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REGIONALITY OF GROUP VELOCITIES OF RAYLEIGH WAVES IN THE PACIFIC AND THICKENING OF THE PLATE

TOSHIKATSU YOSHII

Earthquake Research Institute, University of Tokyo, Tokyo (Japan)

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The relationship between group velocities of Rayleigh waves and the ocean-bottom age in the Pacific is examined. The Pacific basin is divided into four regions by isochrons determined from geomagnetic lineations. A significant change in group velocities of Rayleigh waves is obtained for these four regions by the use of the least-squares method from data for 27 paths in a period range 40–90 s. The present result and other geophysical observations strongly suggest the "thickening of the oceanic plate", and are well explained by a simple plate-thickness/age relation l (km) = 7.49 t (m.y.)$^{1/2}$ inferred from the "mantle gravity anomaly".

1. Introduction

The existence of the mantle low-velocity layer beneath the oceanic region has been confirmed by many surface-wave studies [1–3]. It is now widely believed that the high-velocity lid overlying the low-velocity layer corresponds to the "plate" in plate tectonics. Although there seems to be no doubt that the fine structure of the plate is one of the most important bases of plate tectonics, our knowledge of it is rather poor. For example, the plate thickness beneath the ocean has been often considered as about 70 km [4]. However, it may be an open question whether the plate has such a uniform thickness in the whole oceanic region or whether the thickness of about 70 km is nothing more than an averaged one.

Recently, Kausel et al. [5] and Leeds et al. [6] analyzed phase velocities of Rayleigh waves in the Pacific, and suggested the thickening of the plate. Forsyth [7] also suggested the thickening from the surface-wave analysis.

From studies on the "residual gravity anomaly" (RGA), or the mantle gravity anomaly, Yoshii [8] and Kono and Yoshii [9] proposed a "thickening plate model." In their model, the plate thickness is approximately proportional to the square root of the ocean-floor age. A similar model was presented by Parker and Oldenburg [10]. The thickening of the plate was also inferred from the volcanological discussion [11,12] and from the "resorption time" of the plate sinking at the ocean trenches [13]. The thickening plate model seems to be very plausible in many respects and well explains the surface geophysical observations [9,10].

In the present paper, regionality of group velocities of Rayleigh waves in the Pacific is shown, which can be explained by the variation in the plate thickness. Santo [14] suggested the regionality in the Pacific basin on the basis of Rayleigh wave dispersion. Unfortunately, periods of Rayleigh waves in his study were rather short (less than 40 s). In the present paper, Rayleigh waves of the longer periods are analyzed. In order to examine the thickening of the plate, other geophysical studies are also referred to.

2. Regionality of group velocities of Rayleigh waves

Analyzed records were those obtained with long-period seismographs of W.W.S.S.N. Detailed data of stations, epicenters, 27 great-circle paths and others are given in Tables 1, 2 and Fig. 1. Group velocities along the 27 paths were determined by the use of a traditional peak-and-trough method [15,16]. Long-

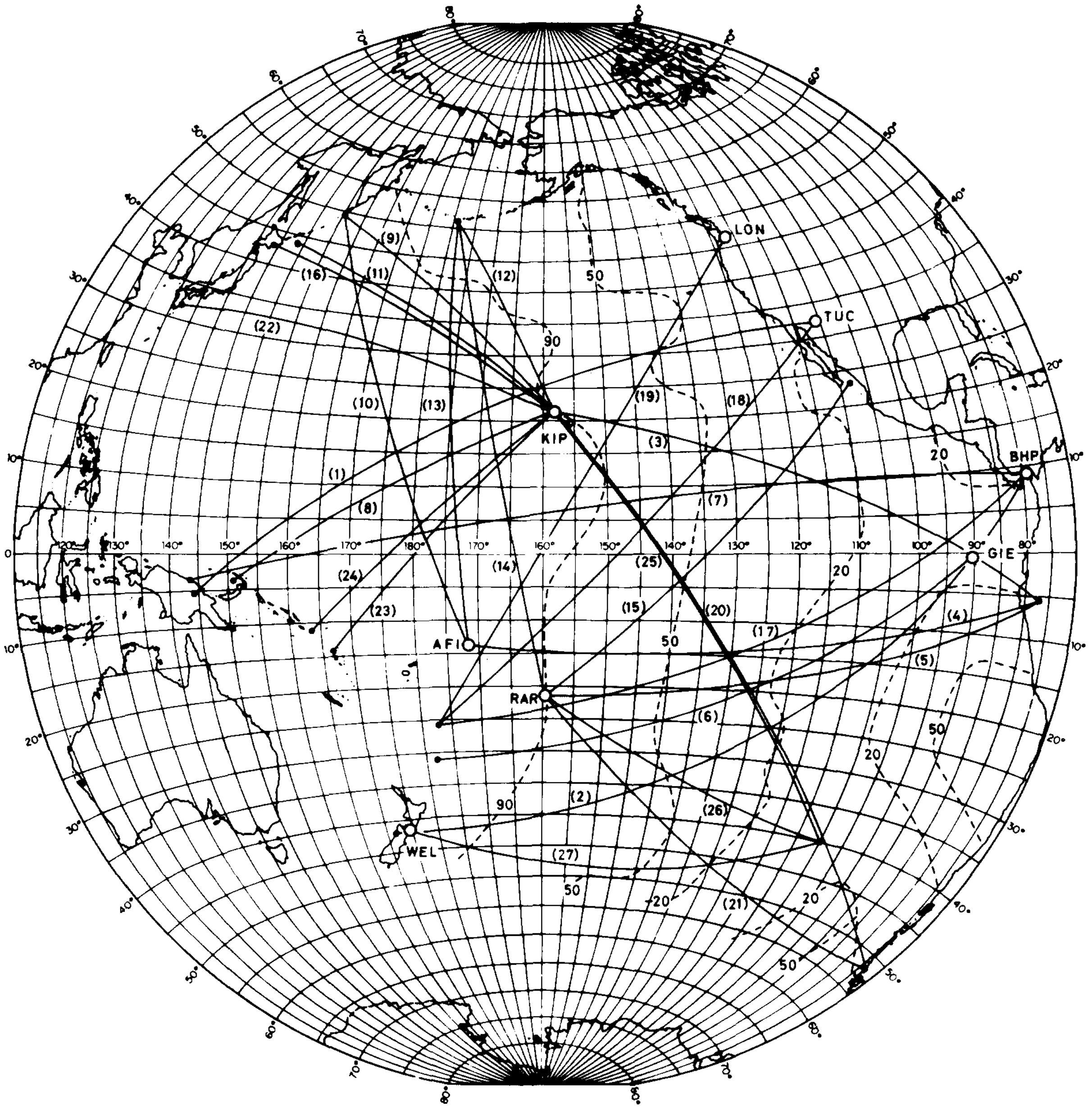

Fig. 1. Location of stations (open circle) and earthquakes (closed circle) analyzed. Path numbers are given in parentheses. Dashed curves indicate isochrons of 20, 50 and 90 m.y.

period branches of inverse dispersion were separated by tracing the mid points of the short-period swings [17]. One example of the long-period branches resolved in this manner is shown in Fig. 2a. Long-period waves were generated by one earthquake of 20 Jan. 1970 (paths 17, 18 and 19), and the long-period branches were directly observed on records as shown in Fig. 2b.

A "key" station in the present analysis may be KIP (Kipapa) which sites in the midst of the Pacific (see Fig. 1.) Rayleigh-wave velocities observed at this station greatly depend on directions of propagation

TABLE 1

Observation stations

Station	Code	Location	
Afiamalu, Samoa	AFI	171°46'38"W	13°54'33"S
Balboa Heights,Panama	BHP	79 33 29 W	8 57 39 N
Galapagos Isl., E	GIE	90 18 00 W	0 44 00 S
Kipapa, Hawaii	KIP	158 00 54 W	21 25 24 N
Longmire, Washington	LON	121 48 36 W	46 45 00 N
Rarotonga, Cook Isl.	RAR	159 46 24 W	21 13 00 S
Tucson, Arizona	TUC	110 46 56 W	32 18 35 N
Wellington, N.Z.	WEL	174 46 00 E	41 17 12 S

TABLE 2

A list of propagation paths, stations and earthquakes

Path	Station	Region	Date	Epicenter		Origin T.	M	Δ (km)
1	TUC	New Guinea	24 Apr 64	144.20°E	5.07°S	5:56:09.8	6.9	11726
2	BHP	New Zealand	23 May 68	172.03 E	41.72 S	17:24:16.8	6.1	12188
3	KIP							9282
4	AFI	N. Peru	19 Jun 68	77.20 W	5.55 S	8:13:35.6	6.1	10350
5	RAR							9016
6	GIE	Kermadic Isl.	25 Jul 68	178.13 W	30.97 S	7.23:02	6.5	9756
7	BHP	New Guinea	23 Oct 68,31 Oct 70	143.29 E	3.38 S	21:23:42.9	6.2	15237
8	KIP	New Ireland	16 Apr 69	150.90 E	3.56 S	1:22:48.2	5.6	6205
9	KIP	Kurile Isl.	13 Jun 69	155.54 E	49.41 N	8:48:28.3	6.0	5116
10	AFI							7707
11	KIP	Kurile Isl.	12 Aug 69,13 Aug 69,14 Aug 69	148.63 E	43.92 N	11:21:23.3	5.6	5474
12	KIP		12 Sep 69,31 Oct 69,15 Jul 70					3787
13	AFI	Andreanof Isl.	12 Sep 69,31 Oct 69	179.17 W	51.27 N	8:57:06.9	5.9	7250
14	RAR		12 Sep 69					8244
15	RAR	G. of Calf.	1 Nov 69	107.99 W	23.19 N	11:08:24.3	5.5	7451
16	KIP	Hokkaido	20 Jan 70	143.04 E	42.48 N	17:33:03.1	6.3	5907
17	BHP							11202
18	TUC	S. of Fiji	20 Jan 70	177.29 W	25.85 S	7:19:51.4	6.2	9535
19	LON							9773
20	KIP	S. Chile	14 Jun 70	74.14 W	51.94 S	0:00:08.8	5.9	11441
21	RAR							7886
22	KIP	Kyushu	25 Jul 70	131.78 E	32.26 N	22:41:12.6	6.1	6959
23	KIP	New Hebrides	11 Aug 70	166.56 E	14.13 S	10:22:20	6.1	5510
24	KIP	Solomon	2 Dec 70	163.41 E	11.03 S	15:54:19	5.8	5530
25	KIP							8733
26	RAR	S. Pacific	9 May 71	104.8 W	39.8 S	8:25:01.7	6.2	5565
27	WEL							6554

TABLE 3

Propagation distances in four regions and group velocities for 27 paths

Path	Distance (km)				Group velocity (km/s)					
	1	2	3	4	40s	50s	60s	70s	80s	90s
1	0	2427	2380	6918	4.005	3.970	3.926	3.886	3.864	3.814
2	5631	2092	2856	1609	3.870	3.852	3.826	3.798	3.772	3.743
3	3642	2882	2754	0	3.917	3.888	3.861	3.836	3.813	3.789
4	2409	4327	2275	1338	3.917	3.888	3.861	3.836	3.813	3.789
5	2306	4739	1971	0	3.890	3.862	3.837	3.813	3.792	3.771
6	3919	2126	2043	1668	3.913	3.862	3.816	3.777	3.742	3.713
7	1658	4168	1837	7574	4.000	3.977	3.937	3.900	3.863	3.825
8	0	0	0	6205	4.063	4.057	4.015	3.974	3.934	3.898
9	0	0	0	5116	4.035	4.015	3.978	3.938	3.895	3.856
10	0	0	0	7707	4.070	4.050	4.012	3.975	3.934	3.899
11	0	0	0	5474	4.070	4.050	4.012	3.975	3.934	3.899
12	0	0	2612	1175	4.003	3.979	3.940	3.903	3.868	3.833
13	0	0	1000	6250	4.066	4.056	4.015	3.972	3.928	3.893
14	0	0	1057	7187	4.066	4.056	4.015	3.972	3.928	3.893
15	681	3449	3321	0	4.025	4.000	3.942	3.883	3.831	3.785
16	0	0	0	5907	4.045	4.021	3.978	3.932	3.886	3.845
17	4696	2542	2197	1766	3.940	3.895	3.852	3.812	3.773	3.740
18	0	2908	4148	2480	4.005	3.976	3.934	3.890	3.848	3.812
19	0	1750	2603	5420	4.005	3.976	3.934	3.890	3.848	3.812
20	3561	4051	2493	1336	3.961	3.917	3.871	3.832	3.795	3.760
21	1856	1948	4082	0	3.985	3.958	3.915	3.874	3.837	3.801
22	0	700	0	6259	4.045	4.025	3.985	3.944	3.910	3.870
23	0	0	0	5510	4.033	3.998	3.954	3.914	3.874	3.835
24	0	0	0	5530	4.057	4.045	4.000	3.953	3.910	3.863
25	1755	3211	2440	1327	3.945	3.900	3.858	3.821	3.791	3.762
26	1193	1855	2518	0	3.990	3.954	3.912	3.869	3.828	3.793
27	1727	1060	2786	981	3.965	3.934	3.893	3.856	3.820	3.788

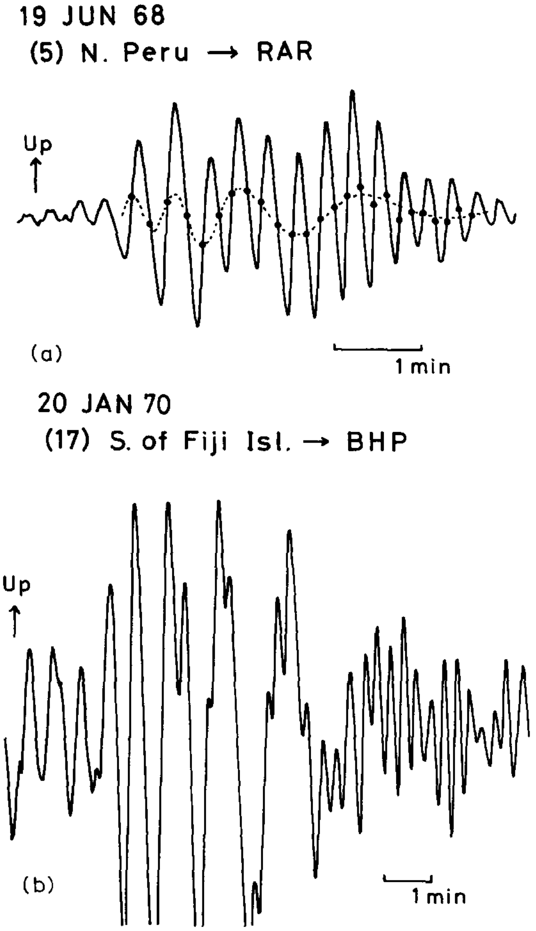

Fig. 2. (a) A traced record for path 5. Small dots indicate mid points of short-period swings. (b) A traced record for path 17 showing a clear Rayleigh-wave train of inverse dispersion.

as shown in Fig. 3; namely, group velocities of Rayleigh waves traveling from the east were very low and those from the west were very high as compared with the theoretical curve for a famous 8099 model [1]. The lowest velocity was observed along path 2 or path 6 among 27 ones. Observed group velocities are given in Table 3.

In order to obtain the relationship between the group velocity and the ocean-floor age, the Pacific basin was divided into four regions by isochrons of 20, 50 and 90 m.y. inferred from geomagnetic lineations [18,19] as shown in Fig. 1; namely, region 1: 0–20 m.y., region 2: 20–50 m.y., region 3: 50–90

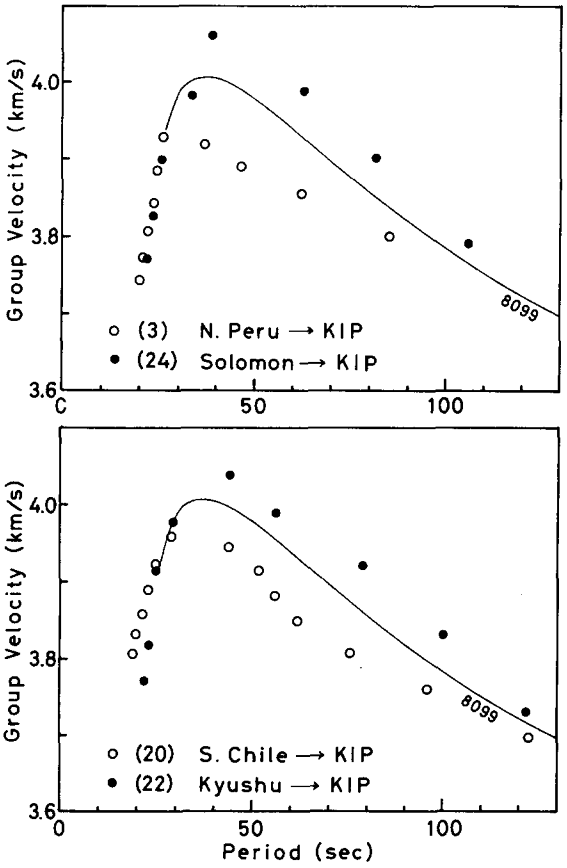

Fig. 3. Some of the observed group velocities at station KIP.

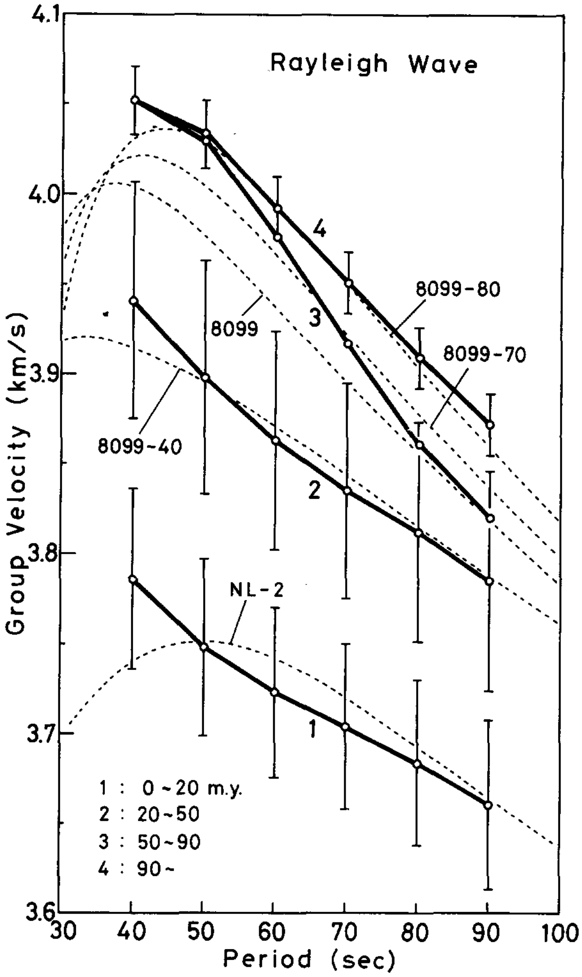

Fig. 4. Regionalized group velocities in four regions. Error bars for region 3 are not given in order to avoid confusion. Dotted curves are theoretical group velocities for models given in Fig. 5.

m.y., and region 4: older than 90 m.y. The division into four regions was made because that into more regions increases greatly the uncertainty in the isolation procedure of the regional group velocities, and the

TABLE 4

Regionalized group velocities of Rayleigh waves.

Period (s)	Region 1		Region 2		Region 3		Region 4	
	U(km/s)	S.D.	U(km/s)	S.D.	U(km/s)	S.D.	U(km/s)	S.D.
40	3.786	0.050	3.941	0.066	4.052	0.069	4.052	0.019
50	3.748	0.049	3.898	0.065	4.030	0.068	4.033	0.019
60	3.723	0.047	3.863	0.061	3.976	0.064	3.992	0.018
70	3.703	0.046	3.835	0.060	3.917	0.062	3.951	0.017
80	3.684	0.046	3.812	0.061	3.861	0.061	3.909	0.017
90	3.661	0.047	3.785	0.061	3.820	0.061	3.872	0.017

ocean-floor age inferred from geomagnetic lineations may be less reliable especially in the Mesozoic region. Propagation distances in the four regions for each path are given in Table 3.

Regional group velocities were isolated by the use of the usual least-squares method [20,21]. The result is shown in Fig. 4 by heavy lines. The numerical result is given in Table 4. The errors shown in Fig. 4 and Table 4 were estimated from those of raw group velocities and scatters in the isolating procedure. The former ones may be caused by timing errors, epicentral errors, origin time errors and others, and they were assumed to total to ±10 s of errors in travel times.

A clear regional change in the Rayleigh-wave velocity was found; namely, the group velocity increases as the ocean-floor age is older. The present regionalized group velocities may include an effect of velocity anisotropy as pointed out by Forsyth [7]. The effect, however, may be rather small because the propagation paths in four regions run in all directions as shown in Fig. 1. It is soon recognized from Fig. 4 that the uniform upper-mantle structures obtained by previous studies are considered as averaged ones because the regionalized group velocity has a clear age-dependent nature.

3. Thickness of the plate

The regionality of the Rayleigh-wave dispersion shown in Fig. 4 clearly suggests a variation in the oceanic upper mantle, presumably gradual cooling, with time. The most notable event in the cooling process may be thickening of the plate [8–10]. In this section, I examine whether the forementioned regionality of the Rayleigh-wave dispersion is concordant with the idea of the thickening plate or not. Of course, a precise inversion procedure is desirable in order to derive the shear-velocity structure from the regionalized group velocities. However, a precise inversion does not always lead to a successful result, because increase in structural parameters yields uncertainty in the solution.

Thermal models of the thickening plate [8,9] suggest a sharp plate/asthenosphere transition and rather small lateral changes in both the plate and the asthenosphere. Consequently, it seems allowable to fix shear velocities in the plate and the asthenosphere as a first approximation since a major purpose of the present study is to confirm the concept of the thickening plate.

As one of possible explanations for the regionality of Rayleigh waves, 8099 model by Dorman et al. [1] was chosen as a standard model, and only the plate thickness in the model was changed. As shown in Fig. 4, observed group velocities in regions 2, 3 and 4 are well explained by modified 8099 models with plate thicknesses of about 40, 70 and 80 km, respectively. The observed velocity in region 1 is very low and cannot be explained by any modified 8099 model in this manner. A model NL-2 with a pronounced low-velocity layer (shear velocity, 4.22 km/s) and without a high-velocity lid satisfied the observed data as shown in Fig. 4. Shear-velocity structure for the modified 8099 models and the NL-2 model are given in Fig. 5. Although Leeds et al. [6] and Forsyth [7] used a shear-velocity of 4.1 km/s in the asthenosphere

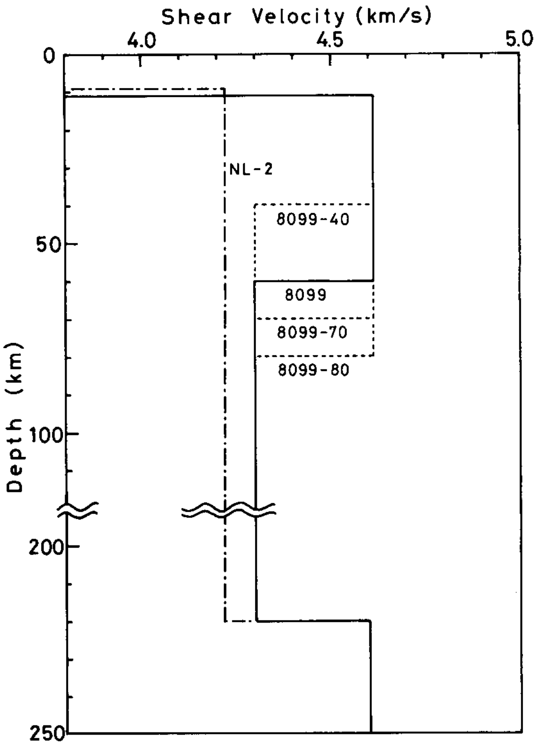

Fig. 5. Shear-wave structures for modified 8099 models and NL-2.

throughout the oceanic region, such a low velocity was not reconcilable with the present group velocity data at least in regions 2, 3 and 4.

When we use the other standard model rather than 8099, such as 5.08 M model [4], somewhat different plate thicknesses may be obtained for each region. However, this does not affect the important result in the present study, thickening of the plate.

Although some uncertainty may exist in the case of region 1, it seems obvious that the plate thickness is less than about 25 km and greater than 8 km which is the approximate crustal thickness in this region. The present NL-2 model has not a high-velocity lid. However, the effect of a thin lid on the theoretical group velocity was rather small. Several surface-wave studies in the mid-ocean ridge region have been reported [14,22,23]. Very low surface-wave velocities obtained by these studies suggest a shallow low-velocity material beneath the ridge regions.

Regional thicknesses of the oceanic plate have been obtained by various methods, and these are compiled in Fig. 6. Magneto-telluric data were included because the asthenosphere is believed to have an electrically high-conductive nature due to partial melting in it. The high-conductive layer may correspond to the seismic low-velocity layer. A dotted curve, l(km) = 7.49 t(m.y.)$^{1/2}$, indicates the plate thickness inferred from the mantle gravity anomaly [9]. The present surface-wave result is given by open squares. The error

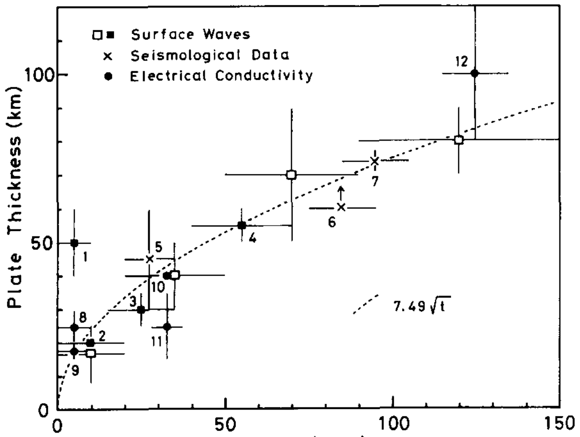

Fig. 6. Plate thicknesses inferred from various methods. The present result is given by open squares. As for reference numbers on the other data, see the text.

bars of these data indicate possible thickness ranges inferred from the comparison between the modified 8099 models and the regionalized group velocities in Fig. 4. Actual error ranges may be larger than those because they depend on the standard model used. The other results were taken from the following studies; heading numbers correspond to those in the figure.

1 = A Rayleigh wave study in the East Pacific Rise region by Knopoff et al. [22].
2 = A Rayleigh wave study in the Mid-Atlantic Ridge region by Weidner [23].
3 = A surface-wave study in the eastern Philippine Sea by Kanamori and Abe [24]. The ocean-floor age was determined as about 25 m.y. by JOIDES drillings.
4 = A Rayleigh wave study in the Peru-Chile Trench region by James [25]. Recently, JOIDES drilled holes in the Nazca plate.
5 = Nuttli and Bolt's [26] low-velocity layer model near the western coast of the United States. This model, however, seems quite arbitrary, and alternative explanations may be possible.
6 = Studies on seismicity near the Hawaiian Islands by Koyanagi and Endo [27]. Almost all the earthquakes are caused at depths of 0–60 km. The plate thickness in the region may be 60 km or more because of the aseismic nature of the asthenosphere.
7 = A study on the S–P converted waves reflected at the plate bottom in the Kurile–Kamchatska Trench region by Shimamura [28].
8,9 = Electrical conductivity studies in the Iceland region by Hermance and Garland [29] and Hermance and Grillot [30].
10,11 = A magneto-telluric sounding off the California coast [31,32].
12 = An electrical conductivity model beneath the Japanese Islands by Rikitake [33]. In this model, the depth to a high-conductivity layer off northeastern Japan is about 100 km.

In all these cases, the ocean-floor ages were inferred from geomagnetic studies [18,19] or JOIDES drillings. As shown in Fig. 6, these data are close to the dotted curve 7.49$t^{1/2}$, and strongly support the "thickening plate model." The plate thickness estimated by Leeds et al. [6] is somewhat larger than the data in Fig. 6 especially in the older region. However, it seems quite difficult to reconcile such a thick plate (about 150 km at 150 m.y.) with heat flow observations (A.R. Leeds, E.G. Kausel, personal communications, 1974). In order to clarify the present problem, accumulation of many other data is hoped for.

4. Conclusion

In order to explain the ocean-bottom topography, heat flow and the gravity anomaly near the mid-ocean ridges, McKenzie [34] proposed a cooling upper-mantle model with a plate of a uniform thickness. Several studies based on his model have been reported with remarkable success [35–37]. It should be noticed, however, that the plate bottom at a constant depth in McKenzie's model merely corresponds to a boundary condition in the theoretical calculation and was not physically meaningful.

On the other hand, the thickening plate model [8–10] is very simple and physically plausible, and well explains all sorts of surface geophysical observations as well as McKenzie's model does. Further studies, such as the petrological model or the driving force of the plate, based on the thickening plate model are hoped for because many geophysical data support this model as shown in the present study.

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