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Seismic Surface Wave Dispersion and the Crust across the Gangetic basin

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ABSTRACT. Long Period seismograph records of Delhi of five earthquakes in the East Pakistan/Burma/India border region have been studied. The dispersion of fundamental and the second mode Rayleigh and Love waves and that of *PL* waves have been computed. Phase velocities of the fundamental Rayleigh and Love waves were also determined by using Brune's method. Inference regarding the structure of the crust across the Gangetic basin was made by comparison with known theoretical models as well as by using the partial derivatives of the phase velocities following Dorman and Ewing (1962), Brune and Dorman (1963) and Anderson (1964). All the data are found to be consistent with the following structure of the crust—

h	α	β	ρ
3 km	3·98	2·30	2·340
17 km	6·15	3·55	2·817
20 km	6·58	3·80	2·922

One of the earthquakes included in its path to Delhi a part of the continental shelf. The close agreement of the group velocities of Rayleigh waves for this mixed path with those from the other earthquakes shows that the dispersion properties of the continental shelf involved are nearly the same as of the Gangetic basin.

The results from the dispersion studies have been discussed with respect to the Geological and Geophysical results bearing on the subject.

1. Introduction

The dispersion of surface seismic waves affords a convenient way of studying the average properties of the earth's crust in a region, and has been used in this way when the more sophisticated methods of explosion seismology had not yet developed. Jeffreys and Bullen, in constructing their famous Travel Time Tables have adopted the structure of the earth's crust partly from Stoneley's studies of the dispersion of surface waves. As a result of advances made in recent times with the help of electronic computers in calculating the dispersion due to a multilayered crust, the method has become capable of giving further details of the structure of the crust, as well as the mantle.

It has, however, been found that the extraction of a crustal structure to explain a given dispersion curve does not result in a unique solution; but that a number of different structures can be found to explain a given curve reasonably closely. To reduce this ambiguity, it has been found necessary to combine data from different modes, *viz.*, Rayleigh and Love, fundamental and higher modes (Oliver and Ewing 1957, 1958; Oliver, Dorman and Sutton 1959, etc). Occasions are, however, few when a multiplicity of modes of surface waves across a particular region are well recorded and studied.

The operation of seismographs with adequate long period response has in recent years provided with good recordings of surface waves for such studies. The records of the WWSS Instruments operating at Delhi gave suitable records of the various modes of surface waves from a number of earthquakes. These have been used in the present study of the Gangetic basin and besides the fundamental Rayleigh and Love waves, higher mode waves and also *PL* waves have been used.

2. Data and Method used

For the purpose of the present study the Delhi Long Period seismograph records from five earthquakes originating in the East Pakistan/Burma-India border have been used. The details of these earthquakes are given in Table 1, and an index map showing the paths of the waves to Delhi is given in Fig. 1. The parameters relating to the epicentres, origin times and the depths of foci have been taken from the Preliminary Epicentre Cards issued by the USCGS. It may be seen that the earthquakes have depths of foci in the intermediate depth range and are in the magnitude range 5·3 – 6·4. The combination of these factors gave unusually clear recordings of the various types of surface waves which made the study possible. Even though the epicentral distance of these earthquakes from Delhi was less than 20°, surface waves of period as long as sixty seconds could be easily picked up.

In Table 1 are also included the epicentral distances from Delhi calculated from the USCGS' epicentres. It may be mentioned that the *S—P*

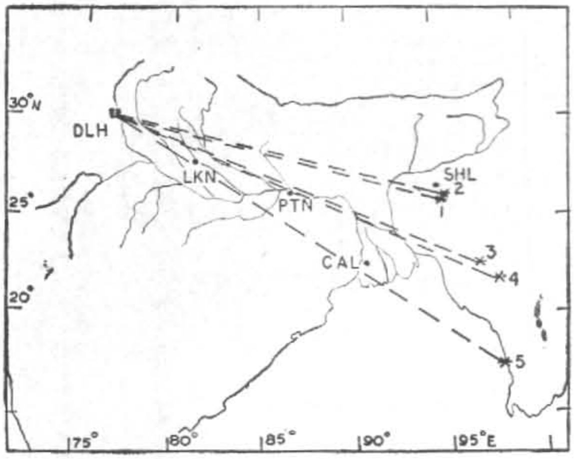


Fig. 1. Index map showing the epicentres of the earthquakes and the wave paths to Delhi

intervals at Indian stations used along with the J. B. Travel Time Tables give a shorter epicentral distance for each of the above earthquakes. Since the recording of the P and S phases in this distance range is likely to be affected by the "20° discontinuity", it was decided to use the calculated distances shown in Table 1 in the computation of the wave velocities.

Copies of the seismograms of some of the earthquakes are shown in Figs. 2 to 5. Fig. 2 shows the *PL* waves, first studied by Oliver and Major (1960), M_2 waves and Rayleigh waves. Fig. 3 from the earthquake No. 1 of lesser magnitude shows besides the Rayleigh waves, a clearer train of M_2 waves than Fig. 2. No *PL* wave could be detected on this record. Figs. 4 and 5 are North—South component records from earthquakes 1 and 2 and show the fundamental and higher mode Love waves. Love waves were not clearly recorded in the case of the other shocks. The dispersion of all these waves have been computed.

For the fundamental Rayleigh and Love waves and the *PL* waves the periods were determined from the slopes of the arrival time *versus* crest/trough number curves as outlined by Ewing and Press (1952). In the case of the higher modes, however, this method could not be used. First, because in the case of earthquakes 3 and 4, these waves were riding on the fundamental mode waves of large amplitudes and the train of waves could not be followed well. Further, as the seismograms had a time scale of only 15 mm/min measurement of the shorter periods showed a scatter comparable with the periods themselves. The position was, however, better on the records of earthquakes 1 and 2 but for purposes of uniformity, the periods were measured directly and taken as having arrived at the midpoint of the intervals. A similar difficulty has also been reported by Crampin (1964) in his studies of higher mode surface waves.

As the distances involved were small, the instru mental phase shift could not be ignored. All the arrival times were, therefore, corrected for the instrumental phase. This was determined from the Phase Response Curve of the instrument as given in the WWSS Operation and Maintenance Manual after correcting it by π radians in accordance with Espinosa *et al.* (1962) and Brune (1962).

The dispersion results are given in the next section.

3. Dispersion results

(*a*) *Rayleigh waves*

The dispersion data on Rayleigh waves are shown in Fig. 6. This figure includes besides the group velocities, phase velocities of the fundamental mode and the group velocity data on the higher mode Rayleigh waves as well. The broken lines are theoretical dispersion curves for different models, details of which are also included. We will come to these curves while discussing the results.

The phase velocities were calculated by the method of Brune *et al.* (1960). The order numbers of the crests were adjusted to get a consistent picture of the dispersion data with respect to a model (Dorman 8021) which appeared to be reasonable for the Gangetic basin. Fig. 7 shows this adjustment for earthquake No. 5. It is clear that $n = 0$ gives the best agreement of the group velocity and phase velocity data. It may be mentioned that only integral and half-integral values were assigned to n in the above process for the same reasons as given by Burne *et al.* (1960 *loc cit.*).

(*b*) *Love waves*

Fig. 8 shows the Love wave dispersion obtained. As mentioned earlier, data on Love waves were available only from two earthquakes. The number of points, therefore, is less than for Rayleigh waves but the agreement of the velocities from the two shocks is good. The phase velocities were also calculated, in a manner similar to the phase velocities of Rayleigh waves. The adjustment of the order number n for earthquake No. 1 is also included in the figure along with the data on the higher mode, for which only group velocities were determined. The solid continuous lines are theoretical curves. For the fundamental mode (both group and phase velocity) the curves have been calculated for a Gutenberg-Brich II model with laminated crust and Upper Mantle with its crust modified to that of Dorman Case 8021 but with 3 km thickness of sediments. The theoretical higher mode curve is for the Gutenberg-Brich II model without any change.

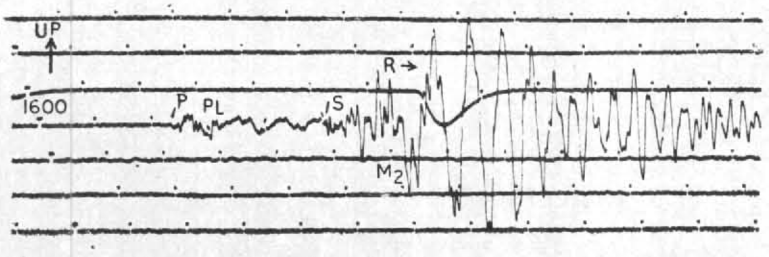


Fig. 2. Delhi Long Period (Vertical) Seismogram of 22 January 1964 (Earthquake No. 3)

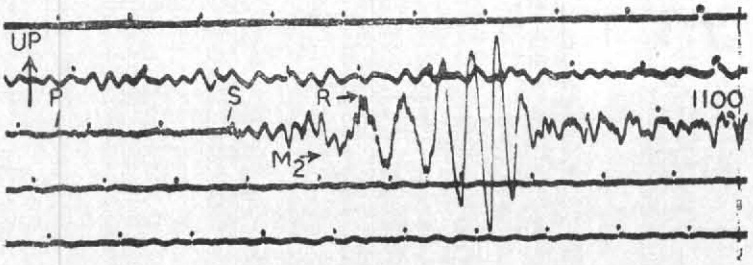


Fig. 3. Delhi Long Period (Vertical) Seismogram of 19 June 1963 (Earthquake No. 1)

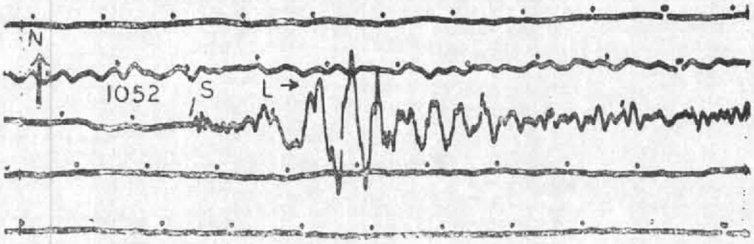


Fig. 4. Delhi Long Period (N-S) Seismogram of 19 June 1963 (Earthquake No. 2)

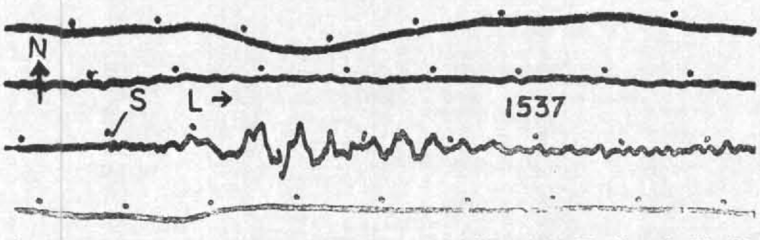


Fig. 5. Delhi Long Period (N-S) Seismogram of 21 June 1963 (Earthquake No. 2)

TABLE 1

S. No.	Date (GMT)	Origin Time (GMT)	Epicentre Lat. (°N)	Epicentre Long. (°E)	Depth of Focus (km)	Mag. (CGS)	Distance from Delhi (Degrees)	Remarks
1	19 June 1963	10-47-24·7	25·0	92·1	51	5·7	13·8	Distance calculated to nearest 0·1 degree
2	21 June 1963	15-26-31·0	25·2	92·2	56	5·6	13·8	Do.
3	22 January 1964	15-58-46·5	22·4	93·6	88	6·1	16·1	Do.
4	27 February 1964	15-10-48·8	21·7	94·4	102	6·4	17·0	Do.
5	28 February 1964	17-47-05·9	18·2	94·3	43	5·3	18·8	Do.

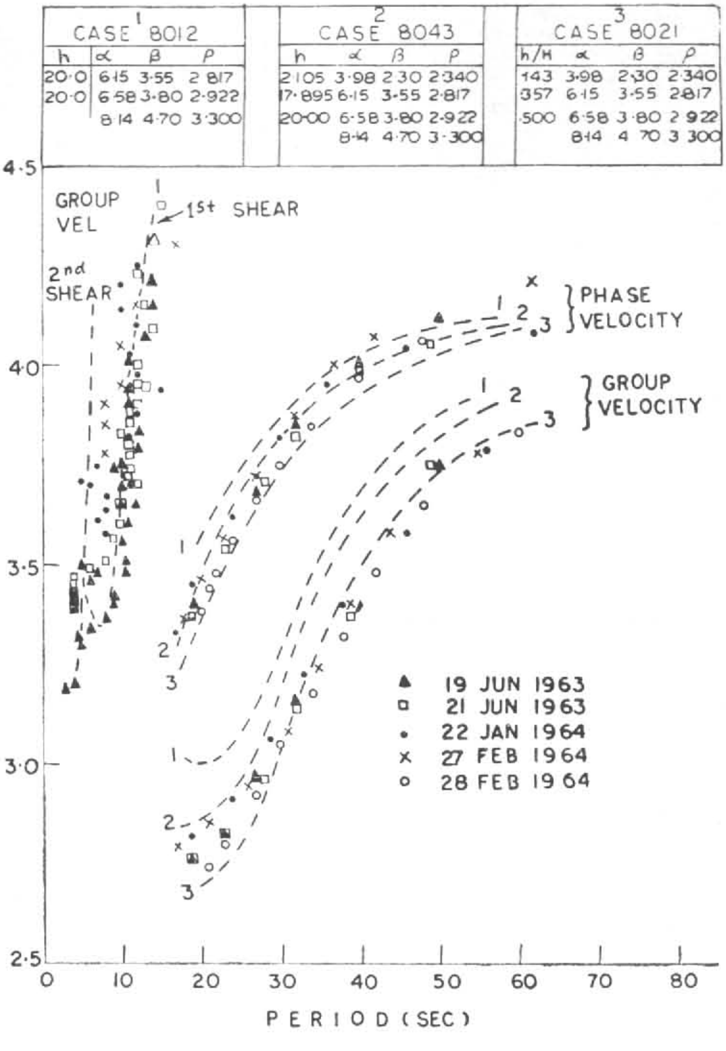
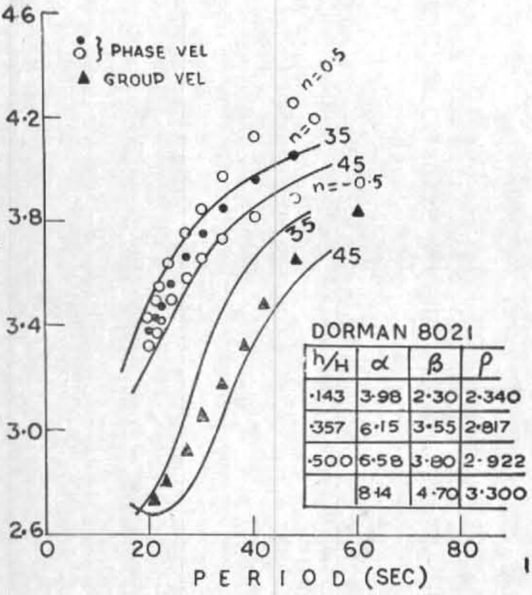


Fig. 6. Dispersion of Rayleigh waves



DORMAN 8021

h/H	α	β	ρ
·143	3·98	2·30	2·340
·357	6·15	3·55	2·817
·500	6·58	3·80	2·922
	8·14	4·70	3·300

Fig. 7. Phase velocity determination of Rayleigh waves

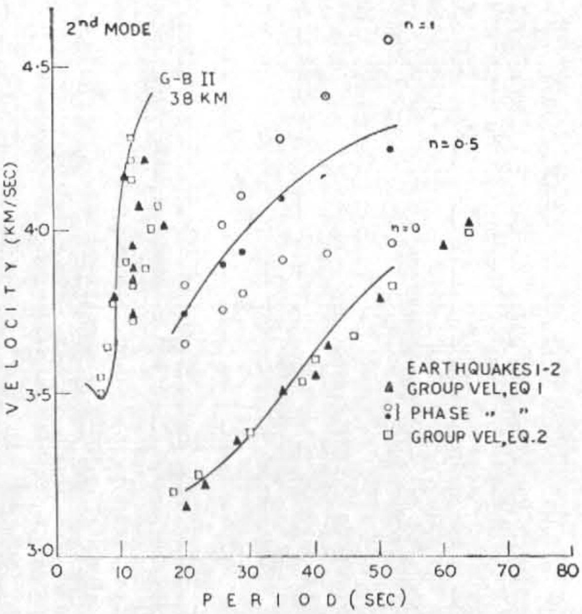


Fig. 8. Love wave dispersion results

(c) *PL waves*

The *PL*, 'leaking' mode waves were recorded only in the two higher magnitude earthquakes, *viz.*, Nos. 3 and 4. The dispersion of these waves is shown in Fig. 9. Also included in this figure are the results of *PL* wave dispersion between Honduras and Palisades (Oliver and Major 1960 *loc cit.*), between Mexico and Resolute (Oliver 1961) and a theoretical curve for a 35 km crust. No attempt was made at the calculation of the phase velocities.

4. Interpretation of results

The essence of the surface wave method of studying the structure of the crust is the extraction from the dispersion curves of the details of the layers. This inversion is usually done by comparing the observed dispersion curves with a set of theoreical curvs for different crustal models and finding out the model which approaches in its dispersion most closely to that observed. We shall follow the same method at the outset.

(a) *Rayleigh waves*

Of the various theoretical models available, Dorman case 8021 was chosen as approximating to the crust over the Gangetic basin and this has already been used in Fig. 7 in calculation of the phase velocities of the fundamental mode. A closer look at these curves and the observed velocities indicate that the crust over the Gangetic basin is about 40 km thick. In the period range 20 to 30 seconds (which are affected by the sedimentary layers at the top), however, the slope of the observed dispersion data is less than that of the theoretical model and suggests a thinner layer of sediments than taken in the model. Thus from the group velocities of the fundamental Rayleigh waves alone we are led to a 40 km crust which includes a sedimentary layer of lower velocity of thickness less than 5·7 km.

Now turning back to Fig. 6, we find dispersion data from all the shocks. Here the theoretical curves all relate to a 40 km crust. In fact the three models are identical except for the varying thickness of the sedimentary layer. A scrutiny of the group velocity data with respect to these curves shows clearly that a sedimentary thickness of about 4 km would explain the data in the period range of 20 to 30 seconds. A 4-km layer of sediments would, however, place the theoretical curve above the observed data in higher periods. Since the model does not take the velocity gradient in the mantle into account, this difference is also to be expected.

It needs be mentioned here that earthquake No. 5 had its epicentre near the Burmese coast and the path of the waves from this earthquake to Delhi included a segment of the continental shelf. Still the group velocities of Rayleigh waves from this shock agreed very well with those from the others.

TABLE 2

Th. 3 (cols. 2-8)

h	α	β	ρ
36*	6·15	3·55*	2·74*
84	8·14	4·70*	3·30
100	8·17	4·20	3·44
	8·49	4·76	3·53

From CANSD (col. 9)

h	α	β	ρ
6·0*	5·64*	3·47*	2·70*
10·5*	6·15	3·64*	2·80
18·7*	6·60	3·85*	2·85
80·0	8·10	4·72	3·30
100·0	8·20	4·54	3·44
100·0	8·30	4·51	3·53
80·0	8·70	4·76	3·60

T (sec) (1)	C_e (observed) (km/sec) (2)	Th. 3 C (km/sec) (3)	$C-C_e$ (km/sec) (4)	C_1-C_e (5)	C_2-C_e (6)	C_3-C_e (7)	C_4-C_e (8)	From CANSD C_c-C_e (9)
20	3·41	3·51	0·10	—0·02	+0·01	+0·02	0	—0·02
25	3·61	3·70	0·09	—0·01	—0·01	+0·01	—0·01	0
30	3·77	3·86	0·09	+0·01	+0·01	+0·02	0	+0·03
35	3·90	3·95	0·05	+0·02	—0·01	+0·01	0	0
40	3·99	4·00	0·01	—0·01	—0·02	0	—0·01	—0·03
45	4·03	4·02	—0·01	—0·03	—0·03	—0·01	0	—0·03
50								+0·01

Col. 5 — $h_1=37\cdot8$, $\beta_1=3\cdot432$, $\rho_1=2\cdot74$, $\beta_2=4\cdot747$
Col. 6 — $h_1=39\cdot6$, $\beta_1=3\cdot515$, $\rho_1=2\cdot74$, $\beta_2=4\cdot70$
Col. 7 — $h_1=39\cdot6$, $\beta_1=3\cdot515$, $\rho_1=2\cdot603$ $\beta_2=4\cdot70$
Col. 8 — $h_1=41\cdot4$, $\beta_1=3\cdot515$, $\rho_1=2\cdot466$, $\beta_2=4\cdot70$
Col. 9 — $h_1=3$, $\alpha_1=3\cdot64$, $\beta_1=2\cdot47$, $\rho_1=2\cdot30$, $h_2=17$, $\beta_2=3\cdot54$, $h_3=20$, $\beta_3=3\cdot80$

This points to the interesting conclusion that the dispersion properties of the crust-mantle system over this segment of the continental shelf are practically the same as those of the rest of the path over the Gangetic basin.

The phase velocity data at the shorter periods confirm the estimate of the sedimentary layer thickness of 4 km but the data at the longer periods appear to suggest a thinner sedimentary layer of about 2-3 km.

The M_2—(the first shear) mode group velocities as mentioned earlier, show appreciable scatter but the mean dispersion curve observed is in very good agreement with the theoretical curve for Model 8012. This model does not include any sedimentary layer but it is seen from a comparison of 8012 and 8043 that there is very little effect of the sedimentary layer on the M_2-group velocities in the period range studied.

Thus from all the data, *viz.*, the group and phase velocities of the fundamental and the group velocities of the M_2 mode Rayleigh waves we may reasonably conclude that the Gangetic basin has a crust about 40 km thick including a low velocity sedimentary layer at the top of about 3 km.

The results were interpreted by the method used by Dorman and Ewing (1962) and the theoretical model Th3 given by them was changed to obtain a close fit with the observed data. The results of a few attempts are given in Table 2 and show that by treating the crust as one uniform layer of about 41 km the dispersion data could be explained. As, however, the equivalence of a single layered crust and a double layered crust has not been found to provide an appropriate value of the layer thickness (Sato 1951, Novotny and Pec 1964), no conclusions can be drawn.

Brune and Dorman's (1963) layered crustal model for the Canadian Shield CANSD was then

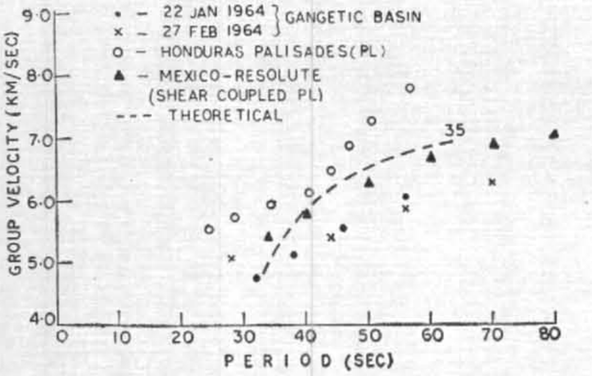


Fig. 9. *PL* wave dispersion

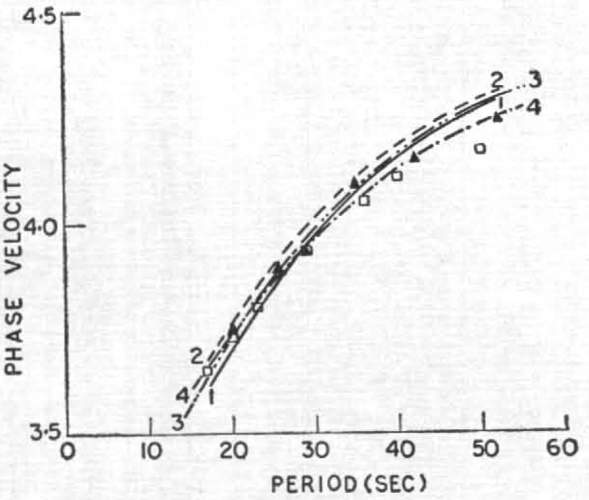


Fig. 10. Phase velocity of Love waves

altered by the same method as above. The structure of the few attempted that came closest to the data is also included in Table 2 and is seen to be consistent with the earlier inference.

(*b*) *Love waves*

We now come to the Love wave data. The group velocities are already shown in Fig. 8. In this figure the theoretical curves do not belong to a model identical to that used in the case of Rayleigh waves. However, the model chosen is a nearer approach to actual conditions in the earth as known from other seismological and geophysical evidence. To bring out the consistency of the Love wave data with the Rayleigh wave data, however, the crust of this Gutenberg-Brich II Model (with laminated crust and Mantle) was changed to conform to that in the model 8012 and different thicknesses of sedimentary layers were introduced. The curves shown in Fig. 8 correspond to such a model with a 3-km thick sedimentary layer. A comparison of the group velocity data shows that the overall thickness of 40 km for the crust as well as the thickness of the sedimentary layer are satisfactory. The 2nd mode Love wave group velocity data compared with the 38 km crustal Gutenberg-Brich II Model also point to a crust slightly thicker than 38 km.

The phase velocity data have been shown separately in Fig. 10. For these data the method of Dorman and Ewing outlined in the case of Rayleigh waves has been used with the help of the tables given by Anderson (1964). Curve 1 relates to a model similar to that in Fig. 8 but with 5 km sediments. Comparison of this curve with the observed data points to a thinner layer of sediments. Curve 2 was, therefore, computed for a 3-km sedimentary layer. This curve is the same as that in Fig. 8. Even this, it may be seen, does not give a satisfactory agreement. The curve 3 for a 4-km sedimentary layer fits with the experimental data at the shorter periods but lies above the observed data at the longer periods. A slight increase of the shear velocity below the crustal layers (or an increase in the density/decrease in the rigidity) appears to be needed to remove this discrepancy. Such a change has been effected and curve 4 is the result, when with 3 km of sediments the rigidity is reduced by 10 per cent in the layers upto 25 km below crust. This is in very good agreement with the data. As such a change in the rigidity, if ended suddenly at 65 km would result in a discontinuity, it would indicate a reduction starting with a lesser amount and gradually decreasing as to finally merge with the original model at a greater depth. The curve 4 could, therefore, be taken to correspond to a 3-km sedimentary layer in a 40 km crust (of 8012 layering) and mantle shear velocities starting with a value about 0·1 km/sec less than in G-B II model. While it is considered unwise to draw any firm conclusions on the above basis, it should suffice to note the agreement to such good extent of the observed data with a 40 km crust model. It would be quite reasonable also to infer that the thickness of the sedimentary layer is about 3 km.

(*c*) *PL waves*

The *PL* wave dispersion over the Gangetic basin (Fig. 9) when compared with the data in other regions and the theoretical curve also point out to a crustal thickness of more than 35 km. In a later study of *PL* waves across the United States

TABLE 3

Wave	Roy (1939) Gangetic valley (km/sec)	Tandon (1954) Northeast India (km/sec)	Nag (1965) Indian region (km/sec)
Pg	5·26	5·58	—
Sg	3·29	3·43	—
*P**	6·21	6·55	—
*S**	3·71	3·85	—
Pn	7·80	7·91	8·0
Sn	4·38	4·46	4·54

Oliver (1964) has shown the clear correlation of the known crustal thickness across different sections with their *PL* wave dispersion curves. As, however, the subject of *PL* wave dispersion is still to develop and attain the refinements of the other surface waves, no further conclusions appear warranted.

Thus the dispersion data of all the surface waves recorded are found to be consistent with the following over-all structure of the crust across the Gangetic basin —

h	β	ρ
3 km	3·30	2·340
17 km	3·55	2·817
20 km	3·80	2·922

with the shear velocity just below the Mohorovicic discontinuity at about 4·5 km/sec and changing as per the Gutenberg-Brich II Model and merging with it near the low velocity channel.

5. Discussion

From the previous section it is clear that the final estimate of the crustal structure adopted could not be unique, even if the phase and group velocities used were correct to 0·01 km/sec. From the scatter of the data, as seen from the Figs. 6, 7, 8 and 10, such an accuracy cannot be claimed. Further, the phase velocities depend on the value of the order number n adopted and it is difficult to assert that n cannot take other than integral and half-integral values as assumed. As mentioned earlier, however, the consistency of the results may be taken as a support to the above assumption. Further support could be expected from the mechanism of the earthquakes in this region. Such a study by Tandon and Mukherji (1956) for an earthquake from the same region seems to suggest the correctness of the assumption made. So far as the first motions at the Indian observatories show the mechanism of earthquakes 1 and 2 appear to be similar to that found by the above authors in the case of the Manipur-Burma border earthquake.

The velocities of seismic waves have been obtained from the study of earthquake records in the past. Some pertinent data in this respect are shown in Table 3. Giving due consideration to the improved time accuracy in the later years, it would appear the seismic velocities adopted in the various models do not differ appreciably from those observed. A further confirmation of the shear velocity in the granitic layer also comes from the *Lg* waves (Saha 1961).

The sedimentary layer with low shear velocity is seen to have a profound effect on the velocities of waves with periods less than 30 seconds and it is, therefore, possible to explain the observed results by a slightly thinner crust if a lower velocity is assumed in this layer. In a geophysical survey of the Delhi-Shahpur Ridge Sinha and Bose (1963) noticed several discontinuities in the sedimentary layer above the bed rock and found *P* velocities exceeding 2 km/sec in the layers above the bed rock. The depth of the bed rock in this region near the ridge is expected to be much less than the corresponding value in the Gangetic basin with its supposed thicker sedimentary layer. This would result in higher *P* and *S* velocities in the layer and the shear wave velocity of 2·30 km/sec assumed in the model may not be far from correct. The conclusions drawn in the previous section may, therefore, be taken as giving a reasonable first approximation on which further and more sophisticated methods could be based.

Tandon and Chaudhury (1964) have studied the surface wave dispersion (Group velocities of Rayleigh and Love waves) across the path Delhi-Shillong and have estimated the average thickness of the crust to be between 40 and 45 km. This path is very close to the paths studied now and the results, considering their scanty observations, are in fair agreement with those of the present study.

Geological and Geophysical estimates

It is generally believed by geologists that the Indo-Gangetic Plain has formed as a result of the downwarping of the earth's crust under the Tethys as Gondwanaland and Angaraland gradually approached each other, and subsequent "filling up by sub-aerial and fluviatile deposits of the Indo-Gangetic trough" (Wadia and Auden 1939). It is further believed that this sunken belt was developed concomitantly with the elevation of the Himalayas and is of the nature of a fore-deep. Various estimates of the thickness of the alluvium have been made from geological evidence, such as 100,000 ft by Burrard (since discarded by the Survey of India), 15000—20000 ft by R.D. Oldham, 20000 ft by Cowie and 6500 ft by Glennie. The estimate of 6500 ft by Glennie based on an analysis of gravity results is reported to fit the geodetic data but not confirm with geological facts. According to Wadia and Auden, it cannot be regarded as definite and may well be greater. It would also appear that the downwarping of the crust as pictured above would result in a thicker crust and a mass defect over the region.

Glennie's calculation of the mass anomalies to match the gravity anomalies over the Gangetic Plains show (cf. Banerji 1957) a "defect of mass in the northern trough reaching the maximum value over the Gangetic alluvium equivalent to a thickness of 6700 ft ". A thickness of about 3 km of lower density alluvium and the crustal structure as estimated from the present studies is found to be consistent with the above calculated mass defect when the mass per unit area is compared with the Himalayas where isostasy is believed to hold. It may also be of interest to note Banerji's (1953) suggestion that the alluvium behaved as a whispering gallery, in the transmission of seismic waves from the Assam Earthquake of 1950 and that "its depth is probably comparable to the wave-length of the seismic waves of short periods of 1 to 3 seconds, that is, the depth probably is of the order of about 10,000 ft".

In a recent statistical study of the gravity data of Indian stations Qureshy (1963) found that isostasy prevails in India in general and that it is more nearly complete in the regions of lower altitude. If complete isostasy is assumed, the thickness of the crust over the Gangetic basin (average altitude taken as $0\cdot15$ km) would according to the Airy-Heiskanen relation be—

$$T_c = T + 0\cdot82 \text{ km}$$

This would result in a crust of $30\cdot8$ km thickness if the normal thickness of the earth's crust is taken as 30 km. The dispersion studies do not agree with this result, and a normal thickness T equal to 40 km for the Gangetic basin would appear to explain the results on the assumption of complete isostasy. This may be compared with the Himalayan Mountains, under which the crust has been estimated as 55 km (Tandon and Chaudhury 1963, Chauhan and Singh 1965). Taking the average altitude of the Himalayas as 4 km, isostasy gives a crustal thickness of $51\cdot8$ km with T equal to 30 km, in reasonable agreement with the above estimates. This would confirm Qureshy's contention that different values of T have to be used for different regions of India for studying the crustal structure from gravity data.

6. Summary and Conclusions

From the above study of surface waves in their various modes, it is concluded that to a close approximation the crust of the earth across the Gangetic basin has a total thickness of about 40 km and that this includes at the top a 3 km layer of low velocity sediments. From the close agreement of the group velocities of the Rayleigh waves from earthquake No. 5 with those from the other earthquakes it is inferred that the dispersion properties of the continental shelf off the East Pakistan/Burmese coasts are almost the same as those of the crust across the Gangetic basin.

The average continental crust is about 35 km thick and the slightly thicker crust over the Gangetic basin appears to be consistent with the geologists' picture of a downwarp and subsequent filling up of the trough with sediments. Glennie's estimate of the mass defect, made from the gravity data, could be explained by the structure of the crust as deduced from the present surface wave study.

If isostasy is supposed to hold, even in the Gangetic basin with its large negative gravity anomalies, a normal crust T of 40 km is required to explain the surface wave data whereas in the Himalayan region a value of T equal to 30 gives a crustal thickness consistent with seismological studies.

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