550·342 : 550·382(54)

Upper Mantle Structure in and around the Indian sub-continent

R. K. DUBE

Central Seismological Observatory, Shillong

(*Received 30 November 1966*)

ABSTRACT. The structure of the Upper Mantle has been studied from the *P*-wave travel times, using the computation of Dowling and Nuttli. Results indicate the presence of a low velocity layer 140 km below the *M*-discontinuity and its thickness is estimated as about 50 km. A steep velocity gradient below the low velocity layer explains the observed results.

1. Introduction

Travel times of seismic waves have enabled the study of the structure of the earth's interior and after successive approximations have resulted in reliable earth models. Jeffrey's and Gutenberg's work are the most quoted in this respect. However, Gutenberg (1954, 1959 a, 1959 b) first suggested the presence of a decrease in *P*-wave velocity with depth in a part of the Upper Mantle. His inference was based on the variation of *P*-wave amplitude with distance. Qualitative discussions about the effect of such a layer are given by Bullen (1953) and Gutenberg (1954).

Since then there have been many investigations about this low velocity layer. Considerable amount of effort was made to use the dispersion of surface waves towards detecting and studying the properties of the layer. Dorman *et al.* (1960) have thus shown conclusively its existence as far as *S*-waves are concerned. Lehman (1961) too has shown the existence of this layer for *S*-waves. *P*-wave observations have also been used to study this layer by Lehman (1961) and Dowling and Nuttli (1964). In India, Choudhury (1966) has mentioned about the low velocity layer while discussing his results on the surface waves along the Indo-Gangetic Basin. In view of the above positions a study of the *P*-waves in the Indian region has been made and the results are reported here.

2. Data

Data on the *P*-wave travel times of about seventy earthquakes, well recorded at almost all the seismological observatories during the period 1962 to 1966 have been used. The earthquakes had their epicentres in and around the Indian sub-continent and were all of similar depth. The focal parameters have been taken from the USC and GS Cards and the *P*-wave arrival times from the *Seismological Bulletins*, published by the India Meteorological Department. In drawing the $T—\Delta$ curves, the epicentral distances have been calculated from the formula —

$$\cos \Delta = 1-\tfrac{1}{2} [(A-a)^2 + (B-b)^2 + (C-c)^2]$$

Further in order to remove any possible effect of the Himalayas, the earthquakes originating to the north of the Himalayas have been considered separately from those having origin in the south. The details of the earthquakes may be seen in Tables 1 and 2.

3. Results

The data are shown as T- Δ plot in Figs. 1 and 2 respectively for the two groups of earthquakes. From these it is seen that the points show an apparent divergence from a linear distribution from about a distance of ten degrees. The data upto this distance have, therefore, been fitted to the equation —

$$T = a\,\Delta + b \qquad (1)$$

by least squares. The results obtained are—

$$T=14{\cdot}00\,\Delta + 4{\cdot}26 \qquad (2)$$

and $$T=14{\cdot}16\,\Delta + 5{\cdot}59 \qquad (3)$$

Thus it is found that the *P*-wave velocity just below the *M*-discontinuity is $7{\cdot}93 \pm 0{\cdot}01$ km/sec to the south of the Himalayas and 7·86 km/sec to the north. The values are in fair agreement with those obtained by Tandon (1954) and Nag (1965). Further it is noted that the value of b is higher for earthquakes originating to the north of the Himalayas. This could be due to the effect of the mountain roots (Airy 1855).

A closer look at Figs. 1 and 2 shows that *P*-wave arrivals are late to the extent of 7 to 8 seconds at a distance of about 11 degrees. In order to bring out the effect better, the reduced travel times $(T-\Delta/7{\cdot}96)$ have been plotted in Fig. 3. The points in this figure do show a discontinuity around 11-degree where there seems to be a jump in the values. This is also brought out by applying the

TABLE 1

Earthquakes having epicentre towards the south of Himalayas

Date	Origin time			Location of epicentre		Focal depth
	h	*m*	*s*	Lat. (°N)	Long. (°E)	(km)
11 Jan '62	03	01	33·0	28·1	84·8	38
15 Feb '62	08	05	45·0	28·0	89·0	..
19 Feb '62	11	11	12·0	22·0	93·0	..
20 Feb '62	09	15	55·1	6·8	92·5	..
	22	02	38·2	26·1	96·8	25
6 Mar '62	05	55	42·3	13·7	93·7	18
21 Apr '62	17	27	30·0	24·8	94·3	..
26 May '62	19	44	17·0	6·7	94·6	60
6 Jul '62	02	12	19·9	13·3	58·0	30
8 Jul '62	23	53	03·0	23·0	94·0	33
22 Sep '62	06	51	32·3	26·5	97·0	33
30 Oct '62	16	13	25·6	26·6	93·3	33
16 Nov '62	21	10	01·8	13·5	93·2	33
26 Nov '62	23	25	16·7	23·9	66·4	34
30 Jan '63	10	33	59·1	29·7	80·5	57
22 Feb. '63	01	32	25·4	27·5	87·7	33
5 Mar '63	02	35	07·8	29·2	81·2	35
9 Apr '63	00	03	35·6	22·2	85·6	33
30 Apr '63	10	20	54·0	10·6	94·4	33
19 Jun '63	10	47	24·7	25·0	92·1	51
21 Jun '63	15	26	31·0	25·2	92·2	56
27 Jun '63	15	32	53·1	14·4	93·7	33
8 Oct '63	02	51	06·0	28·6	95·1	24
27 Nov '63	21	10	39·9	30·8	79·1	33
27 Dec '63	02	51	55·0	12·0	91·5	..
25 Jan '64	07	13	30·8	28·5	86·3	44
1 Feb '64	11	28	19·4	27·4	87·8	33
8 Feb '64	11	54	23·1	29·0	82·2	33
28 Feb '64	17	47	05·9	18·2	94·3	43
27 Mar '64	23	03	41·7	27·2	89·3	32
13 Apr '64	03	20	04·5	27·6	90·2	52
15 Apr '64	16	35	57·5	21·7	88·0	36
1 May '64	01	10	54·0	14·1	93·9	33
1 Sep '64	13	22	36·6	27·2	92·3	33
2 Dec '64	08	21	43·3	29·5	81·3	23
21 Jan '65	13	32	24·0	27·6	88·0	23
18 Mar '65	02	41	27·6	29·9	80·3	33
13 May '65	10	51	15·5	29·8	80·5	33
22 Sep '65	04	24	47·8	20·8	99·3	35
15 Oct '65	14	18	39·8	14·4	93·7	33
5 Dec '65	22	01	27·7	23·3	94·5	13
7 Feb '66	04	26	14·0	29·8	69·7	33
	05	21	45·0	30·0	69·9	10
	08	38	11·3	30·0	69·9	15
	23	06	34·5	30·2	69·8	10
9 Feb '66	08	22	18·0	29·8	69·8	30

TABLE 2

Earthquakes having epicentre towards the north of Himalayas

Date	Origin time			Location of epicentre		Focal depth
	h	*m*	*s*	Lat. (°N)	Long. (°E)	(km)
22 Jan '62	20	22	17·6	30·7	80·6	25
31 Jan '62	00	05	57·0	38·5	70·3	60
20 Mar '62	23	10	38·1	32·0	94·6	25
25 Mar '62	20	49	09·0	27·8	99·6	25
21 May '62	12	02	50·0	37·3	96·0	25
24 Jun '62	01	21	18·0	25·6	101·1	35
26 Nov '62	05	29	30·2	39·8	77·2	14
6 Apr '63	17	48	53·3	33·6	82·8	33
19 Apr '63	07	35	23·7	35·8	96·9	33
11 Jun '63	18	07	24·1	30·7	86·9	33
26 Jun '63	14	09	13·0	36·4	76·9	33
29 Aug '63	08	53	48·4	39·6	74·2	31
16 Oct '63	15	43	00·8	38·6	73·4	33
16 Mar '64	01	05	17·6	36·9	95·5	33
26 Sep '64	00	46	02·8	30·1	80·7	50
21 Oct '64	23	09	18·2	28·1	93·8	37
9 Nov '64	16	12	50·6	29·5	86·0	33
21 Jan '65	13	31	29·4	34·6	86·9	33
29 Jan '65	20	06	02·4	35·6	73·6	33
2 Feb '65	15	56	51·0	37·5	73·4	33

least square fitting to equation (1) of the data from group I successively upto 10, 11, 12, 13 and 15 degrees. The values of a, b, their standard deviations etc shown in Table 3 tell the same thing. Similar analysis for group II could not be done due to scanty data in the range of distance 11 to 15 degrees.

The discontinuity in the T—Δ curve noticed above has also been discussed by Lehman (1961, 1963). According to her, the T—Δ curve has in the presence of a low velocity layer two branches of the curve as shown in Fig. 4. Here, P_d is the branch belonging to the direct P arrivals not affected by the low velocity layer, P, the branch from those that are totally reflected from the lower boundary of the layer and P_r due to refracted arrivals. According to her, the minimum distance between the direct and the reflected branches is dependent on the thickness and velocity distribution in the low velocity layer whereas the smallest distance at which the reflected branch appears, depends on the velocity below the discontinuity. Overlapping of

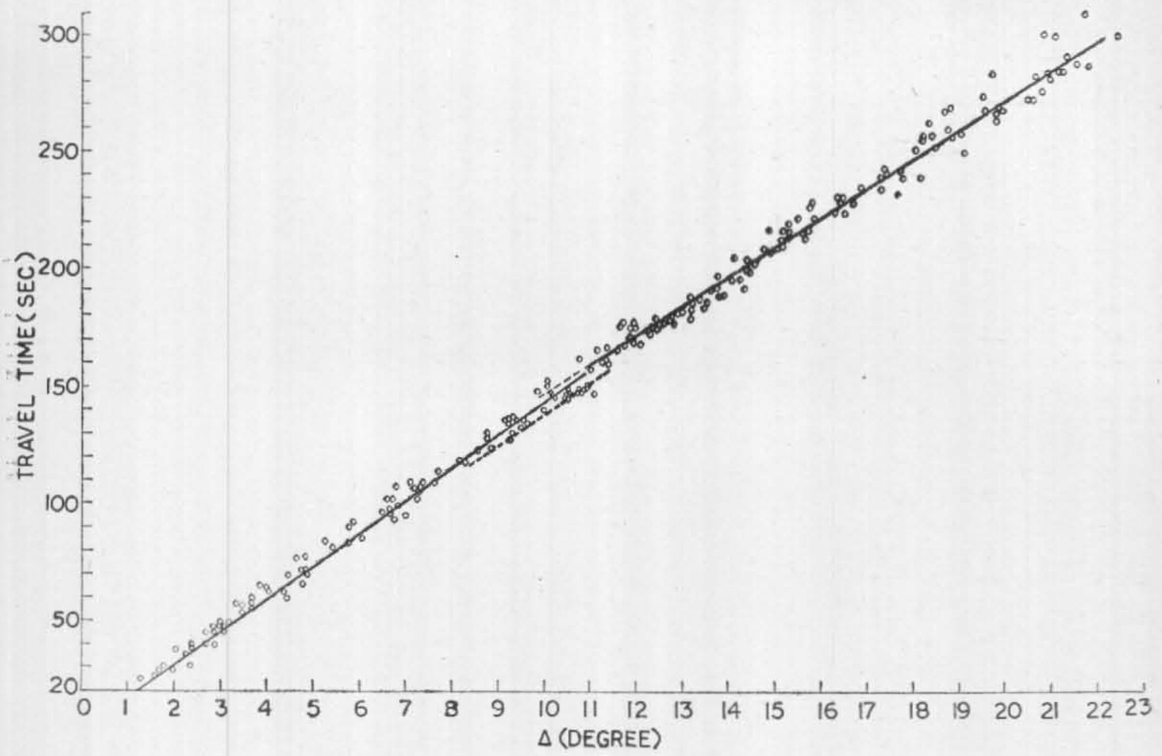

Fig. 1. $T-\triangle$ **curve for** P**-waves (group I)**

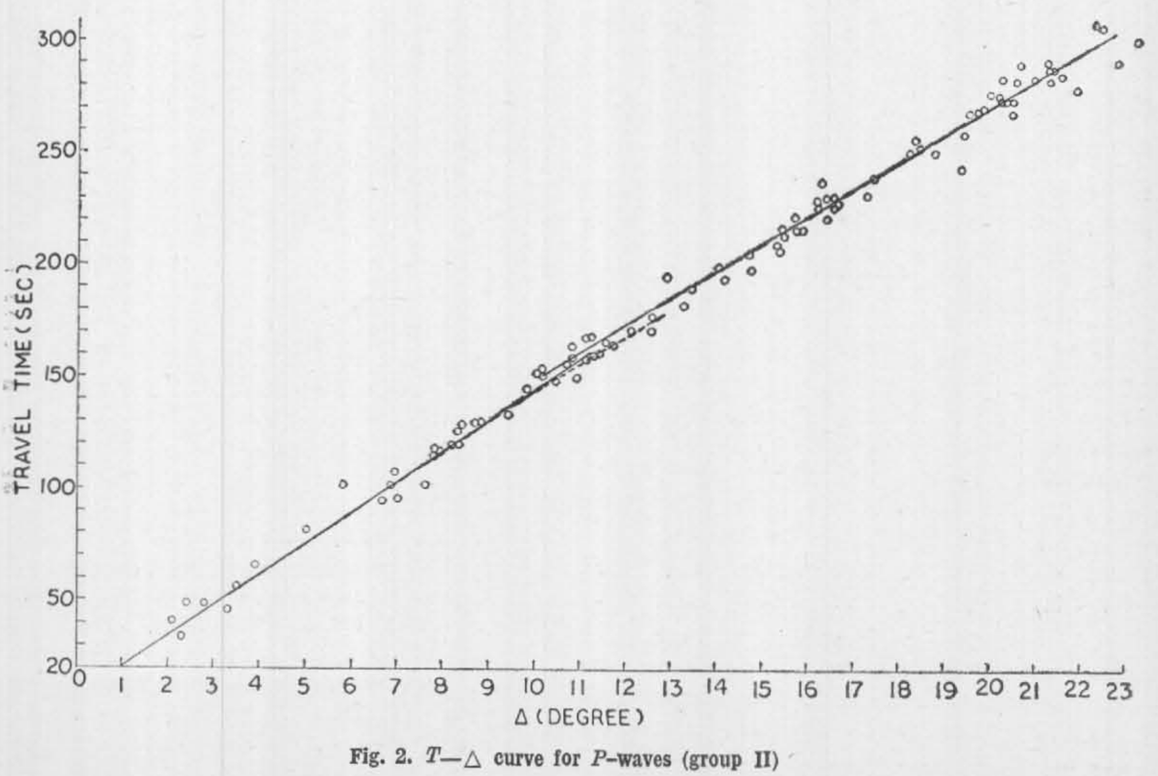

Fig. 2. $T-\triangle$ **curve for** P**-waves (group II)**

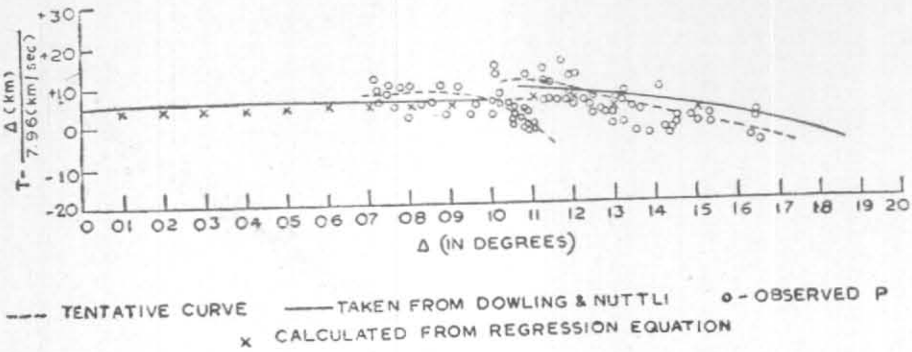

Fig. 3. $T—\Delta$ curve for the observed and the theoretical values of P-waves

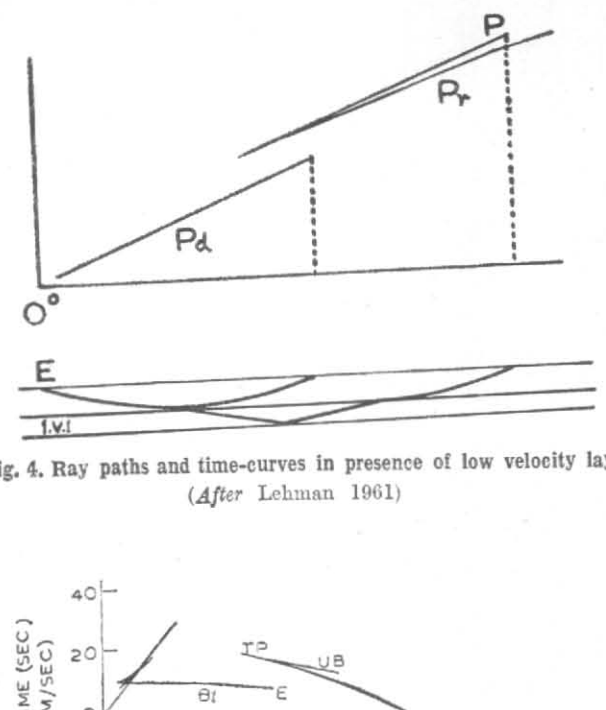

Fig. 4. Ray paths and time-curves in presence of low velocity layer
(*After* Lehman 1961)

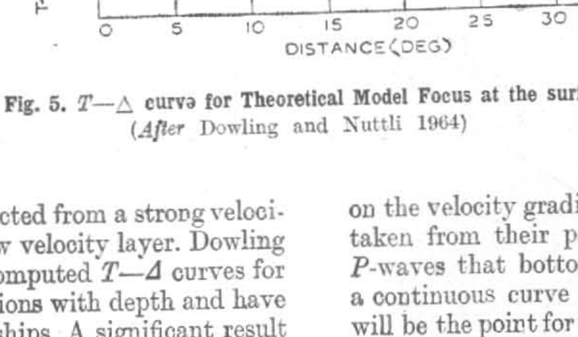

Fig. 5. $T—\Delta$ curve for Theoretical Model Focus at the surface
(*After* Dowling and Nuttli 1964)

the two branches was expected from a strong velocity gradient below the low velocity layer. Dowling and Nuttli (1964) have computed $T—\Delta$ curves for various velocity distributions with depth and have observed similar relationships. A significant result of their studies is that a low velocity channel can exist in the Upper Mantle without producing a shadow zone, whose existence depends primarily on the velocity gradient below the channel. Fig. 5 taken from their paper shows the various rays. P-waves that bottom below the crust fall along a continuous curve terminating at a point which will be the point for the ray that bottoms at the top of the low velocity channel where r/v first increases. The termination point of this branch is the deciding factor for the depth of the channel.

TABLE 3

Quantities a and b, their standard deviation and standard error

Range (degrees)	a	b	Standard deviation a	Standard deviation b	Standard error a	Standard error b	$\Sigma\epsilon^2/n-2$
10	14·00	4·26	0·183	9·71	± 0·019	±1·03	19·76
11	14·13	3·23	0·154	10·14	±10·015	±1·01	22·48
12	14·15	3·26	0·134	10·68	± 0·012	±0·98	24·37
13	13·94	4·25	0·116	10·93	±0·0099	±0·93	25·25
15	13·77	5·39	0·085	9·76	±0·0067	±0·77	19·93

ϵ=Residual n=number of observations

TABLE 4

Upper Mantle velocity distribution suitable for Indian sub-continent as taken from Dowling and Nuttli (1964) computed values

	Distance (km) from the centre of Earth								
	6370	6330	6329	6300	6299	6252	5880	5800	5700
Velocity (km/sec)	6·60	6·60	7·95	7·95	7·80	7·80	9·60	10·00	10·41

Comparing the present results with the above it is inferred that the discontinuity at 11-degree distance in Figs. 1 and 3 could be due to a low velocity layer. The points in the epicentral distance range of 12·5 to 14·5 degrees in Fig. 1 mostly lies below the computed straight line (upto 10 degrees) and could be the refracted arrivals as per Lehman's discussion. The termination point of the first branch is at a distance of 11 degrees and according to Dowling and Nuttli the depths to the top of the channel may correspond to the maximum depth penetrated by the rays that emerge at this distance. Thus the depth to the top of the channel could be inferred to be about 140 km. For getting some further details regarding the Upper Mantle, the results for one of Dowling and Nuttli's models are also shown in Fig. 3. Details of this model are given in Table 4. The first branch of the curve agrees well with the model whereas the observed points fall below the second branch of the model suggesting a slightly higher P-wave velocity. The overlapping of the two branches has been clearly indicated suggesting for a steep velocity gradient below the low velocity layer and the two branches are quite similar to those in the model. The comparison also shows that the points in the range of 10·4 to 11 degrees lie below the theoretical curve, indicative of an increase of velocity with depth from the 'Moho' to the top of the low velocity layer.

4. Conclusions

The study of the P-wave travel times thus shows that (i) the velocity of P-waves just below the M-discontinuity in the Indian region is 7·93 km/sec and it increases with depth upto the top of the low velocity layer. Under the Himalayas a slightly lower velocity has been observed. (ii) There is a low velocity layer, the depth to the top of which corresponds to the maximum depth prenetrated by a ray emerging at a distance of 11-degree. This on comparison with model is about 140 km. (iii) The thickness of the low velocity layer appears to be of the order of 50 km from the agreement of the data with the model. Also a steep velocity gradient appears to be present below the channel.

A similar study on S-wave is also in hand and the results will be communicated soon.

5. Acknowledgement

The author is very much thankful to Shri S.K. Nag for the helpful discussions.

REFERENCES

Airy, G. B.	1855	*Phil. Trans.*, 145
Bullen, K. E.	1953	*Introduction to the Theory of Seismology*, 2nd Ed., Cambridge Univ. Press.
	1961	*Geophys. J.*, **4**, pp. 93-105.
Choudhury, H. M.	1966	*Indian J. Met. Geophys.*, **17**, pp. 385-394.
Dorman, J., Ewing, M. and Oliver, J.	1960	*Bull. seismol. Soc. Amer.*, **50**, pp. 87-115.
Dowling, J. and Nuttli, O.	1964	*Ibid.*, **54**, pp. 1981-1996.
Gutenberg, B.	1954	*Bull. geol. Soc. Amer.*, **65**, pp. 337-348.
	1959(a)	*Geophys. J.*, **2**, pp. 348-352.
	1959(b)	*Ann. Geofisica*, **12**, pp. 439-460.
	1959	*Physics of the Earth's Interior*, p. 82.
Lehman, I.	1961	*Geophys. J.*, 4, p. 124.
	1963	Sci. Rep. Airforce Office of Scientific Research.
Nag, S. K.	1966	*Indian J. Met. Geophys.*, **17**, pp. 281-286.
Tandon, A. N.	1954	*Ibid.*, **5**, pp. 95-137.