BULLETIN OF THE EARTHQUAKE
RESEARCH INSTITUTE
Vol. 39 (1961), pp. 255-283

8. *Crustal Structure in Japan from the Phase Velocity of Rayleigh Waves.*

Part 1. Use of the network of seismological stations operated by the Japan Meteorological Agency.

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(Read March 28, 1961.—Received March 31, 1961.)

Introduction

The phase velocity of Rayleigh waves was first successfully utilized by Press (1956) in a study of crustal structure in the southern California. The application of this new method has been extended to northern California by Press (1957), and to the entire United States by Ewing and Press (1959). Press (1960) and Oliver, Kovach and Dorman (1961) refined the method with the aid of electronic computers. In Japan, an application of the method has been tried by Shima et al. (1960) with the use of the tripartite stations; Matsushiro, Tsukuba and Abuyama.

For successful application of the method, it is essential to use purely isolated Rayleigh waves. Press showed that Rayleigh waves with periods from 35 to 15 sec, which have traversed a long oceanic path before entering the area to be studied, are most suitable for this purpose.

In the present study, we used the records of the Samoa shock of April 14, 1957 (19 h 17 m 57 s GCT, 15.5°S, 173°W.) obtained at the network of seismological stations operated by the Japan Meteorological Agency. This is the same earthquake on which Ewing and Press (1959) based their phase velocity measurement for the entire United States. Rayleigh waves with periods 30 to 20 sec from this earthquake are fairly clearly recorded by Wiechert seismographs at many of the J.M.A. stations. The Wiechert seismographs operated at these stations are adjusted to maintain an uniform characteristic (pendulum period 5.0 sec, geometric magnification 70 to 80, and the damping ratio 6 to 8). The dynamic magnification of this instrument at the period of 30 sec is about 1.5. At these long periods the absolute value of the instrumental phase delay is small, and its variation from station to station can be overlooked. This is the advantage of using a short period instrument.

Table 1. List of stations.

Station	Abbreviation	Longitude		Latitude	
		deg.	min.	deg.	min.
Sapporo	SA	141	19.8	43	03.5
Aomori	AO	140	47.0	40	49.0
Hachinohe	HA	141	31.5	40	31.5
Akita	AK	140	06.0	39	43.0
Morioka	MO	141	10.0	39	41.7
Miyako	MY	141	58.0	39	38.6
Sendai	SE	140	54.0	38	15.5
Toyama	TY	137	12.5	36	42.3
Nagano	NA	138	11.7	36	39.5
Utsunomiya	UT	139	52.2	36	32.7
Kumagaya	KU	139	23.0	36	08.7
Mito	MT	140	28.2	36	22.6
Gifu	GI	136	45.8	35	23.8
Nagoya	NY	136	58.0	35	09.8
Kofu	KF	138	33.5	35	39.8
Kameyama	KA	136	27.8	34	51.3
Omaezaki	OM	138	12.7	34	36.1
Shizuoka	SZ	138	24.3	34	58.3
Mishima	MS	138	55.7	35	06.6
Tokyo	TK	139	45.6	35	41.1
Owashi	OW	136	11.6	34	04.0
Yokohama	YO	139	39.2	35	26.1
Tomisaki	TS	139	49.6	34	55.1
Oshima	OS	139	22.6	34	45.6
Toyooka	TO	134	49.1	35	32.1
Kyoto	KY	135	44.0	35	00.6
Hikone	HK	136	14.7	35	16.3
Hiroshima	HR	132	26.1	34	21.7
Osaka	OK	135	32.2	34	38.8
Sumoto	SU	134	54.5	34	20.0
Tomie	TM	128	45.8	32	36.5
Kagoshima	KG	130	33.1	31	34.3
Miyazaki	MZ	131	25.5	31	55.0
Yakushima	YA	130	29.7	30	27.0
Takamatsu	TA	134	03.5	34	19.0
Kochi	KO	133	32.0	33	33.0

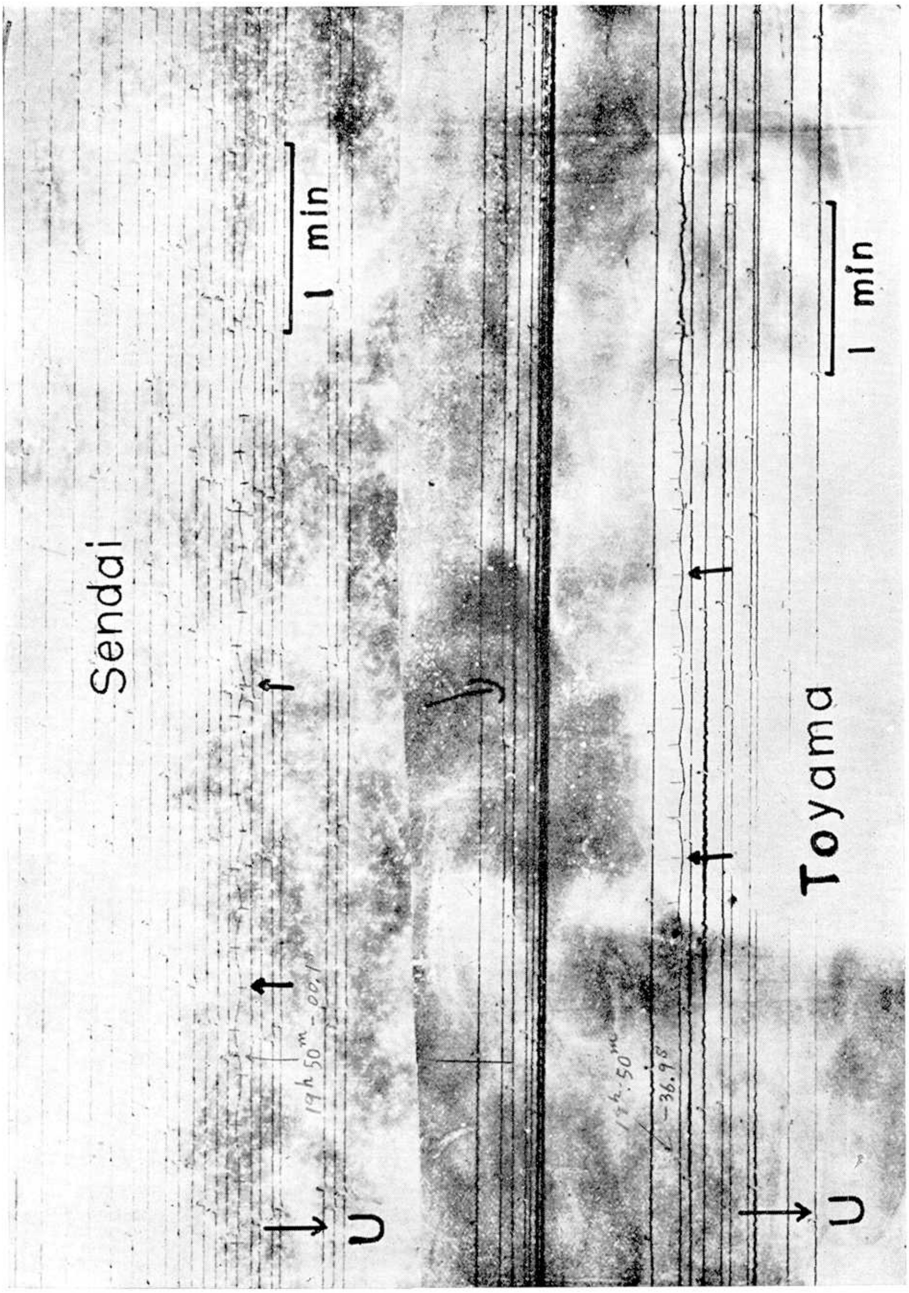


Fig. 1. Rayleigh waves from the Samoa shock of April 14th, 1957 recorded by the seismographs at Sendai (near the Pacific coast) and Toyama (near the Japan Sea coast). The arrows indicate the peaks, of which the wave front charts are given in Figs. 3 and 4.

in the phase velocity study as emphasized by Press.

The seismograms were kindly supplied from about 40 seismological stations through the Seismology Division of the Japan Meteorological Agency. The records of 35 stations are used in the present study. The list of the stations is given in Table 1.

Data

Typical records of the Rayleigh waves are shown in Fig. 1. One of the records was obtained at Sendai near the Pacific coast, and the other was obtained at Toyama near the coast of the Japan Sea. The arrows in the figure indicate the peaks for which we shall trace the propagation throughout Japan. There was no difficulty in tracing these peaks from station to station, because the distances between stations are very small. Misidentification of the peak leads to an impossibly high or low velocity of propagation for Rayleigh waves.

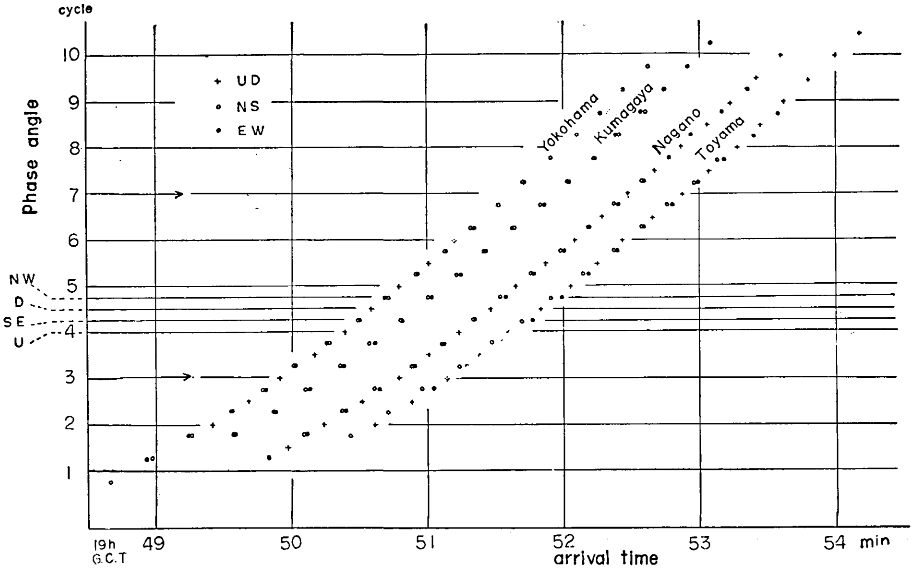


Fig. 2. Arrival times of peaks and troughs in the three component records at the stations in the central part of Japan. A smooth line is drawn to fit the points for each station, and the times at which the smooth line cuts the ordinate for the 3rd and the 7th peak are measured.

The arrival times of all the peaks and troughs are read from the three component records of each station. They are plotted in a figure like Fig. 2, where, the ordinate is the phase angle for the vertical

Table 2. Arrival times and periods of the 3rd and 7th peak at each station.

Station	3rd peak			7th peak		
	period	arrival time		period	arrival time	
	sec.	min.	sec.	sec.	min.	sec.
Sapporo	29.5	51	45.2	23.5	53	22.7
Aomori	29.5	51	13.6	21.8	52	52.6
Hachinohe	28.5	50	55.0	21.7	52	35.3
Akita	28.7	51	04.8	22.5	52	43.1
Morioka	29.0	50	45.5	23.1	52	24.2
Miyako	28.2	50	30.0	22.6	52	09.1
Sendai	28.5	50	23.0	22.8	52	00.5
Toyama	30.0	51	07.1	23.8	52	51.4
Nagano	30.0	50	46.5	23.2	52	29.2
Utsunomiya	28.5	50	09.8	21.1	51	48.0
Kumagaya	29.5	50	14.8	23.5	51	56.2
Mito	28.2	49	56.0	22.2	51	35.0
Gifu	30.0	50	51.4	22.5	52	33.9
Nagoya	29.0	50	43.5			
Kofu	29.0	50	19.7	23.0	52	01.5
Kameyama	29.5	50	47.6	22.2	52	28.3
Omaezaki	28.2	50	07.0	(23.7)	51	49.0
Shizuoka	29.0	50	09.9	22.5	51	49.3
Mishima	29.0	50	01.7	(23.5)	51	41.1
Tokyo	28.5	49	57.8	22.7	51	38.1
Yokohama	28.2	49	55.0	22.3	51	36.2
Tomisaki	28.5	49	40.0	(23.4)	51	19.6
Oshima	28.5	49	44.5	22.0	51	25.2
Toyooka	28.5	51	32.1			
Kyoto	28.5	51	05.5	24.2	52	47.5
Hikone	38.0	50	59.3	20.5	52	39.5
Hiroshima	28.7	52	03.1	22.2	53	45.7
Osaka	28.5	51	04.6	24.0	52	47.5
Sumoto	30.0	51	12.0			
Tomie	29.8	52	55.5	24.8	54	40.0
Kagoshima	30.5	52	02.6			
Miyazaki	28.5	51	47.2	22.6	53	26.3
Yakushima	29.0	51	49.0	24.3	53	30.0
Takamatsu	30.0	51	27.9			
Kochi	28.5	51	27.5			
Average	29.0			22.9		

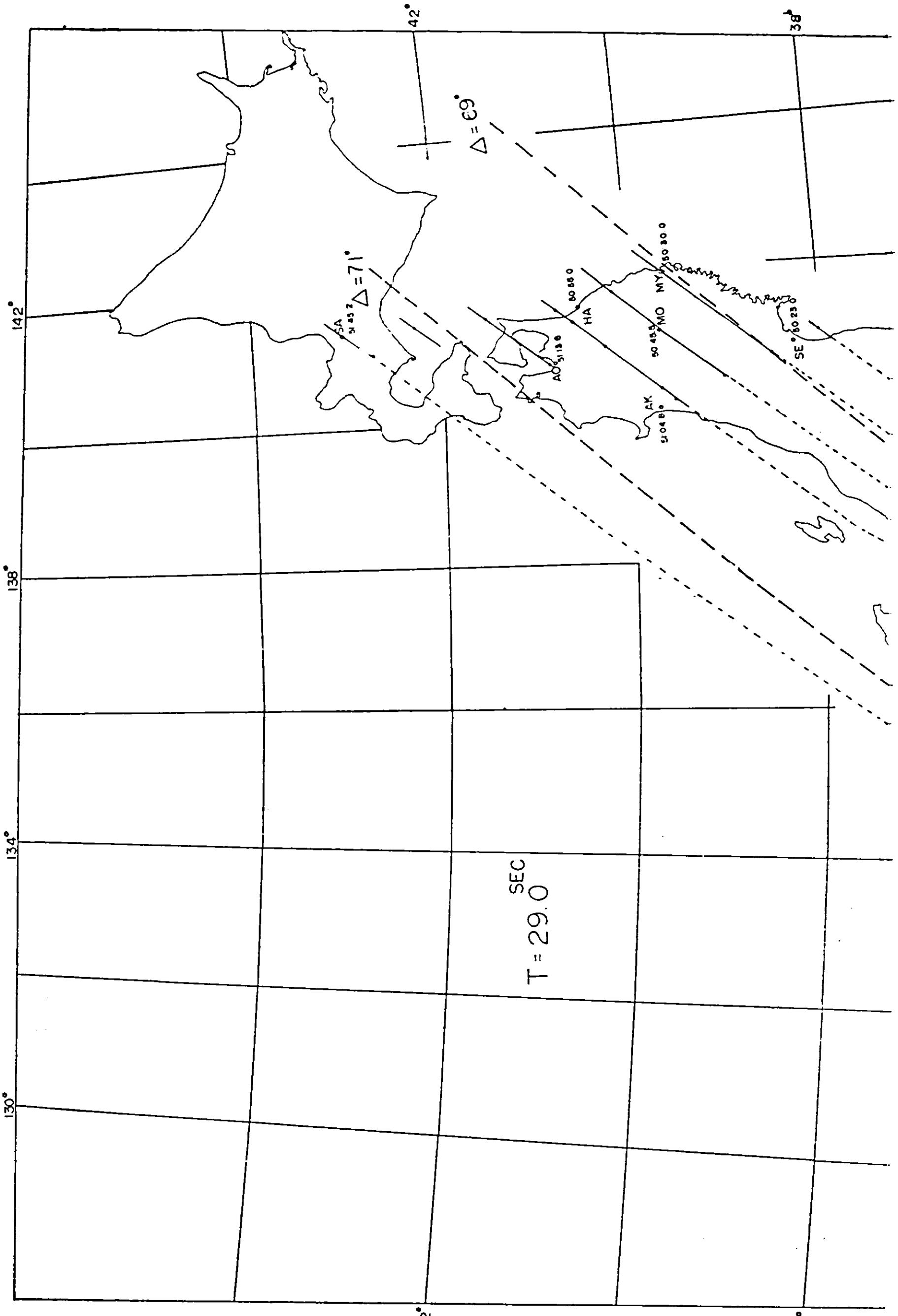
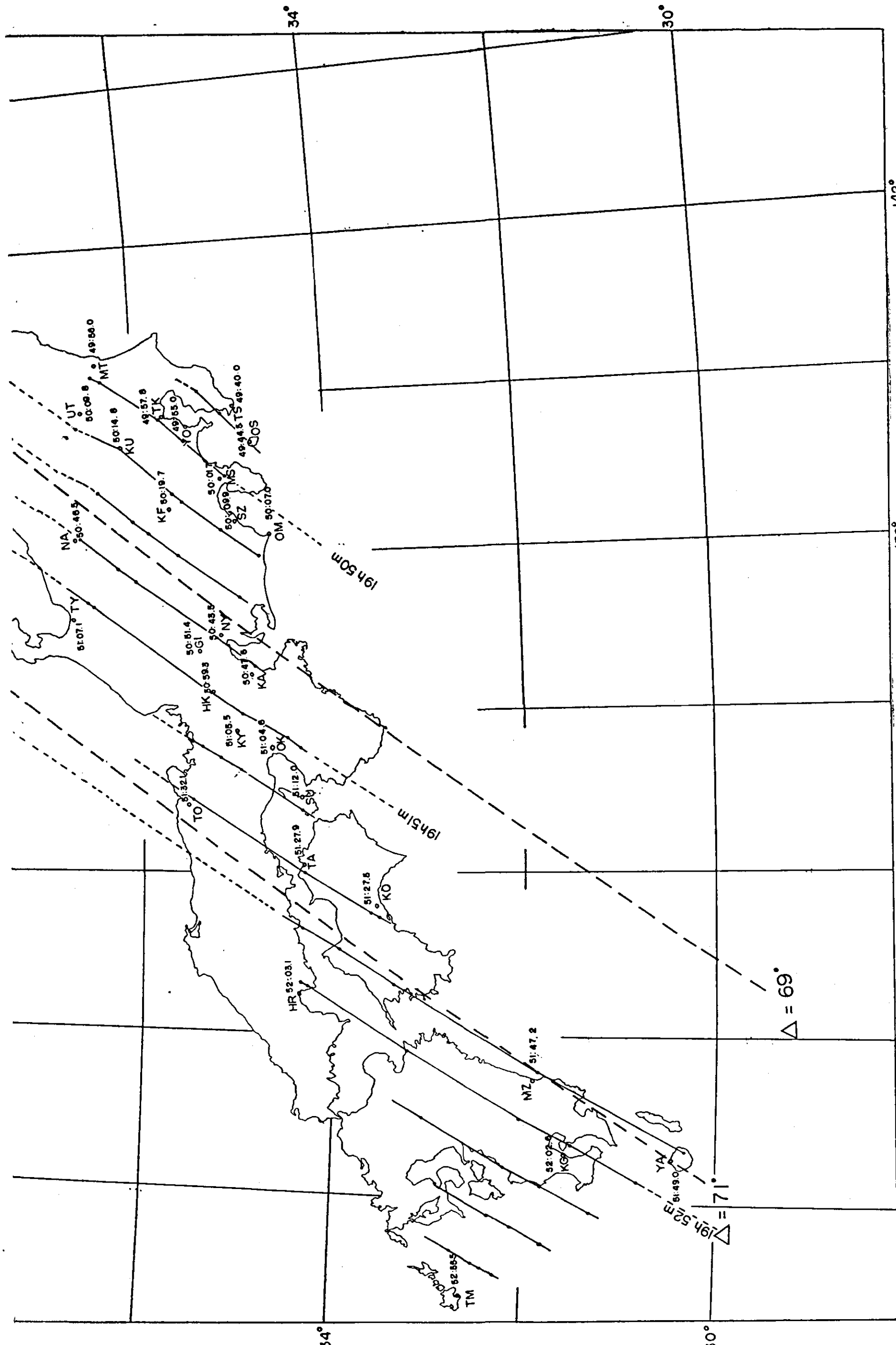


Fig. 3. Wave front of the 3rd peak at every 15 seconds across Japan. The thin dashed
distances of 69° and 71°.



line is used where data are not available. The thick dashed line indicates the epicentral

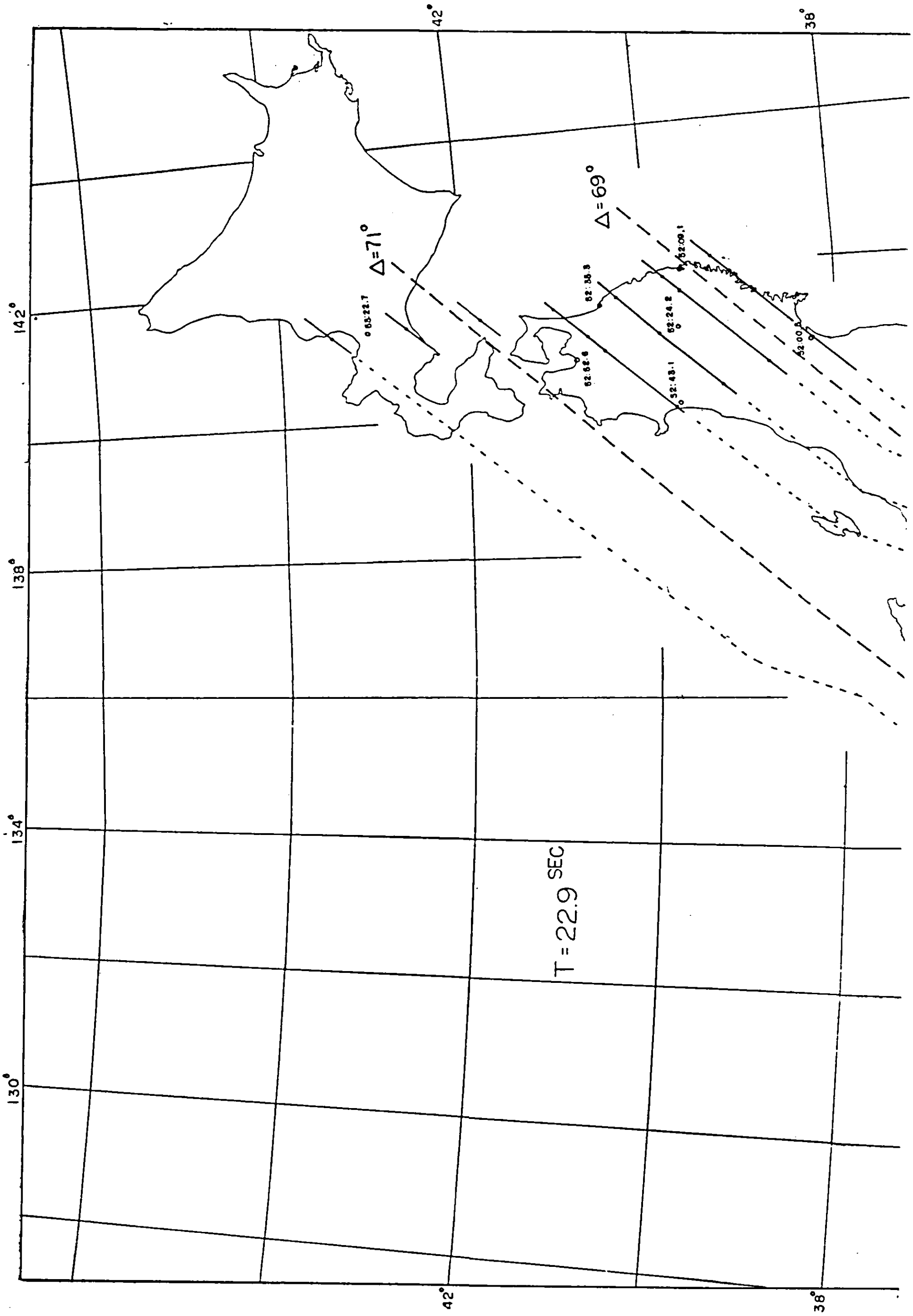
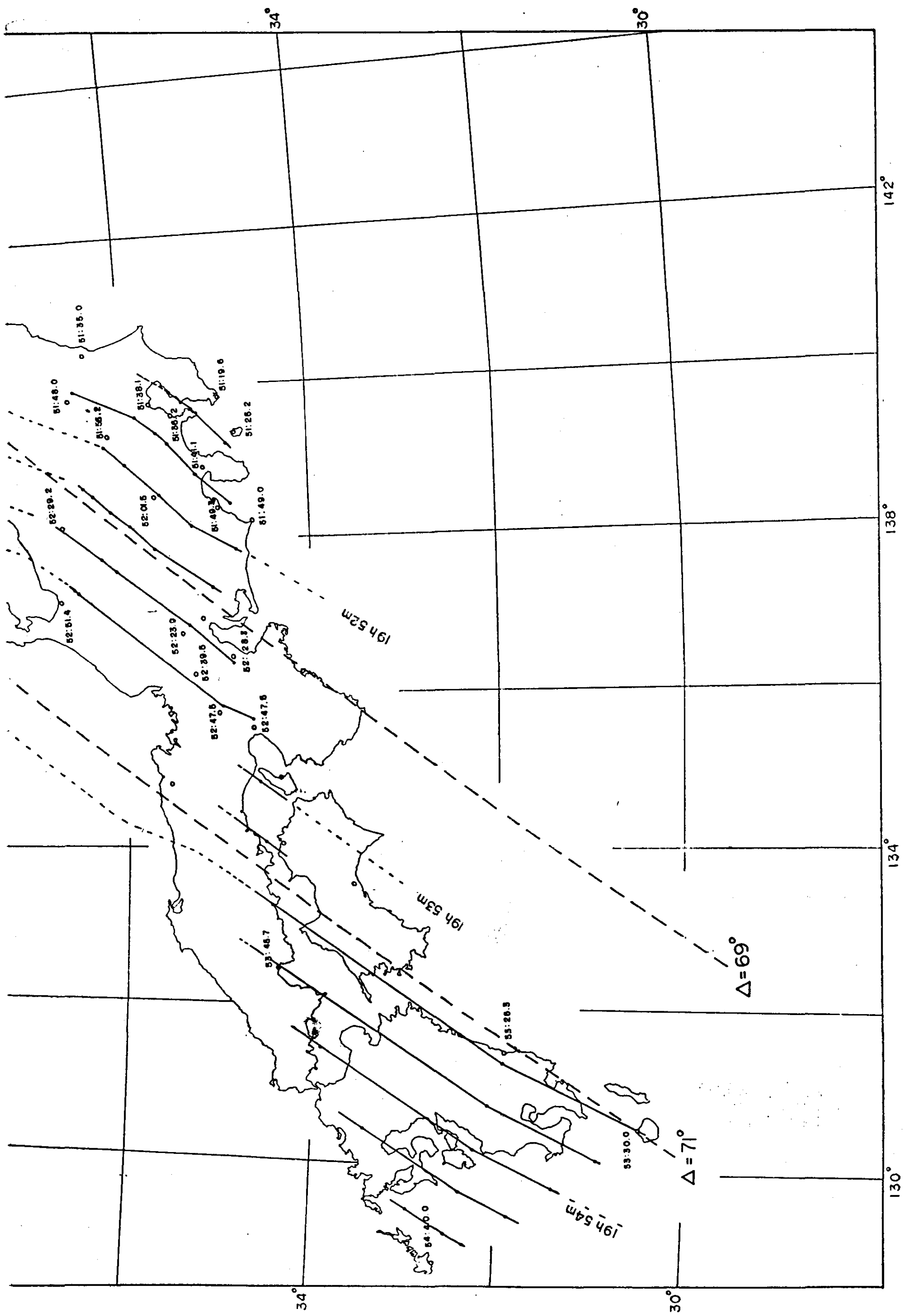


Fig. 4. Wave front of the 7th peak at every 15 seconds across Japan. The thin dashed distance of 69° and 71°.



line is used where data are not available. The thick dashed line indicates the epicentral motion measured in cycle. Since the waves approach Japan from the south-east, the upward peak (for which the phase is integer in cycle) is followed by the southward and eastward peaks, then by the downward, and then by the northward and westward, each separated by an angle of 1/4 cycle for pure Rayleigh waves. Therefore, for instance, a southward peak is plotted at the ordinate of integer plus 1/4.

The arrival times at a station of the 3rd and 7th upward peak are determined in the following way. A smooth line is drawn to give the best fit to the arrival time points for the station, and the times are measured at which the smooth line cuts the ordinates corresponding to the 3rd and 7th peak. Thus our measurement of the time of an upward peak is based on the average over three component records as well as over several neighbouring peaks and troughs. It will be shown later that accuracy better than about 1/2 sec is achieved by this procedure.

The periods of the peak are determined from the slope of the arrival time curve. The arrival times and the periods of the 3rd and 7th peak are listed in Table 2.

Wave Front Chart

In Fig. 3, the arrival times of the 3rd peak, measured by the method described above are indicated on the map of the stations. The position of the peak for successive increments in travel time of 15 sec is interpolated between stations, and is plotted on the map. Wave fronts are drawn to pass through these interpolated points. Thin dashed lines are used for the areas where data are not available.

The thick dashed lines in Fig. 3 indicate the equi-epicentral distance lines for the distances of 69° and 71°.

The wave front chart for the 7th peak is shown in Fig. 4. Unfortunately, this peak was not recorded clearly at some of the stations in south western Japan.

It is clearly shown in Figs. 3 and 4 that the wave fronts for both peaks deviate from the equi-epicetral distance line, indicating a higher velocity of propagation in the path from the Samoa Islands to northern Japan than in the path to the southern Japan. It will be shown later that this fact can be explained by the lateral refraction of the waves at the Andesite line near Japan.

A wave front chart may be used for a rough measurement of phase velocity across any area of geological interest as was done by Ewing and Press (1858). In our chart, we observe, for instance, a lower velocity for the central mountaneous area than for north eastern Japan. However, since the size of our individual network of stations is mostly much smaller than that used by Ewing and Press, the degree of accuracy of our determination of the wave front is less. For an effective use of the phase velocity of Rayleigh waves, the accuracy of its determination is required to be better than about 1.5%. In order to attain this accuracy, we applied the least squares method to the data of many stations within a certain area to compute the phase velocity for the area. Our stations are divided into 7 regions as shown in Fig. 5. It

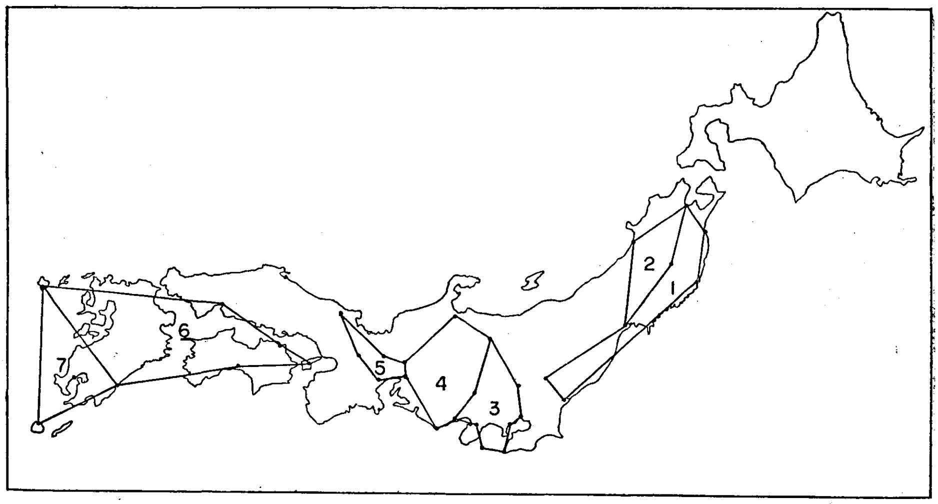


Fig. 5. Division of stations into 7 groups; 1, eastern Tohoku; 2, western Tohoku; 3, south western Kanto; 4, Chubu; 5, Kinki; 6, Seinan; 7, south western Kyushu.

is intended that the boundary of the regions coincides with that separating major geological provinces in Japan. Care is also taken that the wave front is nearly a straight line within each region. From this consideration, Utsunomiya and Mito are excluded from Region 3 (south western Kanto) and included in Region 1 (eastern Tohoku). Osaka is excluded from Region 5 (Kinki) for the same reason.

Application of the Least Squares Method

The arrival time t_m of a peak at the mth station is expressed as

$$t_m = \frac{\cos\theta}{v}(x_m - x_0) + \frac{\sin\theta}{v}(y_m - y_0) + t_0 ,$$

where

v ; the velocity of propagation of the peak.

θ ; the direction of propagation of the peak measured from the north,

x_m ; the latitude of the mth station,

y_m ; the longitude of the mth station,

x_0 ; the latitude of the reference point P_0,

y_0 ; the longitude of the reference point P_0,

t_0 ; the arrival time of the peak at the reference point P_0,

$x_m - x_0$ and $y_m - y_0$ are measured in km by the use of Richter's table (1942).

The above equation involves three unknowns, v, θ and t_0. One of the stations in each region is chosen as the reference point P_0; their list is given in Table 3 together with the epicentral distance and the great circle direction to the epicentre. The unknowns are determined by means of the least squares mothod and are listed in Table 4. For the 3rd peak, velocity and direction of propagation and the arrival time at the reference point are computed for all of the 7 regions. For the 7th peak, they are determined only for 3 regions because of the lack of data in the other regions. Besides, Utsunomiya and Mito had to be excluded from Region 1, because the wave front for this peak is strongly distorted at these points.

Table 3. List of the reference points with their epicentral distances and the great circle directions to the epicentre.

Station	Region	Epicentral distance		Great circle direction	
		deg.	min.	deg. (from north)	min. (from north)
Sendai	1,2	68	44.5	131	50
Yokohama	3	67	39.1	129	59
Shizuoka	4	68	08.9	128	52
Kameyama	5	69	20.0	127	20
Kochi	6	70	31.9	124	48
Miyazaki	7	71	06.1	122	51

The observed arrival time minus the computed time is shown in Table 5 for all the stations for the 3rd peak, together with the unbiased estimate of the probable error for each region. The probable error ranges from 0 to 0.6 sec., since this error is not only due to the reading error

Table 4. The ratios of the variance of $a=\dfrac{\cos\theta}{v}$, $b=\dfrac{\sin\theta}{v}$ and t_0 to the variance of the observed time, the values of a, b, phase velocity v, and direction of propagation θ, and their probable errors for the 3rd and 7th peak.

	Region	1 Eastern Tohoku	2 Western Tohoku	3 South Western Kanto	4 Chubu	5 Kinki	6 Seinan	7 South Western Kyushu
	$r_a^2/r_t^2\times10^4$ (km^{-2})	0.0846	0.252	0.292	0.201	3.025	0.1407	0.438
	$r_b^2/r_t^2\times10^4$ (km^{-2})	0.8429	2.154	0.453	0.359	0.453	0.0982	0.205
	$r_{t_0}^2/r_t^2$	0.16	0.83	0.21	0.35	0.56	0.24	0.91
the 3rd peak	a (sec/km)	0.1707	0.1709	0.1860	0.1684	0.1548	0.1407	0.1177
	b (sec/km)	−0.2033	−0.2042	−0.2102	−0.2356	−0.2174	−0.2290	−0.2362
	v (km/sec)	3.767	3.755	3.563	3.453	3.747	3.722	3.789
	θ (deg.	130	129	131	125	125	121	116
	min.)	01.1	55.5	30.5	32.9	27.4	33.7	28.6
	$r_a\times10^2$ (sec/km)	0.083	0.255	0.316	0.287	0.480	0.519	0.337
	$r_b\times10^2$ (sec/km)	0.263	0.747	0.393	0.383	0.185	0.289	0.230
	r_v (km/sec)	0.030	0.084	0.046	0.042	0.044	0.034	0.030
	r_θ (deg.		1					
	min.)	23.0	06.6	43.1	38.0	52.0	40.0	38.0
the 7th peak	a (sec/km)	0.1782		0.1992	0.1786			
	b (sec/km)	−0.1973		−0.2111	−0.2449			
	v (km/sec)	3.761		3.445	3.299			
	θ (deg.)	132		133	126			
	min.)	05.3		22.2	06.6			
	$r_a\times10^2$ (sec/km)	0.196		0.270	0.420			
	$r_b\times10^2$ (sec/km)	0.518		0.335	0.561			
	r_v (km/sec)	0.058		0.036	00.56			
	r_θ (min.)	48.6		35.8	53.8			

and the error in time keeping at the stations, but is also due to the real irregularity of the wave front, because the computed time is based on the assumption of plane waves. We may, therefore, conclude that

Table 5. List of the observed arrival time minus the computed time.

1. E. Tohoku

Sendai	+0.1 sec
Utsunomiya	−0.5
Mito	+0.5
Miyako	−0.4
Hachinohe	+0.1
Aomori	+0.2
Morioka	+0.0
	$r_t=0.29$

2. W. Tohoku

Sendai	0.0
Morioka	0.0
Akita	0.0
Aomori	0.0
	$r_t=0.00$

3. S. W. Kanto

Yokohama	+0.6
Tomisaki	−0.4
Oshima	−1.3
Mishima	+0.1
Shizuoka	+1.2
Kofu	−0.3
Nagano	−0.8
Kumagaya	+0.6
Tokyo	+0.3
	$r_t=0.59$

4. Chubu

Shizuoka	−0.1
Omaesaki	−0.3
Nagoya	−1.0
Gifu	+1.3
Toyama	−0.8
Nagano	+0.5
Kofu	+0.1
	$r_t=0.64$

5. Kinki

Kameyama	−0.4
Kyoto	+0.5
Toyooka	−0.1
Hikone	−0.2
Gifu	0.0
Nagoya	−0.2
	$r_t=0.28$

6. Seinan

Kochi	−0.2
Miyazaki	−0.3
Tomie	+0.5
Hiroshima	−0.5
Takamatsu	−0.7
Sumoto	+1.2
	$r_t=0.62$

7. S. W. Kyushu

Kagoshima	+0.2
Yakushima	−0.1
Tomie	−0.1
Miyazaki	−0.1
	$r_t=0.18$

both the accuracy of reading and the accuracy of time keeping at the J.M.A. stations are better than about 1/2 sec.

In estimating the error of the velocity and direction of propagation, first, the variance of $a=\frac{\cos\theta}{v}$ and $b=\frac{\sin\theta}{v}$ are computed from the variance of the observed time. Since the number of stations is too small for Region 2 and 7, an average of the variance of the observed time for the other regions was used instead of the estimate from their own values. Table 4 lists the ratios of the variances of a, b and t_0 to the variance of the observed time. The ratio is a constant for a given net of stations, and can be used in future study.

The probable errors of the velocity and direction of propagation are then determined by the formulas,

$$r_v=\frac{1}{(a^2+b^2)^{3/2}}\sqrt{a^2r_a^2+b^2r_b^2}$$

$$r_\theta=\frac{1}{a^2+b^2}\sqrt{a^2r_b^2+b^2r_a^2}$$

where

r_v ; the probable error of the velocity of propagation,
r_θ ; the probable error of the direction of propagation,
a ; $\cos\theta/v$
b ; $\sin\theta/v$
r_a ; the probable error of a,
r_b ; the probable error of b.

r_v and r_θ are given in Table 4 together with a, b, r_a and r_b for various regions.

These probable errors indicate that the accuracy of our determination of the phase velocities is 1 to 1.5%, which is sufficient for their effective use in the study of crustal structure.

Application of Press' Standard Phase Velocity Curve

In determining the crustal structure from the phase velocity of Rayleigh waves, Press (1956) used a set of reference phase velocity curves, to each of which the thickness of the crust is assigned as a parameter. In his first construction of the reference curves, the observed group velocity curve for Africa is integrated with the integration constant determined from the assumption that the African continent is made of a crustal layer 35 km thick with shear velocity 3.51 km/sec overlying a mantle with shear velocity 4.68 km/sec. Later, Press (1960) reconstructed the standard phase velocity curves from a crust-mantle model based on a refraction result in Africa (Hales and Sachs, 1956) and Gutenberg's study (1959) on the mantle under continents. This is the model 6EG, for which the shear velocity distribution is reproduced in Fig. 7. In this model, the crust consists of the top layer 22 km thick with shear velocity 3.53 km/sec and the intermediate layer 15 km thick with shear velocity 3.80 km/sec overlying a mantle with shear velocity 4.60 km/sec. Press showed that this structure explains very well the observed group velocity of Rayleigh waves for Africa. The standard phase velocity curves based on the above structure are shown in Fig. 6.

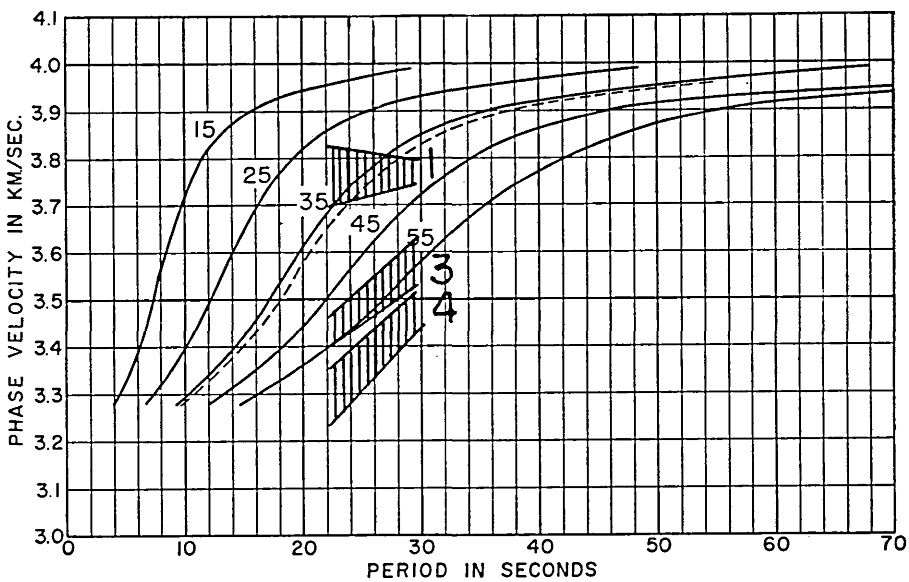


Fig. 6. Press' standard phase velocity curves (Press, 1960). The phase velocity data for Region 1, 3, and 4 are shown with the range of probable errors.

In the standard phase velocity curves, the thickness of the crust is the only parameter that varies from place to place, and it is implicitly assumed that the compressional and shear velocities in all the layers, as well as the density ratios and the proportion of the thickness of the layers, do not vary. This is certainly an oversimplification, but the success of their use in a rough determination of crustal thickness in the United States tempt us to apply the standard curves to our phase velocity data.

The thickness of the crust obtained by the application of Press' standard curves to the phase velocities of our 3rd and 7th peaks are given in Table 6 for various regions. These values are significantly greater than those determined by the refraction study.

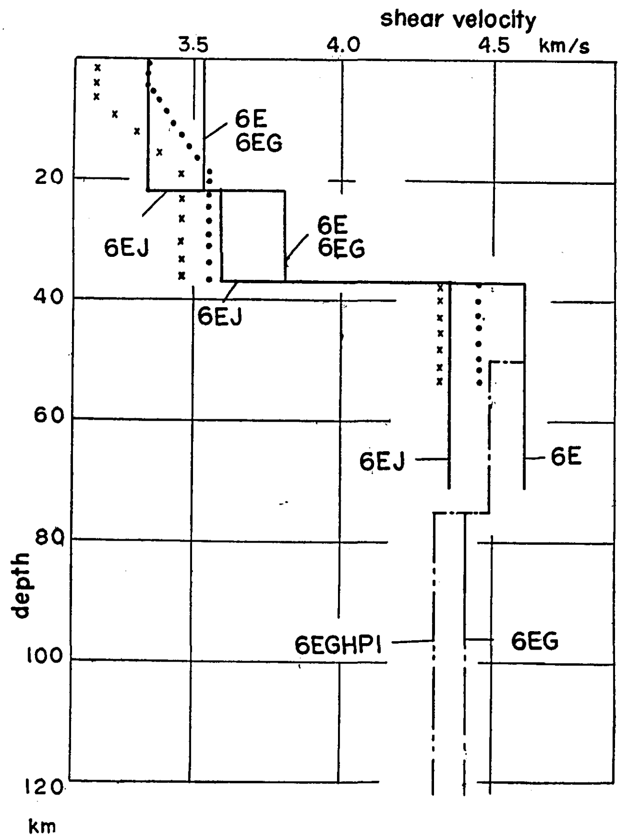


Fig. 7. Shear velocity distribution at depths for various crust-mantle models. 6EG is the model adopted by Press in his construction of standard phase velocity curves. 6EJ is adopted to intepret the phase velocity data in Japan. 6EGHP1 represents the mantle under the Pacific ocean (Aki and Press, in press).

The study of the crustal structure in Japan by means of the explosion generated seismic waves has been carried out by the Research Group for Explosion Seismology since 1950. By the effort of the members of the group, the crustal structures in the Tohoku, the northern Kanto, the northern Chubu and the Kinki regions have been determined. The crust usually consists of a relatively thin upper layer with compressional velocity 5.8 km/sec (for Tohoku) or 5.5 km/sec (for others) and a lower layer with compressional velocity 6.0 to 6.2 km/sec, which overlies the mantle with relatively low velocity of 7.5 to 7.7 km/sec. The crustal thickness was obtained as 20 to 25 km in the Tohoku region (Matuzawa, 1959), about 25 km in the northern Kanto (Usami et al., 1958), about 40 km in the northern Chubu (Mikumo et al., in press), and it was obtained as being about 35 km in one of the solutions and about 28 km in another in the Kinki region (Mikumo et al., in press).

Table 6. Crustal thickness in various regions in Japan obtained under the assumption that Press' standard phase velocity curves are applicable to these regions.

Region	Crustal thickness from the 3rd peak (T=29 sec)	Crustal thickness from the 7th peak (T=23 sec)
1. e. Tohoku	40±2 km	33±4 km
2. w. Tohoku	41±6	
3. s. w. Kanto	55±3	52±3
4. Chubu	63±3	77±15
5. Kinki	42±3	
6. Seinan	44±2	
7. s. w. Kyushu	39±2	

Since the discrepancies between the values of crustal thickness obtained from the refraction study, and the values obtained from the phase velocity data by the application of Press' standard curves, are beyond experimental errors, we conclude that Press' curves do not apply to Japan at least for the regions where the explosion data are available. It should be mentioned that the discrepancy for the Kinki region, if we adopt one of the solutions from the refraction study, is not as great as for the Tohoku and the Chubu region.

In the United States, Press' standard curves give the crustal thickness that agrees well with that obtained in most of the areas from the refraction study. There is, however, an area where they do not agree. That is the high plateau area (Utah, Nevada, and New Mexico), where the thickness from the refraction measurements average close to 35 km, while Press' curves, applied to the phase velocity data, yield the an average thickness of about 48 km. Woollard (1959) attributes this discrepancy to the masking of layering within the crust in the refraction measurements. A similar discrepancy for the California-Nevada area was discussed by Press (1960).

Modified Standard Curves Applicable to Japan

It is not unexpected that Press' standard phase velocity curves may not be applied to Japan, because the velocities in the crust and mantle determined by the refraction studies are a little lower than those adopted by Press for the standard continent. In Fig. 7, the average shear velocity distribution with depth in the Tohoku region (dots) and that in the Kinki region (crosses) are compared with the distribution adopted by Press (6EG). The shear velocity is computed from the compressional velocity obtained from the refraction study, under the assumption that the Possion's ratio is 0.25. The total thickness of the crust is taken as 37 km in the figure, where the proportion of the thickness of each layer to the total thickness is kept the same as that obtained from the refraction study.

Reference phase velocity curves applicable to Japan may be constructed on the basis of the average velocity and the average proportion of the thickness of layers as determined from the refraction study in Japan. In the present study, however, we adopt an alternative way which is more convenient. We modify the case 6E, which is identical with the case 6EG, except that the low velocity layer in the mantle is neglected, in such a way that the velocities in all the layers are reduced by 5.5%. In this modification, all the non-dimensional products such as density ratios, Poisson's ratios and thickness proportions are not changed. This modified case is named 6EJ, and the shear velocity distribution for this is shown in Fig. 7. The new distribution is much

Table 7. Layer parameters and phase velocity of Rayleigh waves for the case 6*EJ*.

Layer	Thickness	Compressional velocity	Shear velocity
1	22 km	5.698 km/sec	3.336 km/sec
2	15	6.332	3.591
3	∞	7.522	4.347

Period	Phase velocity	Period	Phase velocity
70.44 sec	3.853 km/sec	22.74 sec	3.436 km/sec
42.48	3.770	20.22	3.353
33.64	3.686	17.65	3.269
28.85	3.603	14.72	3.186
25.49	3.519	10.55	3.102

closer to the observed one in Japan and probably a sufficient satisfactory approximation for the present purpose. The numerical values for the case 6EJ, which are obtained from the values for 6E given by Press (1960), are listed in Table 7.

The reference phase velocity curves based on the new model 6EJ are shown in Fig. 8, together with the observed velocities for Region 1, 3, and 4, where the shaded area represents the range of probable error. If this figure is compared with Fig. 6, it can be seen that not only the thickness of crust is adequately reduced for each region, but also the agreement between the theoretical and experimental curves is much improved.

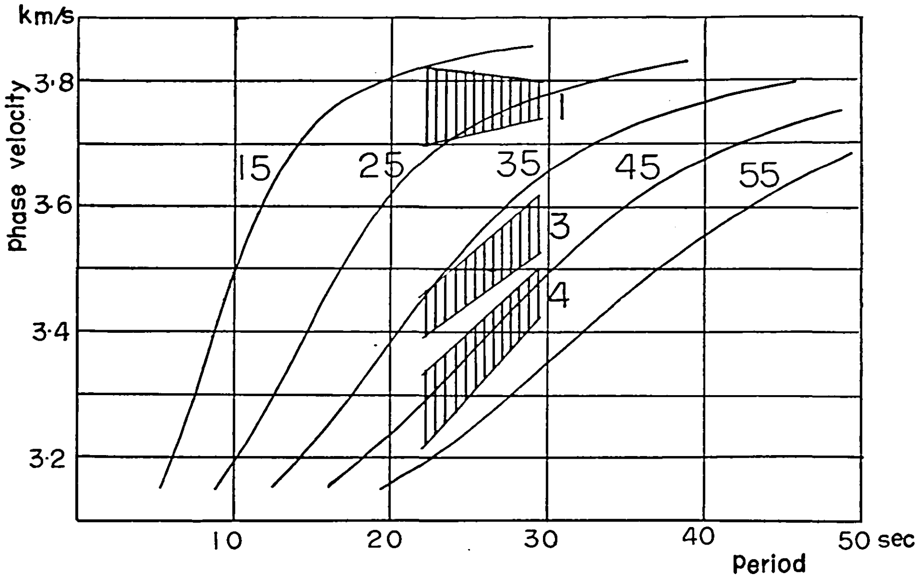


Fig. 8. Modified standard phase velocity curves applicable to Japan based on the case 6EJ. The phase velocity data for Regions 1, 3, and 4 are shown with the range of probable errors.

Table 8 lists the crustal thickness for various regions obtained by the application of the modified standard curves to our phase velocity data. The thickness of 20 to 25 km for the Tohoku region agrees with the thickness obtained from the refraction study (Matuzawa, 1959). The thickness of 27 km for the Kinki region also agrees well with the thickness in one of the solutions obtained by Mikumo *et al* (in press). The crustal thickness in northern Chubu amounts to 43.5 km in one of the solution obtained by Mikumo *et al.* This value is not far from our value of 46 km for the entire Chubu. Our result also agrees very well with the result of Kishimoto and Kamitsuki's (1956) study on the forerunners of near earthquakes in central and south western Japan. Our result is also consistent with the distribution of anomalies in the travel time of *P* waves observed by many investigators (e.g. Honda, 1932).

Table 8. Crustal thickness in various regions in Japan obtained by the use of modified standard phase velocity curves which are based on the case 6*EJ*.

Region	Crustal thickness from the 3rd peak (T=29 sec)	Crustal thickness from the 7th peak (T=23 sec)
1. e. Tohoku	25±3 km	20±5 km
2. w. Tohoku	26±10	
3. s. w. Kanto	39±3	37±3
4. Chubu	46±3	46±5
5. Kinki	27±4	
6. Seinan	29±3	
7. s. w. Kyushu	23±4	

We may therefore, conclude that the case, 6EJ is a closer approximation to the crustal structure in Japan than the case 6EG. In other words, the elastic wave velocities in the crust and at the top of the mantle in Japan are about 5.5% lower than those in the standard continents. The shear velocity in the mantle, adopted in the case 6EJ is as low as the volocity at Gutenberg's asthenosphere low velocity channel as shown in Fig. 7, where 6EG represents the mantle under continents and 6EGHPl represents the mantle under the Pacific ocean (Aki and Press, in press). It is of extreme interest to find out if, in Japan, the shear velocity is kept constant from the top of the mantle down to the low velocity channel, (in other words, the low velocity channel reaches the Mohorovicic discontinuity in this techtonically active area,) or the shear velocity increases to the value for the standard Moho before it decreases at the channel. The latter case is more likely in the California-Nevada area, according to Press (1960). In order to study this, we have to extend our measurements to longer periods.

It should be mentioned here that the application of our modified standard phase velocity curves to the data for the high plateau area in the United States give the crustal thickness as very close to the value obtained from the refraction study. This suggests that the crustal velocities in this area are also lower than those in other parts of the continent. The problem there is, however, rather complicated as discussed by Press (1960). Press studied the crustal structure in the California-Nevada area by means of both the refraction method and the phase velocity method, and suggests the existence of a low velocity zone in the intermediate layer or an unusually high Poisson's ratio for this layer.

The Bouguer Gravity Anomaly and the Phase Velocity of Rayleigh Waves

Ewing and Press (1959) found a remarkable correlation between the phase velocity of Rayleigh waves, topography, and the Bouguer gravity anomaly for various regions in the United States. This implies that the crustal thickness determined from the phase velocity agrees with that from the gravity data and that the isostatic compensation is realized in these regions (Woollard, 1959).

We observed a similar correlation for Japan as shown in Fig. 9, where the phase velocities of Rayleigh waves for the period of 29 sec are shown for various regions in Japan, together with a rough sketch of the topography and the Bouguer anomaly, based on the map compiled by Tsuboi (1959). It can be seen in the figure that, as a general trend,

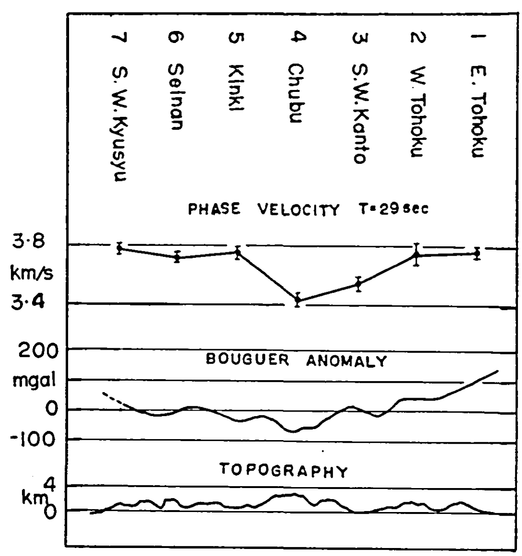


Fig. 9. Phase velocity of Rayleigh waves with a period of 29 sec, Bouguer gravity anomaly and topography for various regions in Japan.

the higher the phase velocity the greater the Bouguer positive anomaly. If we examine it more carefully, however, it seems that the relation between them for south western Japan is a little different from that for central and north eastern Japan. To show this more clearly, we plotted the phase velocity for the period of 30 sec against the average Bouguer anomaly for each region in Fig. 10. We also plotted the data for the United States obtained by Ewing and Press in the same diagram.

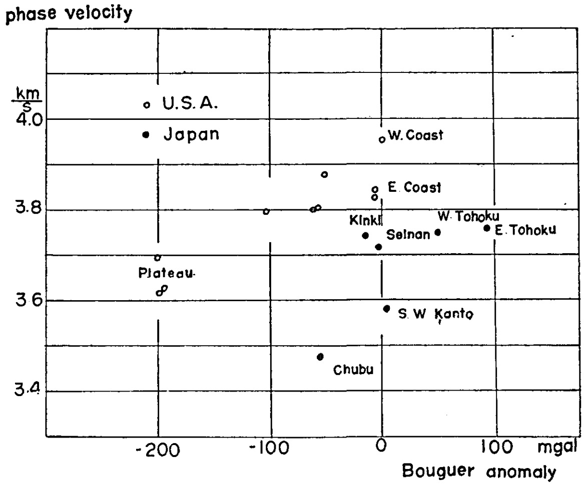


Fig. 10. Relation between the phase velocity of Rayleigh waves with a period of 30 sec and the average Bouguer anomaly for various regions in Japan and the United States. The data for the United States are obtained by Ewing and Press (1959).

The points for central and north eastern Japan in Fig. 10 lie on a straight line, departing considerably from the line for the data in the United States. It is remarkable that both lines are very nearly parallel to each other. The points for south western Japan do not lie on the line for central and north eastern Japan, deviating from it in the sense toward the line for the United States. This fact may have an important bearing on the apparent difference between north eastern and the south western Japan in geology and geotechtonics. Dr. Tsuboi pointed out to the writer that the effect of the neighbouring suboceanic mass must be removed from the Bouguer anomaly in Japan before any detailed discussion of such a diagram is made, and that the reduction will shift the points for Japan in Fig. 10 to the left, closer to the points for the United States. Unfortunately, at present, we do not have enough gravity observations on the ocean near Japan which are necessary for the reduction. If the reductions are applied to the Bouguer anomaly, the diagram will be very useful in discussing the geological conditions at various places, with the aid of the velocity-density relation for various materials under various physical conditions.

Lateral Refraction of Rayleigh Waves at the Andesite Line

The wave front charts shown in Figs. 3 and 4 clearly demostrate that the velocity of propagation of our peak is higher in the path from the Samoa Islands to northern Japan than in the path to southern Japan. Santo (1961) showed, by a group velocity study of Rayleigh waves from many circum Pacific epicentres to Mt. Tukuba, that the Andesite line may be a boundary between two different crustal structures. On the east side of it, the group velocity dispersion curve 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/sec at the period of 30 sec according to Santo.

If the observed deviation of the wave fronts of our peaks from the equi-epicentral distance curve is caused by the lower velocity on the west side of the Andesite line near Japan, the difference in the phase velocity between the two structures on both sides of the line can be accurately determined from our observation. Let the velocity of propagation of a peak with period T be c_0 on the east side of the Andesite line and that on the west be c_1, then the arrival time t_m of the peak at the mth station can be written as (Brune, Nafe and Oliver, 1960)

$$t_m=\frac{\Delta_m-x_m}{c_0}+\frac{x_m}{c_1}+(n+\varepsilon)T$$

where n is an integer, ε is a constant, Δ_m is the epicentral distance to the mth station, and x_m is the portion of the distance from the Andesite line. Since the period of our peak is almost the same for all of our stations (Table 2),

$$t_m-\left(\frac{\Delta_m-x_m}{c_0}+\frac{x_m}{c_1}\right)$$

must be approximately constant. Therefore, $t_m-\frac{\Delta_m}{c_0}$ must be proportional to $\left(\frac{1}{c_1}-\frac{1}{c_0}\right)x_m$, and if we plot $t_m-\frac{\Delta_m}{c_0}$ against x_m, the slope of the plotted points will be equal to $\left(\frac{1}{c_1}-\frac{1}{c_0}\right)$. Assuming that c_0 is 4.0 km/sec for the period 29 sec, which is very close to the value for the case 8099 of Dorman, Ewing and Oliver (1960), we computed $t_m-\frac{\Delta_m}{c_0}$ for the 3rd peak for the stations listed in Table 3, and plotted them against x_m in Fig. 11. Fitting a straight line to the points, we obtain the value of $\frac{1}{c_1}-\frac{1}{c_0}$ as 0.012 sec/km. If c_0 is 4.0 km/sec, therefore, c_1 is 3.82 km/sec. This value is surprisingly low for a phase velocity of Rayleigh waves of the period of 29 sec in an oceanic region where the water depth exceeds 2 km in most of the area, and exceeds 4 km in about a half of it. Besides, this value of the velocity is not much different from those for the land area in south western Japan (Table 4). At present, however, we cannot make any conclusions about the absolute value of the velocity for this oceanic area, for the value depends on

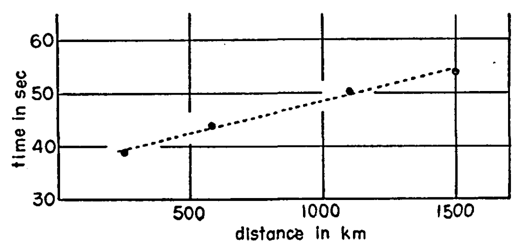


Fig. 11. $t_m-\Delta_m/C_0$ against the distance x_m from the Andesite line to several stations on the Pacific coast (for the 3rd peak.)

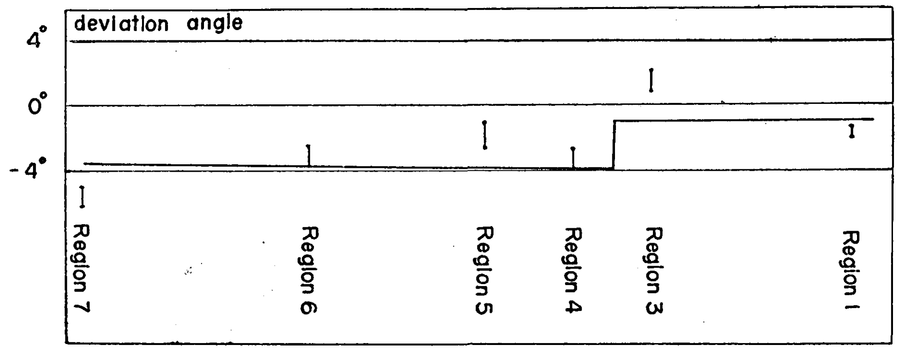


Fig. 12. Theoretical and observed deviations of the direction of propagation of the 3rd peak from the great circle direction to the epicentre.

the assumption on the velocity c_0 for a typical Pacific oceans.

The direction of propagation of Rayleigh waves will also be affected by the lateral refraction at the Andesite line. Fig. 12 shows the deviation of the observed direction from the great circle direction to the epicentre, with the range of its probable error. Assuming that the Andesite line is straight, and c_0 is 4.0 km/sec, and c_1 is 3.8 km/sec, we computed a theoretical deviation of the direction of propagation from the great circle by a refraction at the Andesite line. The following formulas are used in the computation.

$$\sin\delta=\sin(i_1-i_0)\frac{\sin\Delta'}{\sin\Delta},$$

and

$$\frac{\sin i_0}{\sin i_1}=\frac{c_0}{c_1},$$

where

δ; the deviation of the direction of propagation from the great circle,

Δ; the epicentral distance along the great circle path,

$\frac{\pi}{2}-i_0$; the incidence angle at the Andesite line,

$\frac{\pi}{2}-i_1$; the emergence angle at the Andesite line,

Δ'; the distance between the incident point and the epicentre.

As shown in Fig. 12, the agreement between the observed deviation angle and the theoretical angle seems good as a first approximation, supporting the theory that Rayleigh waves are refracted laterally at the Andesite line. The scatter of the observed values from the theoretical must be due to the departure of the actual Andesite line from the mathematical straight line and also to the presence of finer structures such as trench and small islands.

Summary

The phase velocities of Rayleigh waves with periods of 20 to 30 sec are determined for various regions in Japan from the records of a Samoa shock obtained at 35 seismological stations of the Japan Meteorological Agency. By means of the least squares method, the velocities are determined with the accuracy of 1 to 1.5%. Examining these velocities

in the light of Press' standard phase velocity curves for the standard continents, and taking into account the result of refraction studies in Japan, we conclude that Press' curves do not apply to Japan. We modified the standard curves in such a way that the velocities in the crust and at the top of the mantle are reduced by 5.5%. The new velocities are much closer to the values obtained from the refraction study in Japan. The application of the new standard curves gives crustal thicknesses which agree very well with those determined from refraction and other studies.

We found a similar positive correlation between the phase velocity of Rayleigh waves and the positive Bouguer gravity anomaly as Ewing and Press (1959) found in the United States. It seems, however, that the relation depends on the geology of the region, and a single relation does not cover the whole earth.

Our wave front chart suggests that Rayleigh waves are laterally refracted at the Andesite line near Japan. If we assume that the phase velocity for a period of 29 sec is 4.0 km/sec in the oceans to the east of the Andesite line, the corresponding velocity in the area on its west side must be as low as 3.82 km/sec. This value is surprisingly low for an area where the water depth exceeds 2 km throughout most of the area and exceeds 4 km in about a half of it. At present, however, we can only make conclusions about the difference in velocity between both sides of the Andesite line but not about the absolute value of velocity.

Acknowledgment

The writer's thanks are owing to all the seismologists at the stations of the Japan Meteorological Agency and especially to Dr. Takuzo Hirono and Mr. Norio Noguchi for their cooperation in making their records available to him. The writer's thanks are also due Professors Chuji Tsuboi, Hirokichi Honda and Takahiro Hagiwara for their valuable discussions.

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8. レーリー波位相速度法による日本の地下構造の研究 第1報

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1957年4月15日(日本時間)のサモア島の地震による，周期20秒から30秒のレーリー波は，気象庁のヴィーヘルト地震計網によつてかなりよく記録された(第1図). 気象庁の御好意で集められた記録のうち，35カ所の記録を解析して，日本各地でのレーリー波位相速度が求められた. 位相速度の測定には，3成分記録を用い，最小自乗法を応用して，1ないし1.5%の精度が得られた.

Press がアメリカ大陸の地殻の厚さを求めるのに用いた標準の位相速度曲線を，われわれの測定値に応用すると，爆破などから知られている地殻の厚さより，著しく大きい値が出た. つまり，標準の大陸に適用するプレスの位相速度曲線は，日本には適用されない.

日本の地殻およびマントル上部の弾性波速度として，標準の大陸のものより5.5% 小さいものを仮定すると，爆破の結果とよく一致する地殻の厚さが，レーリー波から求められる. 日本の弾性波速度が大陸の標準よりも小さいことは，爆破の結果にも示されていることであり，興味ある重要な事実であることを強調したい. また，この結果，日本のモホ直下のS波速度が，Gutenberg のマントル内の低速層の速度とほとんど同じことによる(第7図). 日本のような所では，低速層がホモまで達しているのかも知れない. このことをはつきりさせるには，より長周期のレーリー波をしらべる必要がある.

Ewing と Press は，重力のブーゲー異常とレーリー波位相速度の間の著しい相関関係をアメリカ大陸について見出している. われわれも同様の結果をえた(第9図，第10図). ただしその関係は，日本とアメリカで異なり，また日本のなかでも中部および東日本と西日本で異なるように見える. 同じ地殻の厚さに対して中部および東日本は，アメリカより位相速度が小さく，ブーゲー異常が大きいように見える. これは大変興味のあることであるが，この関係を詳細に議論するには，重力異常に対する海の影響をとり除く必要があり，今後の問題である.

われわれのレーリー波の第3および第7の山の波面図(第3図，第4図)にはつきりあらわれているように，日本北部には，日本南部より同じ震央距離に対して，約20秒だけ波がはやくついている. このことが三東のいうような安山岩様の東と西の速度差によるとすると，速度差として，約0.2 km/sec の値が得られる. 東側の海について，Dormanらの求めた位相速度を正しいとすると，西側では，29秒の周期の波の位相速度が 3.82 km/sec となる. この値は海として驚くほど小さい値であつて，西南日本の値とほとんどひとしい. 南方の島に長周期地震計をおけば，このことを確かめることができるであろう.