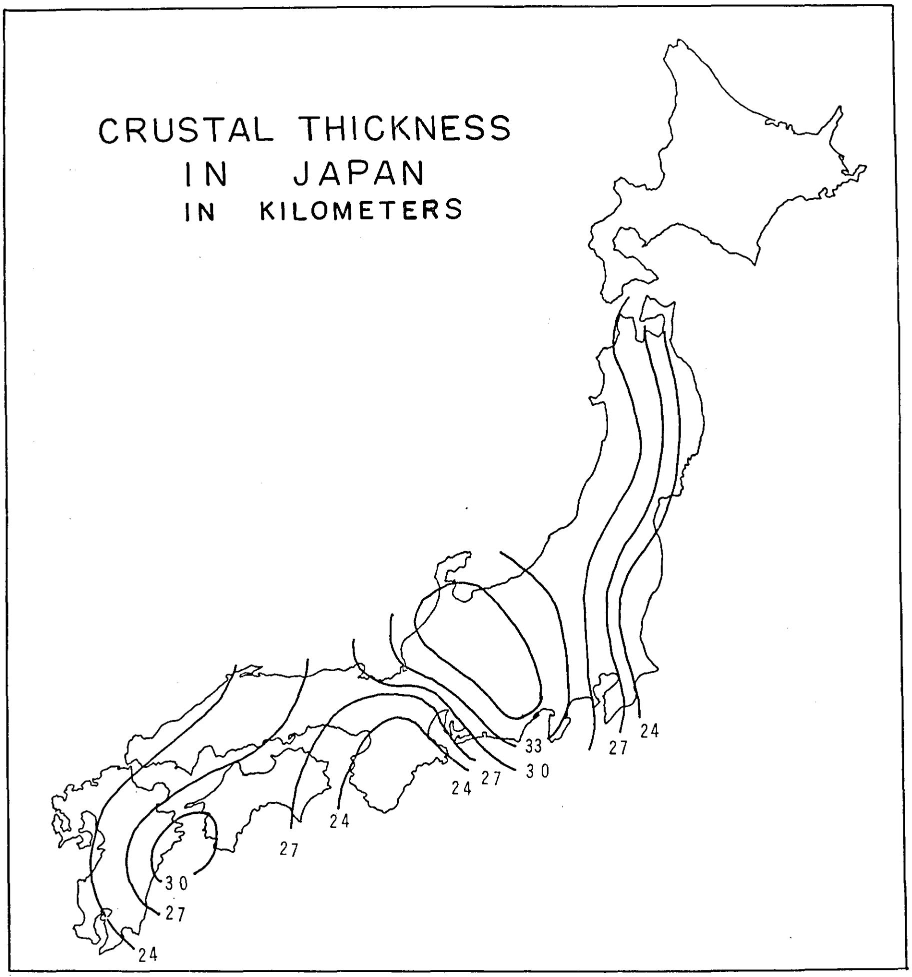

Fig. 11. A map of crustal thickness in Japan determined from the phase velocity of Rayleigh waves.

data. On the other hand, the thickness in the western part of the Kyushu district is about 20 to 23 km from the Samoa shock data. The thickness of 29 km being the value averaged over the region may be a few kilometers thicker than 29 km in the eastern part. Then the hollow may exist in this region. The Bouguer gravity anomaly, based on the map compiled by Tsuboi (1959) shows the large negative anomaly also in this region.

The map is more detailed than that in the previous paper.

7. Discussion

The model 6EJ was obtained by modifying the model 6E in such a way that the velocities in all layers were reduced by 5.5 per cent and all non-dimensional products such as density ratios, Poisson's ratios and thickness proportions were unchanged.

As mentioned above in detail, the model J-S-C1 is based on the P wave velocities as observed from the refraction studies.

The crust in case 6EJ consists of two layers. In constructing model J-S-C1, by increasing the number of layers, we tried to obtain a better agreement with observations from both phase velocity and refraction studies.

In cace J-S-C2 in which the top layer of J-S-C1 was neglected, the dispersion curve is nearly identical to that of 6EJ for periods of 20 to 40 sec. But J-S-C1 with the top layer showed better fit than 6EJ to the observed phase velocity of Rayleigh waves for periods of 20 to 25 sec.

Different values of Poisson's ratio are taken in the upper and lower crust and the upper mantle. The poisson's ratio adopted for lower crust and the upper mantle for J-S-C1 are smaller than values measured at laboratory for rocks, generally regarded as forming the lower crust and upper mantle. The poisson's ratio of 0.27 adopted for the upper mantle agrees with the value determined by Yoshiyama.

8. Acknowledgment

The writer would like to thank Associate Professor Toshi Asada and Dr. Kei Takano for their interesting discussions about the velocity distributions of body waves in Japan, and also to thank Dr. Ryosuke Satô for his help in calculating the dispersion curves of surface waves.

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28. 日本の地殻及び上部マントルの構造

Part 2. レーリー波の位相速度から得られた日本の地下構造

地震研究所　神　沼　克　伊

爆破グループによつて今まで得られている地下構造のモデルに基くと，日本では地殻内においては，5.5～5.8 km/s, 6.0～6.2 km/s の P 波の速度を持つ層が卓越し，モホ面直下の P 波の速度としては，7.7 km/s の速度をもつモデルが最も多い．さらに 6.0～6.2 km/s の層からモホ面までの間には，6.5～6.8 km/s の層の存在が推定されている．

これらの結果をもとに，Part 1 で得たレーリー波の位相速度を使つて，新しい地下構造のモデルを得た．

このモデルは，地殻内に四層があり，地殻の上部，下部および上部マントルのポアソン比が，そ

れぞれ 0.25, 0.26, 0.27 である．これに基づく，中央日本の地殻の厚さは約 34 km である．また，このモデルは，レーリー波の日本の平均的位相速度とも良く一致するので，中央日本ばかりでなく，日本全体の地下構造をあらわすモデルとも考えられる．前論文で求めた位相速度を用いてきめた，日本全体の地殻の厚さを第 10•11 図に示す．