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15. *Phase Velocity of Love Waves in Japan.*
(Part 1)
Love Waves from the Aleutian Shock of March 9, 1957.

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Introduction

The crustal structure in Japan has been investigated by Aki (1961) and Kaminuma and Aki (1962) from the phase velocity of Rayleigh waves in the period range 20 to 40 sec. In the present paper, the phase velocity of Love waves in Japan for the periods 30 to 90 sec is measured from the records of the Aleutian shock of March 9, 1957, and the results are discussed in relation to the previous results from Rayleigh waves.

The data and the method of analysis

Fig. 1 shows the records of Love waves obtained by the N-S component Wiechert type seismograph at the 25 stations of the Japan Meteorological Agency listed in Table 1. The length of one minute in the original record is 60 mm at some stations and 25 to 30 mm at others, but length is made uniform by the photographic enlargement in Fig. 1. Therefore, the record amplitude in Fig. 1 is amplified by a factor inversely proportional to the paper speed at each station (indicated in Table 1).

In Fig. 1, the arrow indicates the time at which Rayleigh wave motions become predominant in each record. In order to avoid the contamination from Rayleigh waves, we applied a so-called "cosine taper" to each record. The record $f(t)$ is multiplied by a function which is $1/2\{1-\cos 2\pi(t-t_R)/T\}$ for $t_R-T<t<t_R$ and zero otherwise, where t_R is

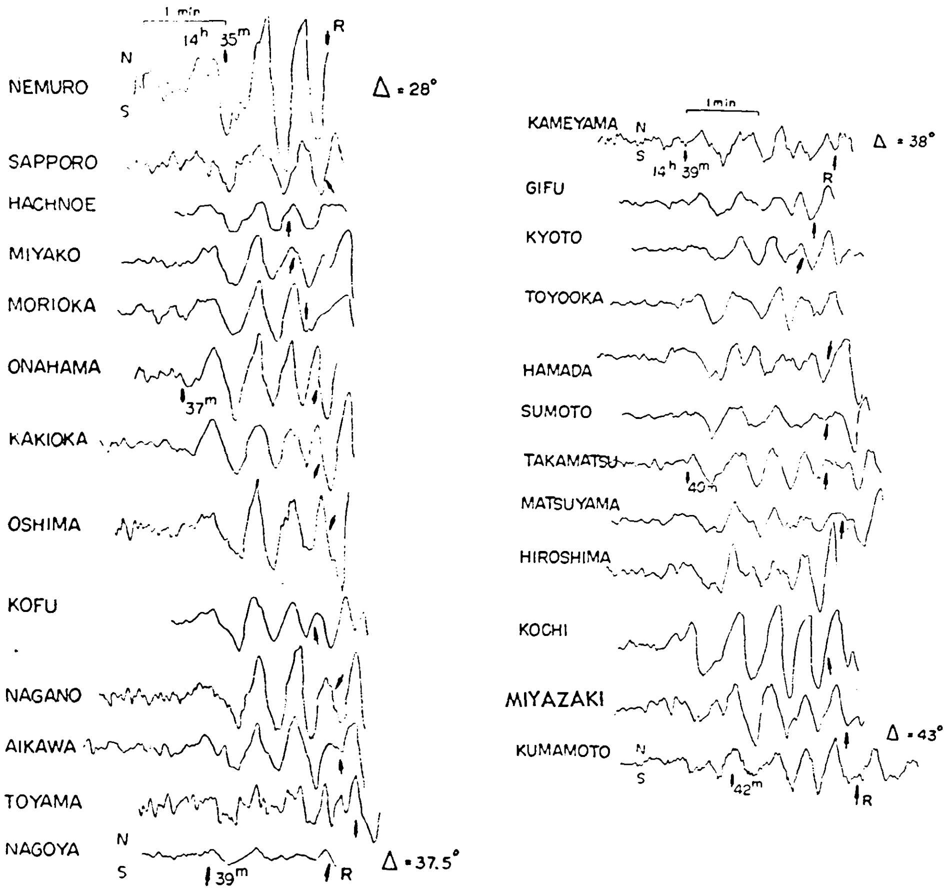

Fig. 1. Love waves from the Aleutian shock of March 9th, 1957 obtained by the N-S component Wiechert type seismograph. The arrows indicate the beginning of Rayleigh waves.

the time at which Rayleigh waves become predominant and T is taken as 200 sec. The tapered record $f^*(t)$ is, then, subjected to the Fourier analysis, and the phase delay spectrum $\phi(\omega)$ is obtained at each station. $\phi(\omega)$ is computed according to the formulas

$$\cos\phi(\omega)=\int_{-\infty}^{\infty} f^*(t)\cos\omega t dt/|F(\omega)|$$

$$\sin\phi(\omega)=\int_{-\infty}^{\infty} f^*(t)\sin\omega t dt/|F(\omega)|$$

where

$$f^*(t)=\int_0^\infty |F(\omega)| \cos(\omega t-\phi(\omega))d\omega \ .$$

The phase delay time t_P is defined by the relation $t_P=\phi(\omega)/\omega$. This is the time at which the Fourier component with the frequency of ω shows the peak value. Table 2 shows the phase delay times for various periods computed from the records at the 25 stations. The values for the periods 30, 42, 60 and 96 sec are indicated at the position of each station on the map in Figs. 2, 3, 4 and 5 respectively. The position of the peak of each Fourier component at every 30 sec is interpolated between the stations, and wave fronts are drawn to pass through the interpolated points.

As a check to the result of Fourier analysis, the arrival time of the zero point of the record that followed the first northward peak of Love waves is read from all the records. The arrival times are plotted on the map in Fig. 6 and the wave fronts are drawn in the same way

Table 1. List of Stations.

Station	Latitude		Longitude		Record paper speed
	deg.	min.	deg.	min.	cm
Nemuro	43	19.7	145	35.4	24.5
Sapporo	43	03.5	141	19.9	59.2
Hachinoe	40	31.6	141	31.5	30.0
Morioka	39	41.7	141	10.2	23.5
Miyako	39	38.7	141	58.1	29.4
Onahama	36	56.7	140	54.3	30.2
Kakioka	36	13.9	140	11.6	25.0
Oshima	34	45.7	139	22.8	30.3
Aikawa	38	01.2	138	14.5	27.4
Toyama	36	42.4	137	12.3	30.0
Nagano	36	39.6	138	11.8	23.8
Kofu	35	39.9	138	33.5	30.7
Nagoya	35	09.9	136	58.1	58.6
Gifu	35	23.8	136	45.9	29.6
Kameyama	34	51.3	136	27.9	29.6
Toyooka	35	32.1	134	49.3	27.6
Kyoto	35	00.7	135	44.3	28.0
Sumoto	34	20.1	134	54.5	29.8
Hamada	34	53.6	132	04.4	25.0
Hiroshima	34	21.8	132	26.2	26.0
Takamatsu	34	19.1	134	03.5	30.1
Matsuyama	33	50.4	132	46.8	29.6
Kochi	33	33.9	133	33.1	25.4
Kumamoto	32	48.6	130	42.6	30.0
Miyazaki	31	55.0	131	25.6	25.5

Table 2. Phase arrival time and relative amplitude of each Fourier component at each station.

Period	30 sec.			36 sec.			42 sec.			48 sec.		
Station	Phase arrival time		Relative amplitude	Phase arrival time		Relative amplitude	Phase arrival time		Relative amplitude	Phase arrival time		Relative amplitude
	min.	sec.		min.	sec.		min.	sec.		min.	sec.	
Nemuro	34	53.5	1.00	34	46.7	2.42	34	43.8	2.85	34	40.8	2.43
Sapporo	36	13.1	1.00	36	08.2	1.43	36	02.8	1.94	35	58.9	2.20
Hachinoe	36	30.1	1.00	36	27.9	1.19	36	25.5	1.21	36	23.3	1.19
Morioka	36	42.2	1.00	36	37.6	0.94	36	34.7	1.10	36	33.5	1.05
Miyako	36	27.9	1.00	36	24.9	1.75	36	23.9	1.88	36	23.2	1.66
Onahama	37	22.4	1.00	37	20.7	0.83	37	19.4	0.63	37	18.3	0.48
Kakioka	37	44.6	1.00	37	42.5	1.02	37	41.1	0.88	37	40.2	0.74
Oshima	38	24.5	1.00	38	19.0	1.08	38	16.1	0.98	38	14.6	0.79
Aikawa	37	55.7	1.00	37	49.8	0.95	37	46.0	0.76	37	44.5	0.62
Toyama	38	36.5	1.00	38	30.2	0.88	38	26.2	0.67	38	25.0	0.63
Nagano	38	19.3	1.00	38	13.6	0.99	38	09.4	0.86	38	07.1	0.73
Kofu	38	23.3	1.00	38	19.8	1.11	38	17.2	1.01	38	15.1	0.87
Nagoya	39	00.8	1.00	38	56.8	1.58	38	54.6	1.69	38	52.8	1.51
Gifu	39	03.3	1.00	38	59.3	1.47	38	56.3	1.35	38	53.4	1.15
Kameyama	39	17.8	1.00	39	12.0	1.65	39	08.1	1.57	39	05.0	1.23
Toyooka	39	37.4	1.00	39	33.6	1.30	39	29.9	1.25	39	26.7	1.10
Kyoto	39	29.4	1.00	39	23.5	1.01	39	18.9	1.02	39	16.2	0.94
Sumoto	39	53.3	1.00	39	47.6	1.44	39	42.3	1.31	39	37.9	1.03
Hamada	40	29.7	1.00	40	26.4	3.63	40	22.7	6.22	40	19.2	7.25
Hiroshima	40	34.7	1.00	40	28.4	1.79	40	24.4	2.15	40	21.0	2.14
Takamatsu	40	10.0	1.00	40	03.1	1.39	39	58.0	1.21	39	54.3	0.93
Matsuyama	40	38.7	1.00	40	30.9	1.58	40	25.9	1.70	40	21.6	1.54
Kochi	40	31.3	1.00	40	23.3	1.86	40	17.9	1.81	40	13.9	1.43
Kumamoto	41	33.8	1.00	41	23.7	0.79	41	16.0	0.68	41	09.8	0.56
Miyazaki	41	35.9	1.00	41	24.7	1.10	41	16.3	1.09	41	09.4	1.91

(to be continued)

Table 2. (continued).

Period	60 sec.			72 sec.			96 sec.		
Station	Phase arrival time		Relative amplitude	Phase arrival time		Relative amplitude	Phase arrival time		Relative amplitude
	min.	sec.		min.	sec.		min.	sec.	
Nemuro	34	36.1	1.55	34	31.9	1.08	34	25.6	0.73
Sapporo	35	53.0	1.94	35	48.6	1.48	35	42.9	0.86
Hachinoe	36	19.8	1.13	36	17.1	1.07	36	12.7	0.92
Morioka	36	32.3	0.78	36	30.7	0.56	36	29.6	0.32
Miyako	36	21.9	1.13	36	20.0	0.84	36	16.9	0.69
Onahama	37	16.6	0.31	37	14.4	0.25	37	10.2	0.13
Kakioka	37	39.9	0.51	37	40.8	0.35	37	46.2	0.17
Oshima	38	13.2	0.53	38	11.5	0.46	38	08.5	0.32
Aikawa	37	42.4	0.60	37	38.5	0.60	37	31.0	0.51
Toyama	38	21.4	0.78	38	15.9	0.73	38	03.4	0.44
Nagano	38	04.9	0.55	38	02.6	0.42	37	56.4	0.21
Kofu	38	11.6	0.65	38	08.5	0.52	38	02.9	0.37
Nagoya	38	49.7	1.02	38	46.4	0.73	38	40.2	0.40
Gifu	38	48.9	0.89	38	45.5	0.68	38	38.1	0.31
Kameyama	39	00.2	0.80	38	56.1	0.64	38	49.4	0.46
Toyooka	39	21.4	0.81	39	16.4	0.63	39	05.8	0.39
Kyoto	39	13.1	0.71	39	10.0	0.51	38	57.8	0.29
Sumoto	39	32.3	0.68	39	28.0	0.57	39	17.7	0.38
Hamada	40	13.0	6.66	40	07.6	5.28	39	59.0	3.25
Hiroshima	40	14.5	1.75	40	08.2	1.36	39	55.5	0.75
Takamatsu	39	49.6	0.62	39	45.8	0.46	39	40.0	0.26
Matsuyama	40	14.3	1.02	40	07.9	0.72	39	53.3	0.44
Kochi	40	08.7	0.89	40	05.0	0.67	39	57.7	0.45
Kumamoto	41	02.5	0.34	40	56.3	0.33	40	35.6	0.25
Miyazaki	40	58.3	1.49	40	49.8	0.26	40	41.4	0.84

as for the Fourier components. The average period of the wave around the zero point concerned is 43.5 sec. In the case of dispersed wave trains, the peak of wave with a certain period in the original record is delayed by about $\pi/4$ from the time of the peak of the Fourier component with that period, if the dispersion is normal, while advanced by the same amount if the dispersion is reversed. Since our waves show a very weak normal dispersion, it is expected that the above delay, if it exists, may be very small, probably negligible. Then, the wave front for the peak of the Fourier component with the period 42 sec (Fig. 3) will be advanced by about $\pi/2$ from the arrival time of the zero point which followed the positive peak and had the average period of 43.5 sec (Fig. 6). The comparison of both figures shows a time advance of about 10.5 sec which corresponds exactly to the phase angle of $\pi/2$ for the waves of period 42 sec. Furthermore, the phase velocity averaged over Japan is obtained as 4.343 km/sec for the Fourier component of period 42 sec and as 4.35 km/sec for the zero-point. These results confirm the validity of the result of our Fourier analysis.

Wave front chart

In the wave front charts shown in Figs. 2 to 6, the epicentral distances of 33 and 40 degrees are indicated. It is interesting to note that the wave fronts are almost parallel to the 33 degree equi-epicentral line

Table 3. The period, wave length and the average direction of approach of Rayleigh and Love waves, from the Aleutian shock of March 9, 1957 observed at the stations in eastern Japan. The theoretical great circle direction to the epicentre is about 52 degrees.

Rayleigh wave			Love wave		
Period	Wave length	Direction of approach	Period	Wave length	Direction of approach
sec.	km	deg. min. deg. min.	sec.	km	deg. min. deg. min.
38.3	145.2	59 54 ± 0 35	96	467.3	48 42 ± 1 05
30.3	111.7	63 17 ± 1 20	72	331.9	52 13 ± 0 38
26.4	95.9	62 29 ± 1 33	60	274.0	53 38 ± 1 03
24.1	86.5	60 30 ± 0 44	48	212.4	53 54 ± 1 21
22.1	77.6	65 38 ± 4 36	42	182.7	54 47 ± 1 37
			36	153.0	57 22 ± 1 31
			30	123.5	60 31 ± 0 51

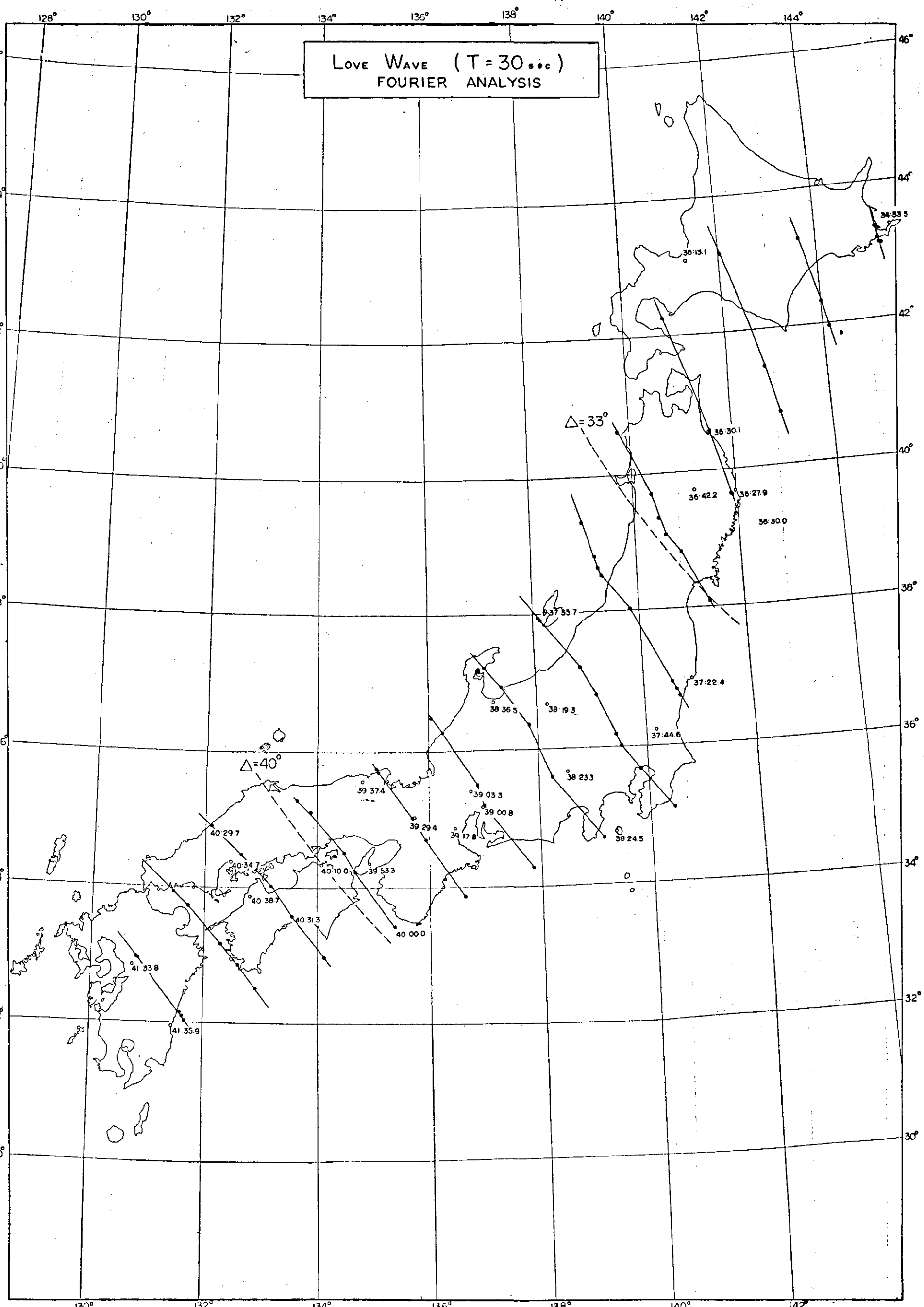

Fig. 2. Wave front of the phase for the periods 30 sec at every 30 seconds across Japan The dashed line indicates the epicentral distances of 33° and 40°.

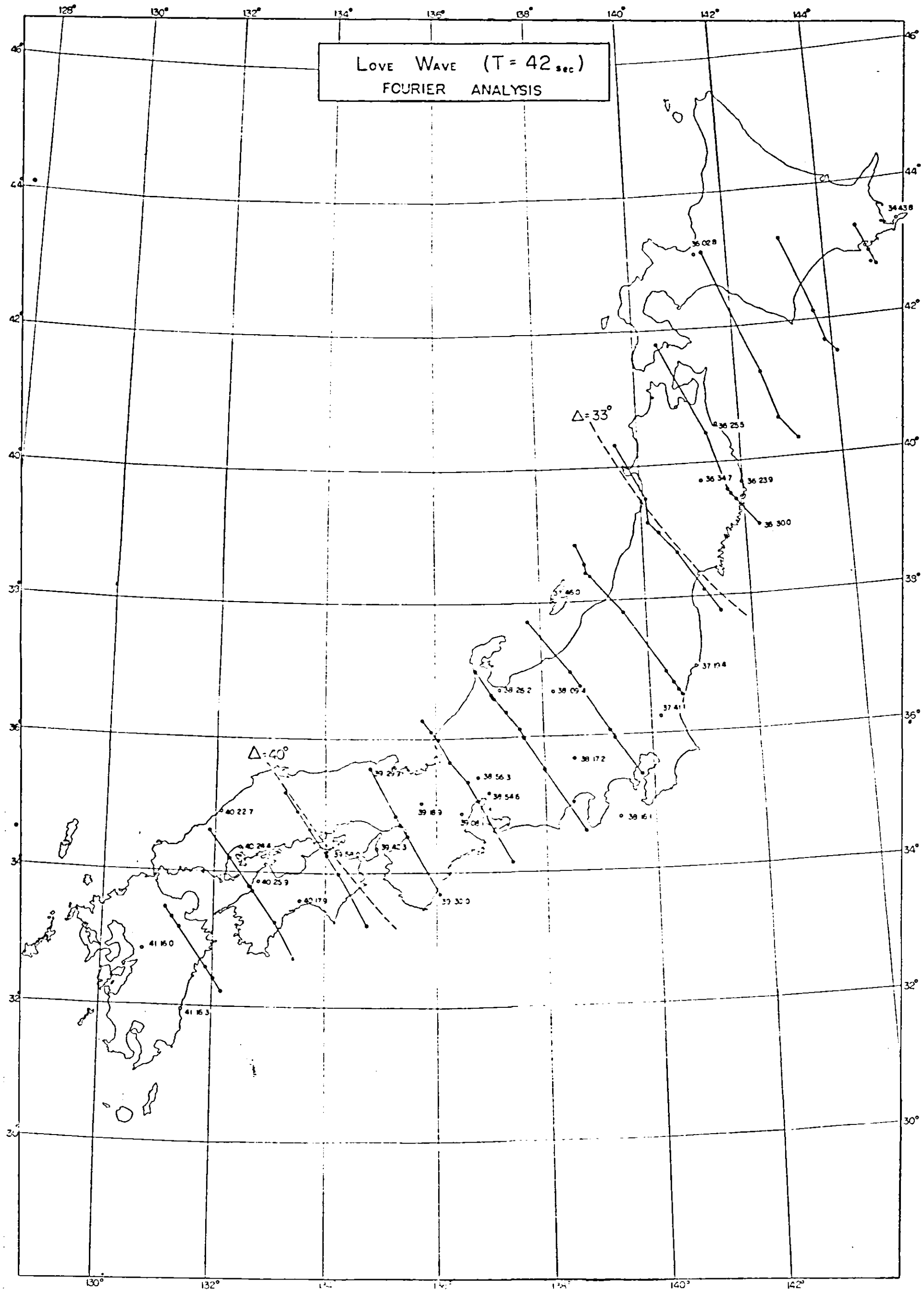

Fig. 3. Wave front of the phase for the periods 42 sec at every 30 seconds across Japan. The dashed line indicates the epicentral distances of 33° and 40°.

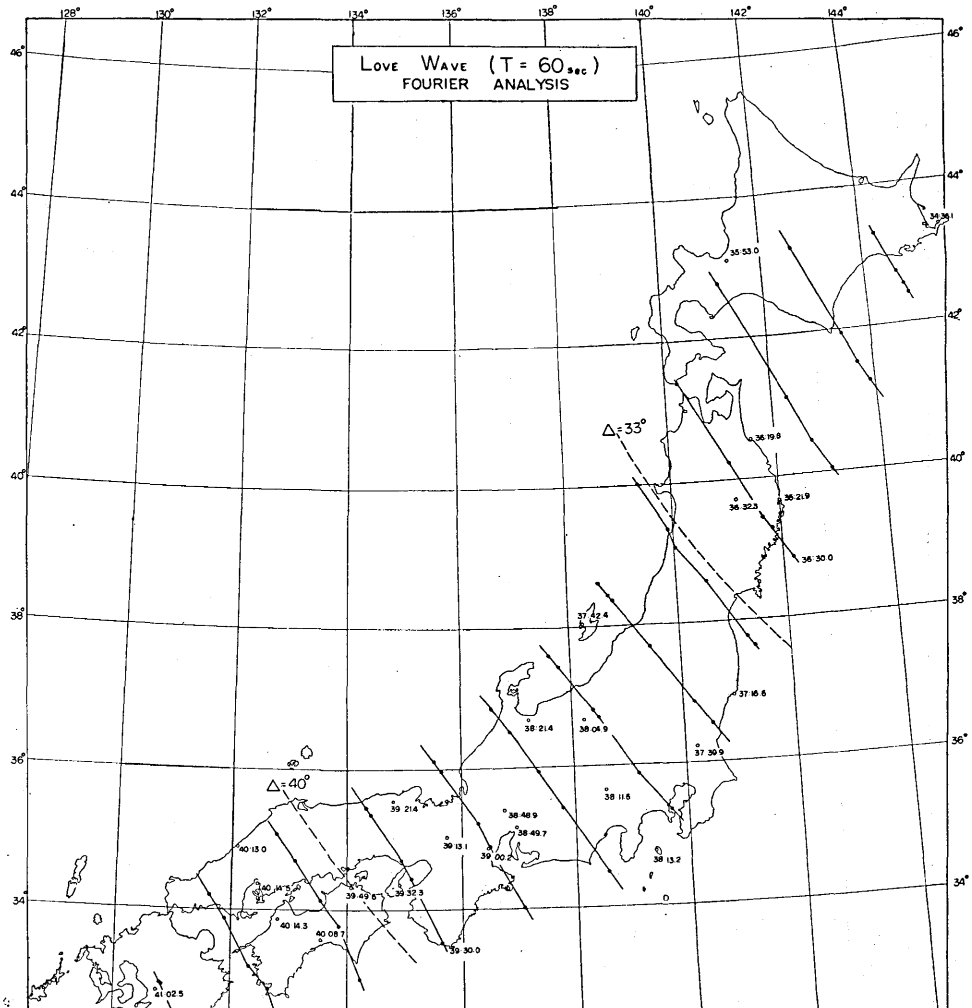

Fig. 4. Wave front of the phase for the periods 60 sec at every 30 seconds across Japan. The dashed line indicates the epicentral distances of 33° and 40°.

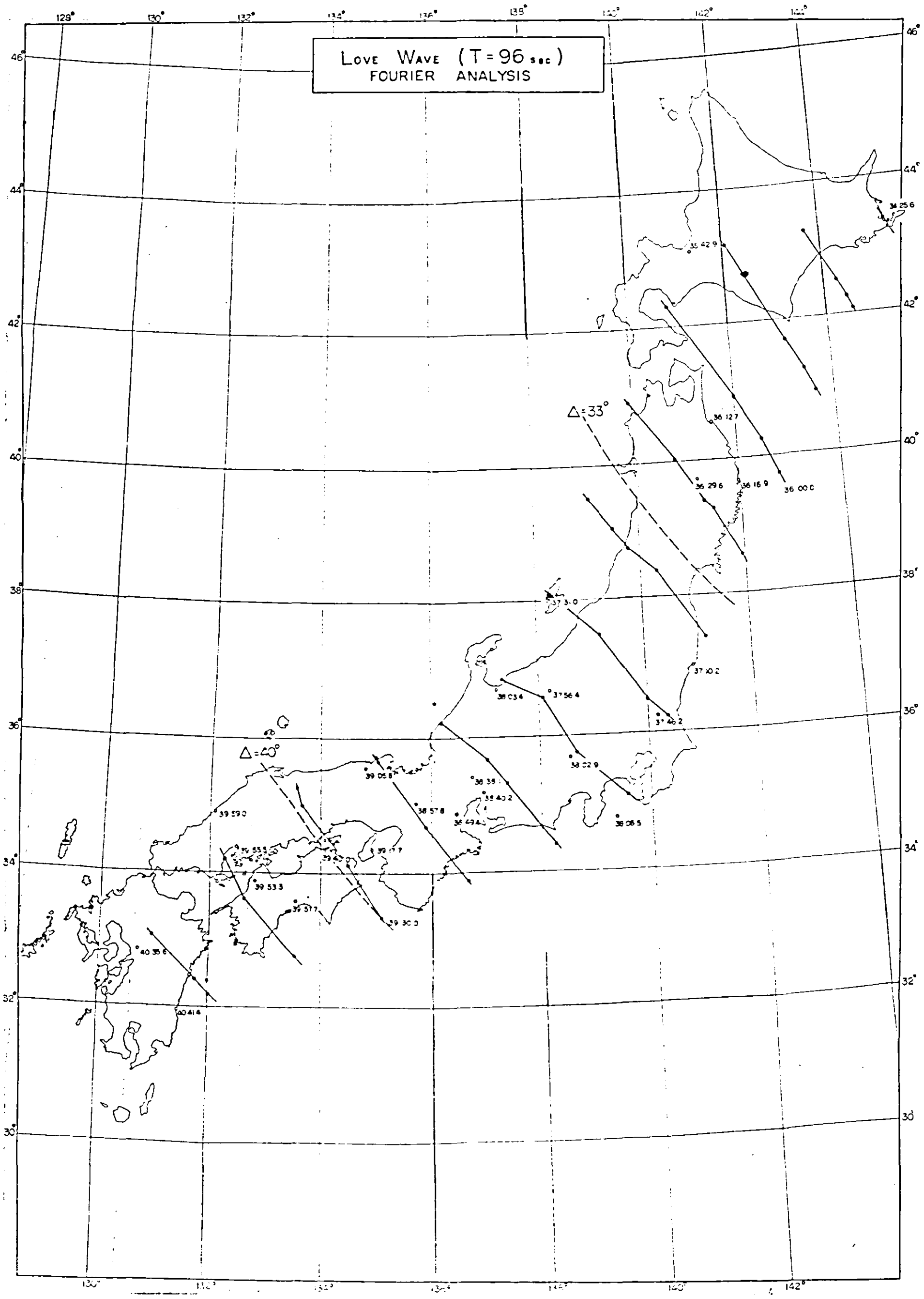

Fig. 5. Wave front of the phase for the periods 96 sec at every 30 seconds across Japan. The dashed line indicates the epicentral distances of 33° and 40°.

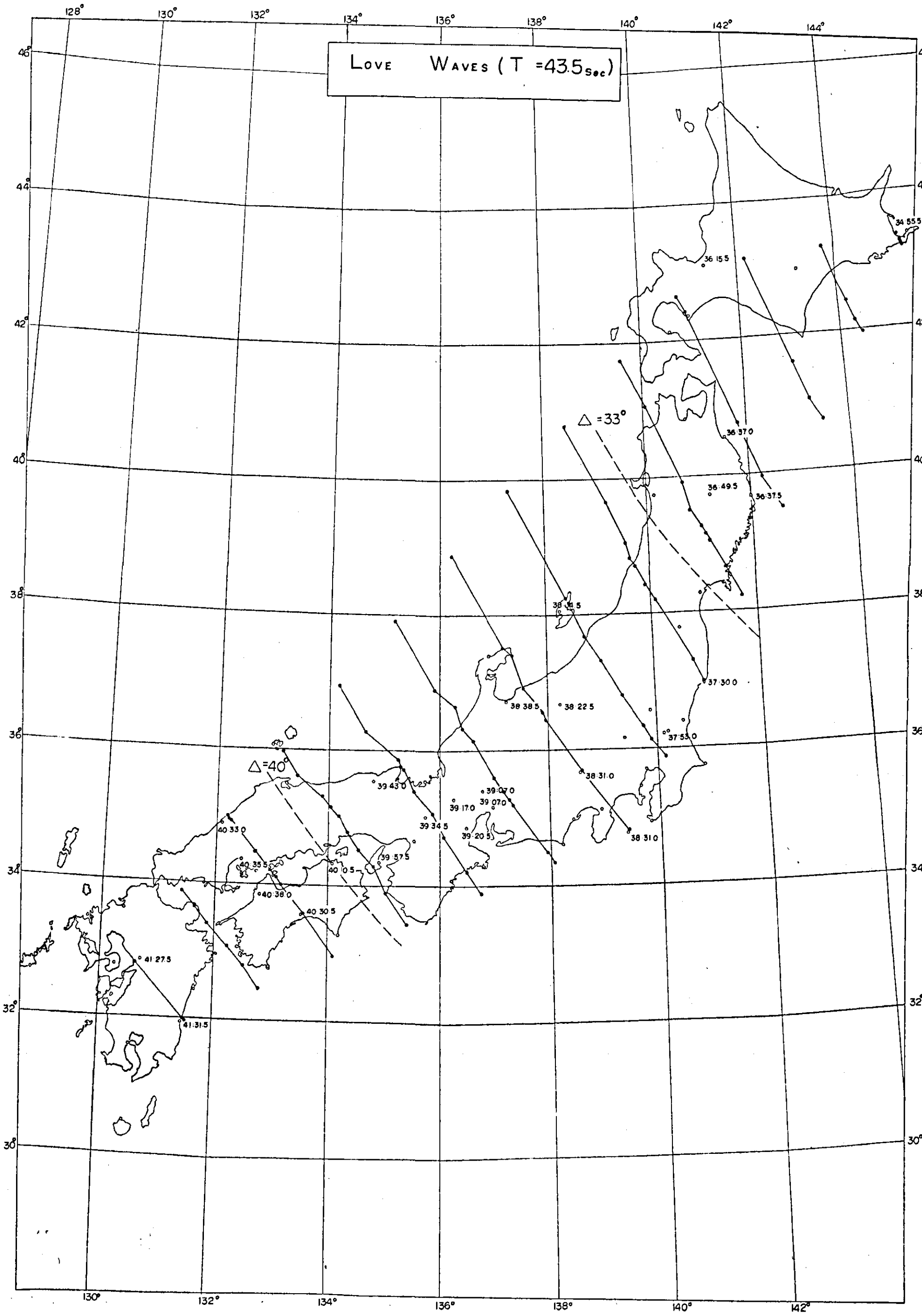

Fig. 6. Wave front of the zero point that followed the 1 st northward peak of Love waves. The dashed line indicates the epicentral distances of 33° and 40°.

for the periods longer than about 50 sec. For shorter periods, the peaks arrive relatively later in the northern stations, and the wave front is distorted as much as 10 degrees. The direction of approach is determined for various periods from the arrival times at the stations in north-eastern Honshu as shown in Table 3. For comparison, the result for Rayleigh waves from the same earthquake is also shown (Kaminuma and Aki, 1962). The average great circle direction to the epicentre from these stations is about N 52 degrees E. The table shows that the direction of approach becomes close to the great circle direction for wave lengths greater than about 250 km. This fact may imply that the variation in the crustal structure across the marginal zone from the Pacific Ocean to the Kurile and Aleutian arcs shows up in the surface wave dispersion only for shorter wave lengths than about 250 km. Rayleigh and Love wave data seems to fall, within the limit of error, on the same curve in the diagram showing the direction of approach as a function of the wave length.

Phase velocity

The stations are divided into three groups; east, central and west Japan as show in Fig. 7. The phase velocities are determined for each group by the method of least squares applied to the phase delay time data listed in Table 2. The phase velocity values and their probable errors are shown for various periods in Table 4. Table 4 also lists

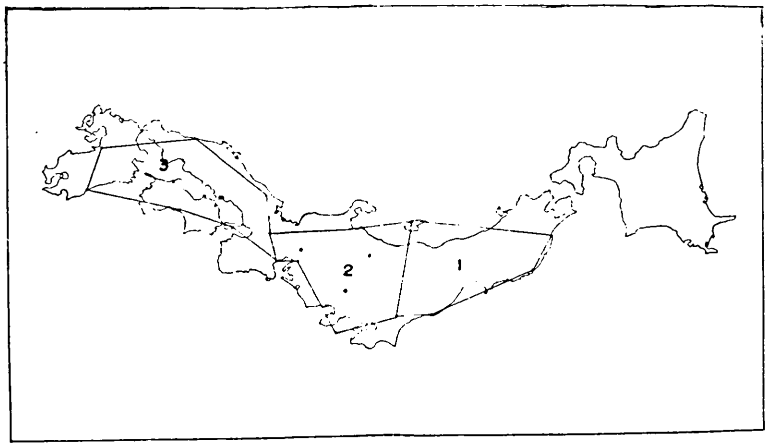

Fig. 7. Division of stations into three groups; 1, Eastern Japan. 2. Central Japan, 3. Western Japan.

Table 4. The phase velocities of Love waves in Japan for various periods and their probable errors determined by the least squares method.

Period	Eastern Japan	Central Japan	Western Japan	Average Japan (weighted)
	km/sec	km/sec	km/sec	km/sec
96	5.023±0.099	4.509±0.118	5.161±0.269	4.873
72	4.750±0.056	4.282±0.073	4.924±0.133	4.632
60	4.642±0.091	4.329±0.058	4.767±0.081	4.567
48	4.621±0.128	4.185±0.042	4.574±0.045	4.428
42	4.606±0.153	4.105±0.036	4.451±0.039	4.343
36	4.489±0.145	4.055±0.029	4.316±0.054	4.246
30	4.324±0.082	4.001±0.047	4.133±0.121	4.118

average velocities for the whole of Japan (except Hokkaido) which are obtained by averaging the values for 3 regions with the weight approximately proportional to the area of each region.

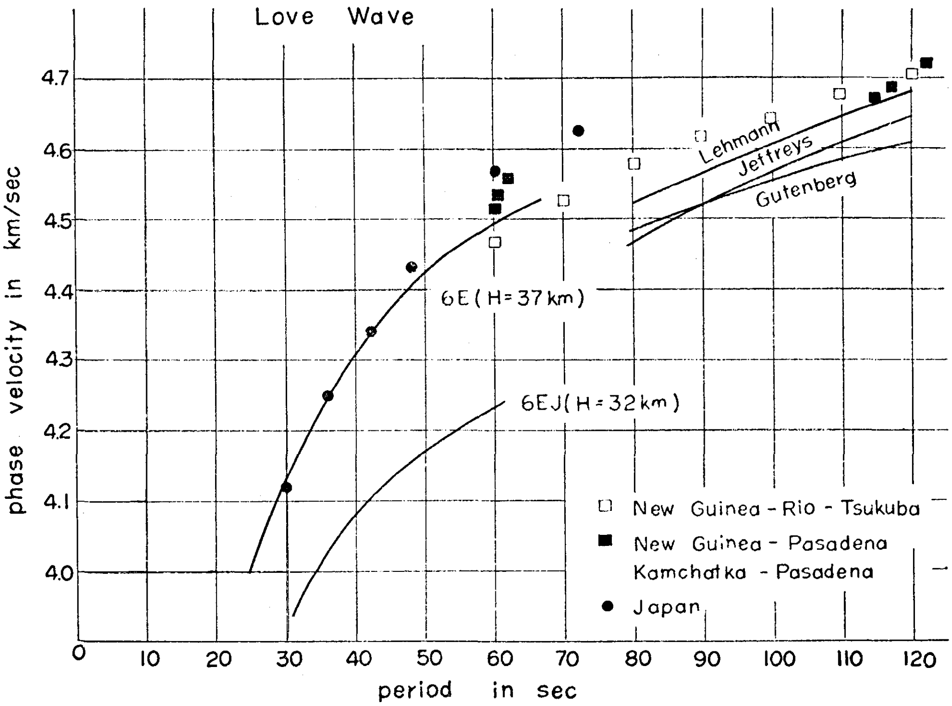

Fig. 8. Observed and theoretical dispersion curves of Love waves. The references are given in the text.

Discussions

The average phase velocity of Love waves in Japan is plotted in Fig. 8 together with the observed phase velocity for several great circles by Satô (1958) and Brune, Benioff and Ewing (1961). In the same figure, we show the theoretical dispersion curves computed by Takeuchi et. al. (1962) for several spherical earth models and those for the flat earth model 6E (Press, 1960) and 6EJ (Aki, 1961). The shear velocity distribution for these models is shown in Fig. 9. The dispersion curves

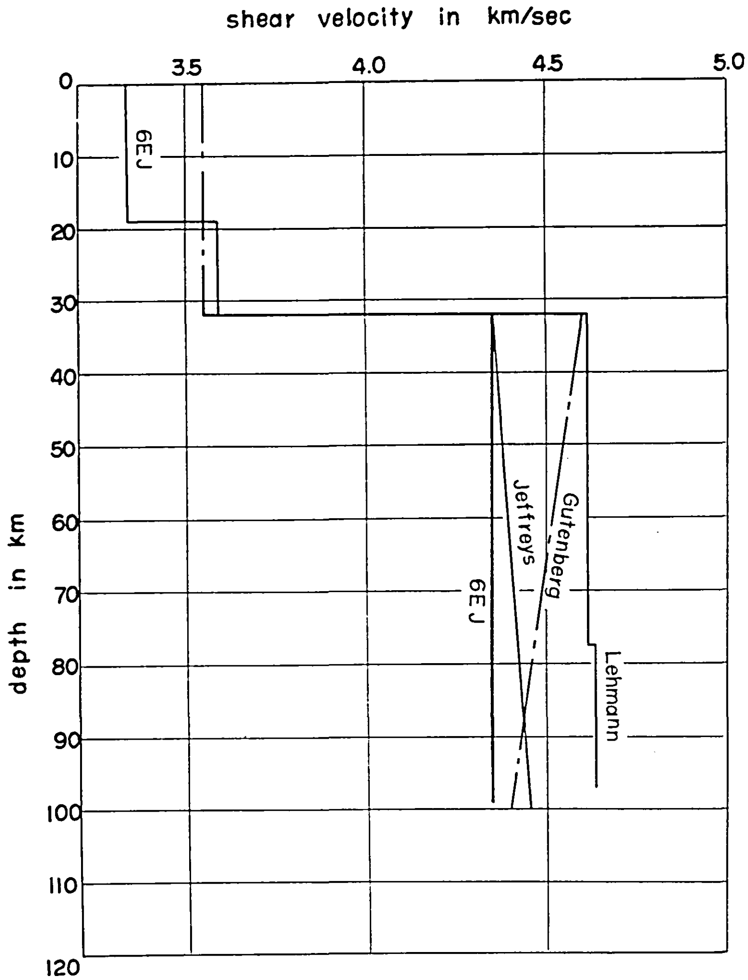

Fig. 9. Shear velocity distribution at depths for various crustal models.

for the model 6E and 6EJ are computed by the use of Dorman's Table (Dorman, 1959).

It is evident from Fig. 8 that the model 6EJ does not explain the observed phase velocity of Love waves in Japan. The shear velocities assumed in the model 6EJ are too low to account for the Love wave dispersion. This fact is very interesting because the model 6EJ explains excellently the dispersion of Rayleigh waves in Japan (Aki, 1961 and Kaminuma and Aki, 1962). Fig. 10 shows the average phase velocity of Rayleigh waves in Japan together with those in the New York-Pennsylvania region (Oliver et. al., 1961) and for several great circles (Brune, Nafe and Alsop, 1961 and Brune, Benioff and Ewing, 1961). Brune (1960) showed that the phase velocity of Rayleigh waves in the period range 80 to 120 sec. are markedly lower along the great circles which traverse tectonically active regions over a large proportion of their length. This low velocity is indicated by the points for the

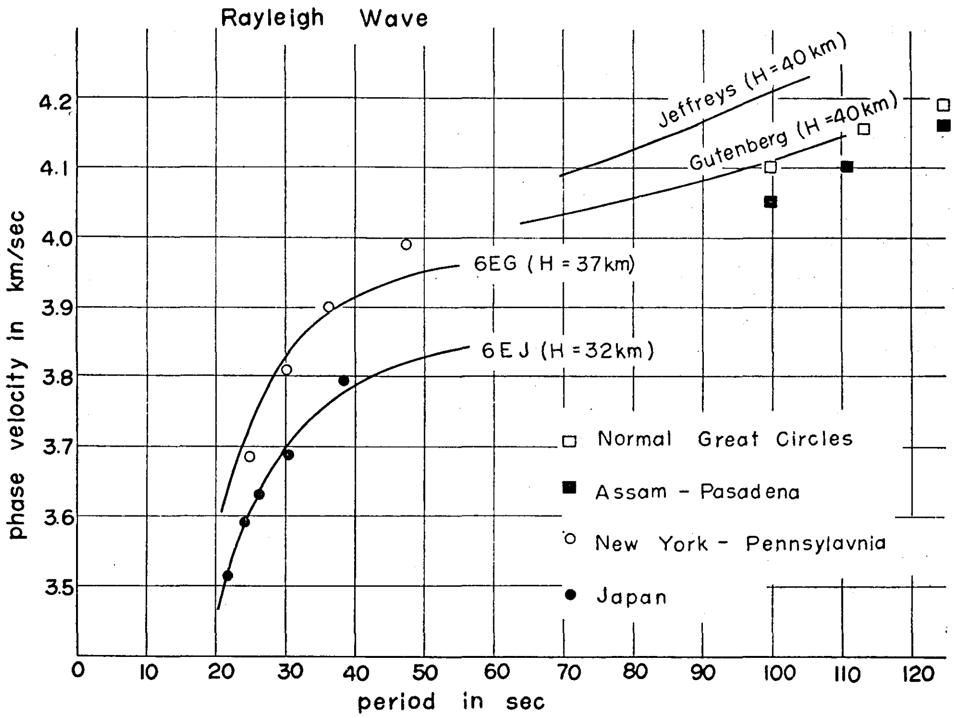

Fig. 10. Observed and theoretical dispersion curves of Rayleigh waves. The references are given in the text.

Assam-Pasadena great circle in Fig. 10. Fig. 10 also demonstrates that the phase velocities for periods 20 to 40 sec are considerably lower in Japan than that in the normal continent despite the fact that the crustal thickness is greater in the continent. These evidences show that the shear velocity in the crust and upper mantle is lower in tectonically active regions than in the normal continents. However, Love dispersion revealled in the present study indicates no such lower shear velocity in the tectonically active regions.

It has been pointed out that there is a small but significant discrepancy between the observed dispersion curve of mantle Love waves and the theoretical curve based on the Gutenberg mantle which coincides best with the Rayleigh wave dispersion (see Fig. 10), the theoretical curves are computed by Bolt and Dorman (1961). Our result shows that this discrepancy is emphasized in such an active region as Japan. Anderson (personal communication) is attempting to explain this discrepancy by postulating anisotropic layers in the upper mantle. The type of anisotropy required to explain the discrepancy is such that the speed of SH waves propagated horizontally is greater than that propagated vertically. In other words, taking the z-axis vertically, the shearing modulus for the shear stress working along the vertical plane (P_{xy}/e_{xy}) is higher than that along the horizontal plane (P_{xz}/e_{xz} or P_{yz}/e_{yz}). This type of anisotropy may be produced by the presence of soft thin layers sandwiched at various depths, or, as suggested by Shimozuru (1962), by the presence of magma pockets having the shape of oblate spheroid. The pronounced discrepancy between the Love and Rayleigh wave dispersion in Japan may indicate a high concentration of such soft layers or oblate magma pockets in the crust and the upper mantle.

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The writers express their thanks to all the seismologists at the stations of the Japan Meteorological Agency for their cooperation in making their records available to them. The writers' thanks are also due to Professor Takahiro Hagiwara and Assistant-Professor Setumi Miyamura.

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15. 日本におけるラブ波の位相速度 (第 1 報)

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東京大学大学院地球物理専門課程 神沼克伊

1957 年 3 月 9 日のアリューシャンの地震によるラブ波は，気象庁観測網のウィーヘルト地震計によりかなりよく記録された (第 1 図)．気象庁の御好意によりお借りした記録のうち，25 カ所の記録を解析して，日本におけるラブ波の位相速度を求めた．

位相速度の測定は，30 秒から 96 秒までの各周期について，フーリェ分析を応用して位相遅れを各点について求め，それに最小自乗法を適用して速度を求めた．

その結果得られた日本の平均のラブ波の位相速度を第 8 図に示した．驚くべきことには日本の平均のレーリー波の位相速度をよく説明した (第 10 図) モデル 6EJ では，このラブ波の分散の実測を説明しない．

マントルレーリー波とマントルラブ波が同じモデルで説明できにくいことは，全地球的にもいわれていることであるが，その一つの説明に異方性が考えられている．問題のくい違いを説明するような異方性は，下鶴の考えているような扁平な形のマグマ溜り，あるいは，やわらかな層と固い層が互層をなしている場合に生じるので，日本のような地震火山活動の激しい所で，このくい違いが大きく現われたことは，まことに興味深いことである．