551·241 (54)

Records of Mantle Rayleigh Waves at Delhi

A. N. TANDON and H. M. CHAUDHURY

Meteorological Office, New Delhi

(*Received 23 September 1964*)

ABSTRACT. Mantle Rayleigh waves, due to the great Alaska earthquake of 28 March 1964 and four other earthquakes following the same great circle path, recorded by the long period seismographs at Delhi, have been studied. In the case of the Alaska earthquake periods as high as 600 seconds were clearly recorded for waves which had made 21 complete revolutions of the earth. With the help of the data obtained, group velocity *vs* period curve in the period range 65 to 600 seconds has been prepared. Amplitude measurements of the waves of different periods and orders show that the absorption coefficient γ is a function of the period and can be given by the following relation within the period range 100 to 600 seconds.

$$\gamma \text{ per degree} \times 10^4 = 200\, e^{-0\cdot01T} + 1\cdot5$$

The dimensionless constant Q which gives the internal friction within the earth's mantle has been found to vary linearly with T in the period range 120 to 400 seconds. At higher periods the rate of change of Q with period decreases due to the effect of the earth's core.

1. Introduction

It is well known that the train of long period oscillations which are prominently recorded by long period seismographs of the Press-Ewing type, after the occurrence of great earthquakes, are surface waves which have circled the earth several times. Press and Ewing (1954 b) studied the actual particle motion of the waves, recorded by the vertical component, and showed that it is retrograde along an ellipse in the plane of propagation. This shows that the waves are of the Rayleigh type. They have given these the name of 'Mantle Rayleigh Waves'. Since these waves penetrate beneath the earth's crust into the mantle, their study has acquired a special significance as they provide very valuable data for gaining information about the earth's mantle. The period of these waves range from about 70 to several hundred seconds. They are dispersive in character. The group velocity generally decreases slightly when the period of the waves increases from 70 to about 220 seconds and then increases.

2. Materials used

For the last few years, the seismograph station at Delhi has been operating a set of Press-Ewing seismographs. In 1963 a set of standardised seismographs was installed by the United States Coast and Geodetic Survey at this station in pursuance of their scheme of world-wide network of standardised seismograph stations. These include three components of long period seismographs having seismometer period of 30 seconds and a galvanometer period of 100 seconds. The peak magnification of all the three components is 1500 and the response curve is well known. After their installation, these instruments have been recording Mantle Rayleigh Waves caused by large earthquakes. Some observations of these waves have already been reported by us (1964).

In the present paper we have made a study of the Mantle Rayleigh Waves recorded by the long period vertical component seismograph for five earthquakes, particulars of which are listed in Table 1. The magnitudes of these shocks cover a range from about $6\frac{3}{4}$ to $8\frac{1}{2}$ and the great circle paths passing through the epicentres and Delhi are almost the same. The epicentres, origin time, depth and magnitude etc have all been taken from the epicentre cards issued by the United States Coast and Geodetic Survey. The small magnitude shocks have the advantage of giving clear records in the period

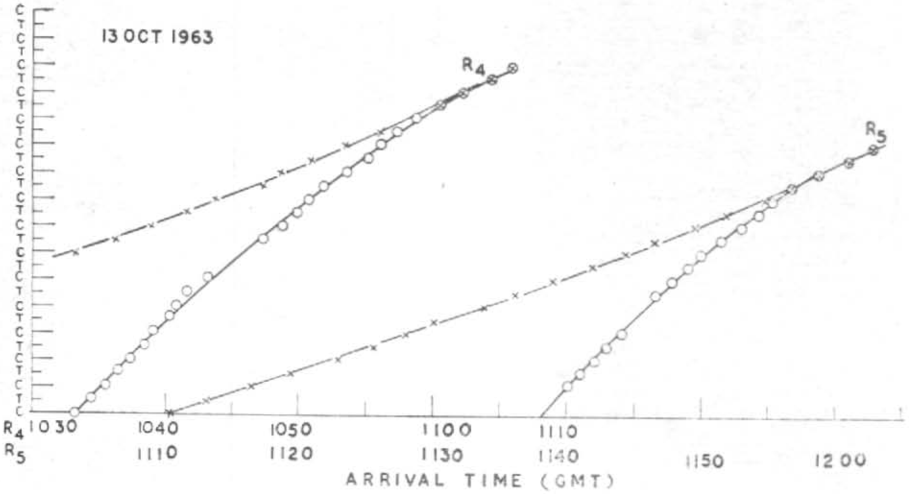

Fig. 1

range 70 to about 200 sec. In shocks of larger magnitude, the earlier orders are generally missed due to the high magnification of seismographs. The large magnitude shocks, however, provide valuable records for the study of very long periods waves which have gone round the earth several times. These waves are not recorded in smaller magnitude shocks.

3. Method of computation

The computations involve the determination of the correct arrival time, period and amplitudes of the waves. In the case of earlier orders (R_2 to R_6) we have followed the usual practice of plotting the arrival times of the crest and trough of waves against their number, and determining the periods at different arrival times from the curve. This procedure, however, is not possible in the case of higher orders, where considerable over-lapping of waves takes place due to simultaneous arrival of waves of different periods. In such cases, we have selected out wave groups which are clearly recorded on the seismograms. The period of these selected waves was directly determined from the record and the mean arrival time was taken into consideration.

Generally, in the orders R_2 and R_3 , only the short period branch, where the periods increase with arrival time, has been recorded. This may be due to the fact that it has not been possible to get records of R_2 and R_3 in the case of large magnitude shocks. In the record of the shock of 13 October 1963 both the short period and long period branches could be very clearly identified in the orders R_4 , R_5 and R_6 , both merging at the Airy Phase. A plot of arrival times against crest and trough for this shock is shown in Fig. 1 for the orders R_4 and R_5 . The record is reproduced in Fig. 2.

There is generally no difficulty in the identification of the lower orders (upto R_6) specially in the case of shocks of small magnitude. In the case of large magnitude shocks the lower orders are generally missed and it is not possible to trace the orders from the very beginning. As has already been mentioned, there is considerable overlapping of periods in higher orders, and it becomes difficult to associate a particular period with a definite order. To solve this difficulty we adopted the following procedure. The arrival times of all the observations were plotted against the recorded periods. In the case of lower orders the points could be joined by a smooth curve for each order, odd or even. From the separation of the

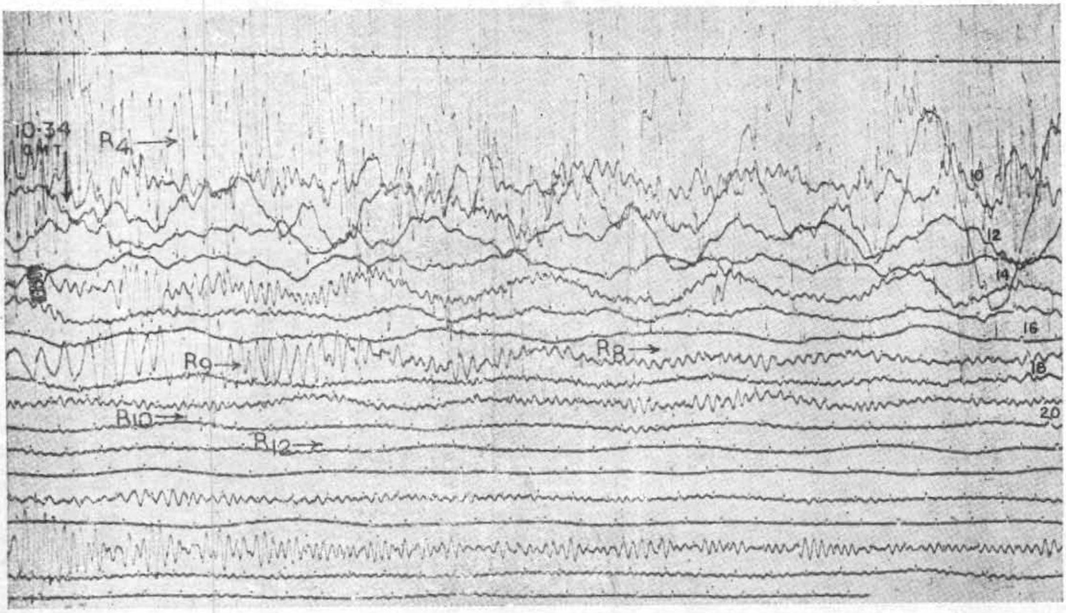

Fig. 2 (Left half)

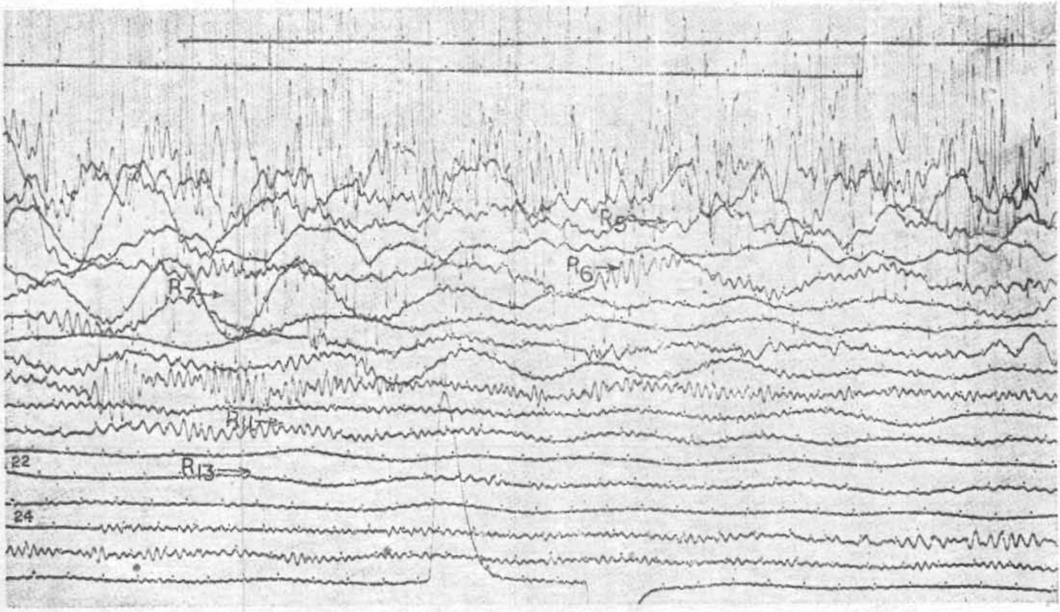

Fig. 2 (Right half)

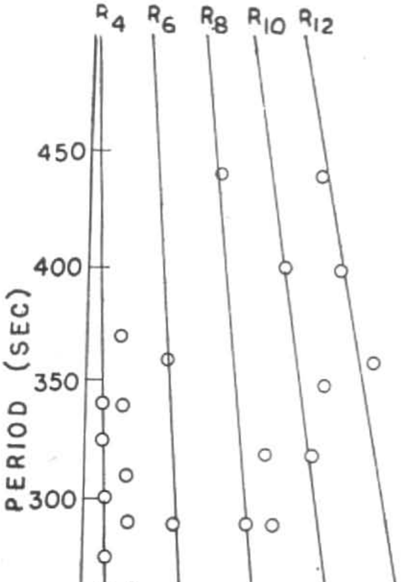

Fig. 3(a)

successive even orders it was possible to obtain an idea of the time interval which the waves, associated with a particular period, would take in going round the earth. The ratio of the interval of time between each successive even and odd number to that between successive odd and even number, should always be in the ratio of $\Delta : 180-\Delta$ for all values of T. The lower orders, which could be identified correctly, with slight extrapolation, provided sufficient data for the construction of a series of expected arrival time *versus* period curves for various orders. A further check on these values, specially in the higher period range was provided by the fact that the intervals between recorded arrival times of even orders or odd orders, corresponding to any period must be an integral multiple of the time interval between successive even or odd orders. After the construction of such a grid, for each large earthquake, there was no difficulty in identifying the order. The observations along with the expected arrival time *versus* period curves for the earthquakes of 13 October 1963 and 28 March 1964 are shown in Figs. 3(a) and 3(b). In the case of the latter we have been able to record clearly period of 600 seconds corresponding to the order R_{43}, a wave which has made 21 complete revolutions of the earth.

4. Results

(*i*) *Group velocity of Mantle Rayleigh Waves*

With the help of the travel time and the distances given in Table 2, the group velocities for different periods were calculated. These have been plotted in Fig. 4. The group velocity curve is in general agreement with those obtained by various other workers, as given in the summary of 'Observed Surface Waves Dispersion' by Oliver (1962) in which Rayleigh Wave group and phase velocities have been given upto periods of more than 1000 secs. The minimum of the group velocity equal to 3·54 km/sec occurs at a period of 225 seconds. The variation of group velocity for the same period as observed in different orders or in different earthquakes does not exceed 0·1 km/sec from the mean values. While there is no systematic variation in the scatter of group velocity variation in the long period branch of the curve, computed from different earthquakes, the group velocities obtained in the case of the Japan earthquake shocks of 7 May 1964 and 16 June 1964 which originate from practically the same source, are systematically higher than those obtained for the other shocks. In view of the small magnitude of this variation and also the fact that only a limited number of earthquakes have been studied, it would be premature to draw any firm conclusions from this.

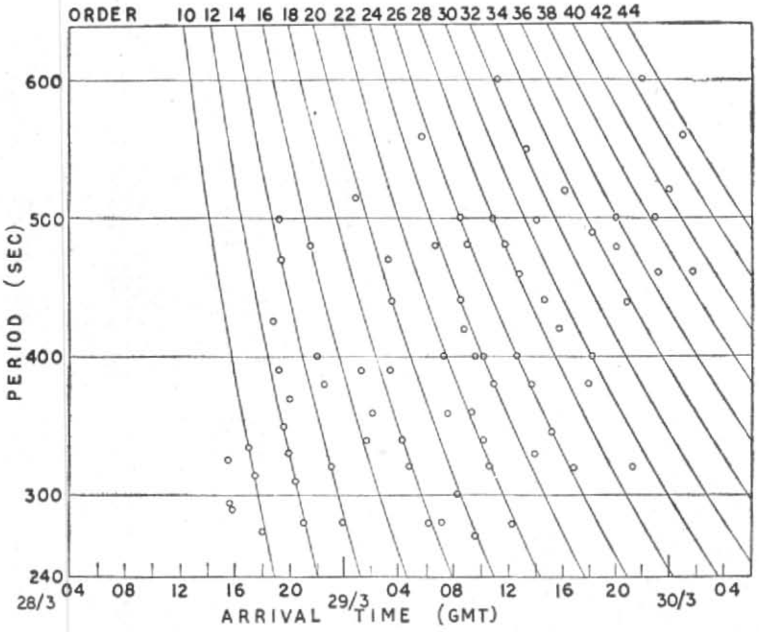

Fig. 3(b)

(ii) Absorption of Mantle Rayleigh Waves

The amplitude A of Rayleigh waves at a distance $\triangle$ from the epicentre is given by the following formula —

$$A = \frac{A_0\, e^{-\gamma\triangle}}{|R_0 \sin\triangle|^{\frac{1}{2}}\, \triangle^{\frac{1}{2}}}$$

for all periods except the Airy phase for which

$$A = \frac{A_0'\, e^{-\gamma\triangle}}{|R_0 \sin\triangle|^{\frac{1}{2}}\, \triangle^{\frac{1}{3}}}$$

where A_0 and A_0' are constants (Ewing, Jardetzky and Press 1957), R_0 the radius of the earth, and γ is the absorption coefficient.

In the present investigation we have used the method adopted by Ewing and Press. In Table 2 the value of the ground motion in microns for the vertical component and the value of $\ln(\triangle^{\frac{1}{2}} \times A_z)$ are given for different periods. Since it is not possible to obtain the value of this quantity at different distances for the same period we have combined the results in ranges of periods. These values are plotted against T and are shown in Figs. 5(a), 5(b) and 5(c) for different shocks. In general it has been observed that the ground amplitudes for odd orders were lower than those for the even orders. In drawing the lines, we have given due weightage to this effect. The slope of the line gives directly the value of the absorption coefficient for different period ranges. The results are given in Table 3. The values of γ for different periods are plotted in Fig. 6, and can be represented fairly well in the range of periods 100 to 600 seconds by the following formula—

$$\gamma \times 10^{4} = 200\, e^{-0\cdot01T} + 1\cdot5$$
(per degree)

(iii) Q values

The value of γ in the different period ranges can be used for the calculation of the internal friction within the mantle. Knopoff (1956), Knopoff and MacDonald (1958) assumed that the amplitude decay of a sinusoidal wave of period T, velocity V is proportional at

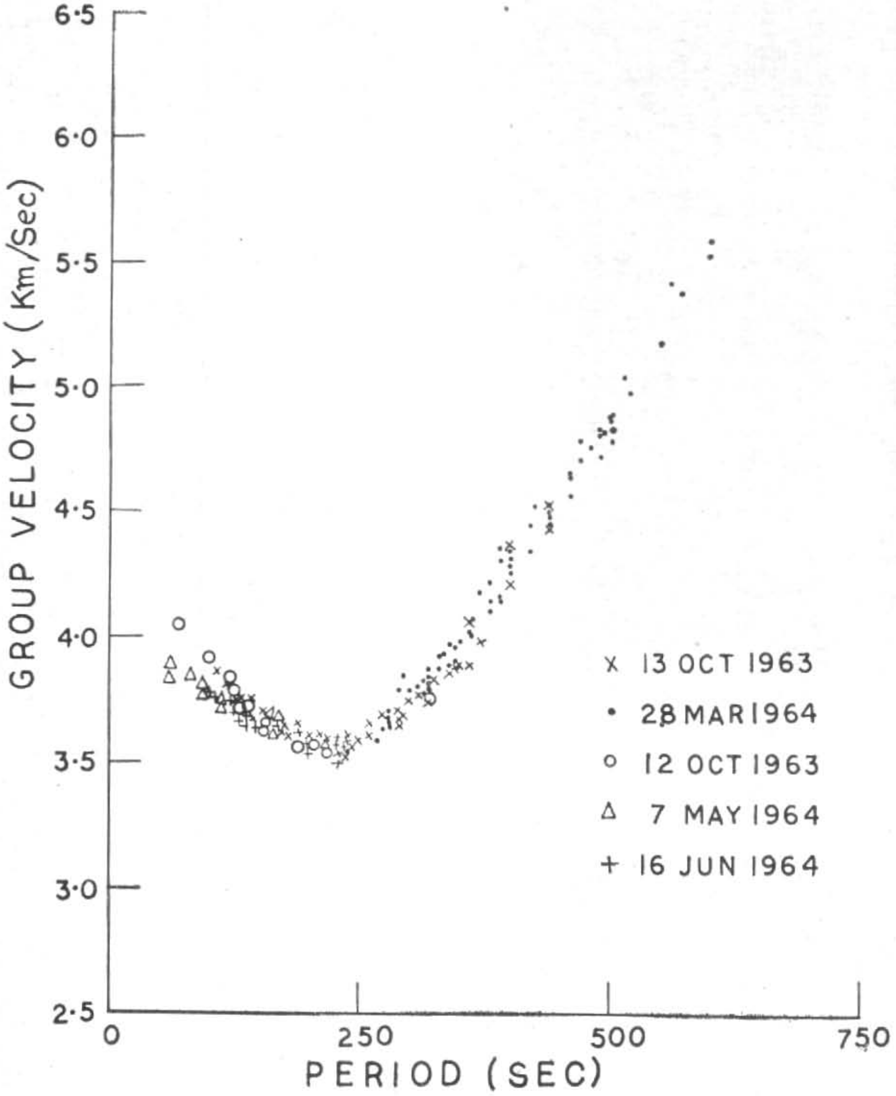

Fig. 4

a distance Δ to $\exp[-\pi\Delta/QTC]$, where C is the phase velocity.

The dimensionless constant Q is the factor which gives the internal friction in the mantle. Brune (1962) showed that it would be more appropriate to use the group velocity U in the place of the phase velocity C. Accordingly the above equation as modified by Brune was used in calculating the value of Q. The values of the constant Q for different periods are given in Table 3, and are plotted against period T in Fig. 7. The relationship between Q and the period is almost linear between the periods of 120—400 seconds. The rate of change of Q with T, however, starts decreasing at a period of about 400 seconds. It seems that beyond this period the effect of the earth's core is coming into play. The Q value corresponding to a period of 600 seconds falls below the general trend of the curve and has not been given full weightage, as the attenuation

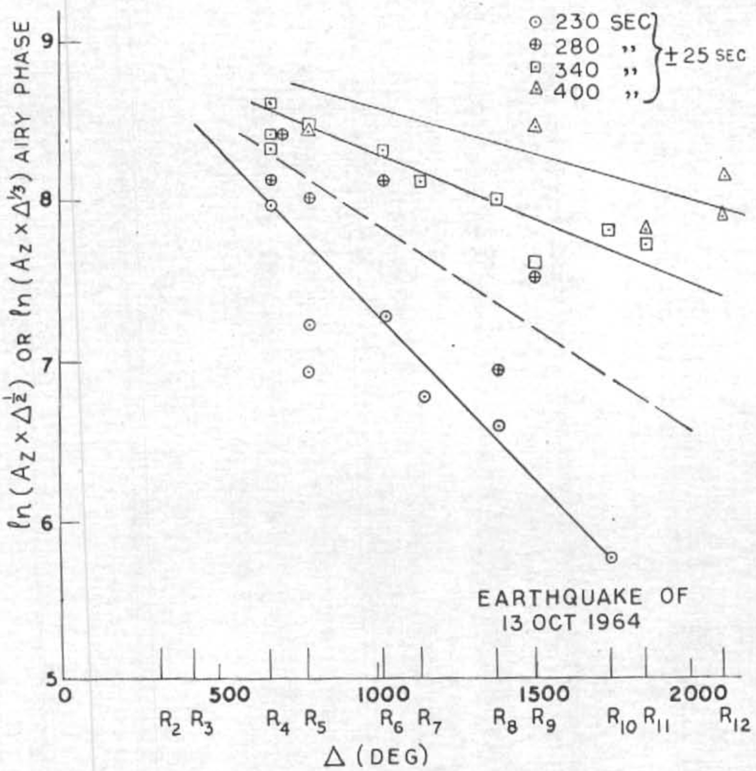

Fig. 5(a)

of this period has been calculated only from two observations, one of which was of an odd order and the other even.

5. Discussion

The method used in the present study for the separation of the wave groups of the various orders may not be as theoretically sound as the other method involving Fourier Analysis. But the results on the group velocities and their agreement with the values obtained from rigorous analysis of wave trains seem to justify the basic approach of the present analysis. We may, therefore, with confidence enter into a discussion of the results.

Ewing and Press (1954a) from the study of the Mantle Rayleigh Waves from the Kamchatka Earthquake of 4 November 1956 calculated the absorption coefficient for Mantle Rayleigh Wave in the period range 250-350 seconds. Earlier they (1954b) studied the Mantle Rayleigh Waves from the Assam Earthquake of 1950 and two other shocks and had obtained the value of 170* for Q corresponding to a period of 140-215 seconds.

A critical study of the attenuation of the seismic waves in the earth's mantle was carried out by Gutenberg (1958). He concluded that "the amplitude of seismic waves through the deep portions of the crust and the upper portion of the mantle are much more affected by the complications in the paths as a consequence of the 'low velocity layers' than by absorption and therefore do not give useful information on the attenuation processes". While this statement may be true for body waves and also for surface waves having smaller periods, the waves which have very

---

*As revised by Brune

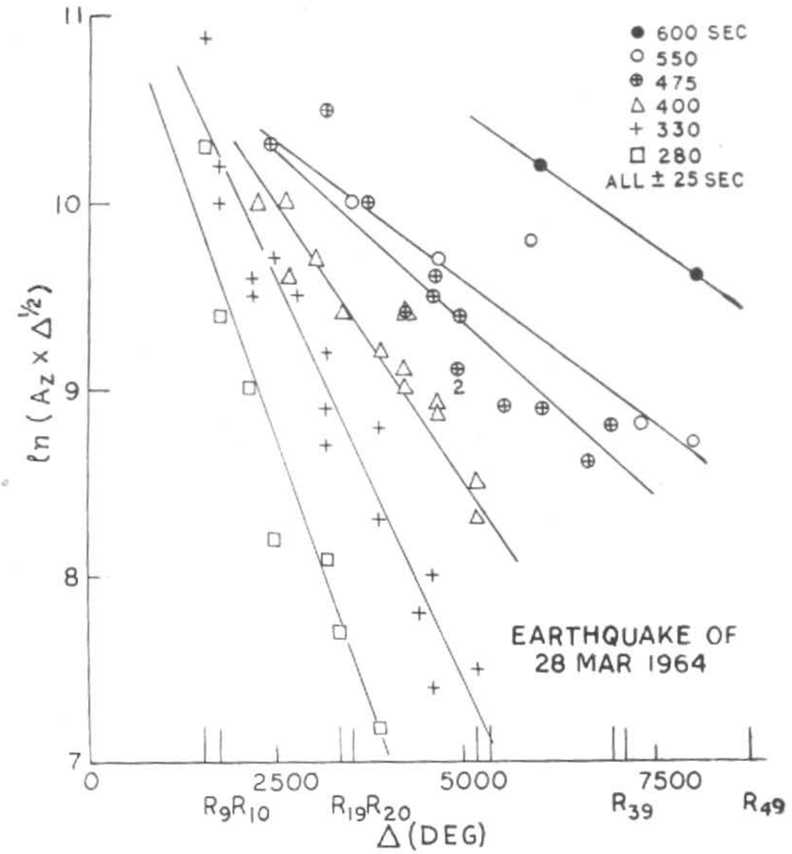

Fig. 5(b)

long period like the Mantle Rayleigh Waves penetrate deep into the earth's mantle and their propagation is not significantly affected by crustal irregularities. Therefore, the amplitude measurements prove sufficiently accurate for determining the absorption coefficient.

Although the $\gamma - T$ curve in the present study has been constructed with the help of observations within the period range 100 to 600 sec, extrapolation of the curve to lower periods with the aid of the formula mentioned above shows that the values obtained are in general agreement with those obtained by Gutenberg for surface waves of period as low as 20 sec. Gutenberg obtained a value of 0·2 per 1000 km while the above formula gives a value of 0·15 per 1000 km. Karnik (1956) combined data for Rayleigh waves of periods between ·001 to 200 sec and found that they could be represented fairly well by the relation $k=0 \cdot 017T^{-1 \cdot 42}$, where k is the absorption coefficient per kilometre. This relationship will give a value of ·24 per 1000 km at a period 20 sec. At a period of 200 sec Karnik's formula gives a value of 20×10^{-4} per 1000 km, while Press and Ewing obtained a value of 220×10^{-4} per 1000 km. The formula obtained by us gives a value of 256 which is in fairly good agreement with that obtained by Ewing and Press. This shows that Karnik's formula although fairly satisfactory in the lower period range, does not hold good for the period range obtained in the Mantle Rayleigh Waves.

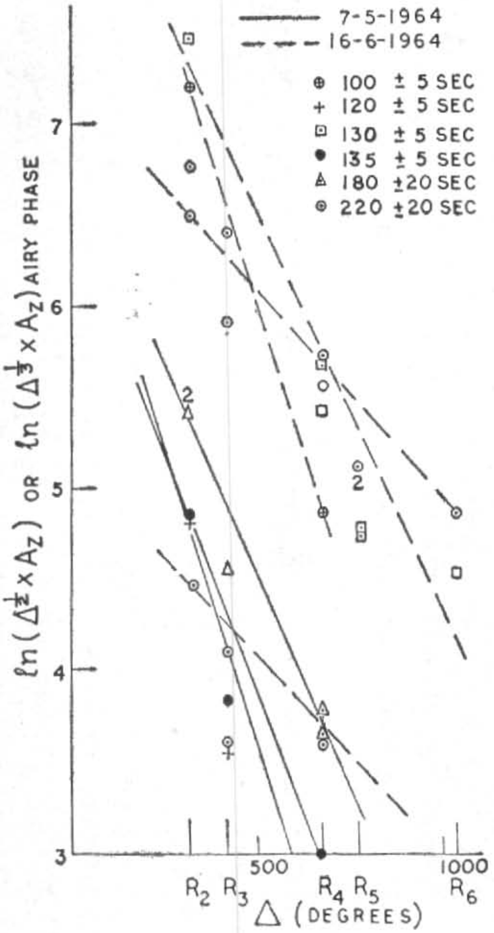

Fig. 5(c)

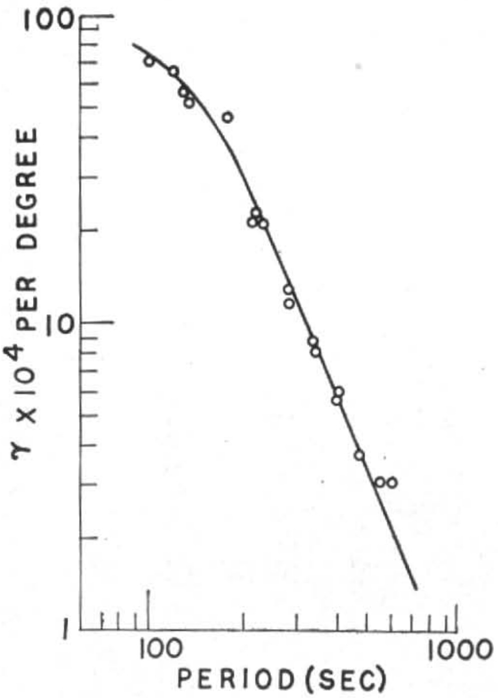

Fig. 6

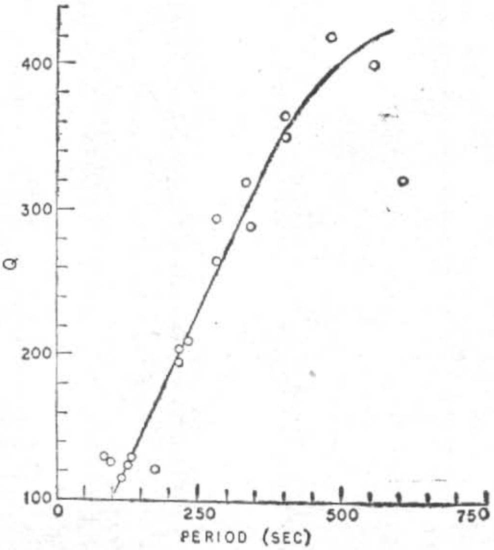

Fig. 7

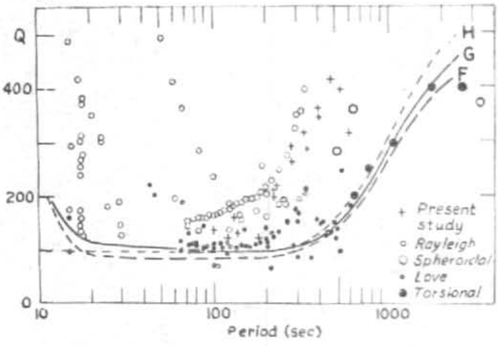

Fig. 8

The extent to which the results of the present study relating to the γ values agree with those of earlier studies holds equally well to those of the Q values. It may be of interest to remember that values of Q in the period range exceeding about 400 sec were few and were derived from love waves or from free oscillations data. In a recent study on the Anelasticity of the Earth, Anderson and Archambeau (1964) have summarised the available Q values. Their figure is reproduced in Fig. 8 on which the values of Q obtained in the present study from Rayleigh waves are also included. While these values are higher than those obtained from Love waves for corresponding periods they are in fairly good agreement with the trend of the Q values for lower periods from Rayleigh waves and also with the Q values from spheroidal oscillation data.

As is well known, waves of longer period are affected by deeper layers in the mantle and therefore the rather steep increase in the observed Q values with period is evidence of the less absorbing properties of the deeper mantle materials. Anderson and Archambeau have performed numerical experiments on the effect of a Q-discontinuity along depth on the variation of Q against period for Love waves. Comparison of their experimental results for a simple model with the available observed Q values, indicate that the discontinuity in Q from a value of 200 above to a value of 1400 below is somewhere between 350 and 600 km deep, "tentalisingly close to the depth of the much discussed inhomogeneous C region of the mantle and to depths of supposed phase changes". Comparison of the Rayleigh wave results with similar calculations are likely to prove interesting from the point of study of the structure of the Upper Mantle.

REFERENCES

Anderson, D. L. and Archambeau, C. B.	1964	*J. geophys. Res.*, **69**, 10, 2071-2084.
Brune, J.	1962	*Bull. seismol. Soc. Amer.*, **52**, 1, 109-112.
Ewing, M. and Press, F.	1954a	*Ibid.*, **44**, 471-479.
	1954b	*Ibid.*, **44**, 127-147.
Ewing, M., Jardetzky, W. S. and Press, F.	1957	*Elastic waves in layered Media, McGraw Hill* Bock Co.
Gutenberg, B.	1958	*Bull. seismol. Soc. Amer.*, **48**, 3, 269-282.
Karnik, V.	1956	Traveau Inst. Geophys., Acad. Tchecoslov Sci., No. 47, 124.
Knopoff, L.	1956	*Bull. seismol. Soc. Amer.*, **46**, 175.
Knopoff, L. and MacDonald, G. J. F.	1958	*Res. Mod. Phys.*, 30, 1178-1192.
Oliver, J.	1962	*Bull. seismol. Soc. Amer.*, **52**, 1, 81-86.
Tandon, A. N. and Chaudhury, H. M.	1964	*Indian J. Met. Geophys.*, **15**, 3, p. 467.

TABLE 1

Date	Epicentre		Origin time (GMT)			Depth of focus (km)	Distance from Delhi (degrees)	Magnitude
	Lat.	Long.	*h*	*m*	*s*			
12-10-63	44°·8 N	149°·0 E	11	26	57·9	40	58·0	6¼ (PAS), 7 (BERK), 6¾-7 (PAL)
13-10-63	44°·8 N	149°·5 E	05	17	57·1	60	58·4	8½ (PAS), 7¾ (PAL)
28-3-64	61°·1 N	147°·5 W	03	36	13·0	33	83·5	8·6 (USCGS)
7-5-64	40°·4 N	139°·0 E	07	58	14·3	33	51·2	7·0 (PAS), 7·0 (BERK)
16-6-64	38°·3 N	139°·1 E	04	01	44·3	57	51·8	7¼-7½ (PAS), 7¼ (PAL), 6·1 (GS)

TABLE 2 (a)

Arrival time (GMT)		Travel time (sec)	Period (sec)	Order	Δ (degrees)	U (km/sec)
hrs	min					
			12 OCTOBER 1963			
13	45	8282	70	R_2	302·0	4·05
13	50	8582	100	R_2	302·0	3·91
13	55	8882	125	R_2	302·0	3·73
14	00	9182	155	R_2	302·0	3·65
14	05	9482	220	R_2	302·0	3·54
14	50	12182	120	R_3	418·0	3·81
14	55	12482	140	R_3	418·0	3·72
15	00	12782	160	R_3	418·0	3·63
15	05	13082	190	R_3	418.0	3·55
17	10	20582	210	R_4	662·0	3·58
17	55	23282	130	R_5	778.0	3·71
18	00	23582	150	R_5	778·0	3·66
18	05	23882	180	R_5	778·0	3·61

TABLE 2 (b)

Arrival time (GMT)	Travel time (sec)	Period (sec)	Order	△ (degrees)	U (km/sec)	Az (microns)	$\rho n(\triangle^{\frac{1}{2}} \times Az)$ or $\rho n(\triangle^{\frac{1}{3}} \times Az)$ for Airy Phase
				13 OCTOBER 1963			
1035	19023	110	R_4	661·6	3·86	12·4	5·75
1035	19023	340	,,	661·6	3·86	15·7	8·30
1040	19323	120	,,	661·6	3·81	18·8	6·20
1040	19323	325	,,	661·6	3·86	225	8·60
1045	19623	145	,,	661·6	3·75	—	—
1045	19623	300	,,	661·6	3·75	180	8·50
1050	19923	155	,,	661·6	3·70	24·0	6·40
1050	19923	275	,,	661·6	3·70	133	8·10
1055	20223	180	,,	661·6	3·65	27·8	6·50
1055	20223	260	,,	661·6	3·65	—	—
1100	20523	205*	,,	661·6	3·58	320	7·95
1100	20523	240	,,	661·6	3·58	—	—
1120	21723	370	R_5	778·4	3·98	166	8·40
1130	22323	340	,,	778·4	3·87	162	8·40
1140	22923	310	,,	778·4	3·77	104	8·00
1145	23223	125	,,	778·4	3·72	7·9	5·40
1150	23523	145	,,	778·4	3·68	25·0	6·50
1150	23523	290	,,	778·4	3·68	109	8·00
1200	24123	250*	,,	778·4	3·58	103·0	6·90
1203	24303	240*	,,	778·4	3·55	147	7·20
1324	29163	360	R_6	1022	3·89	156	8·30
1348	30603	290	,,	1022	3·71	109	8·10
1400	31323	175	,,	1022	3·62	15·8	6·20
1404	31563	260	,,	1022	3·60	62·5	
1405	31623	200	,,	1022	3·59	41·0	
1408	31803	220*	,,	1022	3·57	139	7·25
1507	35343	250*	R_7	1138	3·58	82·0	
1544	37563	440	R_9	1498	4·43		6·90
1652	41643	290	R_8	1382	3·69	36·5	6·90
1717	43143	220*	,,	1382	3·56	65·0	6·57
1742	44643	320	R_9	1498	3·73	50·0	7·60
1758	45603	290	,,	1498	3·65	45·5	7·50
1826	47283	400	R_{11}	1858	4·36	60·0	7·80
1935	51423	320	R_{10}	1742	3·76	62·5	7·80
1955	52623	440	R_{12}	2102	4·52	75·0	8·15
2006	53283	350	R_{11}	1858	3·88	57·0	7·80
2020	54123	240*	R_{10}	1742	3·58	26·5	5·75
2042	55443	400	R_{12}	2102	4·21	60·0	7·90
2209	60663	360	R_{13}	2218	4·06	62·5	8·00

*Airy Phase

TABLE 2 (c)

Arrival time (GMT)	Travel time (sec)	Period (sec)	Order	$\triangle$ (degrees)	U (km/sec)	Az (microns)	$\rho n(\triangle^{\frac{1}{2}} \times Az)$ or $\rho n(\triangle^{\frac{1}{3}} \times Az)$ for Airy Phase
			28 MARCH 1964				
1535	43127	315	R_9	1523	3·92	1380	10·9
1550	44027	295	,,	1523	3·84		
1600	44627	290	,,	1523	3·79	770	10·3
1705	48527	335	R_{10}	1716	3·93	618	10·2
1741	50687	315	,,	1716	3·76	534	10·0
1813	52607	275	,,	1716	3·63	284	9·4
1858	55307	425	R_{13}	2243	4·52	435	9·9
1922	56747	500	R_{14}	2603	4·77		
1930	57227	390	R_{13}	2243	4·35	463	10·0
1937	57647	470	R_{14}	2436	4·70	588	10·3
1942	57947	350	R_{12}	2076	3·98	295	9·5
2008	59507	330	,,	2076	3·87	312	9·6
2013	59807	370	R_{13}	2243	4·18	632	10·0
2027	60647	310	R_{12}	2076	3·80	189	9·1
2111	63287	280	,,	2076	3·64	177	9·0
2146	65348	480	R_{16}	2796	4·75	688	10·5
2215	67127	400	R_{15}	2603	4·31	460	10·0
2240	68623	380	,,	2603	4·22	286	9·6
2310	70427	320	R_{14}	2436	3·87	388	9·7
2400	73427	280	,,	2436	3·68	77	8·2
			29 MARCH 1964				
0050	76427	240	R_{14}	2436	3·54	58·0	
0103	77207	515	R_{20}	3516	5·03	357	10·0
0127	78647	390	R_{17}	2963	4·16	289	9·7
0145	79727	340	R_{16}	2796	3·90	243	9·5
0210	81227	360	R_{17}	2963	4·05	235	9·5
0322	85547	470	R_{21}	3683	4·78	353	10·0
0329	85967	390	R_{19}	3323	4·30	192	9·4
0346	86987	440	R_{20}	3516	4·49	150	9·1
0425	89327	340	R_{18}	3156	3·97	108	8·7
0502	91547	320	,,	3156	3·83	175	9·2
0551	94487	560	R_{26}	4596	5·41	227	9·7
0619	96167	280	R_{18}	3156	3·68	61·5	8·1
0648	97907	480	R_{24}	4236	4·80	188	9·4
0721	99887	280	R_{19}	3323	3·70	38·5	7·7
0721	99887	400	R_{22}	3876	4·31	160	9·2
0751	101687	360	R_{21}	3683	4·02	156	9·1
0820	103427	300	R_{20}	3516	3·78	80·0	8·4
0845	104927	500	R_{26}	4596	4·87	200	9·5
0848	105727	440	R_{24}	4236	4·45	125	9·0
0903	106007	420	,,	4236	4·44	182	9·4

TABLE 2(c)—*contd*

Arrival time (GMT)	Travel time (sec)	Period (sec)	Order	$\triangle$ (degrees)	U (km/sec)	Az (microns)	$pn(\triangle^{\frac{1}{2}} \times Az)$ or $pn(\triangle^{\frac{1}{3}} \times Az)$ for Airy Phase
29 MARCH 1964 (*contd*)							
0911	106487	480	R_{26}	4596	4·80	218	9·6
0928	107507	360	R_{22}	3876	4·01	109	8·8
0945	108527	400	R_{24}	4236	4·34	140	9·1
0948	108707	270	R_{20}	3516	3·59	35·7	7·6
1022	110747	400	R_{24}	4236	4·25	60·0	8·3
1028	111107	340	R_{22}	3876	3·88	108	8·8
1050	112427	320	,,	3876	3·83	62	8·3
1103	113207	500	R_{28}	4956	4·86	133	9·1
1112	113747	380	R_{24}	4236	4·14	125	9·0
1122	114347	600	R_{32}	5676	5·51	333	10·1
1203	116807	480	R_{28}	4956	4·71	125	9·1
1222	117947	280	R_{22}	3876	3·65	23·0	7·2
1250	119627	400	R_{26}	4596	4·27	10·0	8·85
1308	120707	460	R_{28}	4956	4·56	167	9·4
1336	122387	550	R_{32}	5676	5·15	227	9 8
1352	123347	380	R_{26}	4596	4·14	107	8·9
1415	124727	330	R_{25}	4403	3·92	37·5	7·8
1430	125627	500	R_{31}	5483	4·85	100	8·9
1452	126947	440	R_{29}	5123	4·48	75	8·6
1523	128807	345	R_{26}	4596	3·96	44	8·0
1602	131147	420	R_{29}	5123	4·34	68·0	8·5
1702	134747	320	R_{26}	4596	3·79	25·0	7·4
1809	138767	380	R_{29}	5123	4·10	54·0	8·3
1823	139607	490	R_{34}	6036	4·82	94·0	8·9
2005	145727	500	R_{36}	6396	4·88	67·0	8·6
2053	148707	440	R_{34}	6036	4·52	100	9·0
2111	149787	320	R_{29}	5123	3·81	25·0	7·5
2158	152507	600	R_{43}	7643	5·57	167	9·6
2255	155927	500	R_{38}	6756	4·82	83·0	8·8
2312	156497	460	R_{37}	6563	4·65	56·0	8·4
2400	159827	520	R_{40}	7116	4·94	77·0	8·8
30 MARCH 1964							
0100	163427	560	R_{44}	7836	5·44	68·0	8·7
0140	165827	460	R_{39}	6923	4·64	56·0	8·4

TABLE 2 (d)

Arrival time (GMT)	Travel time (sec)	Period (sec)	Order	$\triangle$ (degrees)	U (km/sec)	Az (microns)	$pn(\triangle^{\frac{1}{2}} \times Az)$ or $pn(\triangle^{\frac{1}{3}} \times Az)$ for Airy Phase
			7 MAY 1964				
1025	8806	65	R_2	308·8	3·90	3·2	4·05
1027	8926	85	,,	308·8	3·84	4·9	4·45
1029	9046	95	,,	308·8	3·79	5·7	4·60
1031	9166	115	,,	308·8	3·74	6·8	4·80
1033	9286	135	,,	308·8	3·69	6·8	4·80
1035	9406	180	,,	308·8	3·65	13·2	5·40
1037	9526	190	,,	308·8	3·60	13·3	5·40
1039	9646	220*	,,	308·8	3·56	13·0	4·45
1117	11926	65	R_3	411·2	3·83	1·3	3·26
1120	12106	95	,,	411·2	3·76	1·6	3·48
1123	12286	115	,,	411·2	3·72	1·7	3·55
1126	12466	140	,,	411·2	3·66	2·3	3·83
1129	12646	165	,,	411·2	3·61	4·8	4·57
1132	12826	210*	,,	411·2	3·56	8·0	4·10
1135	13006	235*	,,	411·2	3·51	5·0	3·60
1328	19786	125	R_4	668·8	3·76	0·6	2·55
1331	19966	135	,,	668·8	3·72	0·8	3·0
1334	20146	160	,,	668·8	3·72	0·8	3·0
1337	20326	170	,,	668·8	3·65	1·7	3·77
1343	20686	215*	,,	668·8	3·59	4·2	3·60
1346	20866	235*	,,	668·8	3·56	5·0	3·77

TABLE 2 (e)

Arrival time (GMT)	Travel time (sec)	Period (sec)	Order	$\triangle$ (degrees)	U (km/sec)	Az (microns)	$pn(\triangle^{\frac{1}{2}} \times Az)$ or $pn(\triangle^{\frac{1}{3}} \times Az)$ for Airy Phase
			16 JUNE 1964				
0632	9086	100	R_2	308·2	3·77	77·0	7·20
0635	9266	125	,,	308·2	3·70	99·0	7·45
0637	9386	145	,,	308·2	3·65	93·0	7·38
0640	9566	200*	,,	308·2	3·58	125·0	6·75
0643	9746	230*	,,	308·2	3·52	100·0	6·50
0730	12506	150	R_3	411·8	3·66	39·0	6·68
0733	12686	200*	,,	411·8	3·60	79·0	6·40
0740	13106	230*	,,	411·8	3·49	50·0	5·90
0931	19766	105	R_4	668·2	3·76	5·0	4·85
0933	19986	120	,,	668·2	3·72	8·8	5·4
0935	20106	140	,,	668·2	3·70	11·6	5·65
0937½	20256	150	,,	668·2	3·66	15·20	5·95
0940	20406	170	,,	668·2	3·64	17·50	6·10
0943	20586	180	,,	668·2	3·60	16·70	6·80
0946	20766	230*	,,	668·2	3·57	35·0	5·70
0950	21006	200*	,,	668·2	3·53	29·8	5·55
1031	23366	130	R_5	771·8	3·66	4·3	4·70
1034	23546	140	,,	771·8	3·64	4·2	4·73
1041	23966	200*	,,	771·8	3·57	17·8	5·1
1044	24146	225*	,,	771·8	3·55	18·2	5·1
1244	31346	140	R_6	1028·2	3·65	2·5	4·51
1250	31586	190	,,	1028·2	3·61	6·6	5·37
1254	31826	230*	,,	1028·2	3·58	12·5	4·85

TABLE 3

Date of shock	Period (sec)	γ per degree (observed)	U (km/sec)	$Q=\pi/(\gamma UT)$
13-10-63	230	20·4	3·56	210
13-10-63	280	12·8	3·66	265
13-10-63	340	8·0	3·90	290
13-10-63	400	5·6	4·28	365
28-3-64	280	11·5	3·66	295
28-3-64	330	8·6	3·85	320
28-3-64	400	5·8	4·28	350
28-3-64	475	3·7	4·70	420
28-3-64	550	3·0	5·30	400
28-3-64	600	3·1	5·85	320
7-5-64	120	65·0	3·84	115
7-5-64	135	52·0	3·74	130
7-5-64	180	46·0	3·60	120
7-5-64	220	21·6	3·58	205
16-6-64	100	71·0	3·90	125
16-6-64	130	56·0	3·80	125
16-6-64	220	22·8	3·58	195