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The crustal structure of the Hindukush region

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ABSTRACT. The crustal structure beneath the Hindukush and adjoining region has been investigated using body wave data of near earthquakes. The crustal structure in the region has been found to consist of three layers; *viz*,. granitic 1, granitic 2 and basaltic layers. The velocities in the three layers respectively of longitudinal and transverse seismic waves have been obtained as 5·32±0·03, 5·64±0·01 and 6·43±0·01 km/sec; and 3·28±0.002, 3·53±0.003 and 3·93±0.003 km/sec. The subcrustal velocities for longitudinal and transverse waves obtained are 8·13±0·01 and 4·53±0·001 km/sec, respectively. The average thickness of the three layers has been computed as 17·5±5·5, 15·9±4·1 and 16·7±2·7 km respectively, making the average thickness of the crust as 50±11·9 km. It has been observed that the Mohorovicic discontinuity dips at an angle of 2° from north to south between Taskent and Quetta along 68°E (profile AB, Fig. 1). A dip of only 22′ has been observed for the discontinuity between the points 37°N, 68°E and 44°N, 81°E (profile CD, Fig. 1). The thickness of the crust beneath Quetta has been obtained as 62±15·8 km.

1. Introduction

Several studies made in the past on the geology and seismo-tectonics of the Hindukush and adjoining regions have revealed about the complexity of the region. Convergence of Yaman fracture zone, the Chaman fault and the Hindukush arc has been interpreted as the probable reason for the complexity. Seismicity studies (Santo 1969) and focal mechanism studies of earthquakes in the Hindukush region (Ritsema 1966, Shirokova 1959, Fitch 1970) suggest that the seismic activity is due to stresses in a 'V' shaped lithospheric space in a N-S profile. This, perhaps, is the result of the underthrusting of two continental crusts of India and Asia in the upper mantle. It has, however, been observed by Nowrozee (1970) that the deeper earthquakes in the Hindukush zone occur within a contorted slab like feature which may be remanent of the Tethys Sea floor. According to him the slab is sinking into the upper mantle as a result of its greater density.

In order to have few more observational evidence apart from the above findings, it may be important to investigate in detail the variations in the crustal structure of the region. The present attempt is to investigate the average crustal structure of the Hindukush and adjoining region which may prove useful in studying the regional variations later. The variations in the depth of the Mohorovicic discontinuity in the region have also been studied.

2. Data

Relevant published data, of all the earthquakes which occurred in the region (Fig. 1) during the period 1956 to 1969, has been collected from the bulletins of the International Seismological Summary (ISS) and International Seismological Center (ISC). The selection of earthquakes was restricted to those which had near surface foci and for which P_g and S_g phases were recorded by at least few observatories. Earthquake parameters of the selected earthquakes are given in Table 1. The arrival times of seismic waves as reported by ISS and ISC were collected and used without any modification.

3. Travel time curves

The travel-times of various phases against epicentral distances upto ten degrees are plotted in Fig.2. A perusal of the observations showed that those corresponding to P_n, S_n and P^*, S^* phases fell along distinct lines whereas the points corresponding to P_g and S_g phases are found to arrange themselves along two distinct branches. These have been named as P_{g1}, P_{g} and S_{g1}, S_{g2} respectively. The observations presented permit identification of an additional layer between the conventional granitic and basaltic layers. The results are similar to those obtained for Chinese mountains adjoining eastern Himalayas and Tibetan Plateau region by the authors (1977).

4. Wave velocities

In order to get a statistically best straight line fit to represent travel time curve, observations were subjected to a least square analysis. The slopes (b) and intercept times (a) for each straight line $T = b\triangle + a$ thus obtained for each phase are given in Table 2. The values of velocities, *i.e*,

TABLE 1

Parameters of Earthquakes

S. No.	Date	Origin time (GMT) h	m	s	Location of epicentre Lat. (°N)	Long. (°E)	Depth of focus (km)
1	11 Apr 56	01	45	10·0	38·8	70·3	0
2	8 May 56	19	50	02·0	38·2	74·7	0
3	8 Jun 56	04	07	27·0	35·2	67·5	0
4	9 Jun 56	23	13	51·0	35·1	67·5	0
5	11 Jun 56	02	57	13·0	35·1	67·4	0
6	16 Sep 56	08	37	23·0	33·69	69·51	0
7	22 Sep 56	15	54	23·0	38·41	69·22	0
8	24 Sep 56	10	20	37·0	33·98	69·57	0
9	18 Nov 56	05	19	27·0	39·8	76·77	0
10	14 Jun 57	11	36	53·0	31·81	67·16	0
11	9 Jan 58	17	39	26·0	44·83	84·95	0
12	19 Feb 58	10	33	03·0	39·07	74·86	0
13	22 Mar 58	11	07	47·0	35·30	67·40	0
14	8 Apr 58	09	59	17·0	33·0	68·13	0
15	7 May 58	14	47	36·0	34·72	70·98	0
16	13 Aug 58	01	33	29·0	36·19	66·75	0
17	13 Oct 58	08	58	12·0	41·56	74·96	0
18	21 Dec 58	05	46	26·0	44·56	80·88	0
19	24 Jun 58	04	48	17·0	40·45	78·67	0
20	12 Jul 59	19	21	58·0	41·78	72·57	0
21	31 Jul 59	19	53	03·0	38·78	70·39	0
22	13 Sep 59	19	15	55·0	39·61	74·25	0
23	21 Sep 59	12	19	35·0	40·89	74·72	0
24	15 Dec 59	10	47	41·0	36·36	69·76	0
25	3 Mar 60	14	15	04·0	40·77	78·08	0
26	1 Apr 61	15	18	23·0	39·91	77·73	0
27	4 Apr 61	09	46	39·0	39·92	77·82	0
28	12 Sep 62	20	56	53.0	36·11	69·03	0
29	16 Oct 63	15	42	56·0	38·67	73·30	0
30	16 Jan 64	23	21	50·0	39·0	74·40	0
31	27 Feb 64	09	02	19·1	44·21	79·20	0

TABLE 2

Values of constants (b) and (a) for crustal and subcrustal phases

	Pg_1	Pg_2	P^*	Pn	Sg_1	Sg_2	S^*	Sn
b	20·86	19·67	17·26	13·65	33·83	31·58	28·28	24·47
σb	0·088	0.178	0.149	0.337	0.135	0.15	0.191	0.079
SE	±0.01	±0.04	±0.02	±0.02	±0.03	±0·03	±0.02	±0.01
a	−0·03	1·62	5·45	10·91	1·75	3·94	9·19	15·02
σa	1·52	3·11	4·675	10·20	2·789	0·85	6·305	4·557
SE	±0·21	±0·67	±0·70	±0·52	±0·85	±0·17	±0·72	±0·47

the inverse of the slopes of these curves, are obtained and given in Table 3. Seismic wave velocities obtained for the crust of different regions of the Indian subcontinent by other workers are also given in the same table for comparison. The P and S wave velocities in the basaltic and subcrustal layers respectively are not much different but are significantly lower in the granitic layer.

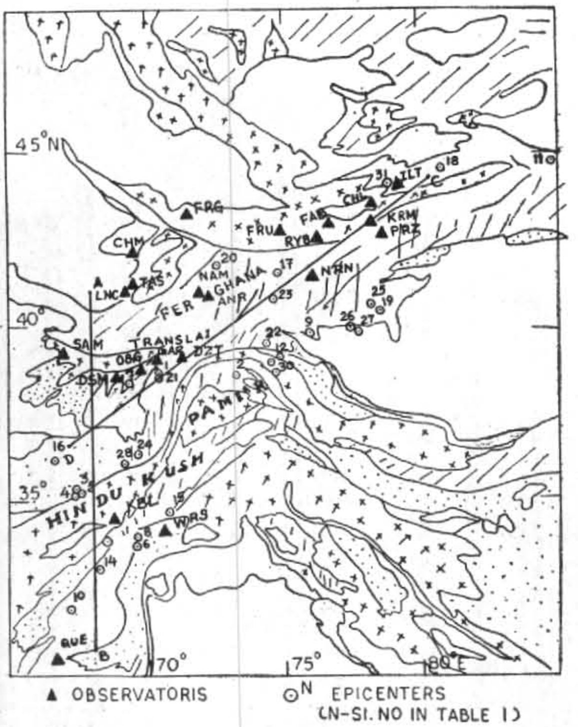

Fig. 1. Index map showing the location of epicentres and observatories

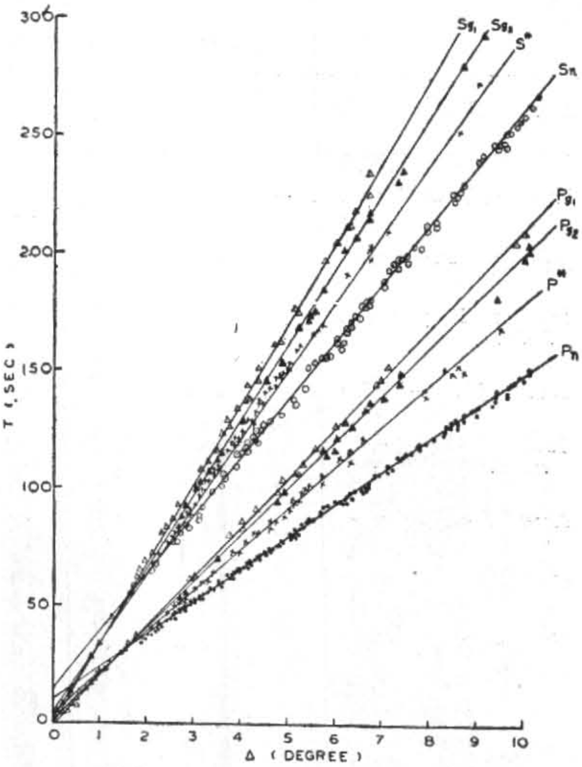

Fig. 2. Travel time curves for crustal and subcrustal phases

It is significant to note that the velocities of P_g and S_g waves are even higher in the Chinese mountains and eastern Himalayan region than those in the Hindukush region suggesting for a regional variation for these velocities within this great mountaineous belt.

5. Focal depth

If T is the travel-time, $\triangle$ the epicentral distance, h the depth of focus and V_{Pg} the velocity of P_g phase, the travel-time for P_g can be given as :

$$T = (\triangle^2 + h^2)^{1/2} / V_{Pg} \tag{1}$$

$$T^2 = \triangle^2 / V_{Pg}^2 + h^2 / V_{Pg}^2 \tag{2}$$

If $y = T^2$ and $x = \triangle^2$ Eq. (2) can be written as : $y = mx + c$ (3)

Let $T = T_i$ at $\triangle = 0$

$$\therefore h = V_{Pg}.\ T_i \tag{4}$$

A plot, for T^2 against $\triangle^2$ for P_g wave observed within the epicentral distance for one degree, was made in Fig. 3. The average depth of focus was calculated from the value of intercept time obtained using relation (4) above. The focal depth has been estimated to be 10 km. This value has been used to calculate the layer thickness.

6. Crustal layers

The thickness of each layer is obtained using standard time-intercept method (Officer 1958). Assumption is made that the interface between the layers is horizontal and each layer has a constant seismic wave velocity. Such an assumption is justified since the travel-time curves for each crustal and subcrustal phases have been represented by straight lines. Thickness of each crustal layer and depth of the Mohorovicic discontinuity is computed separately from the P and S wave data. The values obtained are given in Table 4. The results from P and S wave data are in fair agreement with each other. Since the earthquakes and recording stations are distributed over a large part of Hindukush and adjoining mountains, the thickness obtained for the crust may be taken to represent an average only.

Investigations carried out in the past on the crustal structure using both body as well as surface wave data from controlled explosions and earthquakes (Byerly 1956, Steinhert and James 1965, Kosminskaya and Rizinichenko 1964) indicate

TABLE 3

Wave velocities (km/sec) of crustal and subcrustal phases

Authors—Place	Pg_1	Pg_2	P^*	Pn	Sg_1	Sg_2	S^*	Sn
Tandon and Chaudhury (1968) — Deccan Shield	5·67	—	6·44	8·24	—	—	—	4·73
Arora (1971) — Gauribidnur	5·67	—	6·51	7·98	3·46	—	3·96	4·61
Dube and Bhayana (1974) — Gangetic Plains	5·64	—	6·49	8·06	3·45	—	3·85	4·61
Tandon (1972) — Kashmir Valley	5·6	—	6·5	8·2	3·3	—	3·75	4·75
Tandon *et al.* (1976) — Chinese mountains and Eastern Himalayas	5·65	6·03	6·49	7·97	3·42	3·60	3·90	4·53
Present investigation	5·32 ±0·03	5·64 ±0·01	6·43 ±0·01	8·13 ±0·01	3·28 ±0·02	3·53 ±0·003	3·93 ±0·003	4·53 ±0·001

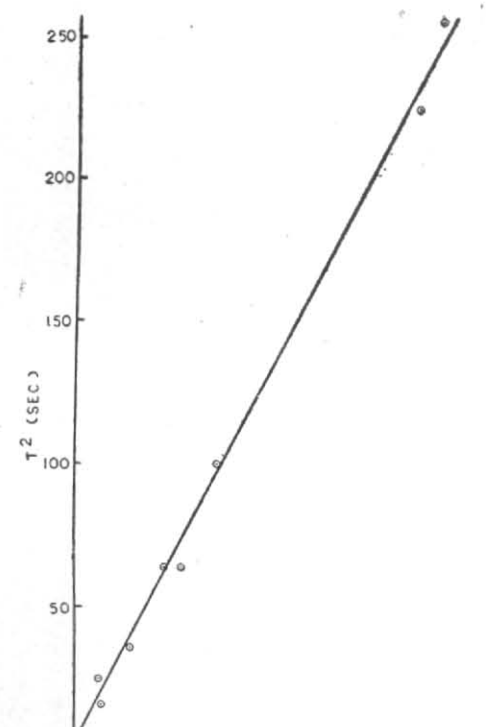

Fig. 3. T^2-$\triangle^2$ curve for P_g phase

that the crust is comparatively thicker beneath the mountains than those under adjoining plains. The comparison of the crustal thickness obtained beneath the plains of the Indian sub-continent by various workers with that beneath the region under study show a thickening of crust below mountains as expected.

TABLE 4

Crustal Model

Layer	Thickness P wave group (km)	Thickness S wave group (km)
Granitic I	17·5±5·5	23·0±4·2
Granitic II	15·9±4·1	11·9±2·9
Basalt	16·7±2·7	11·6±1·8
Depth of the Mohorovicic-discontinuity	50·1±11.9	46·5±8.4

7. Depth of the Mohorovicic discontinuity

Due to the scattered locations of earthquakes and recording stations unlike planned explosions, the data selected cannot permit a detailed study on the structure. The depth of the Mohorovicic discontinuity computed here for the region can be taken as average only, since the geological and seismotectonic investigations (Santo 1969, Nowrozee 1970) suggest variations. However, a number of earthquake epicentres and recording stations lie in two narrow belt along the line AB and CD (*see* Fig. 1) forming a N-S and NNE-SSW profiles respectively. Such an orientation of the observatories and epicentres enabled us to investigate the change in the depth of the Mohorovicic discontinuity in the region using the travel times of P_n waves travelling in direct and reverse directions between the source and recording stations, Non-availability of S_n waves data restricted a similar study from these waves. Travel times against

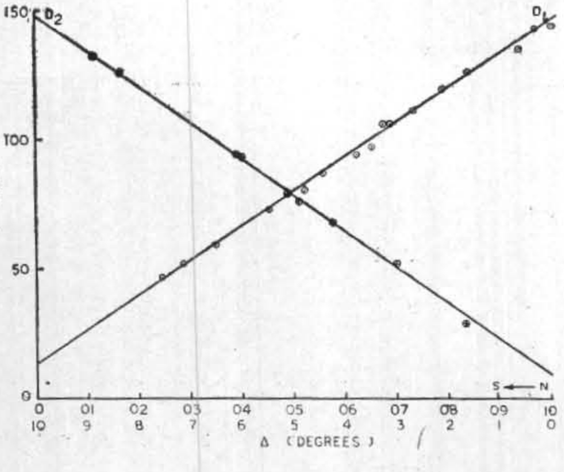

Fig. 4. Travel time curves for P_n phase along the profile AB

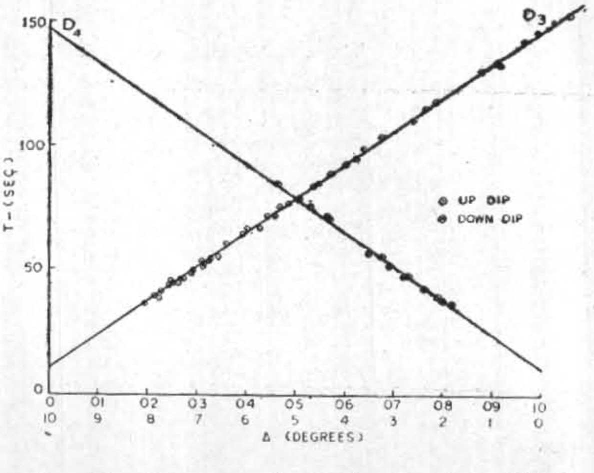

Fig. 5. Travel time curves for P_n phase along the profile CD

TABLE 5

Variation of crustal thickness beneath the Indian subcontinent

	Gauribidnur region (Peninsular India) Arora (1971)	Deccan Shield Peninsular India Tandon and Chaudhury (1968)	Gangetic Plains Dube and Bhayana (1974)	Present study
Thickness (km)	34·7	41·0	40·3	50

epicentral distance for the profiles AB and CD were grouped as D_1, D , and D_3, D_4 respectively depending upon the direction of travel of P_n wave. Figs. 4 and 5 represent plot of these travel times against epicentral distances. The scatter of observations when plotted together in Fig. 2 was much greater than shown in Figs. 4 and 5. The observations have been subjected to least square analysis and a best statistical straight line fit obtained.

The values of slopes, intercept times and velocities obtained along with their standard deviations and standard errors for these travel time curves are given in Table 6. It can be seen from the table that the intercept times obtained for the data of group D_1 and D_3 are higher in comparison to those of D and D_4 respectively. This observation, therefore, suggests that the depth of the Mohorovicic discontinuity in the region increases from north to south along the profile AB and NNE to SSW along the profile CD.

The dip has been calculated from the following relations assuming that except for the Mohorovicic discontinuity the other inter-faces are horizontal.

$$m_d = \frac{1}{V_3} \sin(ic + \alpha) \qquad (5)$$

$$m_u = \frac{1}{V_3} \sin(ic - \alpha) \qquad (6)$$

where m_d and m_u are the slopes of the travel time curves representing downdip and updip ray path respectively. The dip angles calculated for each of the profile are given in Table 6. The change in the depth of the Mohorovicic discontinuity is more along the N-S profile than along NNE-SSW profile. The depth of the discontinuity below the points on the extreme end of the profiles have been calculated. The values are — below the point 44° N and 81°E as $48 \pm 11 \cdot 1$ km, below 38°N and 68°E as $50 \pm 12 \cdot 1$ km, below the point 41°N, 68°E as $36 \pm 15 \cdot 9$ km and below 30°N, 68°E (Quetta) as $62 \pm 15 \cdot 8$ km.

TABLE 6

Values of constants b and a and dip angle of the Mohorovicic-discontinuity

	b	σb	S.E.	a	σa	S.E.	Dip angle
D_1	13·255	0·19	±0·04	15·64	5·01	±1·19	N–S
D_2	13·981	0·24	±0·08	8·09	3·41	±1·21	2°
D_3	13·529	0·13	±0·03	10·94	1·78	±0·50	NNE–SSW
D_4	13·690	0·06	±0·00	10·61	2·16	±0·31	22′

8. Conclusions

Based on the results reported here following conclusions can be drawn with respect to the region —

(*i*) Instead of conventional two layer crust, perhaps one additional granitic layer with slightly different physical properties exists in the region.

(*ii*) The velocities of the P wave in the granitic (1 and 2) basaltic and the subcrustal layers have been found to be $5 \cdot 32 \pm 0 \cdot 03$, $5 \cdot 64 \pm 0 \cdot 01$, $6 \cdot 43 \pm 0 \cdot 01$ and $8 \cdot 13 \pm 0 \cdot 01$ km/sec respectively.

(*iii*) The velocities of S wave in the granitic (1 and 2), basaltic and subcrustal layers have been obtained to be $3 \cdot 28 \pm 0 \cdot 001$, $3 \cdot 53 \pm 0 \cdot 003$, $3 \cdot 93 \pm 0 \cdot 003$ and $4 \cdot 53 \pm 0 \cdot 001$ km/sec respectively.

(*iv*) The seismic wave velocities in the granitic layer of the region are comparatively lower than those determined for the other geotectonic unit of the Indian subcontinent.

(*v*) The average thickness of the granitic (1 and 2) and basaltic layer as calculated from P wave data are $17 \cdot 5 \pm 5 \cdot 5$, $15 \cdot 9 \pm 4 \cdot 1$ and $16 \cdot 7 \pm 2 \cdot 7$ km respectively. Thus the average depth of the Mohorovicic discontinuity in the region is $50 \pm 11 \cdot 9$ km.

(*vi*) It has been observed that the Mohorovicic discontinuity dips at an angle of 2° along Long. 68°E between Taskent and Quetta. The depth of the discontinuity obtained beneath Quetta is $62 \pm 15 \cdot 8$ km. It has also been observed that the Mohorovicic discontinuity dips at an angle of 22′ along a NNE to SSW profile between the points 44° N, 81°E and 37°N, 68°E.

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