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3. *Regional Characteristics of Love Wave Group Velocity Dispersion in Eurasia*

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Abstract

Group velocity dispersion of Love waves has been investigated for Eurasia, which has been divided into thirteen regions according to their dispersion characteristics. Extremely low group velocities have been observed in the Himalayan and the Tibetan Plateau regions. This division is in good agreement with Santô and Satô's Rayleigh wave group velocity division for the same area.

1. Introduction

In 1965, Santô[1] studied Rayleigh wave dispersion along various paths in Eurasia and he divided the continent and its surroundings into 12 regions having similar dispersion characteristics of Rayleigh wave velocity. In another similar study, Santô and Satô[2] extended this division for Africa, the Atlantic Ocean and the Indian Ocean. (From here onwards referred to as *Rayleigh wave division*). A sufficiently large number of earthquakes and recording stations were used by these authors to cover the regions concerned. Crampin[3] similarly divided Eurasia using 2nd Love and 2nd Rayleigh modes. However, the data being very scanty, Crampin's division is not very precise.

In the present work, dispersion of the fundamental mode of Love

1) T. SANTÔ, "Lateral Variation of Rayleigh Wave Dispersion Character Part II: Eurasia," *Pure and Applied Geophysics*, **62** (1965), 67.

2) T. SANTÔ and Y. SATÔ, "World Wide Survey of the Regional Characteristics of Group Velocity Dispersion of Rayleigh Waves," *Bull. Earthq. Res. Inst.*, **44** (1966), 939.

3) S. CRAMPIN, "Higher Modes of Seismic Surface Waves: Propagation in Eurasia," *Bull, Seism. Soc. Amer.*, **56** (1966), 1227.

waves is studied along various paths in Eurasia. The observed group velocity curves are found to be parallel for most of the paths. This makes it possible to utilize the crossing path technique of Santô[4] to divide Eurasia into different regions having similar Love wave dispersion characteristics and to examine whether it agrees with *the Rayleigh wave division* of Eurasia.

2. Observational Data

Compared to Rayleigh waves, which can be picked up from the long-period vertical component seismograms, observation of Love waves is difficult. This difficulty is mainly due to two reasons. Firstly, for the oceanic paths, Love waves are not very dispersive and appear somewhat like a pulse in the seismogram. Secondly, when the direction of the approach of waves at the observation station is around 45°, they are strongly affected by Rayleigh waves and we cannot measure the group velocities of Love waves for the time range in which Rayleigh waves

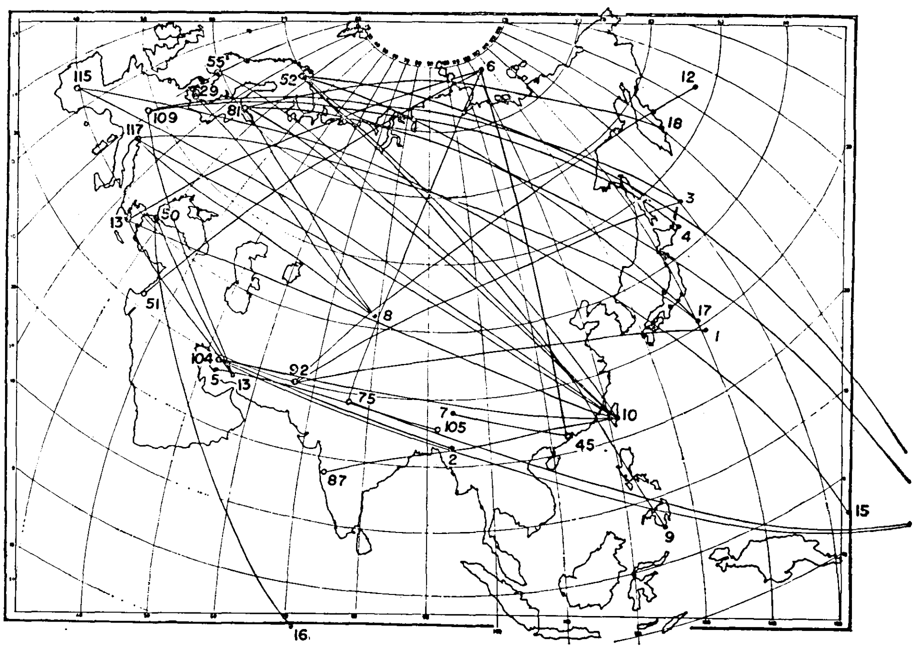

Fig. 1. Seismic stations (open circles), earthquakes (closed circles) and the wave paths.

4) *loc. cit.*, 1).

Table 1

DATA OF EARTHQUAKES USED

	DATE			ORIGIN TIME (G.M.T.)			EPICENTRE			
				H	M	S				
1	JAN	15	64	21	36	05.0	39.1	N	140.8	E
2	JAN	22	64	15	58	46.5	22.4	N	93.6	E
3	MAY	02	64	16	11	00.2	45.5	N	150.3	E
4	MAY	31	64	00	40	36.4	43.5	N	146.8	E
5	AUG	19	64	15	20	13.9	28.2	N	52.7	E
6	AUG	25	64	13	47	20.6	78.2	N	126.6	E
7	OCT	21	64	23	09	18.8	28.1	N	93.8	E
8	MAY	04	65	08	34	39.8	41.7	N	79.4	E
9	MAY	16	65	11	35	46.0	5.3	N	125.7	E
10	MAY	17	65	17	19	25.9	22.5	N	121.3	E
11	MAY	20	65	00	40	10.9	14.7	S	167.4	E
12	MAY	23	65	23	46	12.0	52.2	N	175.0	E
13	JUNE	21	65	00	21	14.5	28.1	N	56.0	E
14	SEPT	04	65	14	32	47.9	58.2	N	152.6	W
15	SEPT	11	65	06	53	01.5	5.3	S	153.0	E
16	SEPT	12	65	22	02	34.3	6.4	S	70.8	E
17	NOV	12	65	17	52	24.1	30.5	N	140.2	E
18	NOV	18	65	21	58	12.4	53.9	N	160.7	E

Table 2

LIST OF STATIONS

	STATION		COUNTRY	LATITUDE	LONGITUDE
13	ATHENS	(ATU)	GREECE	37 58 22 N	23 43 00 E
29	COPENHAGEN	(COP)	DENMARK	55 41 00 N	12 26 00 E
45	HONG-KONG	(HKG)	HONG KONG	22 18 13 N	114 10 19 E
50	ISTANBUL	(IST)	TURKEY	41 02 36 N	28 59 06 E
51	JERUSALEM	(JER)	ISRAEL	31 46 19 N	35 11 50 E
52	KEVO	(KEV)	FINLAND	69 45 21 N	27 00 45 E
55	KONGSBERG	(KON)	NORWAY	59 38 57 N	09 37 55 E
75	NEW DELHI	(NDI)	INDIA	28 41 00 N	77 13 00 E
81	NURMIJARVI	(NUR)	FINLAND	60 30 32 N	24 39 05 E
87	POONA	(POO)	INDIA	18 32 00 N	73 51 00 E
92	QUETTA	(QUE)	PAKISTAN	30 11 18 N	66 57 00 E
104	SHIRAZ	(SHI)	IRAN	29 30 40 N	52 31 34 E
105	SHILLONG	(SHL)	INDIA	25 34 00 N	91 53 00 E
109	STUTTGART	(STU)	GERMANY	48 46 15 N	09 16 36 E
115	TOLEDO	(TOL)	SPAIN	39 52 53 N	04 02 55 W
117	TRIEST	(TRI)	ITALY	45 42 32 N	13 45 51 E

also arrive. Because of the horizontally polarized transverse locus of Love waves, horizontal component seismograms for the stations where waves arrive along one of the coordinate axes are most suitable. With this consideration in mind, seismograms of the Eurasian W.W.S.S.N. stations for 1964 and 1965 were examined. Finally 18 earthquakes recorded by 16 W.W.S.S.N. stations in Eurasia (Fig. 1.) were found suitable. Tables 1 and 2 give the data of the earthquakes and stations used in the present study. Epicentral distances and azimuthal angles are measured using standard trigonometrical relations with the help of a computer. The shortest and the longest distances are 2142 km and 14096 km respectively. In most cases, the azimuthal angle is within $\pm 10^{\circ}$ of either of the coordinate axes.

However, in all cases, the horizontal component seismograms have been compared with the vertical components to confirm the identity of the Love waves. In doubtful cases, particle motion diagrams have been plotted to ensure the identity of waves. R. Sato's[5] technique has been employed for preparing the group velocity dispersion curves.

3. Standard Love Wave Dispersion Curves & Division of Eurasia

Santô[6], in his study of Love waves along various paths to Japan, summarized the Love wave dispersion into eleven categories. He has also shown the various paths around Japan which are responsible for these eleven different dispersion curves. Earthquakes with their epicentres in Northeastern India, Western China, Sinkiang Province and Northern Burma and recorded in Japan belong to dispersion curve 6. Fig. 2 shows these paths plotted on the group velocity division map.

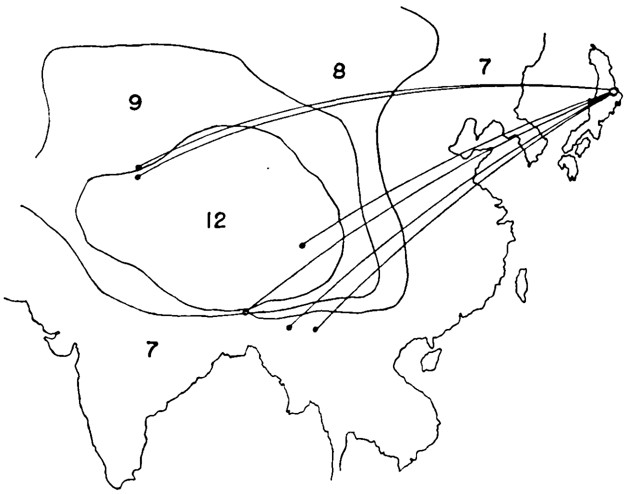

Fig. 2. Earthquakes around Himalayan and Tibetan Plateau region and their wave paths to Japan.

5) R. SATO, "On the Determination of Crustal Structure by the Dispersion Curves of Surface Waves," *Zisin*, **11** (1958), 121.

6) T. SANTÔ, "Dispersion of Love Waves along Various Paths to Japan (Part I)," *Bull. Earth. Res. Inst.*, **39** (1961), 631.

Calculations reveal that the Rayleigh waves travelling along these paths correspond to the Number 8 standard Rayleigh wave dispersion curve of Santô and Satô. Hence Santô's[7] previous Love wave dispersion curve Number 9 has been adopted as Number 8 in the present study. Similar correspondence holds as follows:

Table 3

	Region				
Santô's Love wave study	7	8	9	10	11
Present Love wave study	6	7	8	9	10

Validity of this adoption is further supported by some simple cases. For example, the earthquake of 17th May, 1965, recorded at Poona, traversed only region 7 of the Rayleigh wave division. The Love wave dispersion curve for this path is in good agreement with the adopted Number 7 Love wave disperion curve.

For obtaining Love wave dispersion curves Numbers 0, 1, 3 and 5, such paths are chosen which traverse one of these unknown regions and the other known regions i.e. 6, 7, 8, 9 or 10, on *the Rayleigh wave division*. Then, after subtracting the time corresponding to these known regions from the total travel time, group velocities for the unknown regions are calculated. However, curve Numbers 12 and 13 were taken to explain exceptionally low group velocities across the Himalayan and Tibetan Plateau (details given under discussion). By successive approximation the dispersion curves and the division pattern are adjusted, so that using the crossing path technique, the calculated travel time $\sum \Delta_i/u_i$ (where Δ_i is the length of a segment in region i and u_i is the corresponding group velocity), is within $\pm 1\%$ of the observed travel time for a particular period.

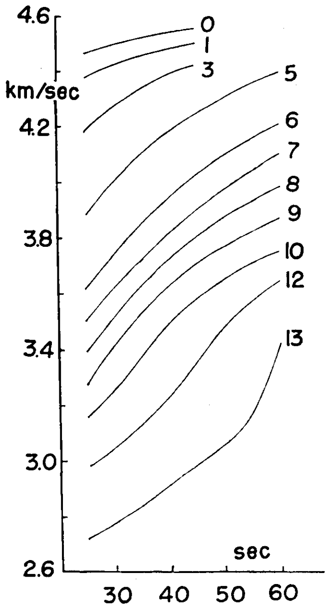

Fig. 3. Standard Love wave dispersion curves.

In all cases, these calculations are made

7) *loc. cit.*, 6).

Table 4

GROUP VELOCITIES (KM/SEC) OF LOVE WAVES FOR VARIOUS STANDARD DISPERSION CURVES AT DIFFERENT PERIODS IN SECONDS

REGION	25	30	35	40	45
0	4.46	4.49	4.52	4.54	4.55
1	4.37	4.42	4.46	4.48	4.50
3	4.18	4.27	4.33	4.39	4.42
5	3.88	4.00	4.10	4.18	4.24
6	3.62	3.74	3.86	3.94	4.02
7	3.51	3.62	3.72	3.82	3.90
8	3.39	3.52	3.63	3.73	3.81
9	3.27	3.41	3.53	3.63	3.71
10	3.16	3.26	3.38	3.50	3.58
12	2.98	3.05	3.14	3.23	3.36
13	2.72	2.77	2.85	2.91	2.98

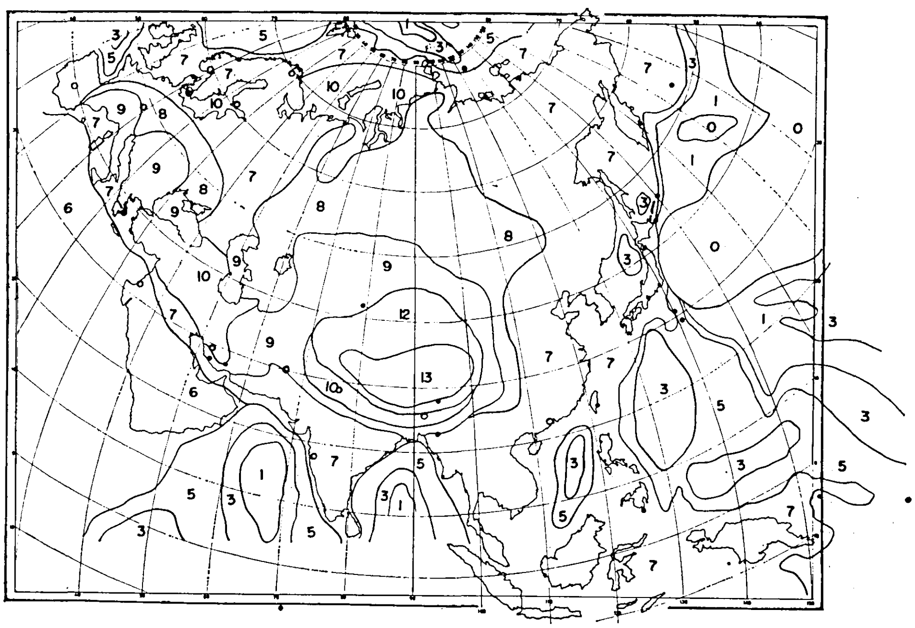

Fig. 4. Love wave division pattern of Eurasia
(Stations: open circles. Epicentres: closed circles.)

for 30, 35, 40 and 45 second periods. However, in some cases, these are extended up to 60 seconds. Fig. 3 and Table 4 show the standard Love wave group velocity dispersion curves and Fig. 4 shows the division pattern of Eurasia. Table 5 gives the frequency distribution of $(T_0-T_c)/T_0$ for all cases.

Table 5

FREQUENCY DISTRIBUTION OF (TO-TC)/TO

[(TO-TC)/TO]·100	NUMBER
+ 1.00	2
+ 0.75	2
+ 0.50	3
+ 0.25	6
0.00	10
- 0.25	4
- 0.50	4
- 0.75	2
- 1.00	2
SUM =	35

4. Discussion

The basic element in this study is the areal division of Eurasia based upon the Rayleigh wave dispersion study by Santô and Satô[8]. When necessary, this division has been altered so as to conform with the observed Love wave dispersion. Principally, however, the two divisions are similar, i.e. the regions with low (or high) Rayleigh wave velocities correspond to regions with low (or high) Love wave velocities.

4.1 Himalaya-Tibet Plateau region

Exceptionally low group velocities are observed in the Himalayan and the Tibetan Plateau region. For the earthquake of 17th May, 1965, the calculated travel time of Love waves at Kevo and Nurmijarvi was equal to the observed time and at Kongsberg 0.8% greater than the observed time. These paths traverse region Nos. 7, 8, 9 and 10. But the observed time of Love waves recorded at Shiraz, was 9.0% larger than the calculation, which traverse the 12th region of the Rayleigh wave division (assuming a 3.2km/sec group velocity for 40 sec. period). The identification of Love waves was indisputable. Fig. 5 shows the NS and vertical component of the seismograms and Fig. 6 the particle motion. Similarly, very low group velocities were obtained for other paths including the Himalayan and the Tibetan Plateau region. Hence, taking topography as the guiding factor, a new region No. 13 was formed for this very high mountainous region. Standard dispersion curves Numbers 12 and 13 were obtained by calculating the travel time

8) *loc. cit.*, 2).

Table 6

PATH	PERIOD SEC	TOTAL Δ	Δ0	Δ1	Δ3	Δ5	Δ6	Δ7	Δ8	Δ9	Δ10	Δ12	Δ13
							PATH LENGTH (KM) SEGMENT						
8-29	35 40 45	4936						1934	827	1685	490		
10-52	35 40 45	7825						2564	3318		1943		
10-104	35 40 45	6815						1387	383	1770	973	619	1682
11-81	35 40 45	14096	1445	1687	1657	1416		5933	1145		813		
16-50	35 40 45	6748			1941	1080	1972	1053			702		

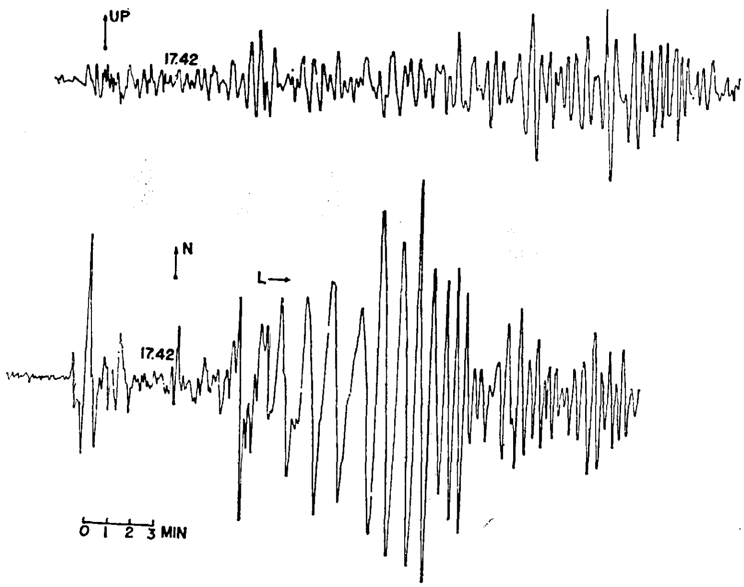

Fig. 5. Seismograms observed at Shiraz.

corresponding to these regions from the total path for different periods. Table 6 shows some exapmles. Very low group velocities in this region were earlier obtained by Gupta and Narain[9]. Porkka[10], Stoneley[11], Tan-

9) H. GUPTA and H. NARAIN, "Crustal Structure in Himalayan and Tibet Plateau Region from Surface Wave Dispersion," *Bull. Seism. Soc. Amer.*, 57 (1967), 235.

10) M. T. PORKKA, "Surface Wave Dispersion for Some Eurasian Paths. II. Love Waves," *Geophysica*, 7 (1961), 151.

11) R. STONELEY, "Rayleigh Waves in a Medium with two Surface Layers," *Mon. Not. Roy. Astr. Soc. Geophys. Supp.*, 7 (1955), 71.

TRAVEL TIME (SEC)

				SEGMENT							TOTAL	
T0	T1	T3	T5	T6	T7	T8	T9	T10	T12	T13	C	O
					520	228	476	145			1369	1366
					506	222	464	140			1332	1334
					496	217	454	137			1304	1307
					689	914		575			2178	2188
					671	889		555			2115	2123
					657	871		543			2071	2078
					373	106	501	288	197	592	2057	2055
					363	103	488	278	192	578	2002	2002
					356	101	477	272	184	562	1952	1955
320	378	383	345		1595	315		241			3577	3556
318	376	378	339		1553	307		232			3505	3485
317	375	375	334		1522	301		227			3451	3438
		449	264	511	283			208			1715	1734
		444	258	500	276			201			1679	1688
		440	254	491	270			196			1651	1668

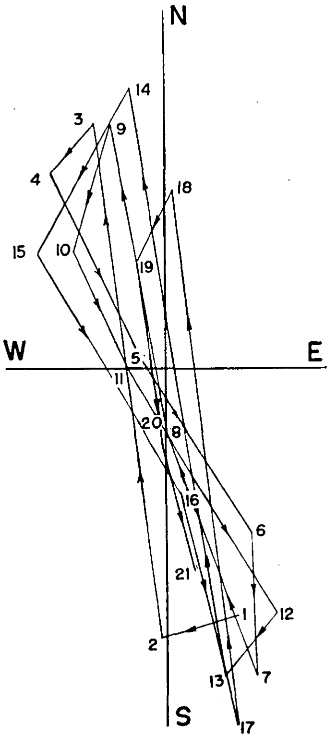

Fig. 6. Orbital motion as obtained from Fig. 5.

don and Chaudhury[12], etc. have also contributed the lower average group velocities for paths crossing the Himalayan and the Tibetan Plateau region to the thick crust beneath them.

In Fig. 4, the concentration of the regional contours towards the Indian Subcontinent and their relative sparseness to the north of the Himalayan and the Tibetan Plateau is also remarkable. This probably reflects the underground crustal structure. In the south, from the low level Indogangetic planes, the elevation increases within a very short distance to the high peaks of the Himalayas, whereas towards the north, from the plateau of Pamir the elevation decreases gradually. Hence it is likely that the crust thickens rapidly from beneath the Indogangetic planes to the high mountainous regions and thins out gradually towards the north. Another important fact is the rapid increase of the group velocities with period on curve Nos. 12 and 13 (see Fig. 3). It

12) A. N. TANDON and H. M. CHAUDHURY, "Seismic Surface Waves from High Yield Atmospheric Explosions," *Ind. J. Met. Geophys.*, **14** (1963), 283.

seems that the mountain roots in this region will affect the shorter period Love waves more than those with longer periods.

In the foot hills of the Himalayas, region 10 has been introduced and region 9 is extended to the Indogangetic planes where thick sediment is known to exist. This explains the observed dispersion of Love waves at Shillong from the earthquake of 19th Aug., 1964, and at Shiraz for the earthquake of 22nd January, 1964. Both mainly traversed the foot hills of the Himalayas. Earlier work by Chaudhury[13] also supports this extension.

4.2 Other regions

The region 6 in East Siberia in the Rayleigh wave division is not delineated by Love waves. Considering it to be region 7, the calculated time agreed with the observed time.

The existence of region 10, corresponding to the high mountainous type, in the water-covered area around Novaya Zemlya and Baltic Sea—an unexpected result according to Santô[14]—is found to hold good for Love waves also. This region around Novaya Zemlya required further eastward extension up to the southern end of Severnaya Zemlya. These low group velocities are probably due to a thick soft sedimentary layer in the sea, similar to those reported by Shurbet[15] for the Gulf of Mexico.

Another change, worth mentioning, has occurred in Turkey, the Caucasian Mountains and the Persian regions. These regions (mostly Numbers 7 and 9 according to the *Rayleigh wave division*) are replaced by Number 10 to explain the Love waves recorded at Istanbul and Athens from the earthquake of 21st June, 1965. Also, in western Europe, around the Alps, Yugoslavia and Rumania, regions 8 and 9 have been extended, based upon Love wave paths crossing those regions.

The above mentioned are the major differences between the Love wave and the Rayleigh wave division pattern of Eurasia.

Since the regionalization of Eurasia by Love wave dispersion agrees reasonably well with *the Rayleigh wave division*, a comparison of the Rayleigh wave and Love wave group velocities for the same numbers is made. Table 7 shows the group velocity ratio of Rayleigh to Love

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13) H. M. CHAUDHURY, "Seismic Surface Wave Dispersion and the Crust across the Gangetic Basin," *Ind. J. Met. Geophys.*, **17** (1966), 385.

14) *loc. cit.*, 1).

15) D. H. SHURBET, "The Effect of the Gulf of Mexico on Rayleigh Wave Dispersion," *J. Geophys. Res.*, **65** (1960), 1251.

Table 7

	T = 30 SEC			T = 40 SEC		
REGION	RAYLEIGH WAVE VEL	LOVE WAVE VEL	RATIO	RAYLEIGH WAVE VEL	LOVE WAVE VEL	RATIO
0	4.08 /	4.49	= 0.91	4.16 /	4.53	= 0.92
1	3.99 /	4.42	= 0.90	4.06 /	4.47	= 0.91
3	3.86 /	4.27	= 0.90	3.94 /	4.38	= 0.90
5	3.66 /	4.00	= 0.92	3.83 /	4.18	= 0.92
6	3.52 /	3.74	= 0.94	3.71 /	3.94	= 0.94
7	3.36 /	3.62	= 0.93	3.59 /	3.82	= 0.94
8	3.24 /	3.52	= 0.92	3.51 /	3.73	= 0.94
9	3.06 /	3.41	= 0.90	3.40 /	3.63	= 0.94
10	2.98 /	3.26	= 0.91	3.30 /	3.50	= 0.94
12	2.68 /	3.05	= 0.88	3.06 /	3.24	= 0.94

waves for 30 and 40 seconds period. The minimum value of this ratio is 0.88 (Region 12, period 30 sec) and the maximum value is 0.94 (Region 6~12, period 30 and 40 seconds). It is remarkable that this ratio for most of the cases is around 0.91. No such correlation could be made for Love wave dispersion curve Number 13 since this region was not delineated by Rayleigh wave study.

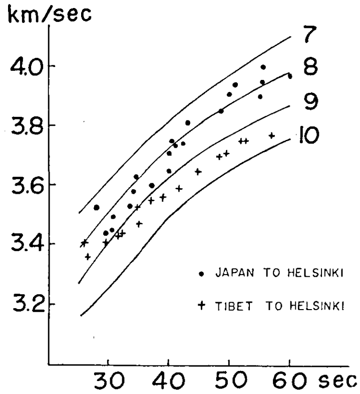

Fig. 7. Love wave dispersion obtained from the Helsinki observation.

Fig. 7 shows Porkka's[16] Love wave group velocity data for paths between (a) Japan and Helsinki and (b) Tibet and Helsinki, and the standard Love wave dispersion curve for Numbers 7, 8, 9 and 10. It is interesting to note that the Love waves recorded from the earthquakes around Japan show distinctly higher group velocities than those from the Tibet region; the former falls around the curve Number 8 and the latter between curve Numbers 9 and 10.

5. Conclusions

Love wave group velocity along various sections in Eurasia has been investigated, and it reveals that

1) It is possible to divide Eurasia into different regions having similar group velocity dispersion characteristics.

16) *loc. cit.*, 10).

2) This division supports Santô and Satô's division of Eurasia based on Rayleigh wave group velocity observations.

3) Extremely low group velocities, probably the lowest in the world, are observed in the Himalayan and the Tibet Plateau regions.

4) In general, a good agreement is observed between the division pattern and the regional topography.

Acknowledgments

The authors are thankful to Dr. T. Santô for useful discussions. Computations were carried out at the University of Tokyo Data Processing Centre.

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3. ユーラシア大陸におけるラブ波群速度の地域特徴

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ユーラシア大陸におけるラブ波群速度の分散を調べ，その分散の特徴に従って同大陸を 13 の地域に分割した. ヒマラヤ及びチベット高原地域は非常に群速度が遅い. なおこの分割は三東及び佐藤の同大陸に対するレーリー波群速度による分割と良く一致する. 又群速度の遅速は地形の高低によく対応するようである.