[Journal of the Faculty of Science, Hokkaido University, Ser. VII (Geophysics), Vol. VI, No. 1, 1979]

The Upper Mantle Structure of the Eurasian Shield as Revealed by Long-Period Surface Waves

Masaki OSADA

(Received Oct. 16, 1979)

Abstract

Group velocities of Love and Rayleigh waves across the Eurasian continent are determined over the period range 30 to 170 sec by using band-pass filtering and group delay time methods. Surface wave trains for 69 paths are analyzed. From these data for mixed paths, pure path group velocities for the Eurasian shield are calculated by using a least square method. The Eurasian shield is defined here as the region of Paleozoic and older times. A shear velocity model, designated as ES-1, is constructed for the upper mantle structure of the Eurasian shield. The effect of earth's anelasticity on the group velocity is included in the construction of the model. ES-1 model is characterized by an undeveloped low velocity layer (V_S=4.47 km/s, 70 km thick) underlying high velocity layer (V_S=4.58 km/s, 80 km thick). A slightly anisotropic dispersion is found for the Eurasian shield.

1. Introduction

The upper mantle of the Eurasian continent has been studied from surface wave data by many investigators[1)-8)]. In these studies, relatively shallow structure has been investigated because relatively short-period surface waves have been analyzed and simple techniques such as a peak-and-trough method were used. Nolet[6)] and Gupta et al.[7)] analyzed long-period surface waves, but the regions studied were not the Eurasian shield proper. A study of long-period surface waves is important to understand the upper mantle structure beneath the Eurasian shield. In this study, group velocities of long-period Love and Rayleigh waves crossing the Eurasian continent are determined over the period range from 30 to 170 sec. Band-pass filtering and group delay time methods are used to obtain accurate data. Group velocities for mixed paths are used for the calculation of pure path group velocities for the Eurasian shield. The shield region is defined here as the region of Paleozoic and older times, although the shield is generally recognized as the region of Precambrian. Finally a shear velocity model appropriate for the Eurasian shield is constructed. For obtaining a better model, the effect of velocity dispersion due to earth's anelasticity is included, according to the theory developed by Liu et al[9].

2. Data and analysis

We used copies of long-period seismograms of Worldwide Standardized Seismograph Network (WWSSN) from Athens University (ATU), Hong Kong (HKC), Kevo (KEV), Kongsberg (KON), Malaga (MAL), Matsushiro (MAT), Poona (POO), Shiraz (SHI), Stuttgart (STU) and Toledo (TOL), for 17 earthquakes which occured from 1964 to 1972. The natural period of pendulum T_0 and the natural period of galvanometer T_g of WWSSN is 30 sec and 100 sec for year of 1964, and 15sec and 100sec for years from 1967 to 1972. Records of High Gain Long Period (HGLP) instruments (T_0=30 sec, T_g=100 sec) from Eilat (EIL), Kongsberg (KON) and Matsushiro (MAT) are used for 19 earthquakes which occured in 1973. Long-period records from Dodaira (DDR) which were analyzed by Abe (personal communication, 1977) are also used in this study. Table 1 lists the earthquake data. Fig. 1 shows 44 great cricle paths. Vertical component seismograms are used for Rayleigh waves. For Love waves we use the transverse component synthesized from NS and EW components. The seismograms are digitized at intervals of 2 or 4 sec, and tapered at both ends. The tapered portion ranges from 10% to 30% of total length, depending upon the nature of the seismograms.

For accurate determinations of group velocities, we employed band-pass filtering and group delay time methods which were devised by Kanamori and

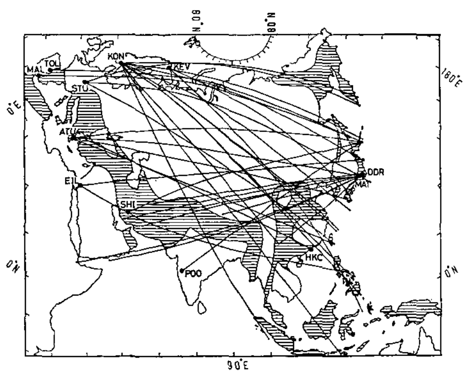

Fig. 1 Propagation paths across the Eurasian continent. Hatched area shows the tectonic region.

Table 1. Earthquake data.

No.	Region	Date	Origin time			Lat.	Long.	Depth
			h	m	s	(°N)	(°E)	(km)
1	Kurile Is.	64 May 31	00	40	36.1	43.43	147.05	42
2	Kurile Is.	64 Jun 23	01	26	36.8	43.16	146.17	76
3	Aegean Sea	67 Mar 4	17	58	09.0	39.25	24.60	60
4	Gulf of Aden	67 Nov 23	08	35	54.7	14.48	51.98	28
5	Kurile Is.	68 Jan 29	10	19	02.9	43.52	146.72	20
6	Aegean Sea	68 Feb 19	22	45	42.4	39.40	24.94	7
7	Iran*	68 Aug 31	10	47	37.4	33.97	59.02	13
8	Molucca	69 Aug 5	02	13	08.8	1.26	126.23	21
9	S. Persia	69 Nov 7	18	34	04.3	27.80	60.02	74
10	Kyushu	70 Jul 25	22	41	12.6	32.26	131.78	47
11	Sakhalin	71 Sep 5	18	35	27.0	46.54	141.15	14
12	Kamchatka	71 Nov 24	19	35	20.5	52.85	159.22	99
13	Taiwan	72 Jan 4	03	16	50.7	22.50	122.07	6
14	S. Honshu	72 Feb 29	09	22	59.3	33.38	140.97	50
15	S. Iran	72 Apr 10	02	06	50.0	28.39	52.78	11
16	Kashimir	72 Sep 3	16	48	29.5	35.95	73.33	45
17	S. Honshu	72 Dec 4	10	16	11.5	33.34	140.82	62
18	New Britain	73 Jan 18	09	28	13.7	−6.88	150.03	38
19	S. Sumatera	73 Feb 25	10	31	42.0	−1.75	99.65	58
20	Philippine Is.	73 Mar 9	10	06	34.0	6.32	127.38	25
21	Kurile Is.	73 Mar 12	19	39	21.6	50.78	157.19	62
22	E. Honshu	73 Mar 16	21	50	01.7	37.01	141.66	45
23	Ryukyu Is.	73 Mar 23	19	42	40.9	29.30	130.41	51
24	S. Honshu	73 Mar 24	00	34	38.8	31.74	139.37	27
25	Ethiopia	73 Apr 1	07	12	41.0	11.63	43.00	65
26	Burma-India	73 May 31	23	39	52.0	24.31	93.52	1
27	Luzon	73 Jul 5	22	46	15.0	13.18	124.65	18
28	Tibet	73 Jul 14	13	39	29.4	35.21	86.54	29
29	Yunnan	73 Aug 2	08	58	15.0	27.80	104.59	28
30	Pakistan	73 Aug 13	02	00	24.0	30.01	68.42	21
31	E. Honshu	73 Sep 5	13	03	14.1	39.57	143.16	35
32	E. Honshu	73 Sep 9	18	25	49.6	39.53	143.24	19
33	Taiwan	73 Sep 11	23	18	50.4	25.65	124.58	137
34	E. Honshu	73 Nov 19	13	01	56.6	38.99	141.93	56
35	Kurile Is.	73 Dec 1	23	16	53.7	43.11	146.99	23
36	Sumba Is.	73 Dec 19	04	42	59.8	−9.52	119.39	42

All the data are taken from Bulletine of International Seismological Centre.
*; USCGS determination.

Abe[10]. In the band-pass filtering method, group velocities are determined from the group arrival time of the wave packet having a limited frequency band around a certain frequency. The group arrival time is determined by numerically fitting a parabola to the wave packet[11]. The instrumental delay time is corrected by using the formula given by Hagiwara[12]. The source group delay time and the effect of source finiteness are neglected because these effects are very small for the moderate-size earthquakes and for long travelling paths, as was discussed by Kanamori and Abe[10]. An example of the band-pass filtered seismograms is shown in Fig. 2.

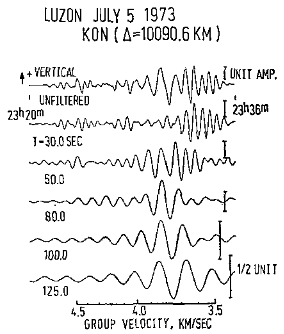

Fig. 2 Band-pass filtered seismograms of the vertical component of the Luzon earthquake of July 5, 1973. Rayleigh wave trains are shown. The vertical bar indicates the unit of the relative amplitude scale. The predominant periods are given by T. The group velocity scale is not corrected for the instrumental delay.

3. Results

Tables 2a and 2b list the group velocities obtained here. The results are interpolated, by means of a 3-point Lagrangean interpolation, at periods of 10 sec. The averages and standard deviations are calculated at the respective period. It is seen that the standard deviation is about 0.07 km/s for Rayleigh waves and about 0.09 km/s for Love waves. These relaitvely large scatter of the data suggest an inhomogeneous structure of the upper mantle beneath the Eurasian continent. For example, group velocities of Rayleigh waves for path (16)-MAT are lower by about 10% than those of path (1)-STU in the period range from 40 to 100 sec. The former path contains a large fractional length crossing Tibetan plateau, while the latter path crosses mainly the Siberian and Russian shields.

4. Pure path group velocities for the Eurasian shield

In this study we attempt to determine pure path group velocities for the Eurasian shield from the observed mixed path group velocities. We applied a least square technique used by Kanamori[13] to our data. We divided the Eurasian continent and adjacent area into shield, tectonic and oceanic regions. Here the shield region is defined as the region of Paleozoic and older times, though in general the shield is recognized as the region of Precambrian. The tectonic region is defined as the region of Mesozoic and later times (Fig. 1). The oceanic region includes marginal seas, Indian Ocean and Arctic Sea.

Calculation of fractional path lengths is based on plate 5 of Umbgrove[14]. The average of fractional path length for the Eurasian shield is 64% for Love waves and 61% for Rayleigh waves. Since this classification is not entirely free from ambiguity, fractional lengths are uncertain to several parcent. If a better way of defining the classification can be found in the future, these values may have to be revised.

The pure path group velocities obtained here are shown in Table 3 and Fig. 3. The standard deviation is small and about 0.03 km/s for Love and Rayleigh waves. Pure path group velocities of Rayleigh waves for the Eurasian shield reach a maximum of 3.84 km/s at a period of 80 sec, and decrease to 3.72 km/s at 170 sec. The pure path data for Love waves do not show appreciable dispersion over the period range from 100 to 170 sec. The pure path data of Love and Rayleigh waves are lower by 0.1 to 0.3 km/s over the period range from 30 to 150 sec than those of the Canadian shield[15]. The pure path group velocities for the Eurasian shield are shown in Fig. 3, where the oceanic group velocities obtained by Kanamori[13] are supplemented for period from 200 to 325 sec. His data are not greatly different from our data. This apparent continuity probably comes from the fact that the structural difference between shield and ocean is limited to the shallower portion of the mantle[13].

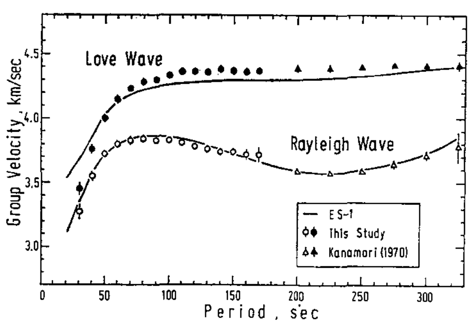

Fig. 3 Pure path group velocities of Love and Rayleigh waves and theoretical dispersion curves of ES-1 model.

5. A model for the Eurasian shield

We construct a shear velocity model of the Eurasian shield on the basis of the pure path group velocities obtained here. We also use Kanamori's[13] data for the long period range from 200 to 325 sec. The CANSD model[15] is

Table 2a. Observed group velocities of Love waves. Earthquake numbers

Path	Period (sec)						
	30	40	50	60	70	80	90
(1)-SHI					4.03	4.13	4.17
(1)-STU		3.79	3.99	4.12	4.21	4.27	4.32
(2)-ATU		3.77	3.95	4.09	4.19	4.27	4.32
(4)-MAT			3.98	4.07	4.07	4.12	4.18
(5)-STU	3.49	3.77	3.97	4.11	4.21	4.28	4.35
(5)-POO	3.58	3.74	3.87	3.97	4.05	4.11	4.15
(5)-ATU	3.64	3.83	3.99	4.11	4.20	4.27	4.32
(5)-MAL			3.96	4.07	4.14	4.20	4.24
(6)-HKC						4.04	4.12
(7)-DDR	3.46	3.68	3.84	3.95	4.03	4.09	4.14
(8)-KEV					4.17	4.20	4.23
(9)-MAT			3.70	3.77	3.90	3.98	4.07
(10)-KEV					4.14	4.20	4.24
(10)-ATU			3.93	4.04	4.12	4.18	4.23
(11)-TOL				4.03	4.10	4.16	4.21
(12)-STU					4.21	4.23	4.24
(13)-ATU		3.74	3.83	4.03	4.13	4.16	4.19
(13)-STU		3.75	4.00	4.10	4.17	4.22	4.24
(14)-STU							4.27
(15)-MAT				3.99	4.05	4.12	4.17
(16)-MAT		3.45	3.65	3.81	3.93	4.03	4.10
(17)-STU			4.10	4.22	4.28	4.35	4.35
(18)-KON		3.97	4.08	4.15	4.21	4.25	4.27
(19)-KON	3.38	3.77	4.00				
(20)-KON	3.50	3.67	3.95	4.12	4.20	4.25	4.28
(21)-KON	3.79	3.92	4.03	4.13	4.21	4.27	4.33
(22)-KON			3.93	4.08	4.19	4.26	4.31
(23)-KON	3.46	3.76	3.99	4.14	4.19		
(24)-KON	3.47	3.71	3.97	4.16	4.22	4.26	4.28
(25)-MAT	3.39	3.70	3.91	3.99	4.08	4.17	4.21
(26)-EIL	3.32	3.50	3.79				
(27)-KON				4.12	4.23	4.27	4.28
(28)-MAT	3.54	3.72	3.85	3.94	4.01	4.05	
(29)-KON	3.40	3.63	3.81	3.95	4.08	4.17	4.24
(30)-KON	3.34	3.61	3.85	4.05	4.20	4.28	
(31)-KON		3.69	3.95	4.11	4.22	4.27	4.30
(33)-KON		3.78	3.96	4.12	4.20	4.25	4.32
(34)-EIL	3.43	3.70	3.89	4.03	4.13	4.19	4.23
(36)-KON	3.50	3.63	3.82	3.98	4.09	4.17	4.22
Average	3.48	3.72	3.92	4.05	4.14	4.19	4.24
S.D.	0.12	0.11	0.10	0.10	0.09	0.09	0.07

used as a starting model, and the layer thickness and shear velocities are modified by trial and error. The thickness of the crust is fixed to 40 km according to the results of refraction study[16]. Theoretical group velocities are calculated for a spherically symmetric, radially heterogeneous and selfcorrespond to those in Table 1. S.D. denotes the standard deviation.

100	110	120	130	140	150	160	170
4.21	4.23	4.24	4.24	4.24	4.24	4.24	4.24
4.35	4.36	4.37	4.37	4.38	4.38	4.38	4.38
4.36	4.37	4.37	4.36	4.35	4.33	4.31	4.30
4.23	4.28	4.33	4.34	4.35	4.34	4.33	4.33
4.18	4.20	4.21	4.22	4.23	4.24		
4.35	4.38						
4.26	4.27	4.28	4.29	4.29	4.30	4.32	
4.18	4.22	4.24	4.25	4.26	4.26		
4.14	4.19	4.24					
4.26	4,27	4.29	4.30	4.32	4.33	4.33	4.34
4.09	4.12	4.15					
4.28	4.32	4.35	4.38	4.40	4.42	4.43	4.43
4.27	4.32	4.36	4.38	4.40	4.41		
4.25	4.29	4.33	4.36				
4.26	4.27	4.29	4.30	4.32	4.33	4.34	4.35
4.23	4.27	4.28	4.27	4.26	4.26	4.26	4.27
4.26	4.28	4.31	4.33	4.34	4.35	4.36	4.37
4.34	4.43	4.45	4.46	4.46	4.46		
4.19	4.20	4.21	4.21	4.22	4.25	4.29	4.30
4.15	4.19	4.21	4.23	4.25	4.27	4.29	
4.39	4.42	4.44	4.43	4.42	4.40	4.38	4.38
4.29	4.31	4.33	4.35				
4.30	4.31	4.31	4.30	4.31	4.32		
4.38	4.42	4.45	4.48	4.50	4.53	4.55	
4.34	4.35	4.36					
4.29	4.30	4.31	4.32				
4.28	4.30	4.31	4.30				
4.35	4.39	4.42	4.42	4.41	4.39	4.39	
4.26	4.28	4.30	4.31	4.32			
4.27	4.29	4.31	4.32	4.33	4.34	4.35	4.34
0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.06

gravitating earth model[17]. Computer programs coded by Kanamori and Abe[10] are used here.

Recently Liu et al.[9] recognized the necessity of correcting the effect of anelasticity in constructing an earth model. For example, correction rate of

Table 2b. Observed group velocities of Rayleigh waves. Earthquake numbers

Path	Period (sec)						
	30	40	50	60	70	80	90
(1)-STU		3.61	3.74	3.82	3.88	3.90	3.91
(3)-MAT		3.54	3.72	3.79	3.80	3.79	3.79
(5)-STU		3.61	3.76	3.89	3.89	3.87	3.86
(5)-POO		3.52	3.62	3.70	3.75	3.78	3.79
(5)-ATU	3.29	3.41	3.69	3.84	3.85	3.84	3.83
(5)-MAL				3.78	3.82	3.78	3.76
(6)-HKC				3.64	3.69	3.72	3.74
(7)-DDR	3.19	3.43	3.61	3.72	3.74		
(8)-KEV		3.50	3.58	3.65	3.69	3.73	3.74
(10)-ATU		3.62	3.71	3.74	3.77	3.78	3.77
(13)-ATU		3.53	3.61	3.70	3.76	3.76	3.76
(13)-STU	3.45	3.62	3.77	3.81	3.83	3.84	3.83
(16)-MAT		3.20	3.37	3.50	3.57	3.62	3.63
(17)-STU			3.77	3.83	3.85	3.84	3.82
(19)-KON	3.12	3.37	3.58	3.76	3.89	3.97	
(20)-KON	3.44	3.61	3.74	3.80	3.84	3.85	3.85
(21)-KON		3.62	3.75	3.84	3.89	3.88	3.87
(22)-KON	3.25	3.62	3.77	3.84	3.87	3.86	3.86
(25)-MAT	3.23	3.43	3.58	3.67	3.71	3.73	3.72
(27)-KON		3.65	3.72	3.80	3.83	3.82	3.82
(27)-EIL	3.22	3.44	3.60	3.69	3.74	3.76	3.75
(28)-MAT	3.41	3.54	3.63	3.68	3.70	3.70	
(29)-KON	3.13	3.40	3.59	3.72	3.80	3.84	3.86
(29)-MAT	3.37	3.61	3.70	3.74	3.79	3.80	3.77
(31)-KON	3.30	3.59	3.77	3.86	3.89	3.89	
(32)-KON		3.45	3.69	3.74	3.78	3.79	3.78
(33)-KON			3.70	3.78	3.81	3.80	3.80
(34)-EIL		3.56	3.69	3.72	3.74	3.74	3.73
(35)-KON	3.31	3.52	3.66	3.74	3.77	3.78	
(36)-KON		3.48	3.62	3.74	3.77	3.79	3.81
Average	3.29	3.52	3.67	3.75	3.79	3.80	3.79
S.D.	0.11	0.11	0.09	0.08	0.07	0.07	0.06

phase velocity against a reference period of 1 sec is about 1.4% at the period of 200 sec for Love wave with $Q \simeq 120$ (figure 4 of Liu et al.[9]). Considering this effect, we correct the Q effect on group velocities against the reference period of 1 sec. The Q data taken of Ben-Menahem[18] are used. We employ the formula of Kanamori and Anderson[19]. Group velocity correction (ΔU) is subtrated from theoretical group velocity for perfect elastic earth model. An iteration is carried out until we get a good fit of the corrected group velocities with the observations.

The final model is shown in Fig. 4 in comparison with CANSD model[15]. This final model is designsted as ES-1. Though ES-1 model is similar to correspond to those in Table 1. S.D. denotes the standard deviation.

100	110	120	130	140	150	160	170
3.89	3.87	3.84	3.82	3.80	3.79		
3.77	3.74	3.70	3.66	3.62	3.60	3.57	3.55
3.86	3.83	3.80	3.79	3.77	3.75	3.73	3.73
3.78	3.77	3.75	3.72	3.69	3.66	3.64	3.63
3.83	3.81	3.78	3.76	3.74	3.71	3.69	
3.73	3.71	3.69	3.67	3.66	3.64	3.63	
3.75	3.74	3.73	3.72	3.70	3.69		
3.75	3.74	3.73	3.70	3.68	3.65	3.63	3.60
3.75	3.73	3.70	3.68	3 66	3.65	3.64	3.62
3.76	3.75	3.75	3.74	3.74	3.74	3.74	3.75
3.82	3.81	3.80	3.78	3.71	3.70	3.71	
3.63	3.62	3.61	3.59	3.56	3.54		
3.79	3.75	3.70	3.69	3.70	3.71	3.73	3.74
3.83	3.77	3.73	3.70	3.66	3.63	3.60	3.58
3.84	3.81	3.77	3.74	3.69	3.63	3.59	3.61
3.86	3.81	3.75	3.69				
3.71	3.69	3.68					
3.81	3.79	3.78	3.77				
3.72	3.69	3.67					
3.78	3.78	3.77	3.75	3.73	3.71	3.69	3.67
3.79	3.77	3.77	3.76	3.75	3.75	3.76	3.77
3.72	3.70	3.68	3.64	3.61	3.58		
3.80	3.77	3.75	3.73	3.71	3.69	3.67	3.69
3.78	3.76	3.74	3.72	3.69	3.67	3.67	3.66
0.06	0.06	0.05	0.05	0.06	0.06	0.06	0.07

CANSD model, the shear velocity of the upper mantle is slightly lower. The ES-1 model is characterized by relatively undeveloped low velocity layer (V_S= 4.47 km/s, 70 km thick) underlying high velocity layer (V_S=4.58 km/s, 80 km thick). The thickness of the lithosphere beneath the Eurasian shield is estimated to be 120 km. The depth of the base of low velocity layer (290 km) can not be resolved because of the limitation of the period range concerned here. The theoretical group velocities of the ES-1 model are shown in Fig. 3. The difference between the model and the observation is very small. However a systematic discrepancy is found for Love waves up to about 0.08 km/s for periods longer than 70 sec. The amount of the discrepancy

Table 3. Pure path group velocities of Rayleigh and Love waves for the Eurasian shield. T, period, sec; U, group velocity, km/s; SD, standard deviation, km/s.

	Rayleigh wave		Love wave	
T	U	SD	U	SD
30	3.27	0.06	3.45	0.05
40	3.55	0.04	3.76	0.04
50	3.72	0.03	4.00	0.03
60	3.80	0.03	4.15	0.03
70	3.83	0.03	4.23	0.02
80	3.84	0.03	4.28	0.03
90	3.83	0.02	4.30	0.02
100	3.83	0.02	4.33	0.02
110	3.81	0.02	4.36	0.02
120	3.78	0.02	4.36	0.02
130	3.76	0.03	4.36	0.02
140	3.74	0.03	4.38	0.03
150	3.74	0.03	4.37	0.03
160	3.72	0.04	4.36	0.03
170	3.72	0.06	4.37	0.02

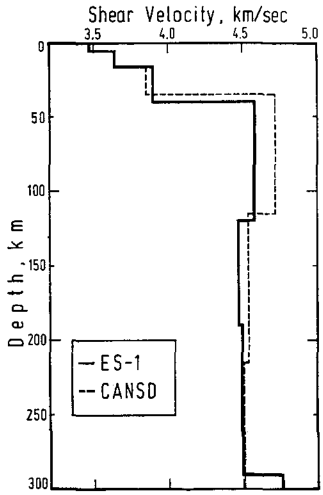

Fig. 4 Comparison between ES-1 and CANSD[15] models.

decreases at long periods. We can not get a better fit for Love waves without deteriorating the fit for Rayleigh waves.

In view of the non-uniqueness of the group velocity method, we make numerical checks to see the effect of the structure on group velocities. Fig. 5

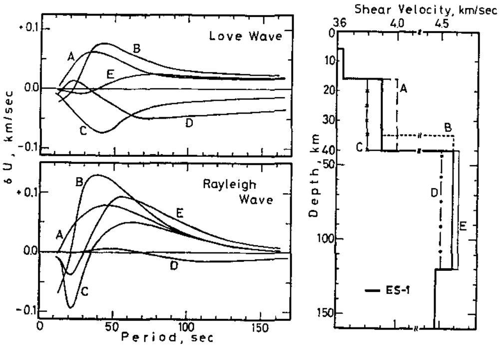

Fig. 5 The effect of crust and mantle structure on group velocities. ES–1 model is taken as standard. The deviation from the group velocities of ES–1 model is shown for five models, A, B, C, D and E.

shows exmaples for five models. The effect of shear velocity in the lowest crust is demonstrated by A and C models. B model has a thin crust. The effect of the modification to group velocities is shown in the left side of Fig. 5, where the deviation from group velocities of ES–1 model is given. From A, B and C models, it seems improvable that the crustal thickness exceeds 40 km or shear velocity in the crust is lower. These effects are mainly limited to the short period range of the dispersion curves. The effect of the upper mantle is demonstrated by D and E models, where the shear velocity is decreased by 2% in D model, and increased by 1% in E model. D model gives too low group velocities for Love wave, while group velocities for Rayleigh wave show a little of difference. In E model, group velocities for Love waves give a better fit with the pure path data than ES–1 model, although this model gives too high group velocities for Rayleigh waves.

6. Discussion

Q data used here are the average values for great circle paths[18], and not the Eurasian shield. Nakanishi[20] showed that the regional variations of Q values of Rayleigh waves are closely correlated with tectonic difference. We examine the effect caused by the uncertainty of Q. Fig. 6 shows the group velocity correction rate as a function of period for CANSD model by using Q data of Ben-Menahem[18], and the effect of difference by $\pm 10\%$ in Q data. It is found that a $\pm 10\%$ difference of Q values causes only 0.2% of the correction rate over the whole period range. We also modified Q values of

Love waves to $Q_L=100$ for $T<200$s, and $Q_L=150$ for $T\geq200$s. Little effect is also found for Love waves. Therefore we can safely neglect the regional difference of Q values in the calculations.

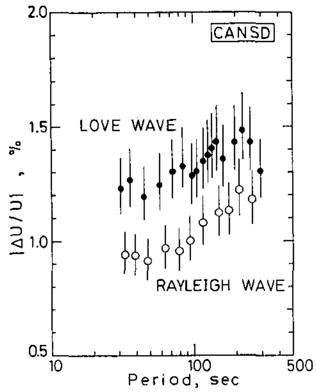

Fig. 6 Correction rate due to the Q effect on the group velocity for CANSD model[15]. Vertical bars indicate the difference caused by a 10% modification of Q values. Q values of BEN-MENAHEM[18] are used.

The theoretical Love wave group velocities of ES-1 model give systematically low values by about 0.08 km/s than the observed values, while the fit of Rayleigh wave is very good. Such a result has been found by several authors; Aki and Kaminuma[21] for Japan, McEvilly[22] for the central United States, and Mizutani and Abe[23] for oceans. In all cases, the observed Love waves velocities are slightly high for models which explain Rayleigh wave data well. This discrepancy has been explained in the term of an apparent anisotropy of the upper mantle[24)–29]. It is of interest to note that an anisotropic feature is found for the Eurasian shield region.

7. Conclusion

We determined long-period group velocities of Love and Rayleigh waves over the period range from 30 to 170 sec for 69 propagation paths mostly crossing the Eurasian continent. The Eurasian continent and adjacent area were divided into shield, tectonic and oceanic regions. Group velocities for paths across the Eurasian shield were calculated by means of a least square technique. Considering the Q effect on the group velocities, the model for the Eurasian shield proper was proposed on the basis of the pure path group velocities. ES-1 model was characterized by an undeveloped low velocity layer (V_S=4.47 km/s, 70 km thick) underlying the high velocity layer (V_S=4.58 km/s, 80 km thick). An anisotropic dispersion of surface waves was found.

Acknowledgements: I am grateful to Professors Izumi Yokoyama and Katsuyuki Abe for their encouragment throughout this work. I wish to express my sincere thanks to Professor Katsuyuki Abe for his critical review and constructive suggestions upon which the manuscript has been greatly revised. This paper is a part of M. Sc thesis which was submitted to Department of Geophyscis, Faculty of Science, Hokkaido Univ., in 1978. The numerical calculations in this study are carried out with a FACOM 230-75 at the Hokkaido University Computing Center.

References

1) KOVACH, R.L.: Seismic surface waves: Some observations and recent developments. Phys. Chem. Earth, **6**, (1965) 251-314.
2) SANTÔ, T.: Lateral variation of Rayleigh wave dispersion character, Part II: Eurasia. Pure Appl. Geophys., **62**, (1965) 67-80.
3) CRAMPIN, S.: Higher mode of seismic surface waves: Propagation in Eurasia. Bull. Seism. Soc. Am., **56**, (1966) 1227-1239.
4) NOPONEN, I.: Surface wave phase velocities in Finland. Bull. Seism. Soc. Am., **56**, (1966) 1093-1104.
5) SAVARENSKY, E.F., G.N. BOZHKO, T.I. KUKHTIKOVA, A.B. PESHKOV, I.I. POPOV, B.N. SHECHKOV, O.I. YURKEVICH and L.M. YUDAKOVA: On the earth structure in some regions of the USSR from surface wave data. Pure Appl. Geophys., **73**, (1969) 99-119.
6) NOLET, G.: The upper mantle under western Europe inferred from dispersion of Rayleigh modes. J. Geophys., **43**, (1977) 265-285.
7) GUPTA, H.K., D.C. NYMAN and M. LANDISMAN: Shield-like upper mantle structure inferred from long-period Rayleigh- and Love- wave dispersion investigations in the Middle East and south Asia. Bull. Seism. Soc. Am., **67**, (1977) 103-119.
8) CHUN, K.Y. and T. YOSHII: Crustal structure of Tibetan Plateau; A surface-wave study by a moving window analysis. Bull. Seism. Soc. Am., **67**, (1977) 735-750.
9) LIU, H.P., D.L. ANDERSON and H. KANAMORI: Velocity dispersion due to anelasticity; implications for seismology and mantle composition. Geophys. J.R. astr. Soc., **47**, (1976) 41-58.
10) KANAMORI, H. and K. ABE: Deep structure of island arcs as revealed by surface waves. Bull. Earthq. Res. Inst., Tokyo Univ., **46**, (1968) 1001-1025.
11) ABE, K.: Group velocities of oceanic Rayleigh and Love waves. Phys. Earth Planet. Int., **6**, (1972) 391-397.
12) HAGIWARA, T.: A note on the theory of the electromagnetic seismogragh. Bull. Earthq. Res. Inst., Tokyo Univ., **36**, (1958) 139-164.
13) KANAMORI, H.: Velocity and Q of mantle waves. Phys. Earth Planet. Int., **2**, (1970) 259-275.

14) UMBGROVE, J.H.F.: *The pulse of the Earth.* 2nd ed. (1947) Nijhoff, The Hague.
15) BRUNE, J. and J. DORMAN: Seismic waves and earth structure in the Canadian shield. Bull Seism. Soc. Am., **53**, (1963) 87–115.
16) BELYAEVSKY, N.A., A.A. BORISOV, V.V. FEDYNSKY, E.E. FOTIADI, S.I. SUBBOTIN and I.S. VOLVOVSKY: Structure of the earth's crust on the territory of the U.S.S.R.. Tectonophysics, **20**, (1973) 35–45.
17) ALTERMAN, Z., H. JAROSCH and C.L. PEKERIS: Oscillations of the earth. Proc. Roy. Soc. London, **A**, **252**, (1959) 80–95.
18) BEN-MENAHEM, A.: Observed attenuation and Q values of seismic surface waves in the upper mantle. J. Geophys. Res., **70**, (1965) 4641–4651.
19) KANAMORI, H. and D.L. ANDERSON: Importance of physical dispersion in surface wave and free oscillation problems. Rev. Geophys. Space Phys., **15**, (1977) 105–112.
20) NAKANISHI, I.: Phase velocity and Q of mantle Rayleigh waves. Geophys. J.R. astr. Soc., **58**, (1979) 35–59.
21) AKI, K. and K. KAMINUMA: Phase velocity of Love waves in Japan, 1, Love waves from the Aleutian shock of March 9, 1957. Bull. Earthq. Res. Inst., Tokyo Univ., **41**, (1963) 243–259.
22) MCEVILLY, T.V.: Central U.S. crust-upper mantle structure from Love and Rayleigh wave phase velocity inversion. Bull. Seism. Soc. Am., **54**, (1964) 1997–2015.
23) MIZUTANI, H. and K. ABE: An earth model consistent with free oscillation and surface wave data. Phys. Earth Planet. Int., **5**, (1972) 345–356.
24) SHIMOZURU, D.: On the possibility of the existence of the molten portion in the upper mantle of the earth. J. Phys. Earth, **11**, (1963) 49–55.
25) AKI, K.: Seismological evidences for the existence of soft thin layers in the upper mantle under Japan. J. Geophys. Res., **73**, (1968) 585–594.
26) TAKEUCHI, H., Y. HAMANO, and Y. HASEGAWA: Rayleigh- and Love-wave discrepancy and the existence of magma pockets in the upper mantle. J. Geophys. Res., **73**, (1968) 3349–3350.
27) ANDERSON, D.L. and C. SAMMIS: Partial melting in the upper mantle. Phys. Earth Planet. Int., **3**, (1970) 41–50.
28) THATCHER, W. and J.N. BRUNE: Higher mode interference and observed anomalous apparent Love wave phase velocities. J. Geophys. Res., **74**, (1969) 6603–6611.
29) BOORE, D.M.: Effect of higher mode contamination on measured Love wave phase velocities. J. Geophys. Res., **74**, (1969) 6612–6616.