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

Part 1. Phase velocities of Love and Rayleigh waves in Central Japan.

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1. Introduction

The phase velocity of Rayleigh waves in Japan has been obtained by Aki (1961), Kaminuma and Aki (1963) and Kaminuma (1964) with periods of 20 to 40 sec using the network of the Wiechert seismographs operated for the Samoa, the Aleutian and the Mindanao shock.

The phase velocity of Love waves has been obtained by Aki and Kaminuma (1963) also using the records of the Aleutian shock obtained by the Wiechert seismographs of J. M. A. stations and Kaminuma and Hirasawa (1964) from the long period seismographs obtained at Tsukuba, Hongo and Matsushiro with periods of 30 to 110 sec.

This paper compares the phase velocity of surface wave in Japan with those in other regions of the world. Additional data for Japan are supplied from two long period seismograph stations, one at Tsukuba, a branch station operated by Earthquake Research Institute and the other at Haibara, a temporary station operated also by E. R. I.. The locations of these stations are shown in Fig. 1.

The phase velocities of Love waves in Japan are 4 to 5 per cent lower than those of the Canadian shield obtained by Brune and Dorman (1963) and the central U.S.A. obtained by McEvilly (1964), and those of Rayleigh waves in Japan are also 3 to 8 per cent lower than the results of any other regions which have the same crustal thickness and where many phase velocity measurements have been made.

2. Data

The location of stations is given in Fig. 1 and Table 1. The seismographs are Press-Ewing type instruments operated at 15–90 sec.

The Haibara station was operated from October 20th to December 20th in 1964 and from February 10th to March 6th in 1965. When measuring the phase velocity from two stations, it is better to eliminate such earthquakes from the phase velocity measurement that the great circle path from the epicenter intersected the great circle path between two stations at an angle greater than 7 degrees. Unfortunately we observe few earthquakes which satisfied this condition. Then the earthquakes are also used that the great circle path from the epicenter intersected the great circle path between the two stations at an angle smaller than about 20 degrees. The corrections of a travel distance

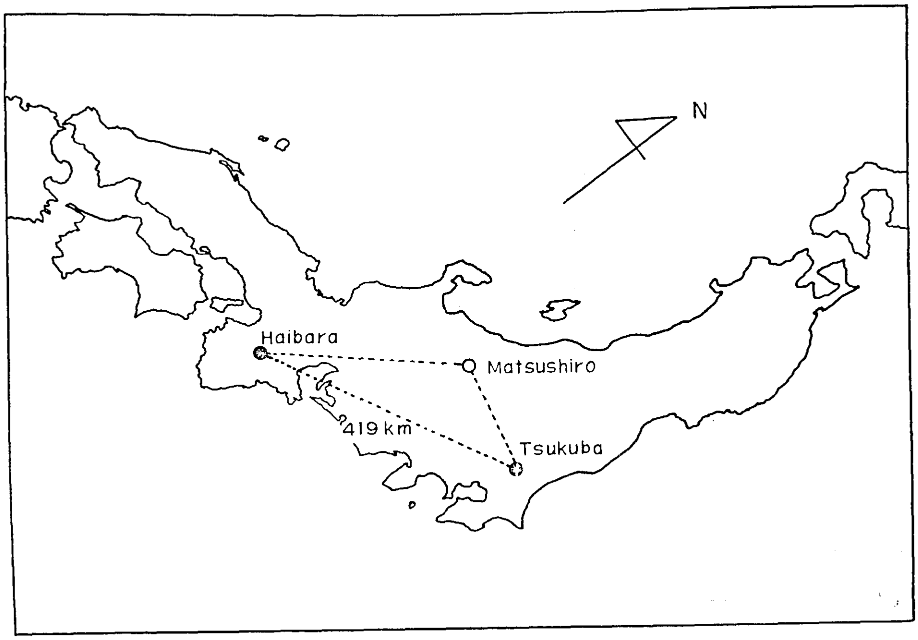

Fig. 1. The position of stations. Matsushiro is used only for the waves from the Pacific Ocean.

Table 1. List of stations.

Station	Latitude	Longitude	Seismograph
	deg. min.	deg. min.	
Haibara	34 30.2	135 59.6	Press-Ewing 15-90 sec
Tsukuba	36 12.7	140 06.6	Colombia 15-90 sec
Matsushiro	36 32.5	138 12.5	Galitzin 7.5-100 sec (V) 15.0-100 sec (H)

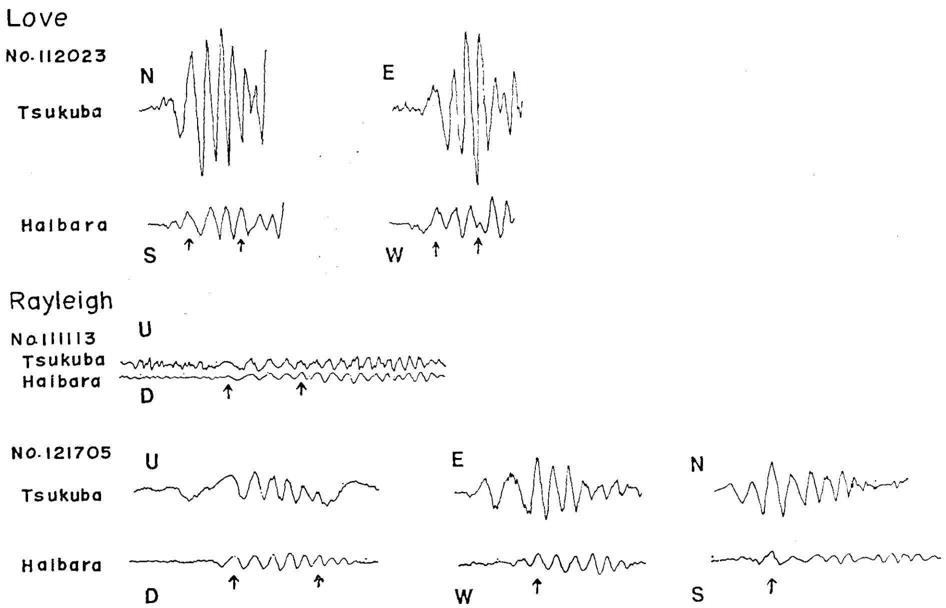

Fig. 2. Typical seismograms of Love and Rayleigh waves. The arrows indicate the correspondence of peaks and troughs.

Table 2. List of Earthquakes studied for phase velocity between Tsukuba and Haibara.

Earthquake Number	Date	Origin time	Epicenter		Depth	Mag.	Location
Love		h m s	lat.	long.	km		
112023	Nov. 20, '64	23 33 08.9	44.6°N	149.7°E	33	5.6	Kulile Islands
121313	Dec. 13, '64	13 15 49.8	20.1 N	122.0 E	33	4.8	Philippine Islands
021501	Feb. 15, '65	01 25 08.8	51.4 N	179.4 E	42	5.8	Aleutian
021919	Feb. 19, '65	18 52 42.1	51.1 N	178.4 E	35	5.6	Aleutian
030513	Mar. 05, '65	13 42 44.1	52.3 N	174.9 E	35	5.3	Aleutian
Rayleigh							
111113	Nov. 11, '64	13 17 37.5	56.6 N	161.4 E	33	5.4	East coast Kamchatka
111119	Nov. 11, '64	19 06 57.1	56.6 N	161.3 E	33	5.6	East coast Kamchatka
121705	Dec. 17, '64	05 18 34.0	45.4 N	150.1 E	17	5.3	Kulile Islands
030108	Mar. 01, '65	08 18 56.4	21.1 N	121.2 E	42	5.2	Taiwan region
030319	Mar. 03, '65	19 29 16.1	45.7 N	150.9 E	33	5.1	Kulile Islands
030513	Mar. 05, '65	13 42 44.1	52.3 N	174.9 E	35	5.3	Aleutian

according to azimuth are described in the latter section.

There remained about 20 earthquakes which propagated from a direction within the above condition. But about 10 earthquakes show complex records probably because of the lateral refraction. 11 earthquakes are used finally in this study, the list of earthquakes being given in Table 2. The typical records at both stations are shown in Fig. 2.

3. Phase velocity measurement

The method of phase velocity measurement is the stationary phase method (Brune; 1961 and Brune *et al.*; 1961). The arrival times of all peaks and troughs of a dispersed wave train are read from the records of both stations.

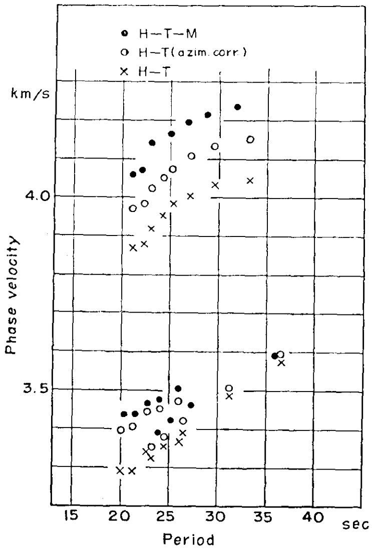

Fig. 3. Phase velocities of Love and Rayleigh waves obtained from two or three stations. The closed circles are the phase velocities obtained from Haibara, Tsukuba and Matsushiro. The open circles are the phase velocities obtained from Haibara and Tsukuba with the azimuthal correction distance.

Each peak or trough at one station is correlated with a peak or trough of nearly the same period at the other station, and the phase velocity calculated from the formula;

$$C = \frac{X \cos \theta}{t - nT}, \qquad (1)$$

where C is the phase velocity, X the distance between Tsukuba and Haibara, t the arrival time difference of corresponding phases, T the averaged period and θ the angle between the direction of the great circle between two stations and of the wave propagation. n is an integer which must be determined.

As shown in Fig. 2 with arrows, there was practically no difficulty in tracing phases from one station to another, because the distance between stations is only 419 km.

As shown in the previous papers (Kaminuma and Aki; 1963 and Kaminuma; 1964), the observed direction of Rayleigh wave propagation deviated from the great circle direction in central Japan in a systematic way. The wave fronts of Rayleigh wave are advanced from the equiepicentral distance curve in the side of the Pacific Ocean in the

Mindanao and the Aleutian shock. This is caused by the fact that the velocity in the Pacific Ocean is higher than that under the Japan Islands in both cases. The angles of deviation in the region between Tsukuba and Haibara are about 6 degrees.

The phase velocities are obtained from the revised distance which is corrected for the deviation of 6 degrees. As shown in Fig. 3, this correction gives proper value for Rayleigh waves. For the Love wave, the correction of 6 degrees seems too small to compare the results which are obtained from Tsukuba, Haibara and Matsushiro.

In the case of Love waves, the deviations of wave fronts of the Aleutian shock are about 8 degrees at the periods about 30 to 40 sec. But the periods between 20 to 30 sec, the deviations are unknown, then we used the same correction as Rayleigh waves for the phase velocity determination of Love waves. The differences of azimuthal corrections of 1 or 2 degrees are caused by errors in phase velocity from 2 to 4 per cent. The phase velocities of Love waves have 7 to 8 per cent error in their determinations.

4. Phase velocity in central Japan

The phase velocities of Love and Rayleigh waves obtained by the above mentioned method are shown in Table 3 and Fig. 4. The results

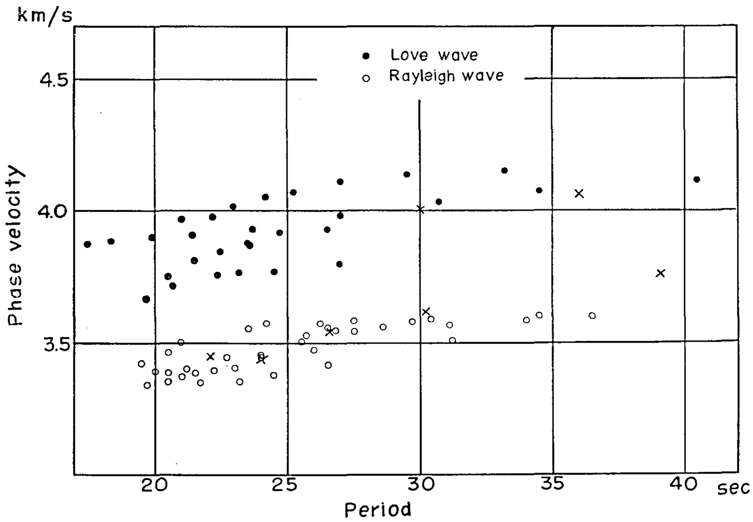

Fig. 4. Phase velocities of Love and Rayleigh waves. The symboles of closed circle are the data of the Aleutian shock (Kaminuma and Aki; 1963).

of Rayleigh waves agree with those interpolated between Tsukuba and Haibara of the Aleutian shock from the wave front charts analysed by Kaminuma and Aki (1963). There is no data of Love wave of the Aleutian shock with periods of shorter than 30 sec. But the period range longer than 30 sec, there is agreement between both data within a limit of probable errors.

The results are compared with the phase velocity of other regions

Table 3a. Phase velocity of Love waves in central Japan determined by correlation of wave trains between Tsukuba and Haibara.

No. 112023		No. 121313		No. 021501	
T	*C*	*T*	*C*	*T*	*C*
34.5 sec	4.074 km/sec	27.0 sec	3.797 km/sec	26.5 sec	3.929 km/sec
30.7	4.034	24.5	3.768	23.7	3.929
27.0	3.982	23.2	3.764		
24.7	3.917	22.4	3.757		
23.5	3.876	20.7	3.717		
22.5	3.843	19.7	3.665		
21.5	3.811				
20.2	3.751				

No. 021915		No. 030513		The Aleutian shock	
T	*C*	*T*	*C*	*T*	*C*
23.6 sec	3.871 km/sec	40.5 sec	4.112 km/sec	30.0 sec	4.001 km/sec
21.3	3.908	33.2	4.150	36.0	4.055
19.9	3.900	29.5	4.133	42.0	4.105
18.4	3.886	27.0	4.108	48.0	4.185
17.5	3.875	25.2	4.072		
		24.2	4.052		
		23.0	4.020		
		22.2	3.977		
		21.0	3.966		

in the world. The regions where the phase velocities of both Love and Rayleigh waves are measured satisfactory, are the Canadian shield (Brune and Dorman; 1963) and central United States (McEvilly; 1964).

Fig. 5 shows the phase velocities of Love and Rayleigh waves in these regions with periods of 20 to 40 sec. The closed circles are the phase velocites in the Canadian shield found by Brune and Dorman and open circles are the data in central Japan. Solid lines are the theoretical dispersion curves for central U.S. obtained by McEvilly. The scatter of observation for central U.S. is about 5 per cent. The phase velocities of Rayleigh waves in central Japan have about 5 per cent error in their observation and those of Love waves have about 8 per cent.

Table 3b. Phase velocity Rayleigh waves in central Japan determined by correlation of wave trains between Tsukuba and Haibara.

No. 111113		No. 111119		No. 121705	
T	*C*	*T*	*C*	*T*	*C*
34.0 sec	3.581 km/sec	31.1 sec	3.566 km/sec	34.5 sec	3.600 km/sec
30.4	3.588	28.6	3.559	29.7	3.578
27.5	3.584	26.8	3.546	27.5	3.543
26.2	3.571	25.7	3.529	25.6	3.497
24.2	3.571	25.5	3.503	24.0	3.443
				23.0	3.406
				22.2	3.397
				21.5	3.386
				21.0	3.374
				20.5	3.355

No. 030108		No. 030319		No. 030513	
T	*C*	*T*	*C*	*T*	*C*
26.5 sec	3.555 km/sec	26.0 sec	3.470 km/sec	36.5 sec	3.598 km/sec
23.5	3.550	24.0	3.453	31.2	3.506
21.0	3.505	22.7	3.447	26.5	3.416
20.5	3.465	21.2	3.401	24.5	3.377
19.5	3.424	20.0	3.395	23.2	3.352
		19.7	3.342	21.7	3.350

The Aleutian shock	
T	*C*
39.1 sec	3.761 km/sec
30.2	3.614
26.5	3.553
24.0	3.441
22.1	3.450

There are clear differences in the velocities of Rayleigh and Love waves in three regions.

The data indicated that the phase velocity of Rayleigh waves in central Japan is about 8 per cent lower than that of the Canadian shield

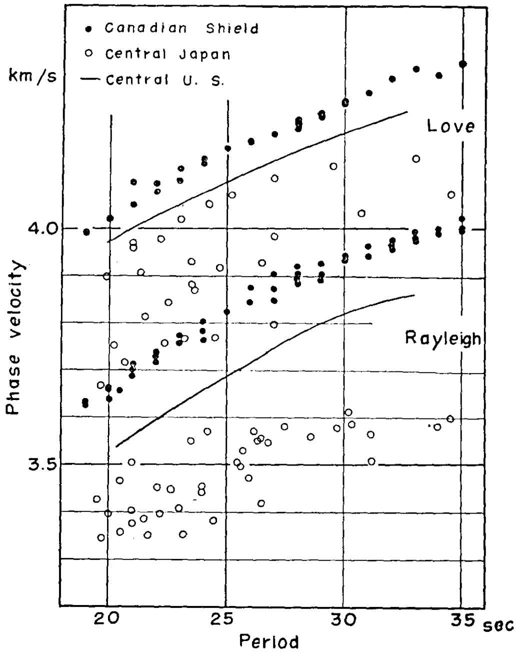

Fig. 5. Phase velocities of Love and Rayleigh waves. The closed circles are the data in the Canadian shield (Brune and Dorman; 1963). The open circles are in central Japan and the solid lines are in central U.S. (McEvilly; 1964).

Table 4. The phase velocities of surface waves in central Japan, the Canadian shield and central U.S.

Period \ Region	Central Japan	Canadian Shield	Central U.S.
Love wave			
27 sec	3.954 km/s	4.203 km/s (5.9%)	4.147 km/s (4.7%)
24	3.900	4.145 (5.9%)	4.079 (4.4%)
21	3.831	4.051 (5.4%)	4.004 (4.4%)
Rayleigh wave			
30 sec	3.596 km/s	3.932 km/s (8.5%)	3.804 km/s (5.4%)
26	3.516	3.848 (8.7%)	3.714 (5.3%)
21	3.404	3.705 (8.0%)	3.561 (4.4%)

and about 5 per cent lower than that of central U.S. and the phase velocity of Love waves is about 4 and 5 per cent lower than that of the Canadian shield and the central U.S. respectively.

The Canadian shield is a stable mass, central U.S. is a younger continental region and central Japan is the youngest tectonically active region with active volcanoes. It is very interesting that the velocity of surface wave increases with the geological age.

5. Comparison of Rayleigh wave data from other regions

Fig. 6 shows Rayleigh wave phase velocity data for central Japan compared with the data from other areas in the world, where the crustal thickness is about 35 km. The standard phase velocity curve of Press (1960) for the crustal thickness of 37 km is also shown for comparison.

The phase velocities of Rayleigh waves in China were obtained by Tung-sheng and Zi-an (1963) with periods of 18 to 28 sec. The results were well explained by Press' standard phase velocity curves (Press; 1960). The phase velocities in central Japan are about 6 per cent lower than those in the southeastern coast of China where the crustal thickness obtained from Press' curves is about 35 km.

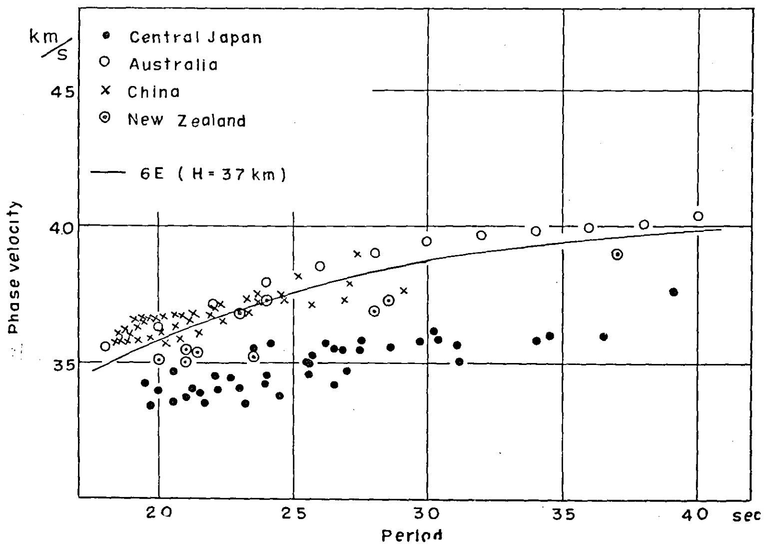

Fig. 6. Phase velocities of Rayleigh waves in Australia (Bolt and Niazi; 1964), China (Tung-sheng and Zi-an; 1963) and New Zealand (Thomson and Evison; 1962). The solid line is the phase velocity of Rayleigh waves for model 6E (Press; 1960).

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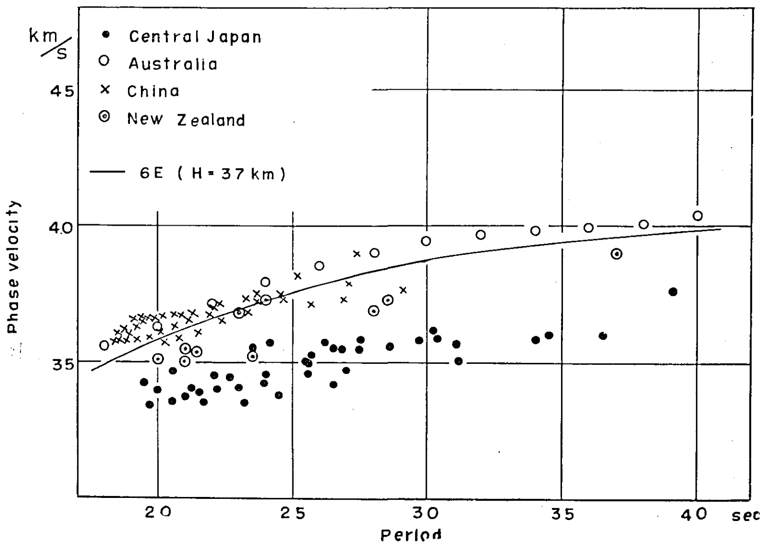

Fig. 6. Phase velocities of Rayleigh waves in Australia (Bolt and Niazi; 1964), China (Tung-sheng and Zi-an; 1963) and New Zealand (Thomson and Evison; 1962). The solid line is the phase velocity of Rayleigh waves for model 6E (Press; 1960).

The phase velocities of Rayleigh waves in Australia were obtained by Bolt and Niazi (1964) with periods of 15 to 40 sec. There was little scatter in the observations. The result agrees with that of the Canadian shield and the crustal thickness is 30 to 35 km. Then the phase velocities in Australia are about 8 per cent higher than those of central Japan.

The phase velocities in New Zealand were obtained by Thomson and Evison (1962) with periods of 20 to 40 sec. Since there were few data and large scatter in the observations, it is very difficult to compare those data with the results of central Japan. But by a rough comparison, the data show 2 or 3 per cent higher velocity than those of central Japan. The crustal thickness of North Island and the northern part of South Island is between 30 to 35 km, and of South Island between 30 to 40 km.

There are many areas where the phase velocities of Rayleigh waves were observed in the United States.

The phase velocities in southern California were obtained by Press (1956). That study was the first attempt to apply the determination of crustal structure from phase velocity dispersion of Rayleigh waves. The phase velocities of the area where the crustal thickness is between 30 to 36 km, are 5 to 7 per cent higher than those of central Japan.

The crustal structure from phase velocities of Rayleigh waves of the New York - Pennsylvania area were studied by Oliver *et al.* (1961) and that of the United States were obtained by Ewing and Press (1959). But as mentioned above, the phase velocity of Rayleigh waves of central Japan is lower than any other region in the world with a crustal thickness of between 30 to 40 km.

As described by Aki (1961), the elastic wave velocities in the crust and top of the mantle in Japan are about 5.5 per cent lower than those in the standard continents. The velocity in the top of the upper mantle is the same as the velocity of low velocity layer under the continents.

6. Rayleigh waves from the Pacific Ocean

Several shocks which occurred near the Kermadic Islands were also observed at Haibara and Tsukuba. We attempted to obtain the phase velocity from three stations, Haibara, Tsukuba and Matsushiro.

The records of these shocks at Tsukuba and Haibara are shown in Fig. 7. The wave forms are very similar to each other at these stations. As shown in broken line, the peaks and troughs are also identified between Tsukuba and Haibara. For any choice of correspondence of peak and trough for wave fronts among three stations it was impossible to obtain reasonable phase velocities. A list of these shocks is shown in Table 5.

Fig. 8 shows the group velocities of each peak at three stations. These group velocities were calculated as the epicentral distance divided by the travel time of each peak at each station. The abscissa is the peak number, it being the most reasonable correction between these stations. There is about 0.02 km/s difference in group velocity between Tsukuba and Matsushiro, and Haibara. This means that the phases that arrived at Tsukuba and Matsushiro are about 8 sec earlier than at Haibara. These time difference between Tsukuba and Matsushiro, and Haibara are shown in the upper part of Fig. 8.

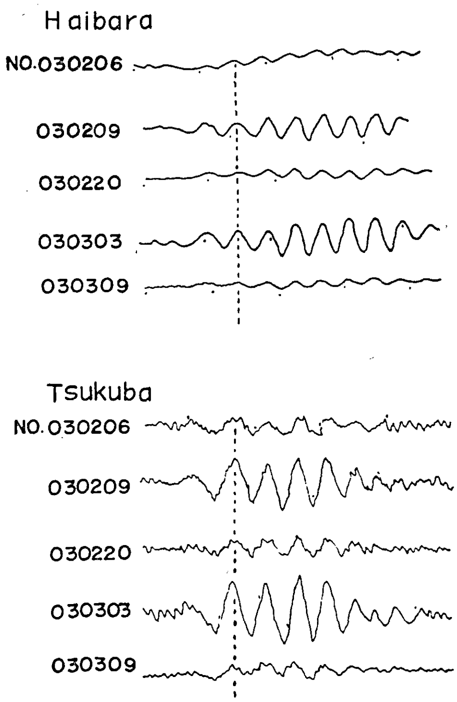

Fig. 7. Vertical component seismograms of Rayleigh waves from the Kermadic Islands.

It was shown by Aki (1961) that the wave fronts in the path from the Samoa Islands to northern Japan indicated a higher velocity of propagation than those in the path to southern Japan. Santô (1961)

Table 5. List of Earthquakes from near the Kermadic Islands.

Date	Origin time			Epicenter		Depth	Mag.
	h	m	s	lat.	log.	km	
March 02, '65	05	57	36.8	27.3°S	177.5°W	33	5.2
March 02, '65	09	19	41.6	27.2	177.9	39	5.6
March 02, '65	19	51	01.0	27.2	177.9	33	5.1
March 03, '65	03	17	04.1	27.2	177.6	33	5.5
March 03, '65	05	52	57.4	27.2	177.6	33	4.7

showed, by a group velocity study of Rayleigh waves from many circum Pacific epicenters to Tsukuba, that the Andesite line (Izu-Mariana line) may be a boundary between two different crustal structures. On the east side of it, the group velocity dispersion is typically oceanic, while on the west side, the group velocity is considerably lower than that on the east; the difference in velocity is about 0.2 km/s at a period of 30 sec according to Santô.

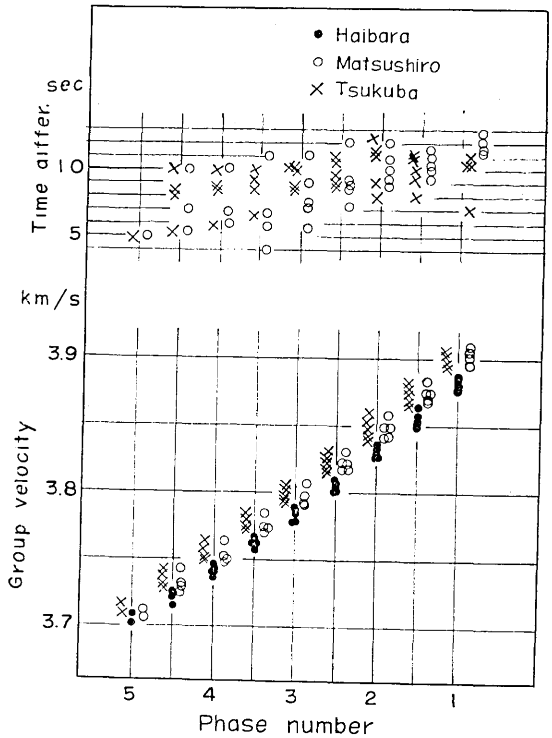

Fig. 8. The group velocity of each phase at Haibara, Tsukuba and Matsushiro and the arrival time differences between Matsushiro and Tsukuba and Haibara.

The path to Haibara lies on the west side of the Andesite line and those to Tsukuba and Matsushiro mostly on the east side near the boundary. For waves propagated over the complicated paths, it may be impossible to measure the phase velocity of surface wave from the Pacific Ocean using these stations. A denser network of long-period seismographs will be needed to make sure of the relation between the phase velocity of Rayleigh waves and the wave approach direction in central Japan.

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27. 日本の地殻及び上部マントルの構造

Part 1. 中央日本における表面波の位相速度

地震研究所 神 沼 克 伊

1964 年 10 月から 1965 年 3 月までのうち，約 3 カ月間，奈良県榛原町において，長周期地震計を使つて臨時観測を行なつた．その結果，約 10 個の地震の Love 波および Rayleigh 波から，それぞれの位相速度を得ることができた．

日本列島の地下構造のモデルが，Rayleigh 波および Love 波の位相速度を同時に説明しえないことは，筆者らによつて，すでに報告されているが，今回は周期 20～40 秒の波についても同じ結果を得た．

得られた位相速度を Canadian shield および Central U.S. の結果と比較すると，Rayleigh 波で 5～8%，Love 波で 4～5%，それぞれ日本における値が遅い．すなわち，表面波の位相速度は地質年代の新しい地域ほど遅い．また Rayleigh 波については，同じ地殻の厚さをもつ，いかなる地域よりも，中央日本の位相速度が遅いことがはつきりした．