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Seismic Waves from high yield Atmospheric Explosions

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ABSTRACT. High yield test nuclear explosions in the atmosphere carried out in 1962 by the U.S.S.R. over Novaya Zemlya were well recorded by the seismographs at Delhi. The paper presents a study of these records. Long period Rayleigh waves were the most prominent and could be detected for most of the explosions. The body phases P, PP and S were also recorded on a few occasions when the yield of the explosions was about 20 megatons or more. A prominent wave recorded on most of the days has been shown to be the Sa (Caloi) wave and has been discussed at some length.

M2-waves in the range of periods 8-15 seconds could be clearly detected. The records also show the presence of longer period M2 waves, which have been analysed. Dispersion of these M2 waves as also of Rayleigh waves has been studied and it is estimated that the thickness of the average continental crust along the path (Novaya Zemlya—Delhi) is 45 km whereas that under the mountain range across the path is 55-60 km.

The pressure wave travelling with the speed of sound was well recorded on a number of days. These waves show clear normal dispersion. Results derived from the records of the vertical component seismograph compare well with earlier experimental and theoretical results. The response of the horizontal component seismographs to these waves appears to be due to ground tilt caused by the propagation of the pressure wave.

1. Introduction

On 5 August 1962 Russia exploded a high yield nuclear bomb in the atmosphere over their testing ground in the Novaya Zemlya. A preliminary report of the records obtained by the long period Press-Ewing seismographs at Delhi has already been published (Tandon and Chaudhury 1962). This explosion was followed by many more similar explosions during the following months, the last of the series being on 25 December 1962. Nearly all these explosions, which had yields in the megaton range, produced records on seismographs at Delhi, and a few, having yields comparable to that of 5 August 1962 or that of 30 October 1961, were also recorded by the ordinary observatory microbarograph. The object of this paper is to present a study of the seismic waves recorded by the P.E. seismographs, installed at the Delhi Observatory. These seismographs were loaned to the India Meteorological Department by the Lamont Geological Observatory, Palisades, New York during the IGY and since then they have been in continuous operation. They were recently calibrated by Father H. J. Miller, S. J., of the Lamont Geological Observatory. The response curves for these instruments are shown in Fig. 1. In the following sections we have discussed some of the salient features of these records, and have made an attempt to utilise the data, for studying the average structure of the earth's crust and the atmosphere between the point of explosion and Delhi. Records of explosions, provide a certain advantage over those obtained from earthquakes in the study of surface waves. The phenomenon is akin to a sudden hammer blow on the ground and is free from complications arising in earthquake records as a result of the large dimension of the source and the duration of the pulse. In the present studies the path of seismic rays is almost entirely continental, and this added to the purity of the records.

2. Observational data

Particulars of the explosions, for which the data have been used are listed in Table 1.

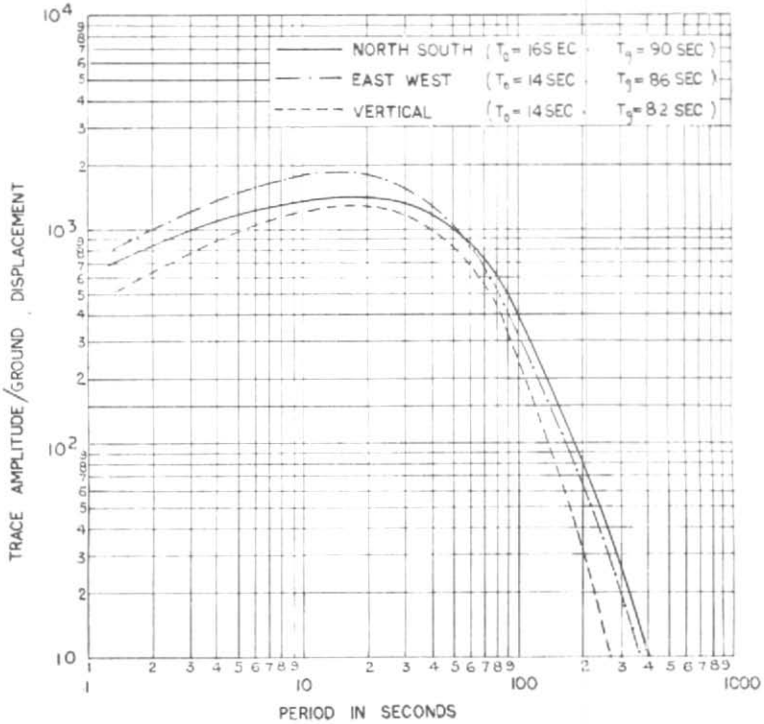

Fig. 1

The epicentres, origin times and the magnitudes listed, were taken from the epicentre cards issued by the United States Coast and Geodetic Survey. Figures for the yield are those given by the Seismological Laboratory, Uppsala, Sweden. In Table 2, we have given the arrival times of the important phases recorded on the Delhi seismograms. It also gives the distances of the explosions from Delhi, calculated from the S-P time intervals, using Jeffreys and Bullen's (1948) Travel Time Tables. The origin times calculated from these observations and the magnitudes of the earth shocks produced by the explosions, obtained from the Delhi records have been given in this table. The magnitudes were obtained from Gutenberg and Richter's nomogram. An average of the maximum ground motion recorded by the horizontal components was used. These values, while in general agreement with those given in Table 1, are a little higher. The small difference may be due to the fact that no station correction has been used.

The origin times obtained by using the S-P intervals of the Delhi seismograms are in good agreement with those obtained by USCGS. It is noteworthy that the distances calculated from the S-P intervals on all the five occasions, when clear P and S phases were recorded, are the same. On the other hand the distances given in Table 1 (calculated from the epicentres given by USCGS) are different on all these occasions. The mean value of the distance obtained from these five observations agrees with the distance obtained from the S-P interval.

TABLE 1

Serial No.	Date	Epicentre (USCGS)		Origin time (USCGS) (GMT)	Distance from Delhi (degrees)	Magnitude (from USCGS cards)	Yield (Uppsala) (megatons)
		Lat. (°N)	Long. (°E)	h m s			
1	5-8-1962	74·2	52·5	09 08 45·8	47·3	—	40
2	20-8-1962	74·4	51·2	09 02 14·5	47·7	—	12
3	27-8-1962	74·7	50·3	09 00 50·9	48·0	—	—
4	8-9-1962	73·7	53·8	10 17 57·7	46·7	$4\frac{3}{4}$	8
5	15-9-1962	74·4	51·5	08 02 13·9	47·6	—	15
6	19-9-1962	73·8	53·8	11 00 56·4	46·8	$5–5\frac{1}{4}$	28
7	25-9-1962	73·7	55·0	13 02 31·7	46·6	$5\frac{1}{4}$	30
8	27-9-1962	74·3	52·4	08 03 16·4	47·4	$5\frac{1}{4}–5\frac{1}{2}$	32
9	22-10-1962	73·4	54·9	09 06 10·1	46·4	$5–5\frac{1}{4}$	24

TABLE 2

	Date (1962)	5 Aug	20 Aug	27 Aug	8 Sep	15 Sep	19 Sep	25 Sep	27 Sep	22 Oct
Arrival time (GMT) of important phases	P	091715	—	—	—	—	110928	131105	081145	091443
	PP	091907	—	—	—	—	111115	131256	081336	091634
	S	092406	—	—	—	—	111619	131756	081836	092134
	Sa (Caloi wave)									
	North	092740	092103	091935	—	082106	111956	132133	082212	092508
	East	092740	—	—	—	082106	111947	132132	082217	092510
	Vertical	092807	—	—	—	082130	112017	132156	082236	092534
	L_R (Z)	093005	—	—	—	082355	112215	132350	082430	092730
	L_R (max.Z)	093826	093150	093025	104736	083149	113039	113217	083258	093554
$\triangle$(S-P) (degrees)		46·9	—	—	—	—	46·9	46·9	46·9	46·9
Origin time (GMT)		090841	—	—	—	—	110054	130231	080311	090609
Magnitude (Delhi data)		5·7	5·1	5·2	4·9	5·1	5·4	5·5	5·6	5·25

We have, therefore, adopted a constant value of $\triangle = 46·9°$ for the distance of the explosions from Delhi. Deviations are generally of the order of $\frac{1}{2}$ a degree and can be attributed to errors in the location of the epicentres.

In Fig. 2 typical records obtained by the Vertical (Z) and North (N) components for some of the larger explosions of this series are reproduced.

Fig. 3 is a graph showing the relationship between the maximum ground motion in Rayleigh waves recorded at Delhi and the yield as given by Uppsala; the recorded ground motion is proportional to $W^{\frac{2}{3}}$,where W is the yield. The same relationship is also observed in the case of the pressure-pulse recorded on microbarographs. In this case, however, only three observations were available.

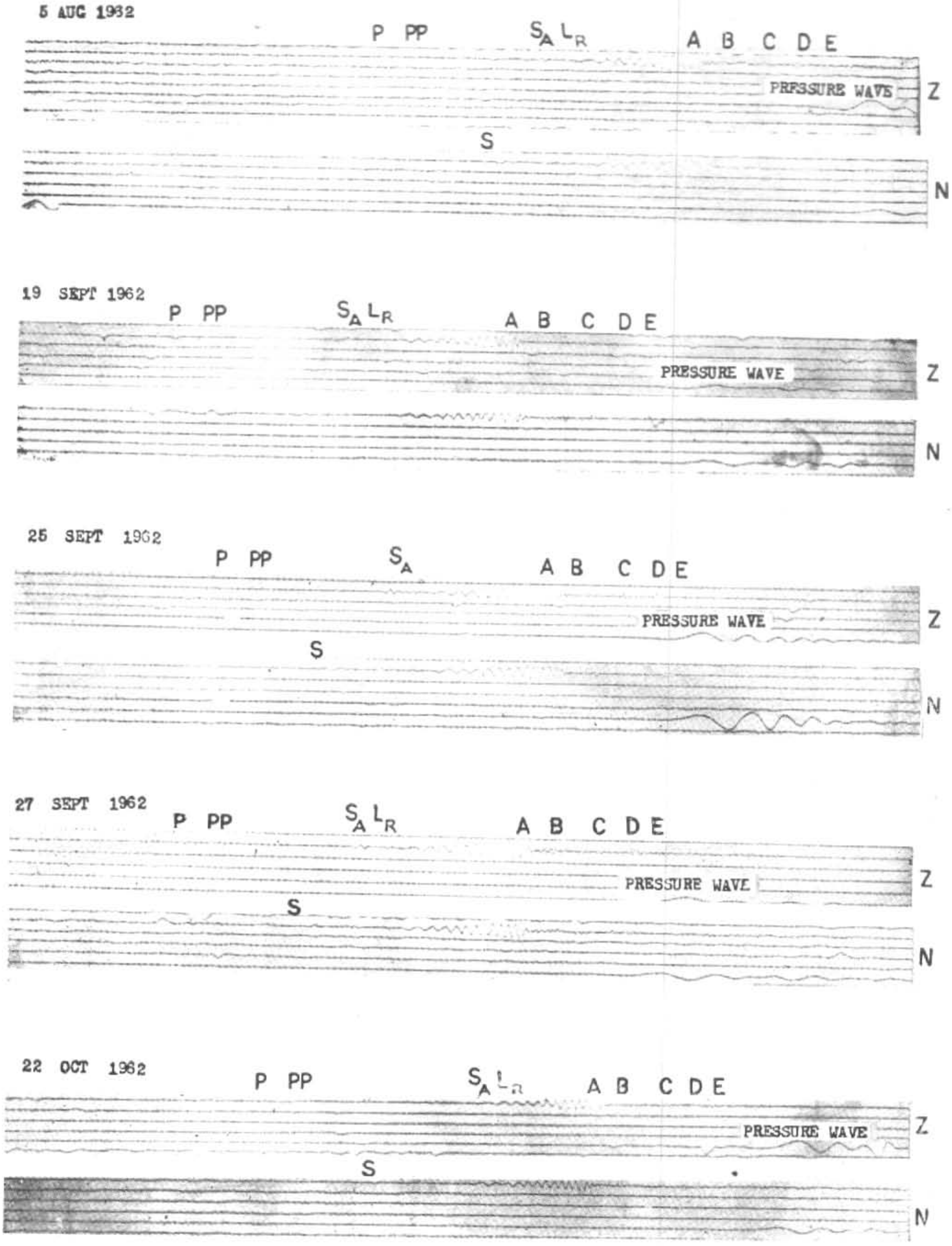

Fig. 2. Seismic records of explosions

3. Body Waves

In general, the body waves, P and S have been recorded clearly only on occasions when the yield was large enough (more than 20 megatons). On such occasions the P appears as a sharp compressional impulse on the Z component. It crosses the zero line after about 3 to 4 seconds, goes through a minimum, and then gradually returns to zero, without any subsequent oscillatory motion. The behaviour is the same as if the seismometer boom was subjected to a sudden tap. On a few occasions the P could also be clearly identified on a short period vertical Benioff seismograph. Here again just one wave could be identified and its characteristics were similar to those of the long period seismograms, except that the time of first zero crossing was less than a second. This type of record appears to be a chief characteristic of the P waves recorded due to atmospheric explosions. In the case of under water explosions, the onset of P is followed by oscillatory motion lasting for several seconds (Tandon 1958).

The horizontal components also exhibited the same characteristics as the vertical, although the recorded amplitudes on the north-south component were smaller than on the vertical and were the least on the E-W component, as expected. The reflected phase PP appeared after an interval of $1^m\ 51^s$ of the arrival of P which agrees well with the calculated interval of $1^m\ 50^s$ obtained from Jeffreys and Bullen's Tables for a distance of $\triangle=46 \cdot 9°$ (obtained from the S-P interval). The general character of this wave, as recorded, was he same as that of P. The onset of PP, on all occasions when it was recorded, showed a movement towards south, *i.e.*, the same as shown by P, which shows that there was no phase change in P during reflection at the free boundary. The onset of the S-phase is usually quite clear on the horizontal components. It is seen that on all the days the S-phase on the north-component is followed after about half a minute by a single wave having a period of nearly a minute. On the vertical the S-phase is not identified with clarity in all the five cases. When it could be identified, it appeared after an interval of $6^m\ 51^s$ of the arrival of P and this gave the distance of the source as $\triangle=46 \cdot 9°$. The ratio of the amplitudes of the S to P wave is much smaller in these records, than usually recorded in the case of shallow focus earthquakes.

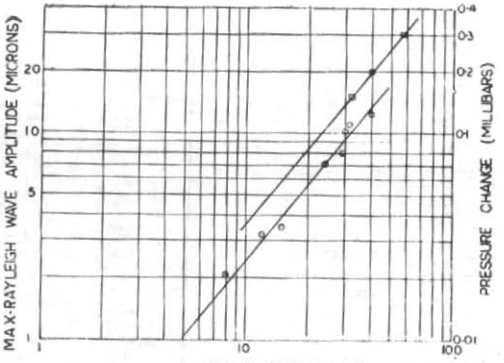

Fig. 3

4. Surface Waves

Surface waves comprise, by far, the most characteristic and dominating part of the seismograms. These waves appear on all the components, about 10 minutes 30 seconds after the onset of P, and continue for about 10 minutes. The vertical component, however, shows these waves most clearly and with the maximum of amplitudes; compared to the horizontal component records, in which the N-S component shows them better. The waves are not well recorded in the E-W component, which happens to be almost transverse to the wave paths from the ground-zero. The group starts with a pulse-like wave in all the components followed by rather complicated record for about two minutes thereafter. During these two minutes waves of more than one system appear to be superimposed. This part of the seismogram is followed by the main Rayleigh waves, which are best recorded in the vertical component. Superimposed on the Rayleigh waves in the first few minutes are small shorter period waves—the M2-waves. They are also clearly recorded in the N-S component but with smaller amplitudes. The E-W component shows the Rayleigh and M2 waves with smaller amplitudes. Both, on the vertical and the N-S component records, the Rayleigh waves show clear dispersion. The waves start with periods in excess of one minute and gradually decrease to about 18 seconds, when they show the maximum amplitudes. There is a rather abrupt cut off of the wave group after this maximum. The whole group of surface waves gives the records from these explosions a characteristic appearance, identical on all the days, except for amplitudes. In fact, identification of the explosions recorded could be made simply from this property.

Surface waves, particularly the Rayleigh waves, are recorded by seismographs in natural earthquakes and have been extensively studied by various workers. The simple symmetrical seismic source function due to the atmospheric explosions has, however, given records which are much more free from any other disturbance. For this reason an attempt has been made to study the various waves in the surface wave group described above. The results of this study are given in the following paragraphs.

5. Sa-Wave

As mentioned earlier, the record of the surface wave group begins, in all the components with a pulse-like wave. On the vertical the wave is recorded with a travel-time of $19^m\ 25^s$, giving a speed of travel of 4·45 km/sec. The pulse has a period of about 30 seconds. In the N-S and the E-W components the wave is recorded about 20 seconds earlier and with a period around 15 seconds. Thus the ground motion in the vertical appears to start just after that in the horizontal is over. For the epicentral distance of Delhi ($\triangle=46\cdot9°$) the travel time of this wave is about 35 sec less than that of SS and about 52 sec less than that of ScS. These differences are more than what could be taken as errors of observation. A further point of interest is the large amplitude of the wave in all the components compared to that of any of the body waves. It would thus appear that the wave is neither SS nor ScS, but Sa, the transverse channel wave first discovered by Caloi (1953).

Caloi observed Sa waves during earthquakes with focal depths of 50 to 250 km and gave a speed of travel of 4·4 km/sec. The presence of these waves was explained as due to the existence of a wave-guide in the upper portion of the Earth's mantle. Press and Ewing (1954, 1955) observed the Sa waves at distances of 52° to 125° from earthquakes with focal depths of 60 to 200 km. They obtained a velocity of 4·58 km/sec for the wave. They also found that the wave was recorded with larger amplitude in the vertical and with a period of 20 to 30 seconds, and that the records of the horizontal components were not coherent with that of the vertical. Khorosheva (1960), in his investigation of these waves, has observed them at distances of 22° to 100°, in records of earthquakes with focal depths from 50 to 640 km. The results of the present study are, therefore, in conformity with those of the above workers. In view of their propogation in a wave guide below the crust, it is interesting that a surface source, such as an atmospheric explosion, could also give rise to these waves.

6. M2-Waves

The M2-waves are best recorded on the vertical component seismographs and are superimposed on the long period Rayleigh waves. For about two minutes after the onset of the Sa wave and the beginning of the clear part of M2-waves, the records show rather a complicated pattern. An enlarged reproduction of this portion of the record obtained on 27 September 1962 is shown in Fig. 4. It may be seen that the later arrivals of the M2-waves show clear normal dispersion, the periods decreasing from about 15 seconds to about 8 seconds. Computation of wave

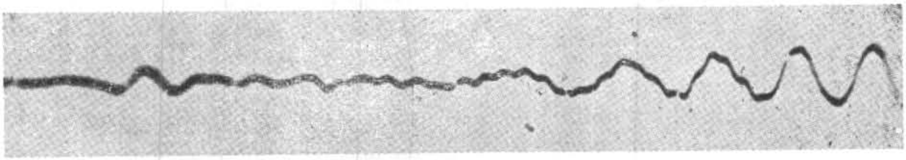

Fig. 4. Portion of record (enlarged) showing Caloi and M2-waves, 27 September 1962

periods and group velocities in the earlier part of the record indicated the presence of waves with both normal and inverse dispersion. It was, therefore, attempted to separate the record into two trains of waves, *i.e.*,those with normal dispersion and those following inverse dispersion. The results of computation are given in Table 3. Fig. 5 shows the dispersion curves obtained from the above data.

The results could be separated into two groups, *viz.*, the part relating to the clearly recorded later arrivals with periods ranging from 8 seconds to about 15 seconds. These waves show normal dispersion. The second part, resulting from the separation into two groups of waves of the earlier part of the record, comprised of waves of periods ranging from about 15 seconds to about 70 seconds. This portion shows the presence of waves with inverse dispersion in the period range of 15 to about 35 sec, followed by normally dispersed longer period waves. The merging of these two branches takes place around a period of 35 sec, and is associated with a minimum in the group velocity curve corresponding to a velocity of 4·1 km/sec.

M2-waves were discovered long ago by Kanai (1948) in the seismic records of some Japanese earthquakes. He observed these waves in the period range of about 4 to 7 seconds, and at short epicentral distances. Oliver and Ewing (1958) have studied M2-waves across the North American continent. Their observations include waves from about 1·5 to 15 sec. Waves of period less than 5 sec, showed inverse dispersion and the longer period waves showed normal dispersion, with a minimum group velocity of 3 km/sec associated with the merging of the two branches. Across the path Alaska to Palisades, they found the minimum group velocity of about 3·4 km/sec at a period of 7 sec. For periods greater than 7 sec their results showed continuous increase in velocity up to a period of 15 seconds. The observations did not extend for larger periods. Their results were in agreement with the theoretical curves of Nagamune's case II (1956) for a crustal thickness of 35 km. Kovach (1959) studied the M2-waves recorded at Uppsala from an earthquake in Sinkiang. His observations, which included waves upto a period of about 13 sec, are in agreement with the theoretical curve of Dorman for a three-layered crust (total thickness 45 km) with a surface sedimentary layer of shear velocity of 2·3 km/sec.

Comparison of the results of the present study with the above shows satisfactory general agreement in the range of 8 to 15 sec. The agreement with Dorman's curve in particular (shown in Fig. 5) is significant. This close agreement thus indicates an average crustal thickness of about 45 km for the continental crust along the path Novaya Zemlya to Delhi.

Earlier observational data regarding the existence of M2-waves of longer periods are not known to us. It may, however, be mentioned that Nagamune's theoretical curve for case 1 shows that, with higher contrast in the velocity of shear waves in the crustal layering, longer period M2-waves are possible. His curve shows waves of inverse dispersion in the period range from 17 to 33 sec with a minimum group velocity of about

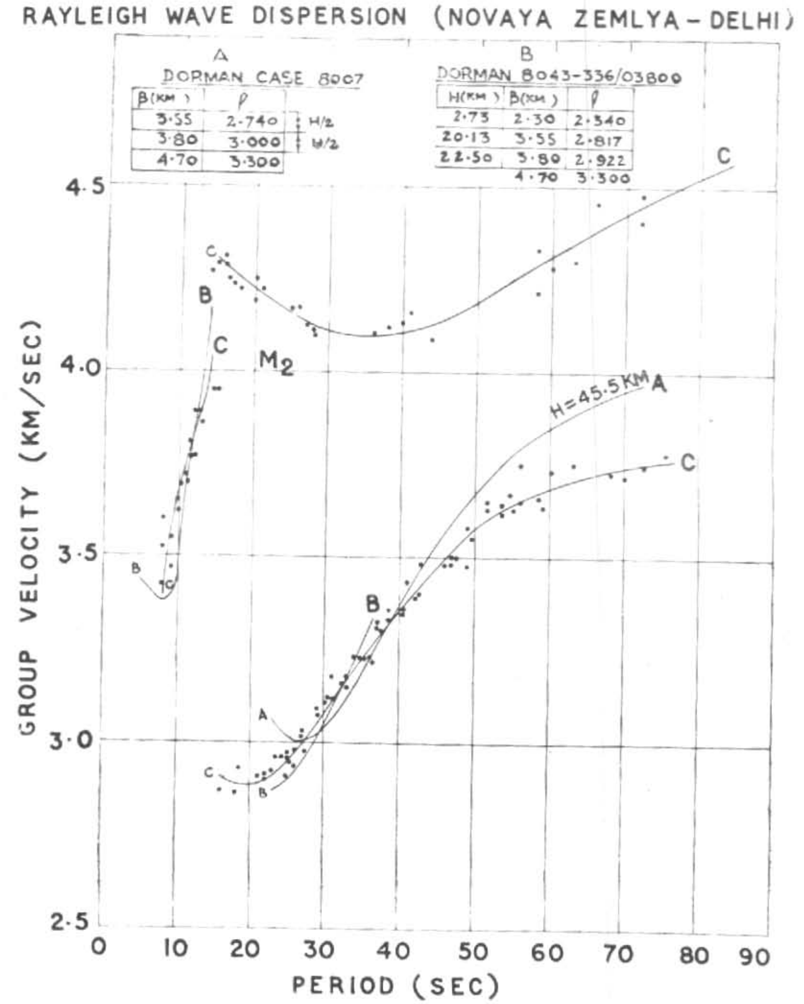

Fig. 5

3·0 km/sec at 33 sec. Further consideration of the effect of the gradient of velocity in the mantle and the curvature of the earth, as pointed out by Oliver and Ewing would result in a "Flattening of the group velocity curve and perhaps another minimum at a velocity of about 4·4-4·7 km/sec at roughly a period of 20 seconds". The extension of the present observations at periods larger than 15 sec, with a minimum of group velocity of 4·1 km/sec around a period of 35 sec, seems to cofnirm these expectations.

7. Rayleigh Waves

These waves start with periods in excess of one minute and a velocity of nearly 4 km/sec and show beautiful dispersion along the train. The gradual decrease in wave periods is accompanied with an increase in amplitudes. The group attains the maximum amplitude at a period of about 18 sec, beyond which there is rather an abrupt cut off. The whole group of waves is identical on the records of all the explosions, except for the amplitudes, which are dependent on the yield of the

TABLE 3
M2-Dispersion

5 AUG 1962		25 SEP 1962		27 SEP 1962	
Period (sec)	Group velocity (km/sec)	Period (sec)	Group velocity (km/sec)	Period (sec)	Group velocity (km/sec)
8·0	3·43	8·0	3·40	8·0	3·53
8·5	3·50	9·0	3·47	8·0	3·60
9·0	3·57	9·0	3·55	10·5	3·69
10·0	3·65	10·0	3·62	12·0	3·77
11·0	3·72	11·0	3·70	13·0	3·86
11·5	3·80	12·0	3·77	15·0	3·95
12·5	3·89	12·0	3·83	44·0	4·09
14·0	3·98	12·0	3·89	50·0	4·19
36·0	4·10	15·0	3·95	60·0	4·28
40·0	4·13	38·0	4·12	72·0	4·41
58·0	4·22	41·0	4·16	20·0	4·19
63·0	4·30	54·0	4·24	18·0	4·22
72·0	4·48	58·0	4·33	16·5	4·25
28·1	4·10	66·0	4·46	16·0	4·28
27·0	4·13	28·0	4·10		
25·0	4·17	30·0	4·13		
21·0	4·21	26·0	4·17		
17·0	4·24	21·0	4·22		
14·0	4·27	20·0	4·25		
16·0	4·31	15·0	4·29		

explosions. Comparison of the records from the vertical with the N-S component showed the phase difference expected of Rayleigh waves.

Another interesting observation in accordance with theory is the ratio of the vertical to the horizontal movement. The E-W component, which is almost transverse to the wave path has not recorded the Rayleigh waves well. The amplitudes of the maximum recorded on the vertical are plotted against those of the N-S component (Fig. 6). The linear relationship between them and the ratio 1·5 for AZ/AN is significant.

The dispersion of the Rayleigh waves was studied on all the days in the manner described by Ewing and Press (1952). The arrival times of every crest and trough were plotted against crest and trough numbers and smooth curves were drawn through them. Periods corresponding to different arrival times were determined from the slopes of the curves and their group velocities calculated. As pointed out earlier, the epicentral distance of Delhi was taken as 46·9° in the above calculations. The results obtained are given in Table 4. They are all plotted in one graph which may be seen in Fig. 5.

It may be seen that the minimum group velocity of 2·9 km/sec appears at a period of 20 seconds, even though many points in the inverse branch could not be observed. The scatter of the results from day-to-day does not exceed 0·1 km/sec and is within the errors of observation. Dorman's theoretical dispersion curve* (case 8007) is also shown in Fig. 5. It is seen that observed values agree

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*Taken from Kovach (1959)

TABLE 4
Rayleigh Wave Dispersion

Period (sec)	Group velocity (km sec)
5 AUG 1962	
73·0	3·75
58·5	3·64
49·0	3·58
43·0	3·48
40·0	3·38
38·5	3·33
37·5	3·30
34·5	3·23
32·5	3·16
30·5	3·06
27·5	2·98
25·0	2·91
20 AUG 1962	
55·0	3·63
46·0	3·48
38·5	3·36
34·0	3·23
34·5	3·12
29·0	3·07
27·0	3·02
24·0	2·90
21·0	2·91
18·0	2·86
27 AUG 1962	
70·0	3·72
49·0	3·57
41·5	3·43
36·5	3·31
33·0	3·18
30·5	3·07
28·0	3·02
25·0	2·97
22·5	2·92
16·0	2·87
8 SEP 1962	
54·5	3·67
47·0	3·52
42·0	3·39
36·5	3·26
31·0	3·18
29·0	3·08
27·0	3·03
25·5	2·98
23·0	2·92
20·5	2·88
15 SEP 1962	
56·0	3·75
51·5	3·63
26·5	3·48
40·5	3·35
36·5	3·22
31·0	3·11
25·5	3·00
21·5	2·90
19 SEP 1962	
75·5	3·78
58·5	3·66
53·5	3·62
49·0	3·48
39·8	3·35
34·0	3·22
30·0	3·11
26·5	3·00
23·5	2·96
18·5	2·93
25 SEP 1962	
59·5	3·73
56·0	3·65
49·5	3·55
42·5	3·40
37·0	3·28
33·0	3·15
29·0	3·05
26·0	2·94
17·0	2·90
27 SEP 1962	
68·0	3·73
53·5	3·64
47·5	3·50
40·5	3·36
36·0	3·23
30·5	3·12
27·5	3·01
25·5	2·95
23·5	2·91
22 OCT 1962	
63·0	3·75
51·5	3·65
47·0	3·50
40·5	3·36
35·5	3·23
31·0	3·12
27·5	3·01
25·0	2·96
22·0	2·91

well with the theoretical curve for $H=45$ km for periods below 35 seconds. The observed points lie below the theoretical curve for periods higher than 40 sec, a result usually attributed to the effect of the velocity gradient in the mantle. Towards lower periods, particularly near the minimum of the curve the observed values are affected by variations and inhomogeneities in the sedimentary column. This effect is clearly brought out by better agreements of the observed values in this range of period with Dorman's theoretical curve for case 8043-336/03800,* which takes into account a sedimentary layer. This curve is also shown in Fig. 5. Comparison with these curves thus indicates an average crustal thickness of about 45 km for the continental path from Novaya Zemlya to Delhi.

Rayleigh wave dispersion for Urasian paths has been studied by a number of workers. Bath and Vogel (1957) have determined the dispersion curve for the purely continental path across Europe, from Turkey to Uppsala. Their observations, extending from a period of about 18 seconds to one minute are given in Fig. 7 along with the results of Kovach (1959), Porkka (1960 a) and of the present study. It may be seen that the values of group velocities for the path Novaya Zemlya to Delhi are generally less than those for the other paths, by more than 0·15 km/sec, for periods greater than 30 sec. For some periods, they fall below the value obtained by Porkka by as much as 0·20 km/sec. This comparison brings out clearly the effect of the Asian mountain range, which constitutes about 25 per cent of the path from Novaya Zemlya to Delhi. Kovach's study was made from the records at Lwiro of an Aleutian earthquake with a very long path. Comparing with Dorman's theoretical curves, he has concluded, that the average crustal thickness for the path is slightly less than 40 km. This was in agreement with the estimate of 40 km by Riznichenko (1957), based on seismic records of large explosions at a place around Lat. 54°N, Long. 60° E close to the great circle path. Porkka studied the dispersion from Kamchatka and Japan to Finland and arrived at a value of 37 to 38 km for the crustal thickness. From a study of M2-wave dispersion for the path Sinkiang to Uppsala, Kovach got a value of 45 km for the crustal thickness. It may be reasonable, therefore, to take the average crustal thickness for these paths (which do not include the Asian mountain system) as 40 km.

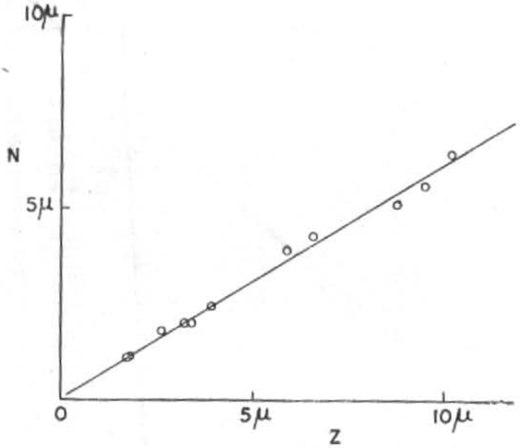

Fig. 6. Ratio of Z/N of Rayleigh waves

The path from Novaya Zemlya to Delhi passes through a nearly uniform terrain upto Lat. 43°N and then encounters the Asian mountain system. If the 1-km contour is taken roughly as the dividing line between high lands and the plains, the former would comprise nearly one-fourth of the total path. Taking Porkka's data as representing the average crust for the non-mountainous part of the path and the observed dispersion curve as given in Fig. 5 as representative for the whole path, it is possible to compute dispersion curve which would be representative of the hilly region provided that the two portions of the path are assumed to be structurally similar, except for the difference in the thickness of the crust. The results of this computation show that the group-velocities for the crust below the mountains are lower than those for the whole path by amounts

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*Taken from Kovach (1959)

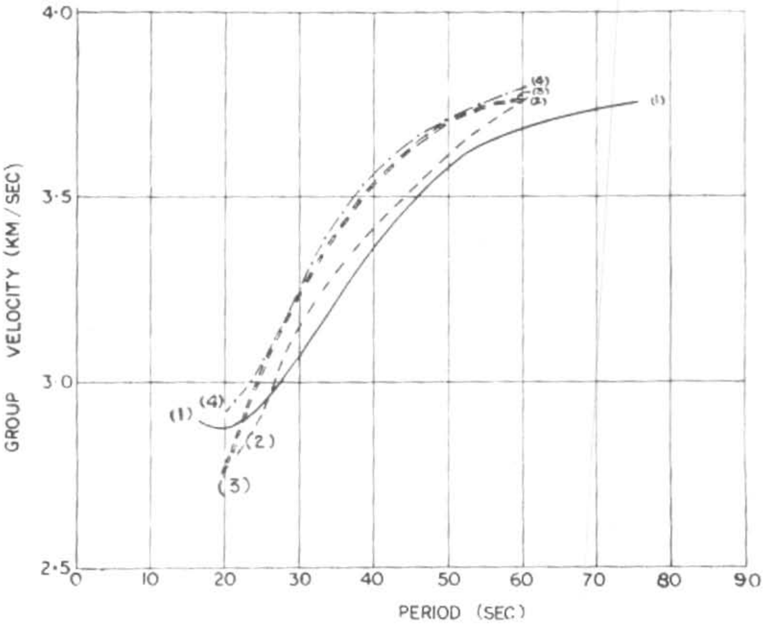


Fig. 7. Rayleigh wave dispersion

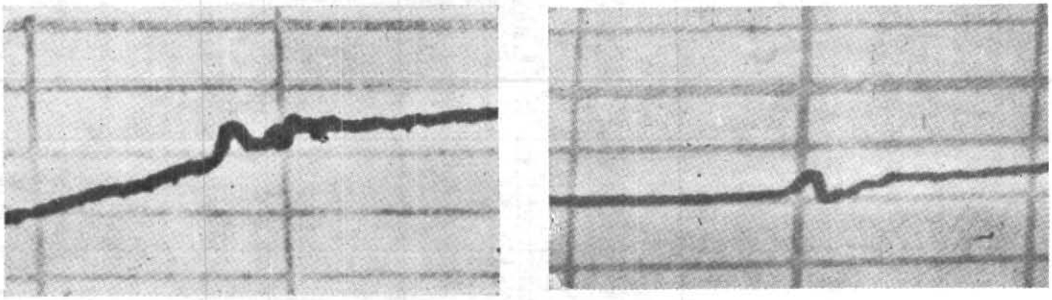
(1) Novaya Zemlya—Delhi (2) Turkey—Uppsala (Bath and Vogel 1957)
(3) Aleutians—Lwiro (Kovach 1959) (4) Kamchatka and Japan—Finland (Porkka 1960)

ranging from 0·2 km/sec for periods around 25 seconds to 0·4 km/sec at 55 seconds. A rough comparison of the group velocity at 40 sec with the group velocity computed from the theoretical phase velocity curves of Ewing and Press shows that this would correspond to a crustal thickness of 55 to 60 km under the mountains. This value falls in line with the results of Porkka (1960 b), who found that the crust under the mountains of Asia in the great circle paths from Tibet, Assam and Eastern China to Helsinki is 20 km thicker than in the plains of the continent.

8. The Pressure Pulse

A chief feature of the seismograms of the high yield atmospheric bursts is the appearance of a train of long period waves long after the arrival of the seismic surface waves. These waves arrive simultaneously with those on microbarographs, showing that they have travelled with the speed of sound. In the seismographic records, at Delhi, they appear more than four hours after the arrival of the maximum of the Rayleigh wave group. They appear both on the vertical as well as the horizontal components. The wave form is that of normally dispersive damped sine waves. Although, their general characteristics appear similar on the records of explosions carried out on different days and having different yields, yet one can notice slight changes in form on different occasions, an effect perhaps attributable to the day-to day variations of the atmospheric characteristics and mode of explosions. A few typical records are reproduced in Fig. 2 along with seismic body and surface waves.

Microbarograph records of the meteorological observatory at New Delhi were examined for all the dates on which the long period waves were recorded on seismographs. It was found that the atmospheric pulse could be clearly identified on only a few occasions. Enlarged records of two of these are shown in Fig. 8. Comparison of these



5 August 1962 27 September 1962

Fig. 8. Records of microbarographs showing pressure waves

records with the ground motion recorded on the vertical component shows considerable similarity of form. In addition to normal dispersion the pressure pulse as recorded on microbarographs also shows an inverse dispersion, an effect not so clearly seen on seismograph records.

It has already been mentioned above that the pressure pulse is recorded by both vertical and horizontal components. This would indicate a direct coupling of the atmosphere and the ground and the propagation of dispersive surface waves travelling along the earth's surface with the velocity of sound. Derivation of the particle motion revealed motion in an elliptic orbit analogous to that in Rayleigh waves but not retrograde. Since the formation of such waves is difficult to comprehend on theoretical ground, the possibility of the horizontal movement of the seismograph booms due to tilting of the ground, was examined. This could be caused by the vertical uplift and dip of the ground, in response to pressure changes in the atmosphere by the propagation of the sound pulse. For this purpose the amplitudes recorded by the vertical component were measured after every 20 seconds and the corresponding ground motion was read from the response curve. The periods could be obtained from the arrival time *versus* period curve. A curve was then plotted with the vertical ground movement against the arrival time. The tilt of the seismograph pillar at any time could be found from the slope of the curve at that time, and another curve could be drawn showing ground tilt *versus* arrival time. If a be the displacement recorded at any time by the horizontal component, this could be caused either by the ground motion of the particle in a horizontal direction or by a ground tilt Ψ_H such that $(4\pi^2/Te^2)\ a = g\Psi_H$, where Te is the wave period. It is thus possible to know the value of Ψ_H at different arrival times and compare it with the value of Ψ_V obtained from the vertical component. In Fig. 9 a comparison of Ψ_V and Ψ_H is shown for three days. The agreement seems to be good, considering the errors involved in the measurement of periods etc. This shows that the variation in atmospheric pressure of the order of a fraction of a millibar in the acoustic-gravity wave is sufficient to cause the ground surface to rise and fall.

Donn and Ewing (1962) analysed the records of pressure pulse due to the Russian Nuclear Explosion of 30 October 1961, of nine stations scattered over the globe. They showed that the waves begin with the highest amplitude and show normal dispersion. On these waves are also superimposed a low amplitude long period train of wave which shows inverse dispersion. The dispersion curves of direct waves significantly showed variations in atmospheric structure along different azimuths. They obtained an average speed of 324 m/sec for the first arrival which compared well with the maximum obtained in the Krakatoa explosion.

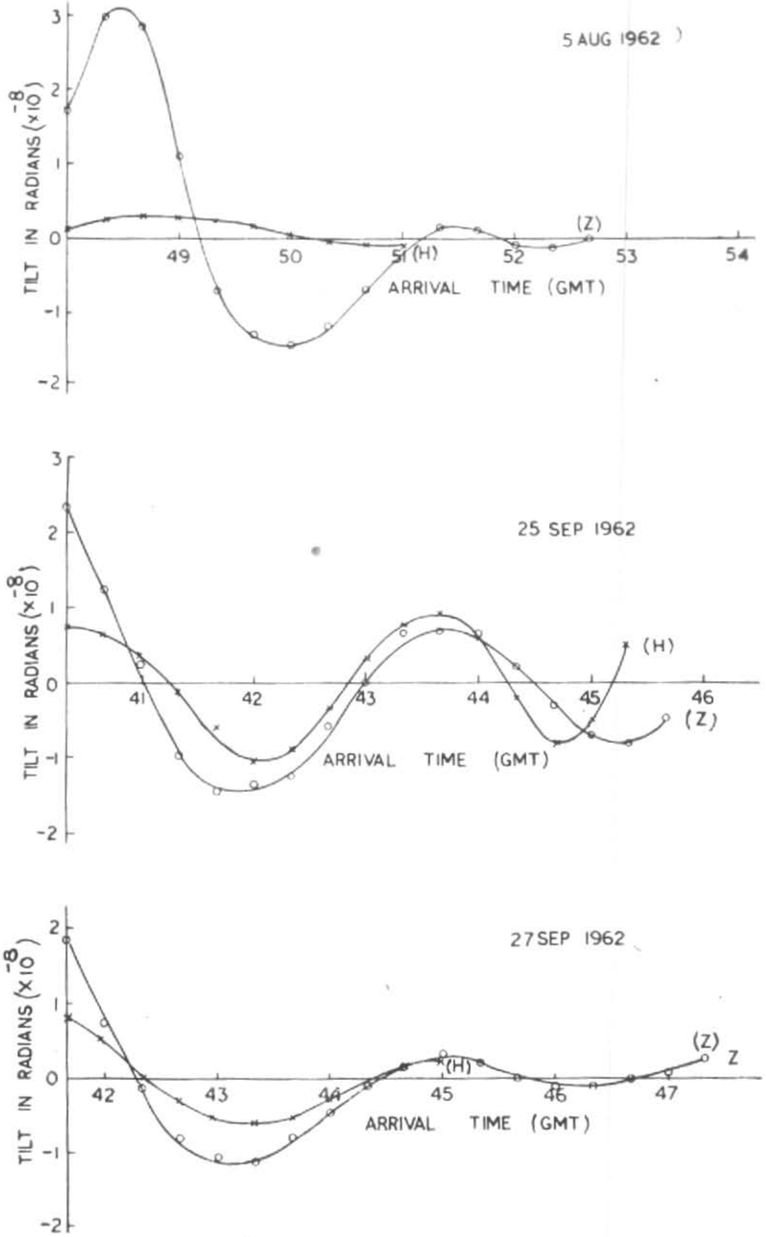


Fig. 9. Ground tilt : Comparison of values from vertical and horizontal components

Pfeffer (1962) has described a theoretical procedure for calculating the horizontal propagation speeds of the acoustic-gravity waves in a stratified atmosphere in which the atmosphere is represented by a large series of isothermal layers. The method used by him was similar to that employed by Thomson (1950), Haskell (1953) and Dorman (1962), for propagation along the solid earth. Pfeffer and Zarichny (1962) applied the method for various three and four layered models and found the results to be in qualitative agreement with the records used by Donn and Ewing (1962).

The records of the pressure pulse by the vertical component seismograph obtained for a few days at Delhi were analysed. The results are given in Table 5 and curves showing the variation of group velocity with period are shown in Fig. 10. For the sake of comparison we have also given in the same figure the dispersion curves for two theoretical models of the atmosphere as an inset. There is slight variation from day-to day in the magnitude of the observed velocities but the nature of the curves is generally the same. Between the period range 70—100 sec the observed values agree better with Model A. For longer periods the agreement is better with Model X. The value of the maximum of group velocity obtained is around 315 m/sec. No inverse branch could be isolated due to low amplitudes and long periods.

TABLE 5

Pressure Wave Dispersion

(Vertical Seismograph)

Period (sec)	Group velocity (m/sec)	Period (sec)	Group velocity (m/sec)
5 AUG 1962		25 SEP 1962(*contd*)	
273	309·7	120	306·1
243	308·6	108	305·2
198	307·5	93	304·0
155	306·5	83	302·9
108	305·4	75	301·8
87	304·3	63	300·9
72	303·3		
27 AUG 1962		27 SEP 1962	
318	314·5	552	313·8
252	313·1	420	312·7
202	312·2	306	311·6
174	311·1	242	310·5
152	309·8	204	309·3
132	308·8	171	308·2
117	307·7	150	307·1
101	306·6	126	306·1
90	305·6	111	305·1
82	304·5	102	304·0
72	303·5	96	302·9
25 SEP 1962		22 OCT 1962	
342	312·7	153	305·8
276	311·6	132	304·7
216	310·5	120	303·6
186	309·4	105	302·5
152	308·4	90	301·4
135	307·2	81	300·4

It may not be out of place here to mention a few words about the propagation of the acoustic-gravity wave due to these explosions. Mention has already been made of the work of Donn and Ewing. Soon after the explosion of 30 October 1961, a number of papers concerning the recording of the pressure pulse appeared. Wexler and Hass (1962) have published a detailed paper on the record of the pressure wave due to this explosion over a very large number of stations in USA and other parts of the world. Using data obtained on ordinary microbarographs they have drawn isochrones of the primary waves and also the returning wave over the entire globe. The variation in the pattern obtained have generally supported the influence of winds and thermal structure on the movement and amplitude of the wave forms.

The explosion of 30 October 1961 was also recorded on a large number of microbarographs in India. A paper incorporating these observations has been published by Rao and Ananthakrishnan (1962). Using this data we have plotted the arrival times of the pressure wave at different stations in India in Fig. 11. For this purpose we have chosen the epicentre as Lat. 74° N and Long. 54° E which is the average of the epicentres of different explosions of the 1962 series determined by USCGS. The arrival times are scattered round a straight line, which gives the average speed of travel as 310 m/sec.

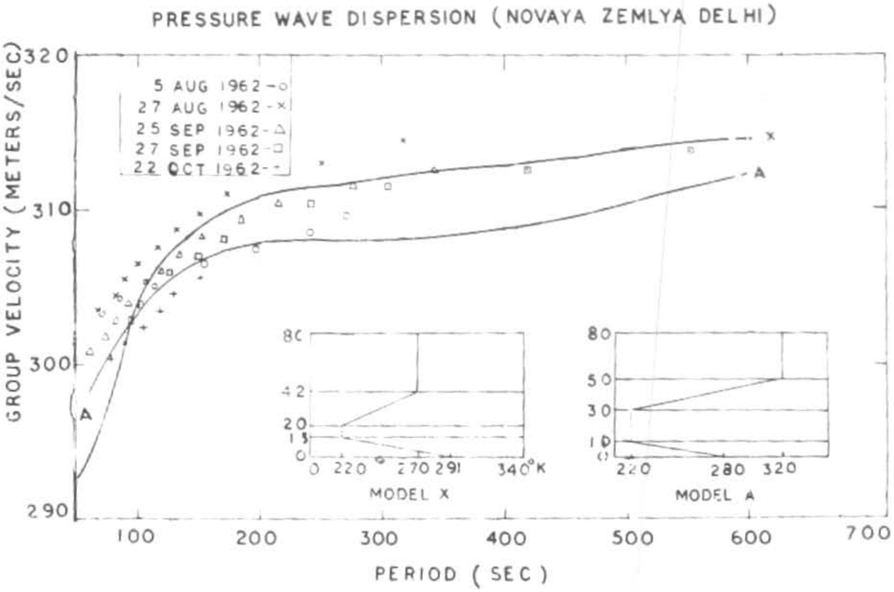


Fig. 10

It is significant to note that the pulse arrived earlier at stations located in west India in comparison to stations in east India. If we shift the epicentre by about 5 degrees westwards, this effect could be minimised, but then the epicentre would not be in conformity with the more reliable seismic observations. We are thus inclined to believe that this effect is geniune. It has not been possible to look into the cause of this effect but it seems that the presence of the great Himalayan mountains across the path of the pressure wave reaching the eastern stations is a contributory cause.

Another feature of the pressure wave observed from microbarograms is the general increase in wave periods with distance. This is also shown in Fig. 11.

9. Coda

In this section we shall describe some of the chief characteristics of the records which appear prominently on seismograms after the appearance of the Rayleigh wave maximum. As in the records obtained from earthquakes, the main Rayleigh wave amplitudes achieve a maximum at a period of nearly 18 seconds. The amplitude then diminishes suddenly, a feature not so prominent for Rayleigh waves recorded in natural earthquakes. The maximum amplitude wave of the Rayleigh waves, which is marked A in the seismograms in Fig. 2 is followed by other wave groups clearly distinguishable from the background. These groups have been marked B, C, D and E on the seismograms in Fig. 2. It will be seen that the same groups are prominent on all the days and their relative amplitudes are also not very different.

In Table 6 we have given the difference in arrival times of the maximum wave in groups B, C, D and E and the arrival time of the Rayleigh wave maxima A. It will be seen that these time differences, *i.e.*, B—A, C—A, D—A and E—A have nearly the same value on all the days. There are slight differences only on two days, *viz.*, 20 and 22 August 1962 in the values of B—A and C—A but D—A is the same as on all the other days. On both these days the recorded amplitudes were small due to lower yields and

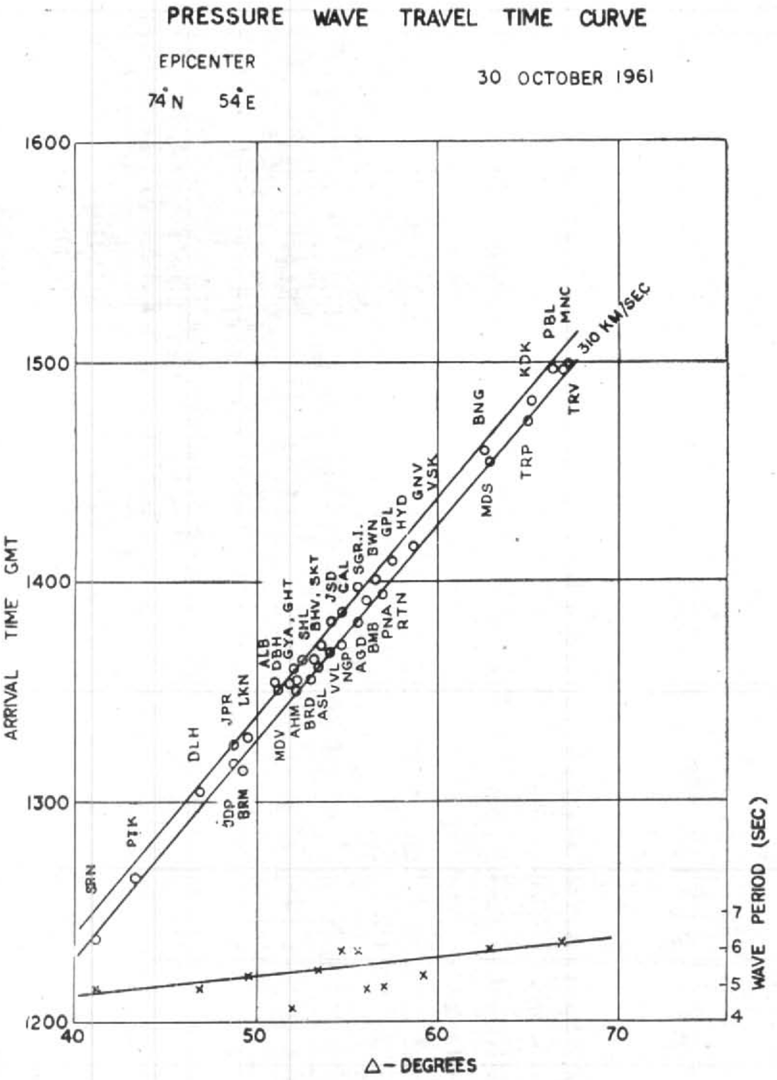


Fig. 11

hence the difference could be attributed to errors in identification and measurement.

Normally the surface waves arriving within 10 to 15 minutes after the group velocity minimum are interpreted as due to scattering and reflections from inhomogeneities in the earth's crust. In this particular case there seems to be another possible explanation particularly for the large wave group D which appears nearly 7 minutes after the maximum Rayleigh wave peak A. This time interval is of the same order as would be expected for the arrival of sound rays from a high altitude source in the first zone of abnormal audibility. It is, therefore, quite possible that the group D as also some of the other waves around D have appeared on the seismograms as a result of the impact of

TABLE 6

Serial No.	Date	B—A		C—A		D—A		E—A	
		min	sec	min	sec	min	sec	min	sec
1	5-8-62	2	16	4	46	6	59	8	34
2	20-8-62	1	59	5	06	6	59		—
3	22-8-62	2	08	5	12	6	59		—
4	27-8-62	2	13	4	53	6	55	8	31
5	15-9-62	2	17	4	47	6	57	8	30
6	19-9-62	2	15	4	54	6	58	8	37
7	25-9-62	2	13	4	46	6	58	8	36
8	27-9-62	2	10	4	46	6	59	8	37
9	22-10-62	2	12	4	54	6	57	8	37

sound waves on the ground, after being reflected by the stratosphere.

10. Conclusion

In conclusion, the results of the above study may be summarised as below—

(1) The impact of the shock from the atmospheric explosions excited seismic waves, which were strong enough to be recorded at long distances.

(2) The P-waves could be detected at Delhi for explosions with yields exceeding about 20 megatons. This was recorded only as a single pulse, unlike in earthquakes in general and underwater explosions, when it is followed by a train of waves.

(3) The S-wave was less prominent in these records compared to those in shallow focus earthquakes of equivalent magnitudes. This is in conformity with the general expectations from compressional source functions.

(4) The guided wave Sa was prominently recorded with a speed of travel of 4·45 km/sec even when the seismic focus happened to be on the surface.

(5) M2-waves were well recorded in the range of periods 8—15 seconds and could also be detected in the higher period range. These waves showed normal dispersion from 8 to 15 sec, inverse dispersion from 15 to 35 seconds and normal dispersion again at higher periods. The dispersion in the range 8—15 sec indicates an average crustal thickness of about 45 km for the path.

(6) Rayleigh waves were beautifully developed and their dispersion could be studied without the interfering influence of other disturbances normally found in records of earthquakes. The dispersion studies also give an average crustal thickness of 45 km for the path. A further rough calculation, on the basis of Porkka's dispersion data indicates that the thickness of the crust under the mountain range across the great circle path from Novaya Zemlya to Delhi is 55—60 km.

(7) The pressure pulse resulting from the explosions was also recorded by the seismographs. On days when the yield of the explosion was more than 30 megatons, they were also recorded, at the same time by ordinary observatory microbarographs.

The nature of the dispersion of the waves in the pressure pulse agrees with the theoretical curves of Pfeffer and Pfeffer and Zarichny.

(8) The response of the horizontal component seismographs to the pressure pulse has been shown to be the result of the ground tilt associated with the passage of the pressure pulse. Computation of the same, made from the seismograms, shows satisfactory agreement in magnitude and phase.

(9) The records of the pressure pulse due to explosion of 30 October 1961 at a number of Indian stations show that the pulse arrived earlier at stations located in west India compared to those in east India. The presence of the great Himalayan mountains across the path of the pressure pulse is, perhaps, a contributory cause of this phenomenon.

(10) A prominent wave group was recorded on all the days about 7 minutes after the arrival of the Rayleigh wave maximum. Though similar arrivals on records of earthquakes are explained as resulting from scattering and reflections from inhomogeneities in the earth's crust, it is suggested that the above group could be the result of the impact of sound waves on the ground after reflection by the stratosphere.

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