Dispersion of surface waves along various paths to Uppsala, Sweden

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PART I
CONTINENTAL PATHS

INTRODUCTION.

Group velocity dispersion data of surface waves along a certain path give information only about the average crustal condition over which the surface waves travelled. But if we observe them at many stations along many paths which cross each other over a wide area, there is a possibility to deduce regional dispersion characters in this area and to get some information about the regional crustal conditions. This possibility was proved in the previous investigations by the present author at Tokyo, Japan (Santo 1961 *b*).

Therefore, it is desirable to accumulate group velocity dispersion data along various paths over the earth, especially since long-period seismographs have been installed recently at many stations.

For this purpose, the present author began to investigate dispersion characters of surface waves along various paths, about two hundred and fifty in all, to Tsukuba, Japan, in 1958 (Santô 1960 *a*, *b*, 1961 *a*, *b*, *c*). The dispersion data of Love waves could be classified into eleven groups. For these representative curves, Roman numerals from (I) to (XI) were given, more continental in this order. The dispersive character of Rayleigh waves could be classified into seven curves, for which Arabic numerals from (1) to (7) were given, also more continental in this order. Of course, if we could get the dispersion data along an infinite number of paths, they must show continuous variation, for instance, from (1) to (7) for Rayleigh waves.

The present writer had an opportunity to continue this research at the Seismological Institute, Uppsala, Sweden, from the beginning of November, 1961. With the cooperation of M. Båth, group velocity dispersion of Rayleigh waves was examined along about fifty paths around Pasadena (U.S.A.) and Huancayo (Peru) using the records of Benioff-type seismographs (Santò and Båth 1962). We then found a new dispersion character (0) which is much more oceanic than the character (1). Further, it was discovered that Rayleigh waves which pass over or near the eastern Pacific Rise exhibit another kind of dispersion characters, denoted *c* to *g*, more continental in this order. The classified dispersion curves hitherto obtained are summarized in Fig. 1.

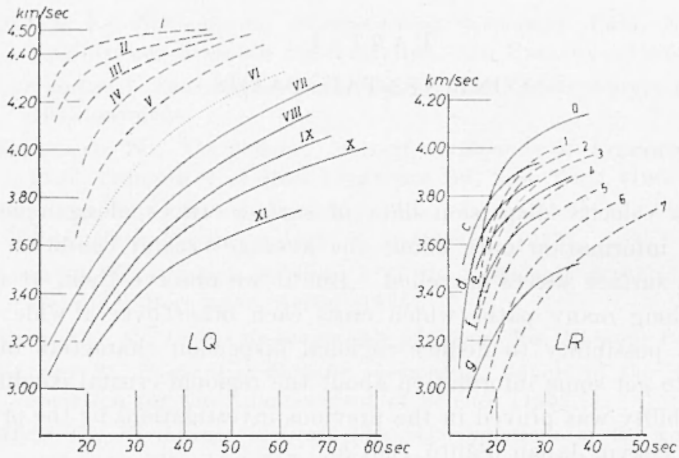

Fig. 1 – Classified dispersion curves of Love (left) and Rayleigh (right) waves.

Left diagram: dashed curves – along Pacific paths to Tsukuba; dotted curves – along mixed paths to Tsukuba; solid curves – along continental paths to Tsukuba.

Right diagram: dashed curves – along Pacific paths to Tsukuba; solid curves – along central Pacific paths to Pasadena (0) and along the paths over or near the eastern Pacific Rise to Pasadena (from *c* to *g*).

The purpose of the present work is to compare the dispersion characters of Love and Rayleigh waves along various paths to Uppsala with the classified dispersion curves previously obtained, and to discuss the average crustal conditions. Furthermore, some regional crustal condition will be discussed by combination with the dispersion data of Tsukuba and other stations as well as with data by other authors.

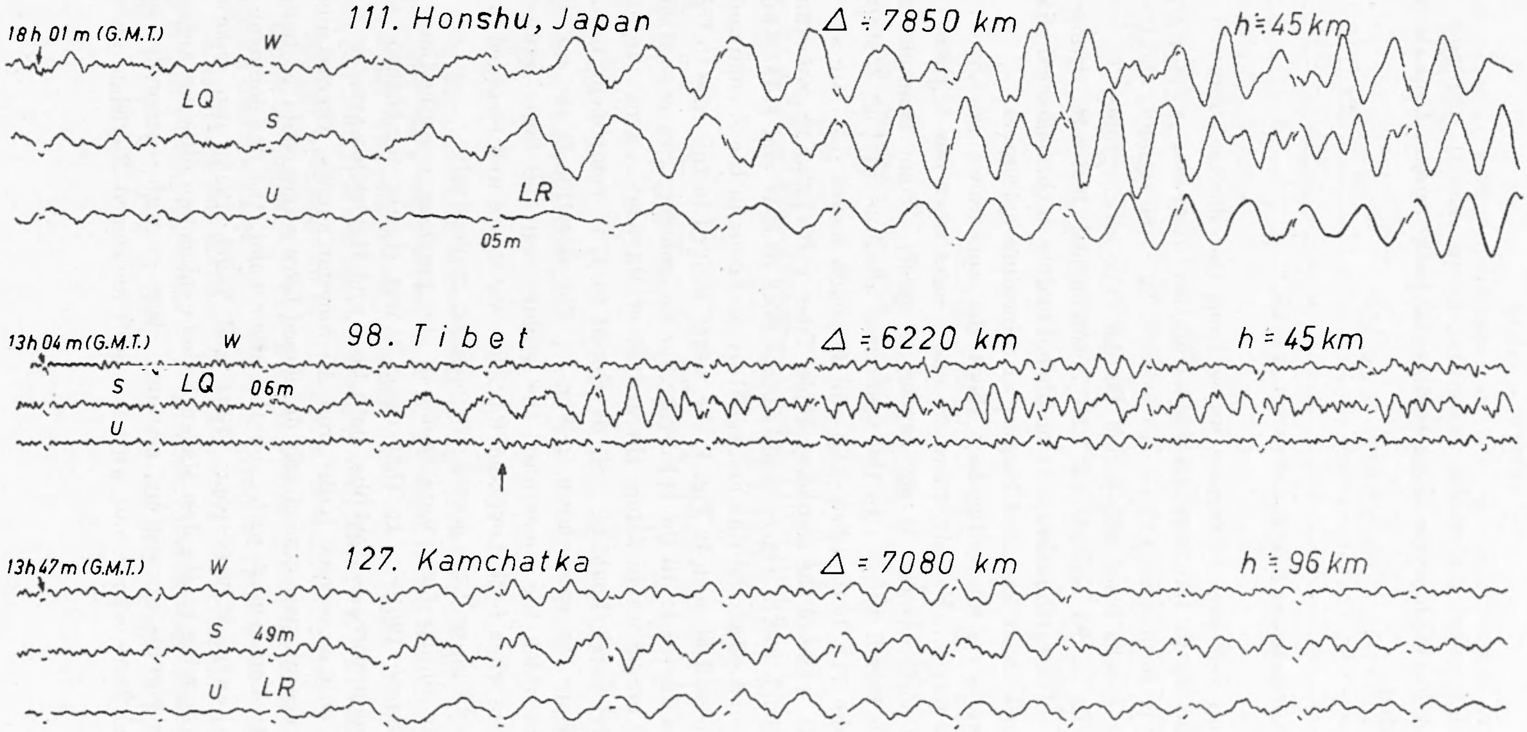

Fig. 2 – Some examples of seismograms in which both Love (LQ) and Rayleigh (LR) waves (above), only Love waves (middle) and only Rayleigh waves (below) were well developed; 6000 km < D < 8000 km.

In this paper, the results concerning group velocity dispersion of Love and Rayleigh waves along continental paths around Uppsala will be reported.

Appearance of Love and Rayleigh waves.

Group velocities of surface waves from the shocks numbered 00 to 60 and 90 to 100 were obtained from the ultra-long-period Press-Ewing type seismograms (To = 15 seconds, Tg = 80 seconds) and those for other shocks from long-period Benioff type seismograms (To = 1 second, Tg = 85 seconds) at the Seismological Institute, Uppsala, Sweden. The earthquakes were numbered mainly in chronological order. Some shocks were excluded because of coinciding epicenters.

There is an interesting fact about the appearance of Love and Rayleigh waves. Namely, there are many cases when one of these two kinds of surface waves is not developed clearly. Some examples are shown in Figs 2 and 3. In the uppermost diagram in Fig. 2, Japan earthquake 111, both Love (LQ) and Rayleigh waves (LR) are shown very well, while in the second example, Tibet earthquake 98, we cannot find Rayleigh waves which should appear both in E-W and U-D components from around the time indicated by an arrow in the Z component record. As will be seen in Fig. 4, the waves arrived in this case to Uppsala from due east. In the third case, on the contrary, we cannot find any long period waves before the arrival of Rayleigh waves. In this case Love waves should be well developed in E-W component record, judging from the path shown in Fig. 4. The situation is the same in Fig. 3, in which the uppermost, the middle and the lower example mean cases when both Love and Rayleigh waves are well recorded, and when Rayleigh or Love waves are missing, respectively.

Quite similar facts were found in the previous investigations in Tokyo (Santô 1961 *c*). In that case, it was clearly established that along Pacific paths to Tsukuba, both Love and Rayleigh waves are well recorded only on oceanic paths from Micronesian shocks, whereas along all other oceanic paths, no clearly developed Love waves could be found. Along the continental paths, on the other hand, the development of Rayleigh waves is very poor. Båth and Vogel (1958) also reported that earthquakes in the Jan Mayen region exhibit two different appearances on records of near-by stations: class *a*) with extremely well developed Love waves and with less well developed Rayleigh waves, class *b*) with poorly developed or missing Love waves but clear Rayleigh waves.

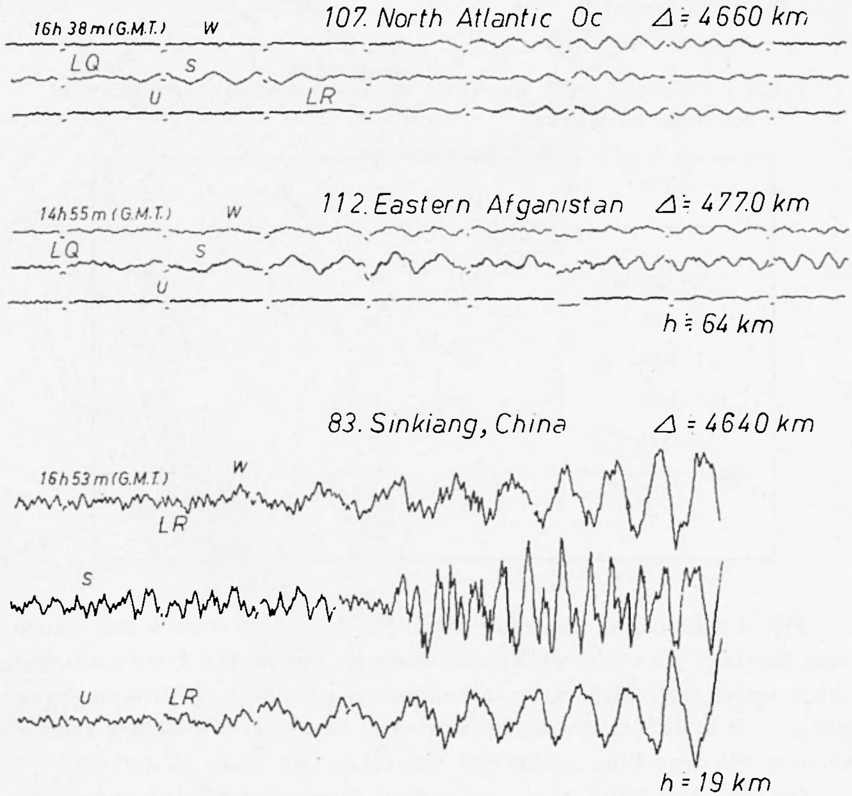

Fig. 3. – The same as Fig. 2 in the case of $D \simeq 4600$ km. 107: June 8, 1960. 16 19 48. 35°N, 35°W.

In Fig. 4, which shows most of the travelling paths to Uppsala, the three cases are marked, that is: 1) when both Love and Rayleigh waves are well developed, 2) when Love waves only could be well recorded and 3) when Rayleigh waves only could be well found.

A trial was made to find if this phenomenon has any correlation to the focal depth h. The frequency correlation between the focal depth h and the cases 1), 2) and 3) is given in Table I.

A glance at this indicates no dependence between these two factors. If we use χ^2-test, the value of χ^2 becomes 7.338 in this case. As probability ($\chi^2 \geqslant 7.338$) > 0.45 for N (degree of freedom) $= 8$, we must accept the independence hypothesis between these two factors, even if we take the level of significance as 0.05. It is also clear, for instance by the examples in Figs 2 and 3, that the phenomenon does not depend upon the path length.

Table I – CORRELATION BETWEEN FOCAL DEPTH AND APPEARANCE OF SURFACE WAVES.

h	1)	2)	3)	Σ
0– 25 km	10	6	12	28
26– 50	9	8	10	27
51–100	12	5	8	25
101–150	3	0	3	6
151–200	0	2	1	3
Σ	34	21	34	89

Fig. 4 tells us, on the other hand, the fact, that with a few exceptions, Rayleigh waves hardly appear along paths over the Asian continent, which agrees well with the result obtained previously at Tokyo (Santô 1961 *c*). It is difficult in the present case, however, to find any relation between the travelling paths and the other two cases 1) and 2).

On the other hand, there are several cases in which the appearance of surface waves is quite different for two or three shocks with almost the same location and therefore quite the same travelling paths. Some of these examples are given in Fig. 5. The upper two are the three component records due to shocks with almost the same epicenters 110 (40.0°N, 126.6°W, h = 25 km) and 108 (41°N, 125°W, h unknown). In the first record, Love and Rayleigh waves can be seen very clearly, while in the second one, Love waves are not present, though the amplitudes of Rayleigh waves are almost the same as in the first one. The lower two show another example. Two kinds of surface waves can be well recognized in the first record due to the shock 56 (35.7°N, 141.2°E, h = 75 km), while Rayleigh waves are very obscure in the second record due to the shock 16 (33.3°N, 141.3°E, h = 93 km). Moreover, the present writer observed at Tsukuba, that four shocks in the Solomon

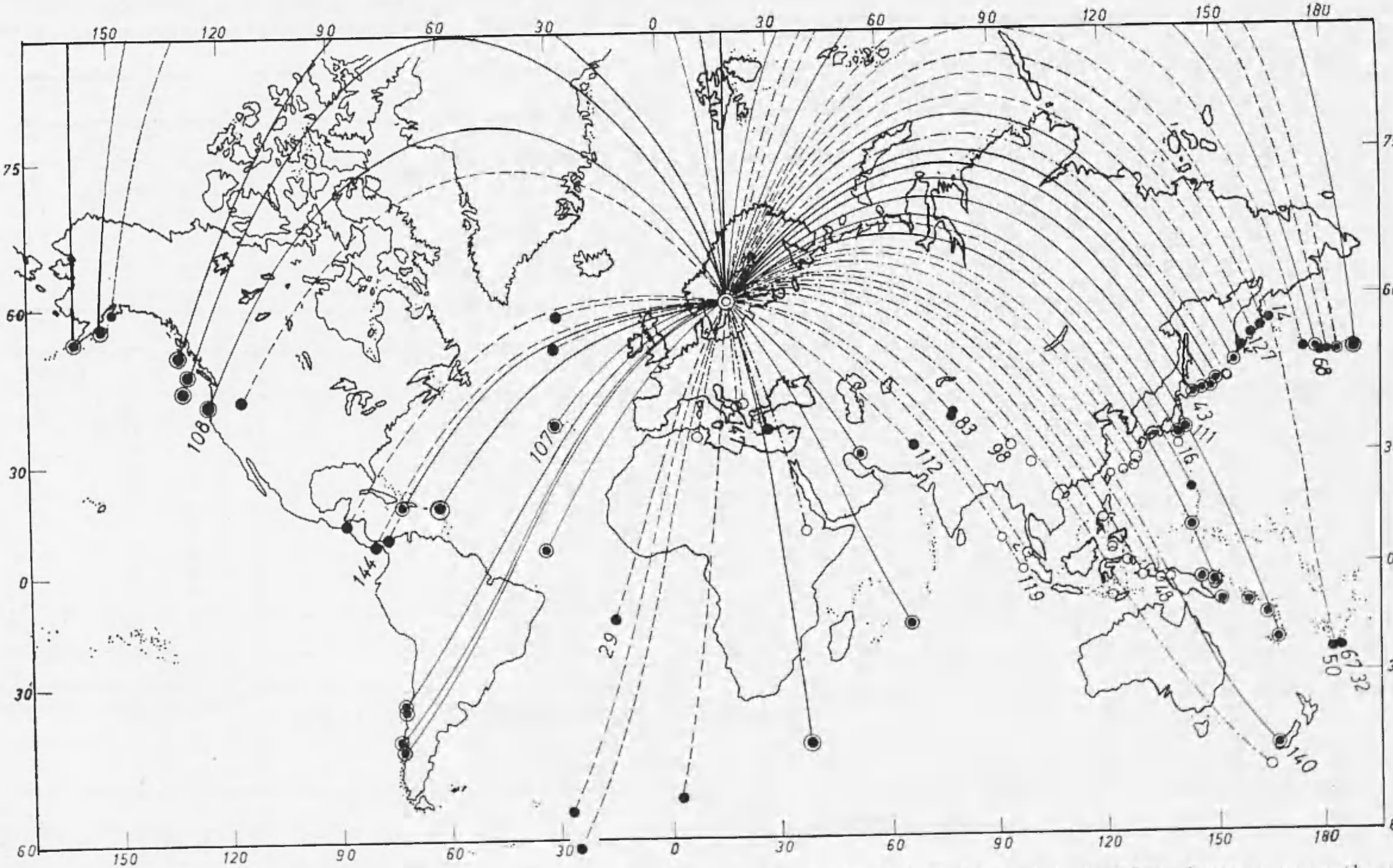

Fig. 4 – Travelling paths of surface waves to Uppsala. The paths drawn by solid, dashed and dashed-dotted curves mean those along which both Love and Rayleigh waves appear, only Rayleigh waves and only Love waves are well developed respectively. These three distinctions are also shown by the mark of epicenter, double filled, open and filled circles respectively. Shock numbers are limited to those mentioned in the text.

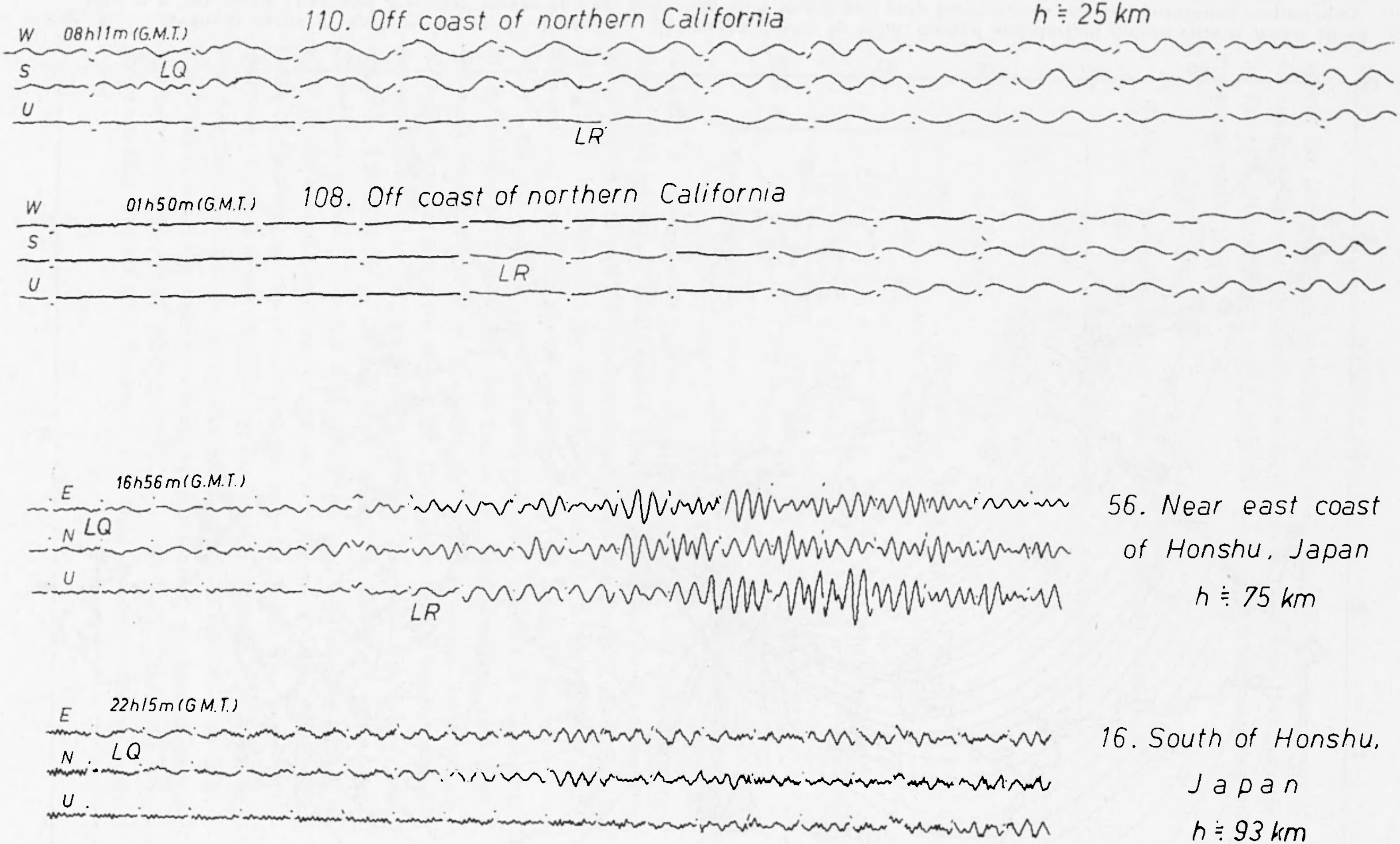

Fig. 5 – Some examples of seismograms with different appearance of surface waves for two pairs of shocks with approximately the same epicenters. 110: Aug. 9, 1960, 07 38 22.6, 40.0°N, 126.6°W. 108: June 6, 1960, 01 17 48, 41°N, 125°W.

Islands region on August 24, 1959, did not send Tsukuba any clear Rayleigh waves (Santô 1960 *a*).

The phenomenon seems to depend, at least in some cases, upon the shock mechanism. If the absence of Love waves for instance depends upon the shock mechanism, there must be a positive correlation between the appearance of SH and Love waves, that is, there must be no SH waves on the records with no Love waves and clear SH waves on the records with clear Love waves. Such correlation was checked for the shocks with epicentres in nearly N-S or E-W direction from Uppsala.

In Fig. 6 we can see the results of the check. In the case of shock 83, the seismic waves arrive from due east. As we can see well in the records, Rayleigh waves appear clearly near the end of both E-W and U-D components, but Love waves are extremely poorly developed. Also there is no trace of S on N-S component. Therefore, the absence of Love waves in this case seems to result from the shock mechanism, which produces no transversal movement in the direction of the station. The situation is quite the same for the following two examples. From the shock 144, Love waves were not developed. The waves arrive from due west and SH waves cannot be seen in the N-S component. The next one, 147, sends Love waves only. The waves arrive from south and the records have a remarkable SH but poor SV waves. These three are positive examples. There are, however, also some examples which show negative correlation, as seen in the last two. In the case of 127 which does not show Love waves, the waves come from nearly north, and in spite of this, the records show large amplitude SH waves in the E-W component. The same thing can be seen in the last case, in which no Love waves were recorded at Uppsala.

We conclude that the absence of Love or Rayleigh waves on certain seismograms depends in some cases upon shock mechanism, in other cases upon crustal condition along the travelling path.

Dispersion characters in area A.

In the following, we shall discuss the dispersion characters of Love and Rayleigh waves along continental paths to Uppsala by dividing the area into four parts, A: an area bounded by the paths from 14 and 43, B: bounded by the paths from 111 and 140, C: bounded by the paths from 48 and 119, and D: bounded by the paths from 112 and 29 (see Fig. 4).

The data for area A are given in Table II, after the Preliminary Reports of U.S.C.G.S., and in Fig. 7.

In the diagrams *a*) and *b*) of Fig. 7, as well as in following figures, classification curves of Fig. 1 are given for comparison as dashed curves with Roman and Arabic numerals for Love and Rayleigh waves respec-

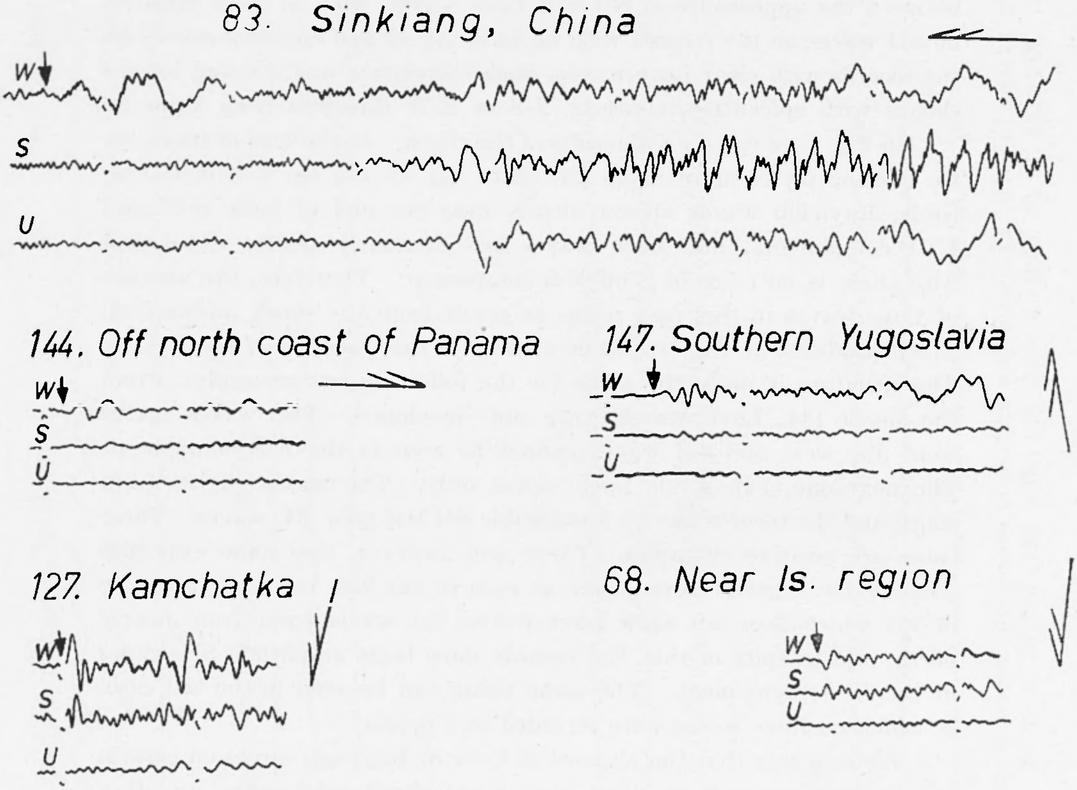

Fig. 6 – Some examples of seismograms demonstrating the relation between SH and Love waves. A short and a long arrow mean the onset of S waves and the direction of arrival respectively.

tively. For instance in diagram *a*), Rayleigh wave dispersion data from shocks 14 and 115 lie well on a classified curve (7). By such comparison, a characteristic number (7) is assigned to Rayleigh wave dispersion along the corresponding path. The dispersion data of Love waves from the shock 74 in the diagram *a*) and from others in the diagram *b*), however, coincide with another (solid) theoretical curve F (after Wilson 1933). In diagram *b*) another theoretical curve D (Dorman's case 208,

Table II – LIST OF THE SHOCKS FOR " A " REGION
h = focal depth, M = magnitude, D = distance.

No.	District	Date	Origin Time (G.M.T.)	Epicenter	h km	M	D km
14	Off coast of Kamchatka	June 02 1961	$01^h13^m25.4^s$	56.1°N 164.8°E	29	—	6840
116	Near coast of Kamchatka . . .	July 25 1960	03 41 05	55 N 163 E	—	6	6910
130	Kamchatka	Oct. 13 1960	14 52 34.7	54.8 N 161.2 E	35	6.5	6875
115	Kamchatka	July 25 1960	11 12 00	54 N 159 E	110	7	6930
127	Kamchatka	Oct. 28 1960	13 18 14.3	52.0 N 157.4 E	96	—	7080
74	Kurile Islands	Jan. 16 1961	14 22 18.2	49.9 N 156.2 E	29	6.5	7290
28	Kurile Islands	Aug. 27 1961	16 22 08.1	46.6 N 154.1 E	31	—	7550
39	Kurile Islands	Aug. 04 1961	22 52 49.2	45.3 N 151.5 E	20	—	7600
10	Kurile Islands	June 15 1961	23 24 40.4	45.4 N 151.3 E	35	—	7620
82	Kurile Islands	Apr. 23 1961	09 01 41.8	44.6 N 150.2 E	44	6.5	7625
80	Kurile Islands	Apr. 26 1961	07 38 54.1	44.6 N 149.9 E	20	6	7620
72	Kurile Islands	Feb. 12 1961	21 53 43.5	43.7 N 147.6 E	45	7	7650
43	Eastern Hokkaido, Japan . . .	Aug. 11 1961	15 51 35.4	42.9 N 145.1 E	71	7	7650
32	Tonga Islands region	Aug. 14 1961	18 50 50.3	24.2 S 175.7 W	21	6	15910
67	Tonga Islands region	May 22 1961	17 32 21.6	22.8 S 176.1 W	35	6.5	15720
50	Tonga Islands region	July 29 1961	16 27 19.0	23.9 S 176.1 W	23	5.5	15900

Dorman 1959) is presented for reference. The notation for the theoretical curves is also taken from the previous paper of the present author. In such cases, the notation of theoretical curves, instead of classified ones, is used to express the corresponding dispersion character.

Rayleigh wave dispersion along paths from several Kamchatka shocks in diagram *a*) and from one Kurile Islands shock 10 in diagram *b*) lie on another curve, denoted (8'), a little different from curve (7). This result is ascertained by Porkka's (1960) data for approximately the same path from Kamchatka (54.0°N, 161.0°E) to Helsinki, Finland. His dispersion data were smoothed into one curve and is given by a dotted curve in Fig. 7 *a*.

The characteristic numbers were determined in such a way for all observed data and are given on each travelling path in Fig. 7. The dispersion characters along most of the paths in this area are nearly the same, both for Love and Rayleigh waves, and they are all quite continental. The fact that the paths contain different percentage of water-covered segments, suggests approximately the same continental crustal structure in the water-covered areas.

Group velocities of Rayleigh waves along the southern four paths from 80, 82, 72 and 43 are a little greater that those along other paths. These four paths contain an oceanic segment, with water depths exceeding 3000 m in the south-western part of Okhotsk Sea. But the segments of this deep oceanic part are too small (approximately 250 km in length) to have any effect on the resulting dispersion along the total paths. For instance, even if we assume that this deep oceanic region in south-western Okhotsk Sea has such a crustal structure as to make the Rayleigh wave dispersion character (1) and the remaining part corresponds to character (8'), the resulting group velocity decreases only 0.02 km/sec for a period of 30 seconds. This decrease is too small to be discovered, compared to the difference of 0.1 km/sec between (8') and (7) for the same period. The writer cannot give any explanation at present for the above-mentioned group velocity difference of Rayleigh waves.

Three dispersion curves of Rayleigh waves in Fig. 8 are from shocks in Solomon Islands region. As seen in the map of the same figure, their paths run over the epicenter 14. Therefore, we can calculate the group velocities of Rayleigh waves along the purely oceanic part from any one of these three epicenters of Solomon Islands shocks to the epicenter 14 by subtracting the travel-times of Rayleigh waves along the shorter path from those along the longer ones. The results are given in the same diagram of Fig. 8 by cross marks. They lie very near a

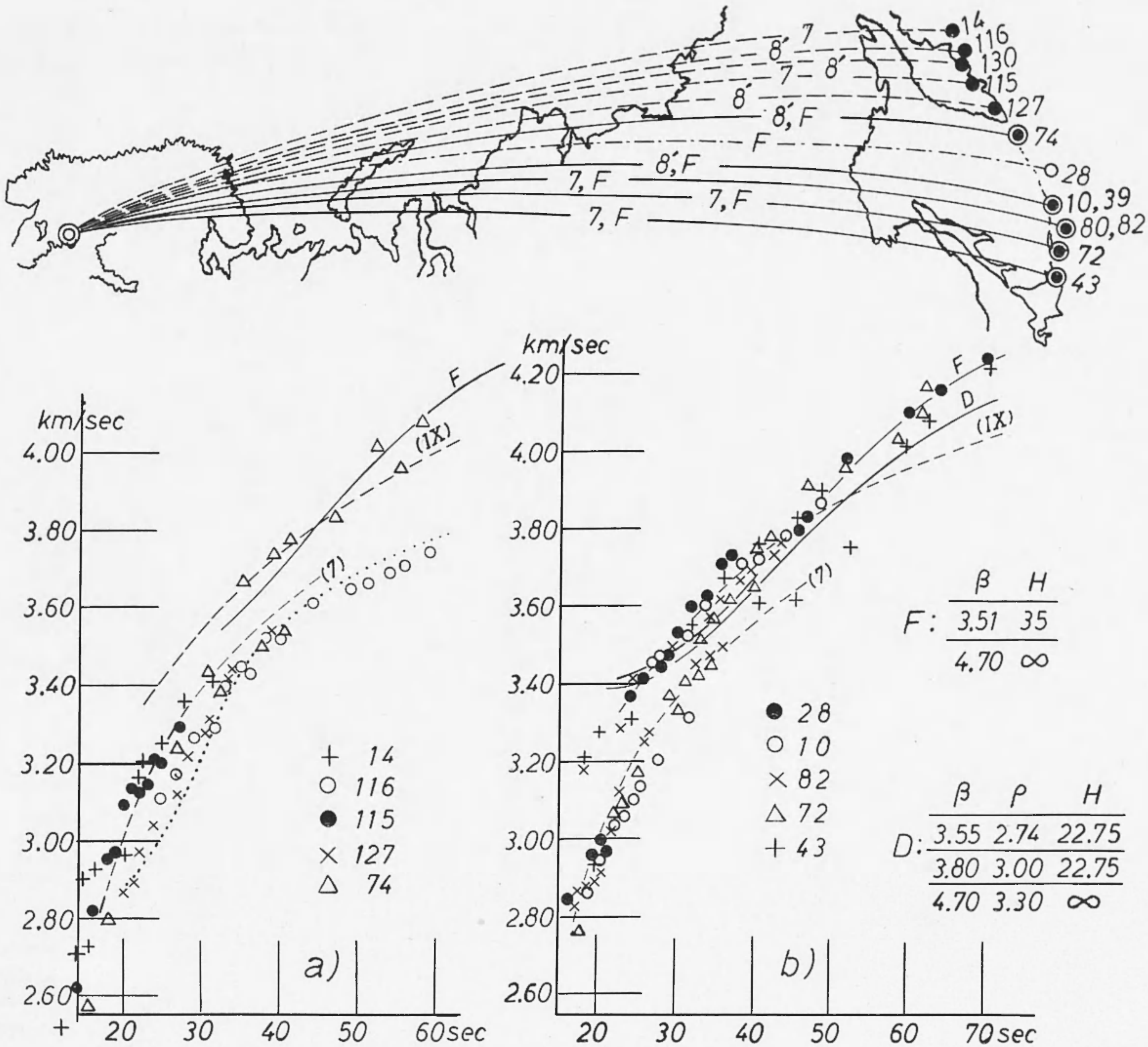

Fig. 7 – Travelling paths of surface waves in the area « A ».

a) *b*) Dispersion data of surface waves along various paths in the area « A ».

Dashed curves with two kinds of numbers in bracket are classified dispersion curves of Love (with Roman numerals and Rayleigh waves (with Arabic numerals) respectively. Two theoretical curves F and D are given for reference. (H: thickness in km, β: shear wave velocity in km/sec, ϱ: density in gr/cm^3). A dotted curve in diagram *a*) means the smoothed dispersion curve of Rayleigh waves from Kamchatka to Helsinki as observed by Porkka (1960).

reference curve (1), which tells us that the average crustal structure of the Pacific Ocean between Solomon Islands and Kamchatka along the great circle is nearly typical oceanic, which agrees well with previous results (Santo 1961 *b*).

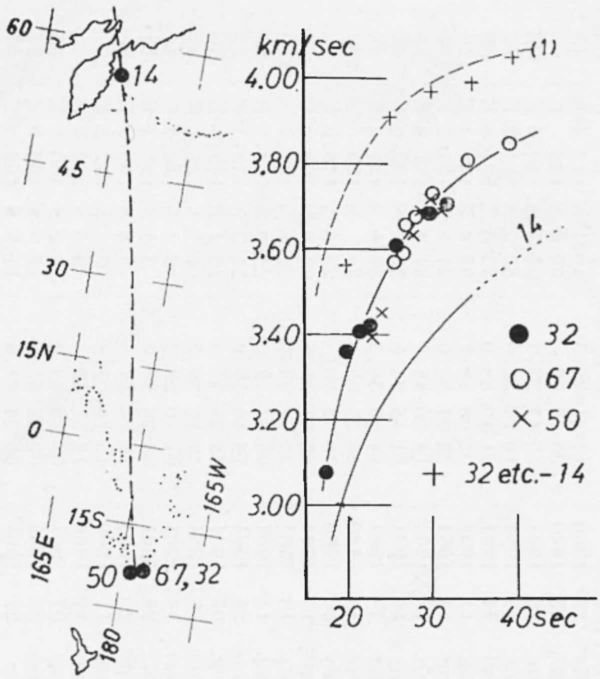

Fig. 8 – Left map: Travelling paths of Rayleigh waves from shocks 32 etc to shock 14.

Right diagram: Dispersion data of Rayleigh waves from shocks 32 etc. and calculated dispersion data along the path from 32 etc. to 14.

Dispersion characters in area B.

The epicenters and the travelling paths in the area B are given in the map of Fig. 9, and the data of shocks in this area are given in Table III. Though B contains many mixed paths, the dispersion data will be compared with Rayleigh wave dispersion obtained previously along various paths to Tsukuba over the same oceanic region. Diagrams *a*) and *b*) show respectively the similarity of dispersion from the shocks

Table III – List of the shocks for " B " region

No.	District	Date	Origin Time (G.M.T.)	Epicenter	h km	M	D km
111	Honshu, Japan	July 29 1960	17h31m39.5s	40.1°N 142.3°E	45	7	7850
145	Near coast of Honshu, Japan .	Mar. 23 1960	00 23 22	39.5 N 143 E	—	6.8	7900
73	Near east coast of Honshu . . .	Jan. 16 1961	15 41 23.3	36.4 N 140.6 E	147	—	8150
56	Near east coast of Honshu . . .	July 17 1961	16 20 22.6	35.7 N 141.2 E	75	—	8200
16	South of Honshu, Japan	Sept. 24 1961	21 40 58.0	33.3 N 141.3 E	93	—	8460
35	Eastern Kyushu, Japan	Aug. 11 1961	06 08 18.2	32.6 N 131.4 E	25	—	8110
31	Off south coast of Kyushu . . .	Aug. 14 1961	22 04 59.0	31.8 N 131.2 E	14	—	8190
71	Near coast of Kyushu	Feb. 26 1961	18 10 48.7	31.4 N 131.2 E	54	7.3	8225
69	Ryukyu Islands	May 16 1961	21 45 24.0	30.0 N 132.0 E	25	5.5	8400
54	Northern Ryukyu	July 18 1961	14 03 36.5	29.4 N 131.6 E	21	6.8	8425
142	Ryukyu Islands	May 18 1960	06 35 09	29 N 130 E	100	—	8400
120	Ryukyu Islands	July 09 1960	00 42 29	25.5 N 125.5 E	—	—	8530
18	Off coast of Formosa	Sept. 17 1961	08 41 53.6	23.9 N 122.2 E	35	—	8520
59	Off east coast of Formosa . . .	July 13 1961	21 44 38.0	22.8 N 122.7 E	100	—	8620
33	Near north coast of Formosa . .	Aug. 13 1961	06 01 02.0	25.3 N 121.5 E	25	—	8330
04	North of Mariana Islands . . .	June 25 1961	16 46 32.9	21.7 N 143.1 E	13	—	9740
40	Mariana Islands region	Aug. 03 1961	23 33 37.7	12.1 N 143.8 E	20	—	10740
48	New Guinea	Oct. 10 1961	17 24 58.9	4.7 S 138.2 E	36	—	12100
92	Near north c. of New Guinea .	Dec. 14 1961	07 10 23.2	3.1 S 140.9 E	44	—	12060
46	Bismark Sea	Oct. 26 1961	00 38 20.3	3.1 S 147.4 E	14	6	12400
17	New Britain	Sept. 20 1961	19 03 37.1	3.6 S 150.9 E	30	—	12600
105	D'Entrecasteaux Islands	June 11 1960	15 14 07	9 S 152.5 E	—	6	13230
106	D'Entrecasteaux Islands	June 11 1960	16 37 40	9.5 S 152.5 E	—	—	13290
42	Solomon Islands region	Aug. 01 1961	05 39 53.2	9.8 S 160.5 E	50	6.5	13660
00	New Hebrides Islands	June 29 1961	09 22 55.8	13.8 S 166.0 E	37	—	14300
70	Santa Cruz Islands	Jan. 22 1961	03 24 04.5	11.9 S 166.2 E	25	6.5	14080
76	Santa Cruz Islands	Jan. 02 1961	10 11 56.9	12.4 S 166.4 E	161	6.8	14140
30	New Hebrides Islands region . .	Aug. 14 1961	23 28 46.5	20.3 S 169.4 E	97	6	15080
36	New Hebrides Islands	Aug. 09 1961	16 02 36.1	19.1 S 168.7 E	68	6	14920
140	South Is., New Zealand	May 24 1960	14 46 34	44.5 S 167.5 E	—	6.8	17250

of southern Kyushu and Ryukyu Islands (diagram *a*) and from the shocks of Santa Cruz and New Hebrides Islands regions (diagram *b*).

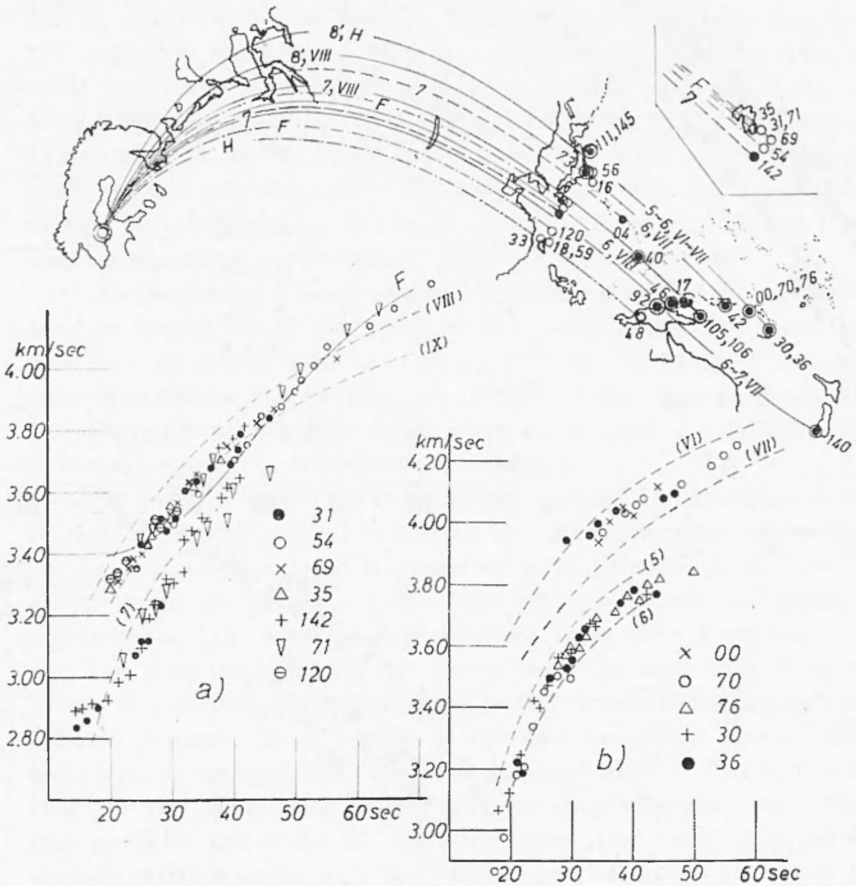

Fig. 9. – Travelling paths of surface waves in the area « B ».

a) Dispersion data from shocks of Kyushu and Ryukyu Islands.

b) Dispersion data from shocks of Santa Cruz and New Hebrides Islands regions.

In Fig. 10 *a* we see the variation of surface wave dispersion for shocks along an arc from Honshu through Ryukyu Islands to Formosa. In this diagram, a theoretical curve H after Wilson (1940) based upon a crustal structure as shown in the left upper part, is given by a solid curve together with the theoretical curve F previously used. The Love wave dispersion data are a little scattered in these diagrams, and it is rather

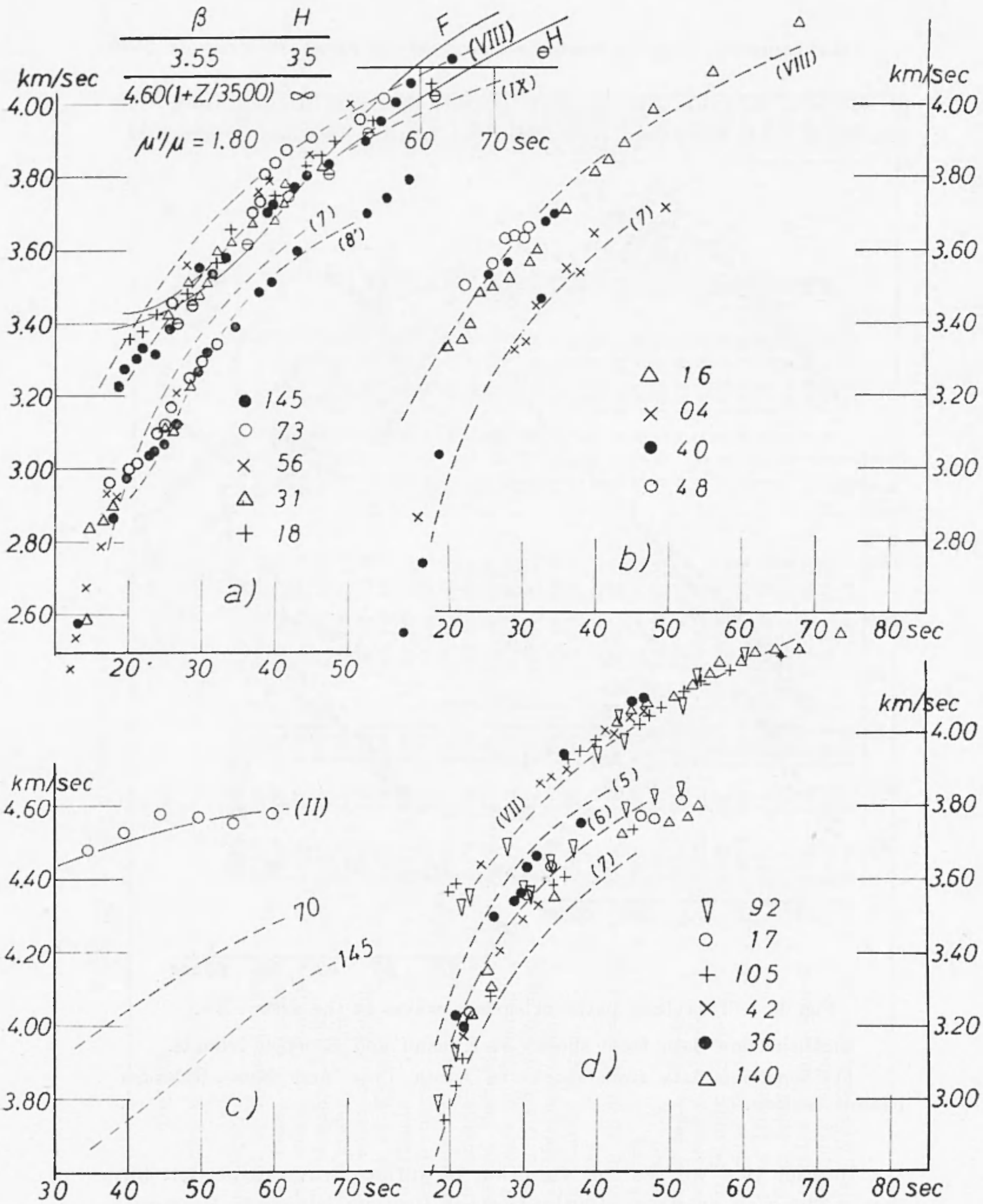

Fig. 10 – *a*) Dispersion data from shocks along the arc from Japan to Ryukyu Islands. *F* and *H* are theoretical curves. Circles with horizontal bar are Love wave dispersion data observed by Båth (1959) along a path from Formosa to Uppsala.

b) Dispersion data due to the shocks from 16 to 48, that is, from Japan to west New Guinea along Mariana and Marshall Islands.

c) Calculated group velocities of Love waves (open circles) along the paths between two epicenters 70 and 145. The original dispersion data used for calculation are shown by dashed, smoothed curves.

d) Dispersion data from shocks in the arc from New Guinea through Santa Cruz Islands to New Zealand.

difficult to give them decisive characteristic symbols. However, by taking account of their feature in longer period range, the following symbols shall be given for the moment: (II) for 145 and 18, (VIII) for 73, (VIII-IX) for 56 and (F) for 31. For the last determination, the dispersion character of 71 with approximately the same epicenter as 31 was taken into account (see the previous diagram *a*) of Fig. 9). Båth (1959) also observed the Love wave dispersion at Uppsala from the Formosa shock (24°N, 122°E) with nearly the same epicenter as our shock 18 (23.9°N, 122.2°E). His data (circles with a horizontal bar in Fig. 10 *a*) lie also near the solid curve H. Further to say, he could also not observe Rayleigh waves along that path.

Though Rayleigh wave dispersion data from 56 and 73 are limited to short period range, they seem to lie on the same curve as for 145. The data agree well with the curve (8') which was obtained for paths from Kamchatka shocks (Fig. 7). Porkka (1960) also observed that the dispersion of Rayleigh waves along paths from Japan to Helsinki is the same as from Kamchatka to Helsinki.

These results lead to the following conclusions: 1) Among the shocks in Honshu, Kyushu, Ryukyu Islands and Formosa, only the northern shocks send well developed Rayleigh waves to Uppsala. 2) The average crustal structure along the paths from all these shocks to Uppsala is approximately the same, as inferred from Love wave dispersion.

The diagram *b*) in Fig. 10 shows the dispersion data from the shocks 16 (off coast of Honshu) down to 48 (western New Guinea) along Mariana Islands. Though some of the data are rather scanty, all of them seem to agree, both for Love and Rayleigh waves. This fact means that the increasing path length of water-covered region along these four paths in this order has no effect upon the resulting dispersion character. This agrees with the author's previous investigations of the crustal structure in these sea regions. The path from 40 to Uppsala contains the largest percentage of rather oceanic structure between its epicenter to Kyushu, according to the author's previous investigation. But, its path length is only about 130 km, i. e. its ratio to the total path length is only about 1.2%, which is too small to have any effect upon the resulting dispersion along the total path. These situations will become much clearer by Fig. 11.

Diagram *d*) of Fig. 10 gives dispersion data due to several shocks from 92 to 140 on an arc through small islands. Most of them, except those from shock 36, agree closely with each other and lie around the reference curve (VII) for Love waves and (6) for Rayleigh waves re-

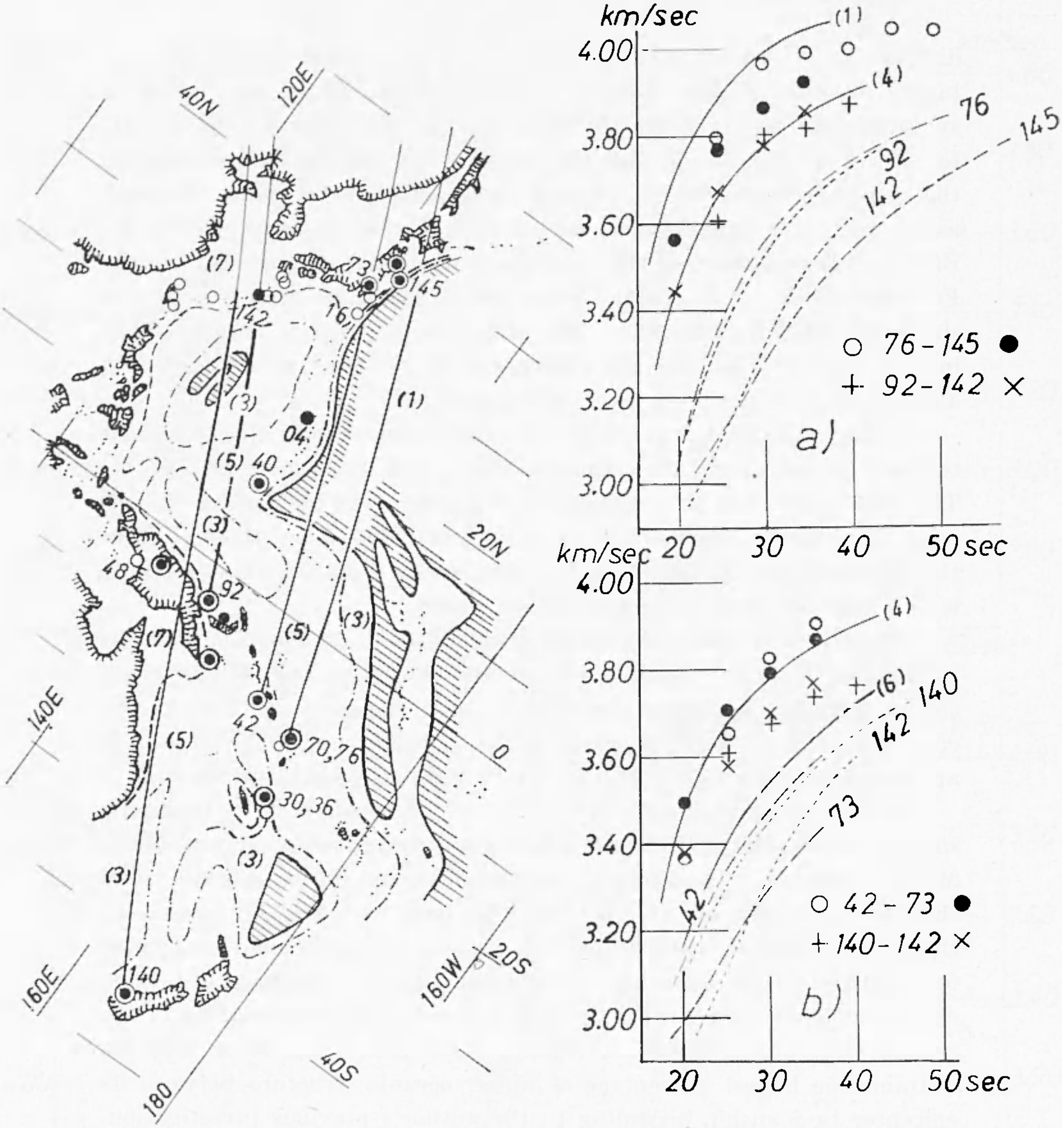

Fig. 11 — Division map of south-western Pacific Ocean which was previously made by the present author, and the travelling paths of Rayleigh waves between two epicenters (heavy lines). Shock numbers are limited to those mentioned in the text.

a) Open circles: group velocities of Rayleigh waves calculated from the travel times between two epicenters 76 and 145.

Filled circles: group velocities of Rayleigh waves calculated from the division map along the same path as above.

Crosses and multiplication signs have the same meaning respectively, concerning the path between 92 and 142.

b) Same diagram as *a*) for the group velocities of Rayleigh waves along two paths 42-73 and 140-142.

spectively. A little oceanic dispersion character along the path from shock 36 for both Love and Rayleigh waves and a little continental one from 110 for Rayleigh waves are both reasonable.

These two paths contain the most typical oceanic and continental parts according to the present author's previous investigations (this will also be cleared by Fig. 11).

In the B area, we can get some information about regional dispersion of Rayleigh waves along oceanic paths between two epicenters. The results are shown in the diagrams *a*) and *b*) in Fig. 11. In diagram *a*), open circles and crosses respectively mean group velocities of Rayleigh waves calculated from the travel times between two epicenters (76-145) and (92-142). Open circles and crosses in diagram *b*) have a similar meaning.

On the other hand, we can also estimate the group velocities of Rayleigh waves from the division map (Fig. 11), obtained previously (Santô 1961 *b*). This division map was made from the abundant dispersion data for Tsukuba (Japan), Hongkong (China), Honolulu (Hawaii) and Suva (Fiji Islands) for many paths which cross each other in this oceanic area. In this map, regions denoted by (1), (3), (5) and (7) correspond to Rayleigh wave dispersion characters (1), (3), (5) and (7) respectively. On this map, we can measure the travel lengths D_1, D_3, D_5 and D_7 along the paths between 76-145, 92-142, 42-73 and 140-142, in which D_i means the path length across the region (i). These values are given in the first line of Table IV. As the dispersion of Rayleigh waves characterized by (1), (3), (5) and (7) is known, we can calculate the travel times of Rayleigh waves in each region along the paths. These values (t_1, t_3, t_5 and t_7) are also given in Table IV. By adding them all, the total travel times ($\Sigma_i t_i$) along the paths between two epicenters are obtained. The group velocities calculated from $\Sigma_i D_i / \Sigma_i t_i$ are given in the last column and they are also plotted by filled circles and multiplication marks in diagrams *a*) and *b*) of Fig. 11. These calculated velocities agree well within error limits with those observed in the present investigation. This is a confirmation of the structure of southwestern Pacific, determined earlier.

In diagram *c*) of Fig. 10, the group velocities of Love waves obtained by calculating the travel times between two epicenters 70 and 145 are shown. The results (open circles) lie well on the reference curve (II), representing the oceanic type. This result is also very reasonable.

Table IV – Calculated results of group velocities of Rayleigh waves from division map. (Units: km and second)

From shock 76 to 145

T	D_1 3300	D_3 440	D_5 2500	D_7 0	ΣD_i 6240	V
T	t_1	t_3	t_5	t_7	Σt_i	V
20	880	124	740	0	1744	3.58
25	840	117	695	0	1652	3.78
30	825	114	675	0	1614	3.87
35	818	112	660	0	1590	3.92

From shock 92 to 142

T	D_1 290	D_3 2000	D_5 1000	D_7 370	ΣD_i 3660	V
T	t_1	t_3	t_5	t_7	Σt_i	V
20	77	565	296	125	1063	3.44
25	74	530	278	115	997	3.67
30	73	518	270	109	970	3.77
35	72	510	264	106	952	3.84

From shock 42 to 73

T	D_1 2210	D_3 660	D_5 2200	D_7 440	ΣD_i 5510	V
T	t_1	t_3	t_5	t_7	Σt_i	V
20	590	186	650	148	1574	3.50
25	562	174	611	137	1484	3.71
30	553	170	595	130	1448	3.81
35	548	168	582	126	1424	3.87

From shock 140 to 142

T	D_1 580	D_3 3680	D_5 3000	D_7 1650	ΣD_i 8850	V
T	t_1	t_3	t_5	t_7	Σt_i	V
20	155	1037	888	555	2635	3.36
25	148	975	834	512	2469	3.58
30	145	950	810	485	2390	3.70
35	144	938	794	472	2348	3.77

Table V – List of the shocks for " C " region

No.	District	Date			Origin Time (G.M.T.)	Epicenter		h km	M	D km
83	Sinkiang, China	Apr.	13	1961	$16^h 34^m 39.1^s$	40.1°N	77.8°E	19	—	4640
87	Sinkiang, China	Apr.	04	1961	09 46 36.6	40.1 N	77.8 E	16	—	4640
88	Sinkiang, China	Apr.	01	1961	15 18 22.8	39.6 N	77.7 E	21	6	1440
98	Tibet	Dec.	04	1961	12 38 11.9	33.2 N	95.8 E	45	—	6220
03	Yunan Province, China	June	27	1961	07 03 42.2	27.8 N	99.4 E	33	—	6950
78	Flores Islands	Mar.	16	1961	13 45 35.6	8.2 S	122.0 E	74	6.5	11590
77	South of New Zealand	Mar.	18	1961	14 54 59.3	49.9 S	163.3 E	36	6.5	17550
15	Northern Celebes	Sept.	29	1961	19 06 13.4	0.5 N	122.4 E	110	—	10750
41	Ceram Islands	Aug.	03	1961	06 51 44.1	3.5 S	130.8 E	22	—	11600
19	Aroe Islands	Sept.	11	1961	19 57 58.2	4.1 S	134.3 E	19	—	11810
48	New Guinea	Oct.	10	1961	17 24 58.9	4.7 S	138.2 E	36	—	12100
60	Nicobar Islands region	July	11	1961	09 31 57.2	8.3 N	93.3 E	163	—	8425
131	Nicobar Islands region	Oct.	08	1960	20 40 06.6	7.9 N	92.9 E	84	—	8430
05	Sumatra	June	24	1961	09 36 08.8	4.1 N	97.5 E	188	—	9025
45	Off west coast of Sumatra . . .	Oct.	26	1961	15 27 02.2	0.4 S	98.6 E	18	6	9550
119	Off west coast of Sumatra . . .	July	10	1960	00 05 18	0	98 E	—	—	9475

DISPERSION CHARACTERS IN AREA C.

Data for shocks and dispersion in area C are given in Table V and Fig. 12.

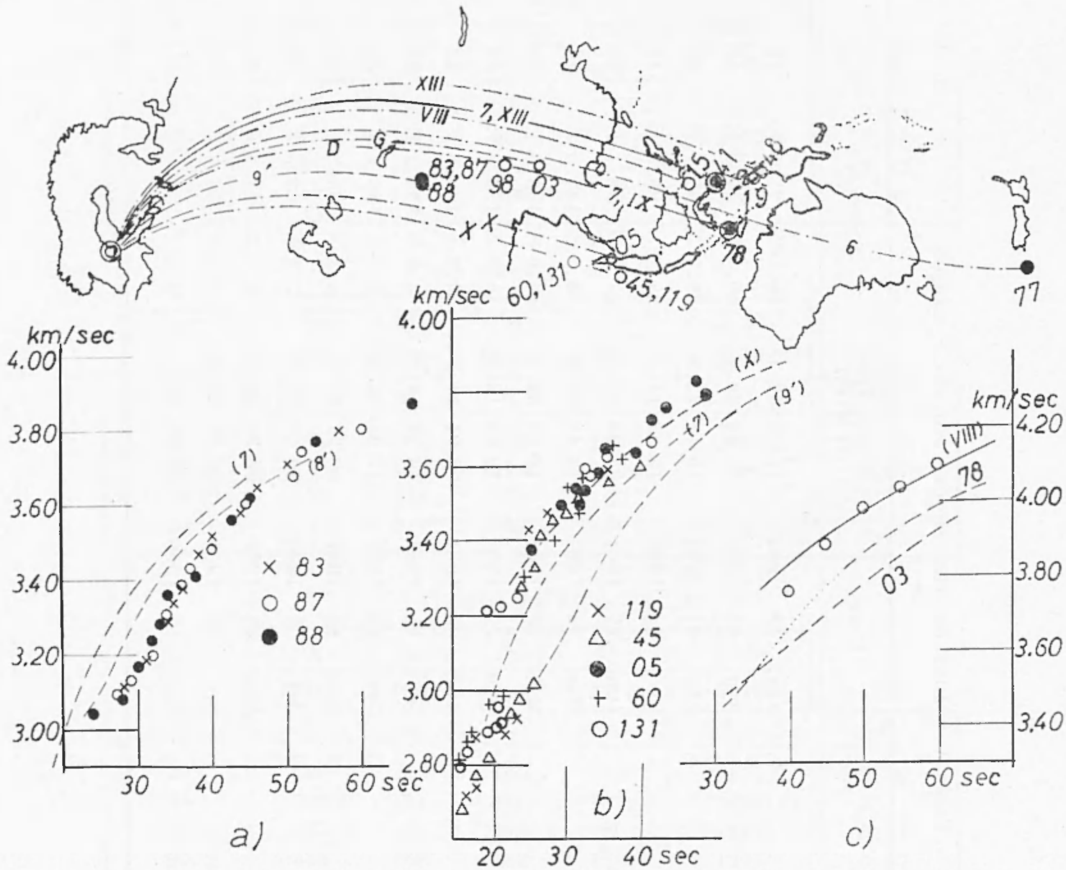

Fig. 12 – Travelling paths of surface waves in the area « C ».
a) An example of Rayleigh wave dispersion data along the same path, corresponding to a characteristic number (9').
b) Dispersion data of Love and Rayleigh waves from shocks around Sumatra.
c) Calculated group velocities of Love waves between the two epicenters 78 and 03.

A remarkable fact is that long period Rayleigh waves are absent along most of the paths in this area (see Fig. 12). The same pheno-

Table VII – List of the shocks for " D " region

No.	District	Date	Origin Time (G.M.T.)	Epicenter	h km	M	D km
112	Eastern Afghanistan-Pakistan . .	July 29 1960	$14^h33^m46.1^s$	31.7 N 67.0 E	64	—	4770
64	Southern Iran	June 11 1961	05 10 26.0	28.9 N 54.6 E	38	6.5	4440
103	Southern Iran	Aug. 01 1960	02 20 52.4	27.9 N 54.2 E	110	—	4525
141	Mascarene Islands region	May 19 1960	10 11 51	17 S 66 E	—	—	9530
65	Ethiopia	June 01 1961	23 29 21.1	10.6 N 39.3 E	51	6.5	5770
66	Dodecanese Islands	May 23 1961	02 45 16.0	36.4 N 28.3 E	49	6.3	2700
91	Prince Edward Is. region . . .	Dec. 26 1961	06 17 30.6	44.2 S 38.1 E	22	—	11700
139	Albania-Greece border	May 26 1960	05 10 05	40 N 20 E	—	6.5	2220
147	Southern Yugoslavia	Mar. 12 1960	11 54 00	42 N 21 E	—	—	2000
118	Bouvet Island region	July 13 1960	07 55 54	53.5 S 1.5 E	—	6	12600
99	Northern Tunisia	Dec. 02 1961	12 40 17.8	36.5 N 8.6 E	62	—	2680
135	Sandwich Islands	Nov. 09 1960	03 17 58.5	60.7 S 24.8 W	37	6.5	13870
21	Sandwich Islands region	Sept. 08 1961	11 26 32.8	56.1 S 27.3 W	125	8	13450
29	South of Ascension Island . . .	Aug. 16 1961	16 15 57.5	13.8 S 14.7 W	25	—	8630

menon is also observed at Tsukuba, Japan (Santô 1961 *c*) along many continental paths covering the same area. These situations will be cleared in Fig. 16.

Good Rayleigh wave dispersion data are obtained in this area only from shocks 83, 87 and 88 (diagram *a*), which correspond to another type, denoted (9') different from the classified curve (8'). Rayleigh wave dispersion data, although limited to short period range, from several shocks around Sumatra Island seem to show the same nature (diagram *b*) of Fig. 12). The dispersion character of Love waves along these paths, on the other hand, is the most continental (X) in the present investigation.

Table VII – Calculation of Rayleigh wave dispersion for the African continent

Vo: assumed group velocities of Rayleigh waves along the oceanic part.
Vc: calculated group velocities of Rayleigh waves along the continental part.

T	Assumed Vo, km/sec		Calculated Vc, km/sec		Reference V, km/sec	
sec	(1)	(3)			(6)	(7)
20	3.75	3.55	2.83	3.02	3.10	2.97
25	3.95	3.76	3.28	3.31	3.41	3.22
30	4.00	3.87	3.48	3.53	3.55	3.40
35	4.03	3.92	3.61	3.66	3.65	3.50

Fig. 13 *a*) shows dispersion data of Love waves along paths with approximately the same direction to Uppsala but with different lengths. In the same diagram, two kinds of Rayleigh wave dispersion data from the shocks 78 and 77 are also shown. The dispersion character of Love waves is the most continental one for the path from the shock 03 and seems to correspond to a solid curve G calculated by Ewing, Jardetzky and Press (1957) assuming the crustal model given in the same figure. As seen in Fig. 16, the path from the shock 03 contains the largest percentage of high mountain region in Tibet plateau. Considering this, our results are quite reasonable. By using the Love wave dispersion data from 78 and 03, we can calculate the group velocities of Love waves between these two epicenters. The results are shown in diagram *c*) of Fig. 12. They lie on a continental curve (VIII). This means that the water-covered region between 03 and 78 has a continental crustal structure, which agrees well with the Rayleigh wave dispersion. Dispersion data from shocks in the region from eastern Borneo to the west part of New Guinea are given in Fig. 13 *b*). They are similar and quite continental, especially for Love waves.

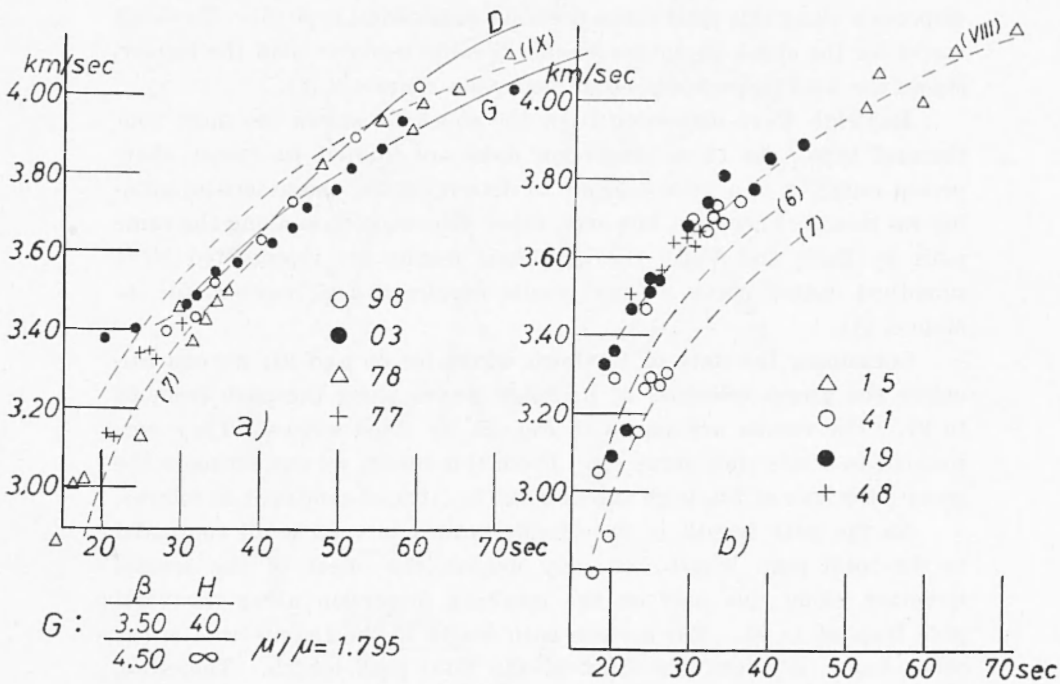

Fig. 13 – *a*) Dispersion data of Love waves along paths in the same direction towards Uppsala. A new theoretical curve *G* is given.
b) Dispersion data from shocks near Borneo and New Guinea.

Dispersion characters in area D.

The data for shocks in area D are given in Table VI.

The travelling paths in this area are shown in the map of Fig. 14 and the diagram *a*) in Fig. 15 shows the dispersion data from five eastern shocks in this area. The dispersion data of Love waves along the path from a shock 141 which partly passed through the Indian Ocean show a rather less continental character (VII) than the others. These have paths, which mostly cover the continent, and lie well on a continental theoretical curve H. In this diagram, we notice that Rayleigh wave dispersion data along the purely continental paths from 64 and 103 lie on a classified curve (8'), discovered in the present paper.

The dispersion data along the paths in the central part of the present area are shown in diagram *b*). The Love wave dispersion for the shocks 139, 117 and 91 has quite the same character. The path from the shock 118 contains a large part of South Atlantic Ocean, and Rayleigh wave dispersion along this path shows the least continental type (5). Rayleigh waves for the shock 91 with a smaller oceanic segment than the former, shows the little more continental dispersion character (6).

Rayleigh wave dispersion from the shock 66 shows the most continental type. As these dispersion data are limited to rather short period range, it is a little difficult to determine the characteristic number for them. There are, however, other dispersion data along the same path by Bath and Vogel (1957). Their results are represented by a smoothed dotted curve. Their results require a new number, for instance, (8).

Combining the data of Rayleigh waves for 66 and 91, we can calculate the group velocities of Rayleigh waves along the path from 66 to 91. The results are shown in Fig. 14 by filled circles. They correspond to a reference curve (5). From this result, we can estimate the group velocities of Rayleigh waves over the African continent as follows.

As the path length in the Mediterranean is very small compared to the total path length, we may neglect the effect of the crustal structure along this part on the resulting dispersion along the total path from 66 to 91. The oceanic path length in the Indian Sea, on the other hand, is about one-third of the total path length. Therefore, assuming the dispersion character of Rayleigh waves along the oceanic path, we can find the dispersion along the continental path. The results are given in Table VII.

In Table VII, two series of Vc were calculated from two series of Vo, based upon the dispersion characters (1) and (3). In the last two columns, group velocities of Rayleigh waves corresponding to the dispersion characters (6) and (7) are given for comparison with Vc. The results tell us that the dispersion character of Rayleigh waves along the African continental path lies between (6) and (7).

The dispersion characters of surface waves along paths in western part of area D are given in diagram *c*) of Fig. 15. As dispersion data from 99 are limited to a short period range both for Love and Rayleigh waves, the determinations of characteristic numbers along this path were given up. The path from 21 contains about half of Atlantic Ocean, and therefore, the dispersion data lie on a rather oceanic curve (VI).

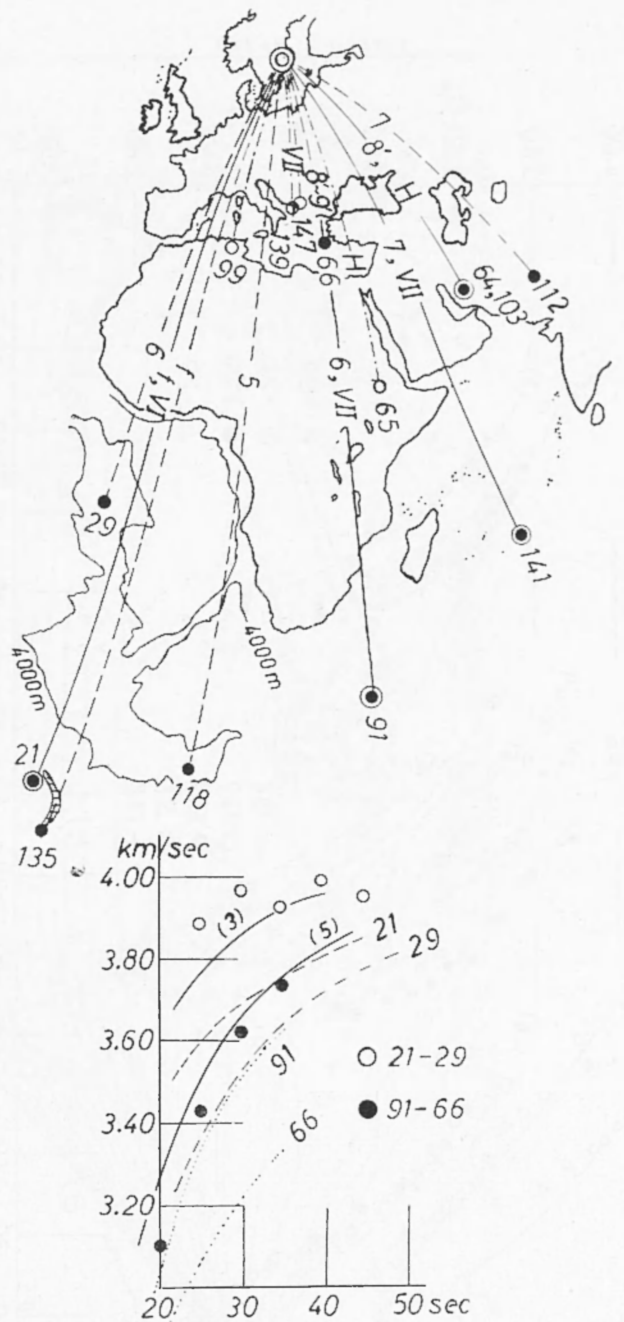

Fig. 14 – Travelling paths of surface waves in the area « D ». Calculated group velocities of Rayleigh waves between two epicenters (21-29) and (91-66).

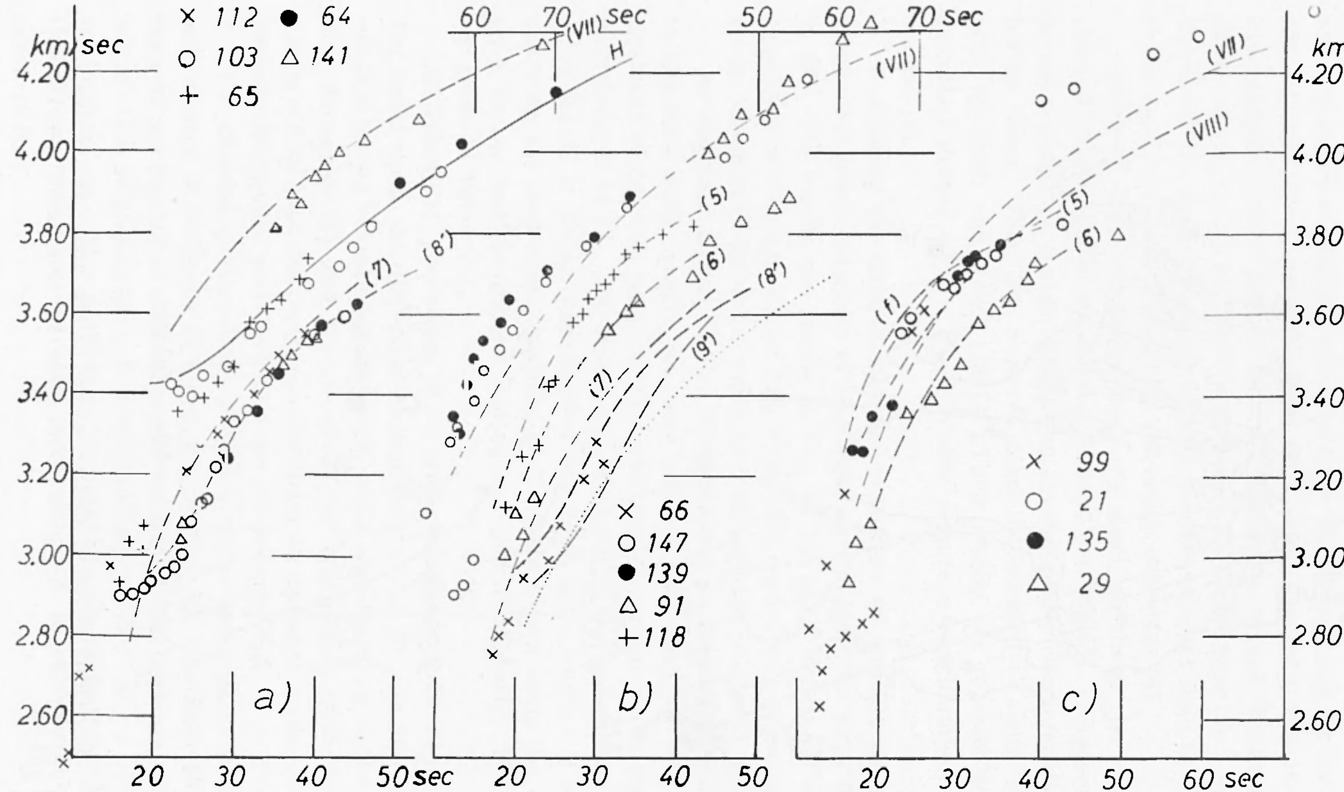

Fig. 15 — *a*) Dispersion data for the eastern part of the area « D ».
b) Dispersion data for the central part of the area « D ». The dotted curve represents the Rayleigh wave dispersion data by Båth and Vogel (1957) along the same path as from 66 to Uppsala.
c) Dispersion data for the western part of the area « D ».

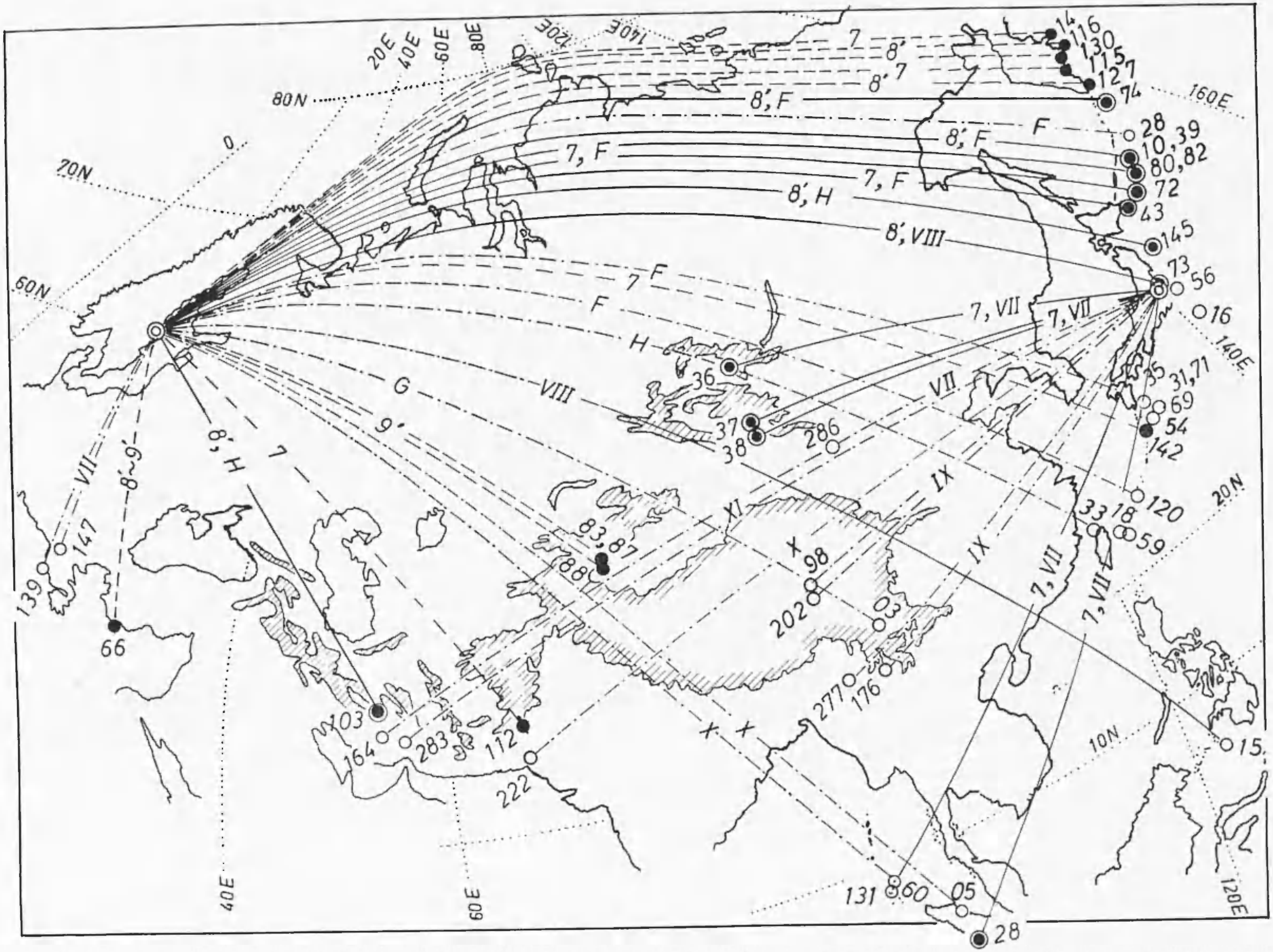

Fig. 16 – Travelling paths of surface waves along Eurasian continent, and the characteristic symbols of surface wave dispersion along each path. Tsukuba's data are added for comparison. Only representative paths to Uppsala are given in this map. The hatched regions mean mountains with heights of more than 9000 ft (ca. 2740 m).

Rayleigh wave dispersion data in this diagram show an interesting fact, namely, two of them along the paths from 21 and 135, which cover a great amount of Mid-Atlantic Ridge, are similar to character (*f*). This dispersion character is typical for paths in and around the eastern Pacific Rise (Santô & Båth 1962). This fact will be discussed in Part II together with the dispersion data along other parts of the Mid-Atlantic Ridge. Open circles in the diagram of Fig. 14 shows the calculated group velocities of Rayleigh waves along the path which covers the Ridge between 29 and 21. Just as we expected, these data exhibit rather high velocities in their shorter periods and low in greater periods, which is characteristic of this type.

Conclusions.

Dispersion characters of Love and Rayleigh waves along purely continental paths over Eurasia are summarized in Fig. 16 together with those around Tsukuba (Santô 1961 *c*). In this figure, high mountain regions with heights of more than 9000 ft (2740 m) are shown by hatched lines. The meaning of different kinds of marks used for every path and epicenter, and the notation on each path are all the same as used hitherto in all maps. The shock numbers for Tsukuba are the same as were used previously. In order to investigate regional dispersion characters in such a vast continental area by the same method as in previous works (Santô 1961 *b*), we need much more information about group velocity dispersion along other paths crossing the paths shown in this figure. Therefore, this investigation must be postponed to the future. From this figure, however, the following general features can be recognized:

1) High mountain regions seem to prevent the propagation of Rayleigh waves.

2) Love waves which travel through high mountain regions show the most continental types.

3) If we restrict our attention to the northern paths from 14 to 73, that is, due to the shocks at Kamchatka through Kurile Islands to the central part of Japan, it is noticed that only the northernmost paths from Kamchatka shocks do not transmit Love waves to Uppsala.

4) Both Love and Rayleigh wave dispersion characters along many paths in northern Eurasia are almost the same in spite of various

percentages of water-covered regions. Moreover, they are approximately the same as along the paths which cross East China Sea. From these results, these water-covered regions (Barents Sea, Nordenskjöld Sea, part of Okhotsk Sea and East China Sea) are suggested to have a similar, continental crustal structure.

5) Along some continental paths, dispersion characters of new types, (8') and (9'), were observed for Rayleigh waves.

Furthermore, the following two points must be added at the conclusions of this paper, that is,

6) Some cases were found for which the appearance of Love and Rayleigh waves seems to depend upon the shock mechanism.

7) By subtraction of travel times, regional dispersion characters of surface waves could be obtained. For instance, Rayleigh wave dispersion was deduced for the western Pacific Ocean, which agrees well with previous results.

8) From Rayleigh wave dispersion characters along paths partly traversing the southern Mid-Atlantic Ridge, a special crustal structure is suggested, which might be the same as beneath the eastern Pacific Rise.

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SUMMARY

Group velocity dispersion of surface waves has been investigated for nearly one hundred and fifty paths to Uppsala, Sweden. The dispersion data are compared with the classified dispersion curves obtained previously by the same author from records at Tsukuba, Japan, Pasadena, U.S.A., and Huancayo, Peru. On the basis of these data, some discussion is made about the crustal structures.

In this paper, the descriptions are restricted to the dispersion of surface waves along continental paths.

It is found that either Love or Rayleigh waves are absent along some paths or for certain shocks.

The effect of the special crustal structure beneath the high mountain region in south Asia appears well on the dispersion characters.

Combining the dispersion data of two earthquakes with partly coinciding paths, regional group velocities are calculated by subtraction of travel times. Group velocity data of Rayleigh waves thus obtained along oceanic paths in western Pacific Ocean agree with previous results in this area.

A special dispersion character is found for Rayleigh waves along paths which partly traverse south Mid-Atlantic Ridge.

Some water-covered regions are suggested to have continental structure.

RIASSUNTO

Ad Uppsala è stata studiata, per circa 150 tragitti, la dispersione delle onde superficiali. I dati ottenuti sono stati paragonati alle curve della dispersione ricavate dallo stesso Autore, da sismogrammi delle stazioni di Tsukaba (Giappone). Pasadena (USA), e Huancayo (Perù). Basandosi su questi dati, l'A. discute la struttura della crosta.

In questa nota le descrizioni sono limitate alla dispersione di onde superficiali lungo tragitti continentali.

Si è inoltre trovato che lungo alcuni tragitti o per particolari scosse, mancano sia le onde di Love che quelle di Rayleigh.

Nel carattere della dispersione, si fa sentire chiaro l'effetto della speciale struttura della crosta al di sotto delle alte montagne nell'Asia meridionale.

Combinando i dati della dispersione con i tragitti in parte coincidenti di due terremoti, sono state calcolate le velocità di gruppo sottraendo i tempi di tragitto. I risultati così ottenuti per le velocità di gruppo delle onde di

Rayleigh lungo tragitti oceanici attraverso l'Oceano Pacifico occidentale, vanno d'accordo con quelli avuti precedentemente nella stessa zona.

Un particolare tipo di dispersione è stato trovato per le onde di Rayleigh lungo tragitti che in parte hanno attraversato la dorsale Media-Atlantica meridionale.

Si suggerisce l'ipotesi che alcune regioni coperte dall'acqua abbiano una struttura continentale.

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