BULLETIN OF THE EARTHQUAKE
RESEARCH INSTITUTE
Vol. 52 (1977), pp. 1-10

1. *Group Velocity Distribution of Rayleigh Waves for the Period 50 Seconds in the Pacific Ocean.*

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(Received February 7, 1977.)

Abstract

On the basis of the WWSSN observation data the group velocity of Rayleigh waves in the Pacific Ocean was synthesized by spherical surface harmonics for the period 50 seconds. It was revealed that the group velocity near the East Pacific Rise is remarkably low showing a minimum value and continuously increases towards the west. The area with high velocities is located in the Northwest and Mid-Pacific Basins, extending from the northwest to southeast. The velocity difference between the maximum and minimum in the Pacific is estimated to be more than ten percent. A map of the synthesized group velocity distribution is shown, the maximum order of spherical surface harmonics being four.

1. Introduction

Surface wave propagation in the Pacific Ocean has been investigated by a number of seismologists for the purpose of making clear the dispersion characteristics and the crustal and mantle structure under the ocean bottom (SATÔ, 1956; KUO, BRUNE, and MAJOR, 1962; SANTO, 1963; SAITO and TAKEUCHI, 1966; ABE, 1972; YOSHII, 1975, YOSHIDA and SATÔ, 1976). It has been found that the Rayleigh wave group velocity determined for normal oceanic basins is significantly higher than that for pseudo-oceanic basins for periods shorter than 40 seconds (SANTO, 1963) and for periods of 30-110 seconds (YOSHIDA and SATÔ, 1976). From the regionality of the dispersion characters of the Rayleigh wave group velocity, YOSHII (1975) estimated the thickness of the oceanic plate in relation to the age of the ocean floor.

The underground structure and the earth model are often constructed based upon the dispersion data of surface waves, and the observed data are interpreted as representing the average dispersion characteristics along the great circle path between the epicenter and observation station. When the regional dispersion characteristics are investigated with the long distance data, the path is divided into a number of sections defined by the depth of the ocean or the ocean-floor age, and then the method of least squares is often employed for the determination of the velocity of each section.

In the present work, however, the velocities are obtained without assuming any boundaries in advance. The method employed is the same as that derived by SATÔ and SANTO (1969). In that work the velocity distribution of surface waves was expressed in terms of spherical surface harmonics and the group velocities of Rayleigh waves were calculated all over the world for the period 30 seconds. A high correlation between the topography and the velocity distribution was found in that study.

The present paper aims to make clear the group velocity distribution of Rayleigh waves in the Pacific Ocean for a longer period using the method of Satô and Santo.

2. Method and data

The essence of the method is summarized as follows. The (reciprocal of) surface wave velocity is expanded into a series of spherical surface harmonics

$$\frac{1}{v(\theta, \varphi)} = \sum_{n=0} \sum_{m=0}^{n} A_n^m \cdot P_n^m(\cos\theta) \cdot \cos m\varphi + \sum_{n=1} \sum_{m=1}^{n} B_n^m \cdot P_n^m(\cos\theta) \cdot \sin m\varphi \,. \quad (1)$$

Then the travel time of the wave between the epicenter Q and the observation station P is given by an expression

$$t = \int_{(PQ)} \frac{d\Delta}{v(\theta, \varphi)} \,. \quad (2)$$

Here we assume that the surface waves are propagated approximately along the great circle path between the epicenter and the station. If we have many travel time data the coefficients A_n^m and B_n^m in the above equation can be determined by the method of least squares.

The dispersion data reported by ABE (1972), YOSHII (1975), and YOSHIDA and SATÔ (1976) were compiled and used in the present work. The locations of epicenters and stations, and the observed group velocities are listed in Table 1 and the great circle paths are shown in Fig. 1.

All these data have been obtained from the records at the stations belonging to the World Wide Standard Seismograph Network. Group velocities by Abe are determined by means of the band-pass filtering technique and the group-delay time method (KANAMORI and ABE, 1968), those by Yoshii are by the peak and trough method and those by Yoshida

Table 1. List of epicenters, stations, and observed group velocities.

No.	Epicenter		Station		Distance	Group Velocity	Station Abbre-
	Latitude	Longitude	Latitude	Longitude	km	km/sec	viation
1	− 5.07	144.20	32.310	−110.782	11726.	3.970	T U C
2	−41.72	172.03	8.961	− 79.558	12188.	3.852	B H P
3	− 5.55	− 77.20	21.423	−158.015	9282.	3.888	K I P
4	− 5.55	− 77.20	−13.909	−171.777	10350.	3.888	A F I
5	− 5.55	− 77.20	−21.217	−159.773	9016.	3.862	R A R
6	−30.97	−178.13	− 0.733	− 90.300	9756.	3.862	G I E
7	− 3.38	143.29	8.961	− 79.558	15237.	3.977	B H P
8	− 3.56	150.90	21.423	−158.015	6205.	4.057	K I P
9	49.41	155.54	21.423	−158.015	5116.	4.015	K I P
10	49.41	155.54	−13.909	−171.777	7707.	4.050	A F I
11	43.92	148.63	21.423	−158.015	5474.	4.050	K I P
12	51.27	−179.17	21.423	−158.015	3787.	3.979	K I P
13	51.27	−179.17	−13.909	−171.777	7250.	4.056	A F I
14	51.27	−179.17	−21.217	−159.773	8244.	4.056	R A R
15	23.19	−107.99	−21.217	−159.773	7451.	4.000	R A R
16	42.48	143.04	21.423	−158.015	5907.	4.021	K I P
17	−25.85	−177.29	8.961	− 79.558	11202.	3.895	B H P
18	−25.85	−177.29	32.310	−110.782	9535.	3.976	T U C
19	−25.85	−177.29	46.750	−121.810	9773.	3.976	L O N
20	−51.94	− 74.14	21.423	−158.015	11441.	3.917	K I P
21	−51.94	− 74.14	−21.217	−159.773	7886.	3.958	R A R
22	32.26	131.78	21.423	−158.015	6959.	4.025	K I P
23	−14.13	166.56	21.423	−158.015	5510.	3.998	K I P
24	−11.03	163.41	21.423	−158.015	5530.	4.045	K I P
25	−39.80	−104.80	21.423	−158.015	8733.	3.900	K I P
26	−39.80	−104.80	−21.217	−159.773	5565.	3.954	R A R
27	−39.80	−104.80	−41.287	174.767	6554.	3.934	W E L
28	− 7.60	146.20	32.310	−110.782	11685.	4.05	T U C
29	− 7.60	146.20	44.586	−123.303	10638.	4.01	C O R
30	−30.04	−177.65	44.586	−123.303	9933.	3.99	C O R
31	55.72	−155.95	−13.909	−171.777	7857.	4.01	A F I
32	− 5.07	144.20	44.586	−123.303	10602.	3.98	C O R
33	40.39	139.05	−13.909	−171.777	7866.	4.03	A F I
34	18.31	−100.50	−13.909	−177.777	8594.	3.99	A F I
35	− 5.4	151.5	64.900	147.793	9221.	3.055	C O L
36	− 5.4	151.5	46.750	−121.810	10193.	4.005	L O N
37	− 5.4	151.5	40.195	−112.813	10880.	3.989	D U G
38	− 5.4	151.5	32.310	−110.782	11058.	4.005	T U C
39	− 5.4	151.5	34.942	−106.658	11453.	3.970	A L Q
40	− 5.4	151.5	− 0.733	− 90.300	13134.	3.990	G I E
41	− 5.4	151.5	− 0.200	− 78.500	14445.	3.967	Q U I
42	− 5.4	151.5	−11.988	− 76.842	14348.	3.780	N N A
43	− 5.4	151.5	−16.462	− 71.491	14716.	3.823	A R E
44	− 5.4	151.5	−16.533	− 68.098	15041.	3.970	L P B
45	− 5.4	151.5	−33.144	− 70.685	13857.	3.921	P E L

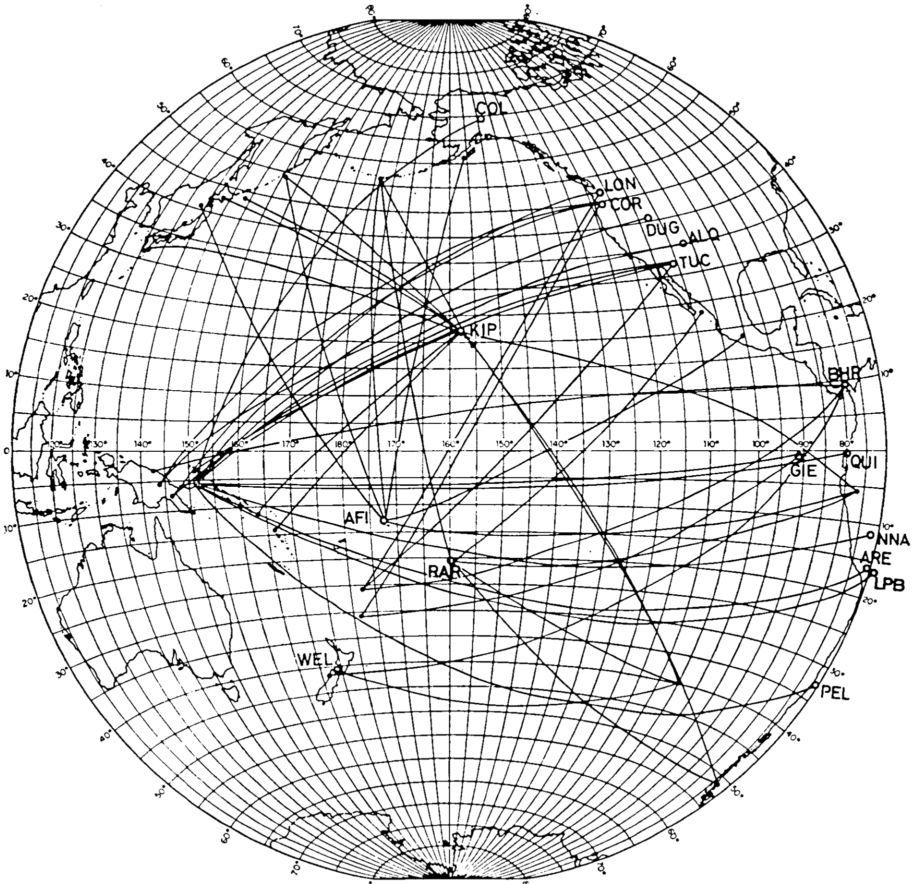

Fig. 1. Great Circle paths between epicenters (solid circles) and observation stations (open circles).

and Satô by the moving-windowed-power-spectrum (HAMADA and SATÔ, 1970).

The group velocity in Table 1 is the average value for the whole path, hence the travel time t in the expression (2) is the ratio of the epicentral distance and this group velocity. In the equation (1) the spherical surface harmonics of order up to four were employed in the following calculation and they were evaluated for the great circle paths shown in Fig. 1. The number of paths is 45 and these data covering the Pacific Ocean seem to be sufficient to reveal the features of the lateral heterogeneity.

3. Result

Twenty-five unknown coefficients (A_n^m and B_n^m; n, m up to 4) were

Table 2. Coefficients of the expansion of $1/v(\theta, \varphi)$ into spherical surface harmonics.
A_n^m; $P_n^m(\cos\theta)\cdot\cos m\varphi$, B_n^m; $P_n^m(\cos\theta)\cdot\sin m\varphi$

n	m	A_n^m	B_n^m
0	0	−0.2267	
1	0	−0.5422	
	1	−0.7856	−0.6412
2	0	0.1190	
	1	−0.4689	−0.2118
	2	−0.0642	−0.2468
3	0	0.4043	
	1	−0.0222	0.0043
	2	−0.0409	−0.0533
	3	0.0089	−0.0253
4	0	0.0332	
	1	0.0392	0.0246
	2	−0.0020	0.0009
	3	−0.0003	−0.0027
	4	0.0008	−0.0007

determined by the method of least squares. Once the coefficients are obtained the local group velocity at any location can easily be calculated from the equation (1).

The accuracy was checked as follows. The synthesized velocity was substituted into the expression (2) for each great circle path and the travel time (TC) was calculated. It was then compared with the observed travel time (TO). Three data Nos. 26, 28 and 42 in Table 1 gave the residuals ($TO-TC$) not small, and the $|TO-TC|/TO$ value exceeded 1%. These three data, which give no good Rayleigh wave phases, were rejected and the coefficients were redetermined using remaining 42 data. The coefficients and residuals thus obtained are listed in Tables 2 and 3, respectively. Table 3 indicates that all the residuals are less than 1% and the average is 0.28%. These small values suggest that the coefficients listed in Table 2 are reliable as the parameters expressing the velocity distribution.

By employing the coefficients in Table 2 the group velocities over the whole Pacific were calculated and they are given in Fig. 2. The velocity difference between different areas is obvious. High velocities 4.10–4.20 km/sec are distributed in the Northwest and Mid-Pacific Basins and this pattern coincides with the results for the period 30 seconds reported by SATÔ and SANTO (1969), and AVESTIYANA and YANOVSKAYA (1973). Low velocities 3.60–3.80 km/sec are distributed along the East

Table 3. Residuals of the Rayleigh wave travel time.
No.: Data number corresponding to the one in Table 1.
TO: Observed travel time.
TC: Travel time calculated by the synthesized velocity.

No.	TO (sec)	TC (sec)	TO−TC (sec)	|TO−TC|/TO (%)
1	2953.7	2939.7	13.9	0.47
2	3164.1	3169.8	− 5.7	0.18
3	2387.3	2387.3	0.0	0.00
4	2662.0	2649.2	12.9	0.48
5	2334.5	2348.2	−13.7	0.59
6	2526.2	2526.8	− 0.7	0.03
7	3831.3	3840.2	− 8.9	0.23
8	1529.5	1523.2	6.3	0.41
9	1274.2	1272.8	1.4	0.11
10	1903.0	1905.8	− 2.8	0.15
11	1351.6	1353.2	− 1.6	0.12
12	951.7	949.6	2.2	0.23
13	1787.5	1793.6	− 6.1	0.34
14	2032.5	2028.9	3.7	0.18
15	1862.8	1874.8	−12.0	0.65
16	1469.0	1459.7	9.4	0.64
17	2876.0	2867.7	8.3	0.29
18	2398.1	2389.9	8.3	0.34
19	2458.0	2462.3	− 4.4	0.18
20	2920.9	2913.2	7.7	0.26
21	1992.4	1993.4	− 1.0	0.05
22	1728.9	1725.1	3.8	0.22
23	1378.2	1367.2	11.0	0.80
24	1367.1	1368.4	− 1.3	0.09
25	2239.2	2249.4	−10.2	0.45
27	1666.0	1653.6	12.4	0.74
29	2652.9	2661.4	− 8.5	0.32
30	2489.5	2492.3	− 2.8	0.11
31	1959.4	1965.4	− 6.1	0.31
32	2663.8	2659.7	4.2	0.16
33	1951.9	1962.0	−10.2	0.52
34	2153.9	2147.0	6.9	0.32
35	2331.4	2326.9	4.5	0.19
36	2544.8	2550.3	− 5.5	0.22
37	2727.6	2726.6	1.0	0.03
38	2761.1	2769.4	− 8.2	0.30
39	2885.1	2869.9	15.2	0.53
40	3291.8	3287.8	4.0	0.12
41	3641.4	3636.5	4.9	0.14
43	3849.3	3843.4	5.9	0.15
44	3968.6	3966.7	2.0	0.05
45	3533.9	3541.4	− 7.5	0.21
Average				0.28

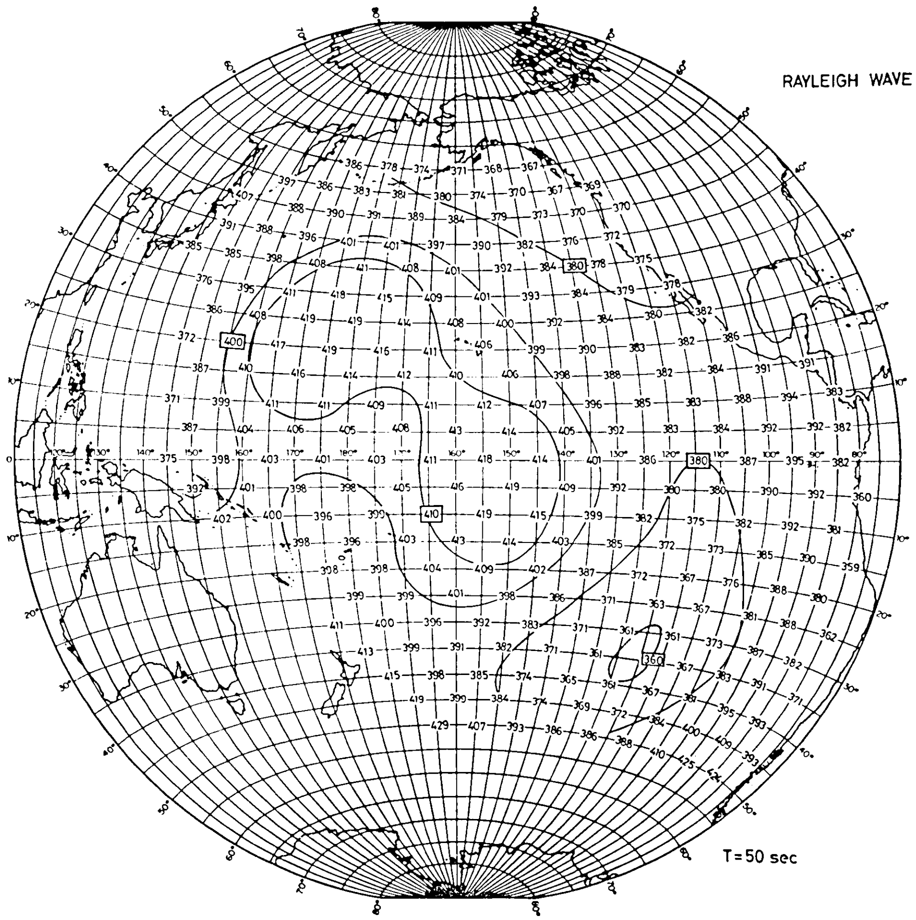

Fig. 2. Group velocity distribution of Rayleigh waves in the Pacific as synthesized in terms of a series of spherical surface harmonics. Unit: 10 m/sec.

Pacific Rise.

In Fig. 2 the velocity along the west coast of South America is also low. However it is not resolved in detail because this region is covered rather inadequately in the present work. The velocity distribution along the west coast of South America and North America is well determined in the studies by Satô and Santo, and Avestiyana and Yanovskaya, showing the low velocity there.

Using the coefficients in Table 2 the local group velocities along a couple of great circle paths were calculated and are shown in Fig. 3 together with the observed average group velocities. The paths Nos. 11 and 10, from Kurile Is. to Hawaiian Is. and Samoa Is., respectively, traverse mainly the Northwest Pacific. The path No. 1 from New Guinea to the western part of North America passes most of the north

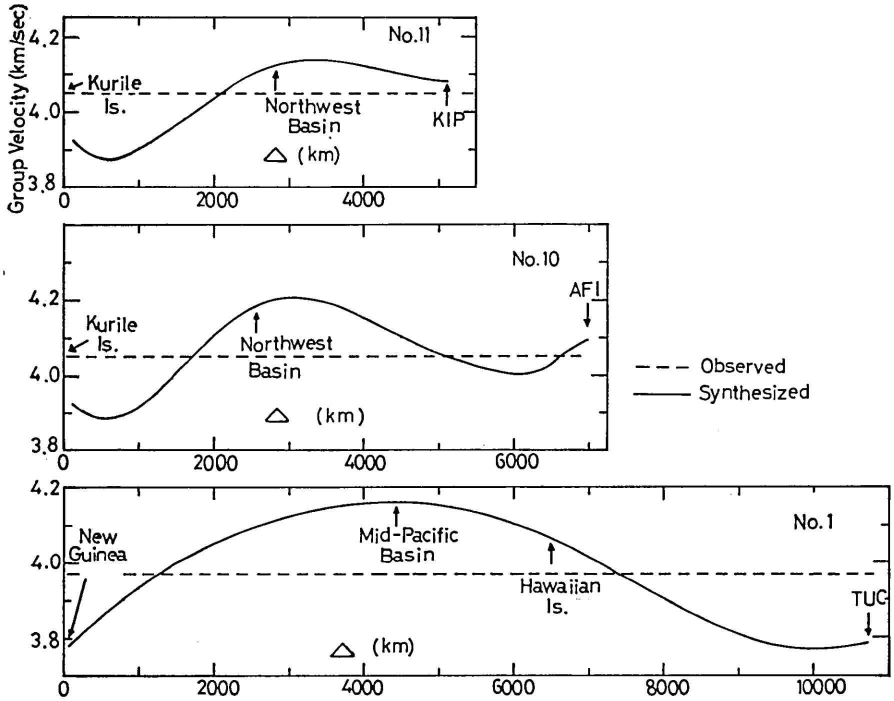

Fig. 3. Example of the local group velocities along the great circle paths (solid lines). Dashed lines are the observed group velocities. Numbers in the upper right correspond to the ones in Table 1. Abscissa is the distance from the epicenter.

Pacific Ocean. In these three curves we can easily see the variation of group velocities between the epicenters and stations; for example, the velocity in the west of Hawaiian Is. is high in comparison with that in the east of the Islands.

In the present work, since the data covers only a part of the earth, we did not apply the coefficients in Table 2 for the area outside the Pacific Ocean.

4. Discussion

Fig. 4 shows the schematic velocity distribution together with the isochrons of 20, 50 and 90 m.y. of the ocean-floor age. The lowest velocity area A is located at the youngest region of the ocean-floor age near the East Pacific Rise, and the highest velocity area C at the oldest regions of the Northwest and Mid-Pacific Basins. In region B, the west coast of North America which belongs to a comparatively young ocean-floor age, the velocity is lower than the average in the normal oceanic basin. In this way, high correlation is found between the group velocity and the ocean-floor age (see Fig. 4), and our results agree with the

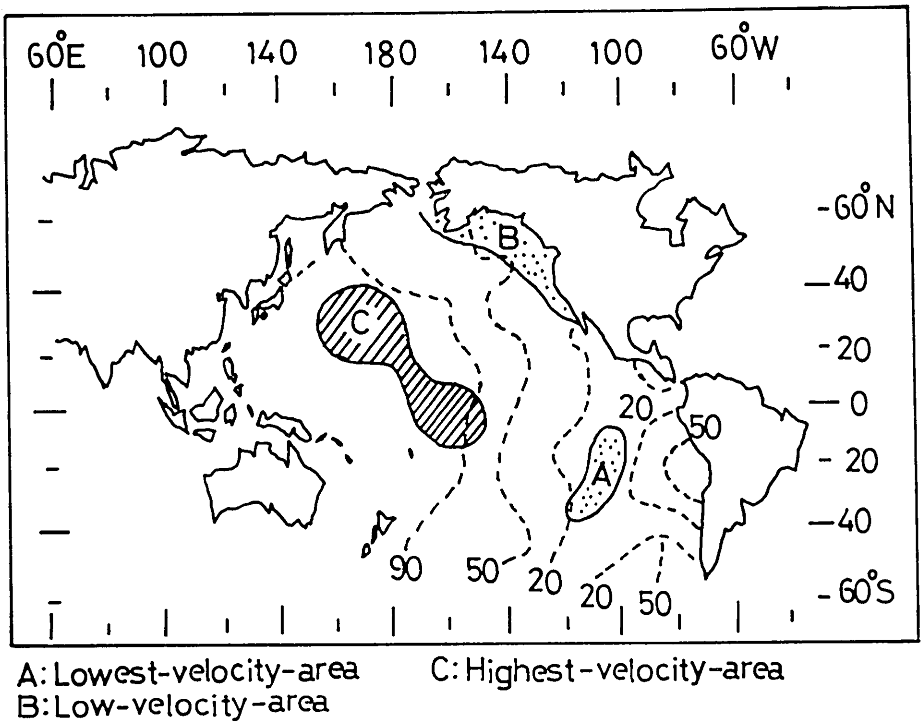

Fig. 4. Map of the group velocity and the ocean-floor age in the Pacific. In the region A the velocity is the lowest and it is the highest in the region C. The velocity in the region B is comparatively low. Dashed curves indicate isochrons 20, 50, and 90 m.y. of the ocean-floor age.

regionality of the group velocity obtained by YOSHII (1975).

The velocity contrast between the maximum and minimum is estimated to be more than ten percent (Fig. 2). This suggests that the shear wave velocity distributions in the upper mantle are remarkably different.

In the vast Pacific seismic stations are scarce, therefore, some technique had to be devised to obtain the local velocities. The method employed in the present work, first used by Satô and Santo years ago, seems to be very effective in revealing the velocity distribution. In the Pacific even the lowest velocity area with a slender shape, extending from north to south, is finely determined along the East Pacific Rise (Fig. 4) and this result agrees well with reports by many investigators.

5. Conclusions

Group velocities of Rayleigh waves in the Pacific have been obtained in terms of a series of spherical surface harmonics. It is revealed that group velocities are highly correlated with the ocean-floor age, namely the velocity is low in the young eastern Pacific, while it is high in the old western Pacific. The high velocities 4.10–4.20 km/sec are distributed in the Northwest and Mid-Pacific Basins, and the low velocities 3.60–3.80 km/sec near the East Pacific Rise.

In the present work we examined the velocity distribution only for the period 50 seconds which correspond to a wave length of about 200 km. Though it seems that the velocities are affected by a comparatively shallow part of the upper mantle, more analyses with different periods will be helpful in determining the lateral heterogeneity under the Pacific, and this work is now in progress.

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1. 太平洋における周期50秒のレイリー波群速度分布

地震研究所　吉　田　　満

WWSSN 観測データに基づき，太平洋における周期 50 秒のレイリー波群速度を表面球関数によって合成した．東太平洋海膨付近の群速度は著しく低く，最小値を示し，西に向かって連続的に増加していることが明らかになった．速度の高い地域は西太平洋海盆及び中央太平洋海盆に位置し，北西から南東へのびている．太平洋における群速度の最大値と最小値の差は 10% 以上あると思われる．最高次数 4 の表面球関数によって合成された群速度分布図が示されている．