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Crustal studies in the Himalayan region: Part-I Dalhousie-Mandi section

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ABSTRACT. The parameters of 30 shocks in the Beas Project area in the foothills of Himalayas have been determined and from them the velocities of different phases within the crust have been calculated. All the 30 events were found to be of shallow focal depth, their foci lying within the granitic layer. The mean thickness of granitic and basaltic layers in this area was calculated as 24 and 21 km respectively and the depth of Moho as 45 km. The results have been verified for different focal depths.

1. Introduction

The Beas-Sutlej Link Project is spread over the Siwalik range in foothills region of seismically active Himalayas. A knowledge of the earth's crust in this area is therefore important. The proper demarcation of fracture zones and fault planes is possible only if the determination of earthquake parameters is done precisely and this could be done only after the structure of the crust is known.

The great Kangra earthquake of 4 April 1905 (32·5°N, 76·25°E, Mag. 8·0) in which 20,000 lives were lost, occurred in this area. The Chamba earthquake of 22 June 1945 (32·6°N, 75·9°E, Mag. 6·0) was another major shock. Recent observations show that there is activity in the grid defined by 32° to 33°N and 76° to 77°E, where a large number of minor tremors were detec ted during the past few years.

2. Tectonic features

According to geological studies (Wadia 1966) the rocks of Siwalik system have undergone a great deal of crumpling and deformation. Rock folds, faults, thrust planes and other evidences of movement within the crust are observed in this region on an extensive scale. There are a number of well known tectonic features in this region. The Nahan and Krol thrusts form a very prominent bend in the Dharmsala-Sundernagar (Fig. 1) section of the project area. The trace of the Satlitta thrust is hardly three kilometres away from the Pong Dam site. Hoshiarpur and Jwalamukhi thrusts are the other important tectonic features in this area.

The Nahan and Krol thrusts represent flat, recumbent folds of great amplitude. At a number of places along the trace of these thrusts between Nahan and Kalsi extensive land-slide zones are present. The chain of lakelets and topographic depression near Bakan may be sagponds indicative of active status of the Nahan thrust. The zone of land-slips may have been connected with earthquakes which occurred in the past on Krol and Nahan thrusts. Recent measurements carried out in the Kala-Amb drift have given a positive indication of the continuance of the creep movement on Nahan thrust at the present time. Triangulation studies suggested a general northwesterly movement of the hanging wall of Satlitta thrust by 40 cm and northeasterly movement of foot wall by 40 cm (Krishnaswamy *et al.* 1970).

The other important tectonic features in this area are Chamba tear in the *Ravi* river section and Rupar tear in the *Sutlej* river section. The Chamba tear is believed to have been connected with the Chamba earthquake of 1945.

3. Observational network and collection of data

With the help of project authorities, a close network of observatories was established by the India Meteorological Department in the Project area. These observatories are equipped with highly

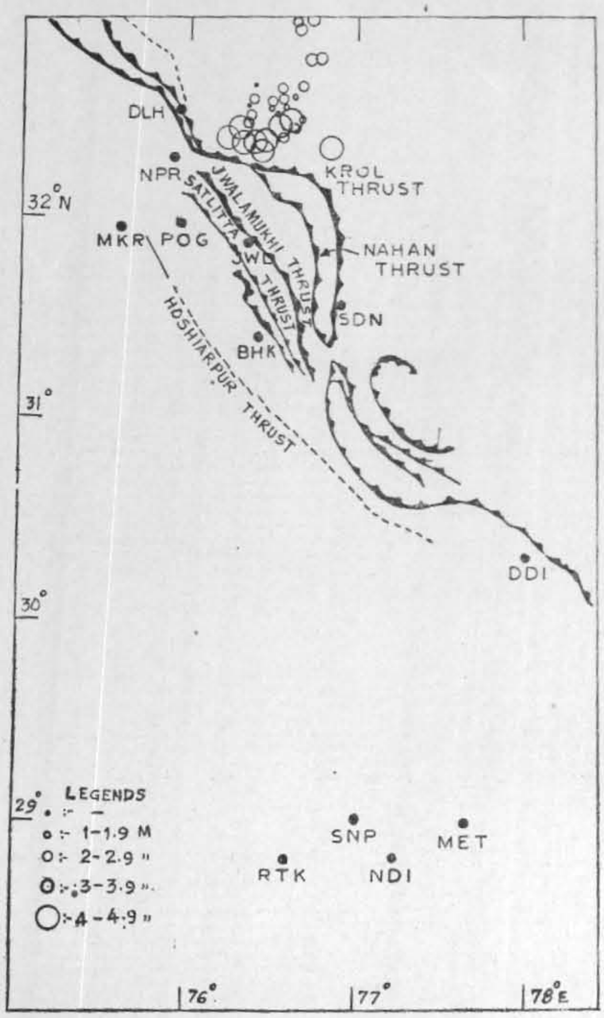


Fig. 1 (a)
Map of northern India showing the observatories and epicentres

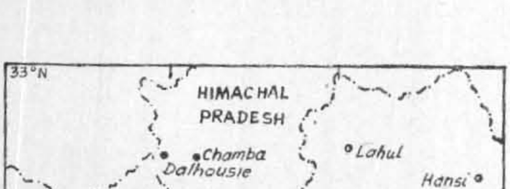


Fig. 1 (b)
Map showing the region studied

sensitive three component Hagiwara electromagnetic seismographs. The observatories are also provided with two component Wood-Anderson seismographs for precise determination of magnitudes. Each observatory is supplied with a crystal clock to maintain high accuracy in timing. In addition, the India Meteorological Department runs a close network of mobile observatories near Delhi. These observatories are equipped with sensitive electromagnetic seismographs. The observatory at Ridge (Delhi) is provided with a standard seismograph system. Table 1 gives the location of stations and the constants of instruments operating at these stations. An index map showing the network of observatories whose data have been used in the present study, as well as epicentres of the events, is given in Fig. 1.

Though a vast amount of data is collected from Beas Project observatories, earthquakes with large magnitudes occurred mostly away from the network. Recently two major shocks of 15 November 1968 and 5 March 1970 occurred well within the network. These shocks and their aftershocks have been used in the present study. Some typical seismograms are shown in Fig. 2 (a, b and c). The parameters of the main earthquakes as determined by USCGS are given in Table 2.

4. Determination of earthquake parameters

Initial travel time curves were constructed using epicentres and origin times as determined by USCGS. The average velocities calculated from these shocks are given in Table 3. From these, the structure of the crust was determined and using this as the basis, travel time curves were constructed for different depths from 0 to 30 km at an interval of 5 km.

Origin times from a minimum of four to five stations were determined for each shock from S-P timings. Only those origin times were accepted where the differences did not exceed 0·5 sec from the mean 0-time.

A scrutiny of the original seismograms of the events showed the presence of the crustal phases P_g and S_g indicating that the foci lay within the granitic layer. The origin time of each shock was also therefore determined by using the following equations (Gedney and Berg 1969).

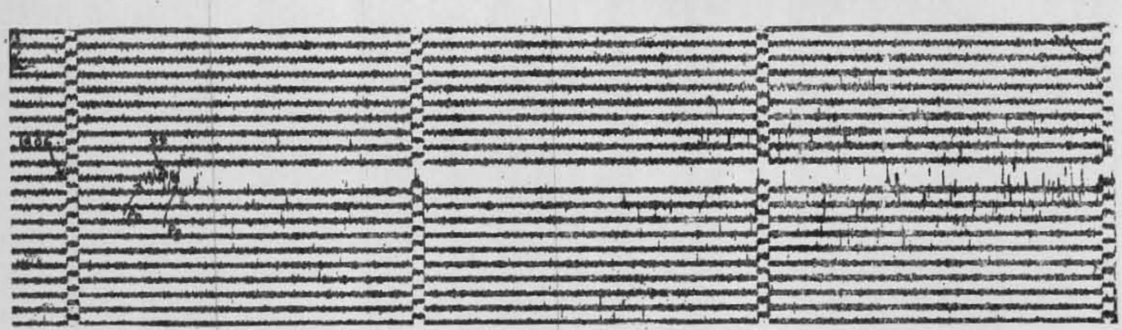
$$T_0 = T_{pg} - (T_{sg} - T_{pg})\,[1/(C-1)]$$

and

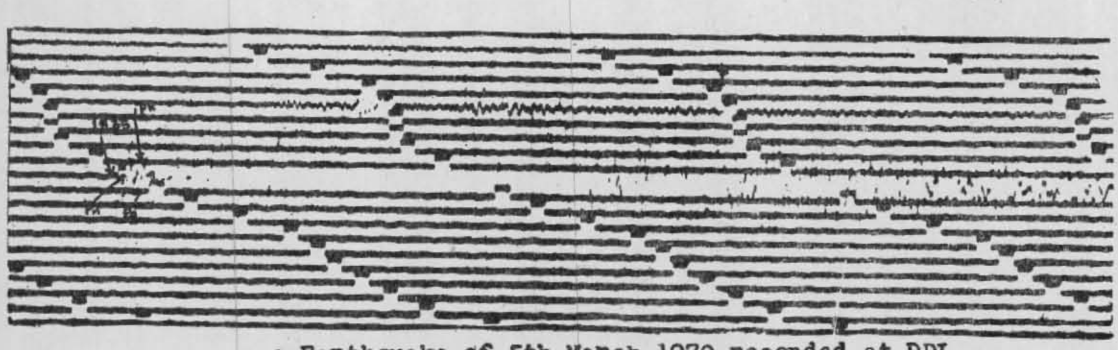
$$T_0 = T_{sg} - (T_{sg} - T_{pg})\,[C/(C-1)]$$

where T_{pg} and T_{sg} are arrival times of P_g and S_g and C is the ratio of V_{pg} and V_{sg}.

a- Earthquake of 5th Nov. 1963 recorded at RHT.



b-Earthquake of 12th Oct.1968 recorded at NDI.



c-Earthquake of 5th March, 1970 recorded at DDI

Fig. 2

Some typical seismograms

Wherever a large number of observations were available, S_g-P_g intervals were plotted against arrival times of P_g and S_g. The points were fitted by straight lines using least square method. The intersection of these curves on Y-axis gave the origin time. The slope gave a value of C. These values showed excellent agreement with those determined by the other method. This method is illustrated in Fig. 3. The 0-time for the shock of 5 March 1970 was calculated as 17 hr 34 min $21 \cdot 5 \pm 0 \cdot 1$ sec whereas the S_g-P_g method gave the value of 17 hr 34 min $21 \cdot 8$ sec.

The preliminary determination of epicentres was done using the mean 0-time. The epicentres were determined from P_g-0 intervals, using as P_g wave velocity the value of $5 \cdot 75$ km/sec obtained from the main events. In fixing the epicentres several checks were applied. Bhakra and Jwalamukhi which lie almost on the same line passing southwards through the aftershock area provided an immediate check from the southern side. Also the observatories in the mobile network around Delhi provided additional control over the epicentres of main shocks. A number of shocks were having almost the same P_g arrival time at Dalhousie and Nurpur. The epicentres of these shocks were checked by drawing the perpendicular bisector of the line joining these stations. The same method was also applied for the other pair of stations, *viz.*, Pong Dam and Jwalamukhi.

Shocks originating from the aftershock showed characteristic first arrivals having large period than the shocks originating from other areas. The first arrivals at Dalhousie and Nurpur, in majority of cases, were identified as P_g.

TABLE 1

Location of stations and instrumental constants

Station	Coordinates		Instruments	Magnification			*To* (sec)	*Tg* (sec)
	Lat. (°N)	Long. (°E)		*Z*	*E*	*N*		
Dalhousie	32° 32½′	75° 58′	Hagiwara E.M.	100,000	100,000	100,000	1·0	1·0
			W.A.		1,000	1,000	0·8	—
Nurpur	32° 18′	75° 52′	H.E.S.	104,000	106,000	100,000	1·0	1·0
			W.A.		900	900	0·8	—
Mukerian	31° 57′	75° 37′	H.E.S	3,100	5,700	5,400	1·0	1·0
			W.A.		1,000	1,000	0·8	—
Pong Dam	31° 55′	75° 55′	H.E. S.	43,000	55,000	43,000	1·0	1·0
			W.A.		1,000	1,000	0·8	—
Jwalamukhi	31° 52′	76° 20′	H.E.S.	100,000	100,000	100,000	1·0	1·0
			W.A.		1,000	1,000	0·8	—
Sundernagar	31° 33′	76° 54′	H.E.S.	100,000	100,000	100,000	1·0	1·0
Bhakra	31° 25′	76° 25′	H.E.S.	5,600	5,600	5,500	1·0	1·0
			W.A.		1,000		0·8	—
Dehradun	30° 19′	78° 02′	Wilson-Lamison	—	—	—	1·3	1·3
			W.A.		1,000	1,000	0·8	—
Rohtak	28° 54′	76° 36′	E.M.	3,500	3,500	—	1·6	1·6
Sonepat	28° 59′	77° 00′	E.M.	4,300	4,300	—	1·6	1·6
Meerut	28° 55′	77° 40′	E.M.	4,800	3,600	—	1·6	1·6
Delhi	28° 41′	77° 13′	Benioff S.P.	50,000	50,000	50,000	1·0	0·75
			Sprengnether LP	1,500	1,500	1,500	15	100
			W.A.		1,000	1,000	0·8	0·8

TABLE 2

Main shocks

(Earthquake parameters as determined by USCGS)

Date	0-Time			Epicentre		Mag. (Mb)	Depth (km)
	h	*m*	*s*	Lat. (°N)	Long. (°E)		
5 Nov 1968	02	02	44·2	32·4	76·4	4·9	N
5 Nov 1968	03	07	08·3	32·4	76·6	—	N
23 Jan 1969	20	01	19·5	32·2	76·1	4·0	N
23 Jan 1969	23	46	26·0	32·2	76·0	—	N
5 Mar 1970	18	34	22·5	32·4	76·5	4·9	N

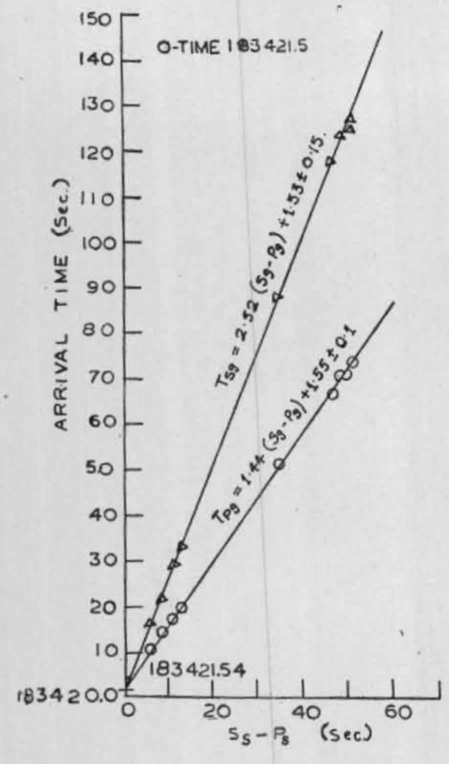


Fig. 3

Determination of 0-time

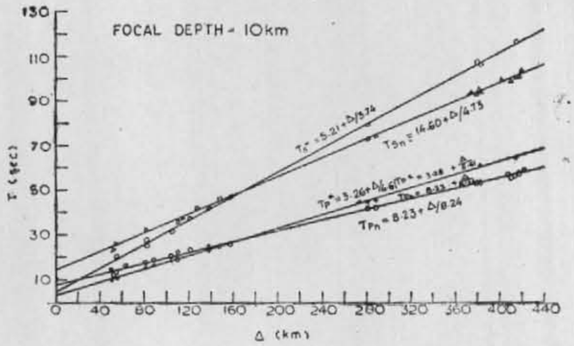


Fig. 4

Travel time curves for P_n, S_n, P^* and S^* for focal depth 10 km

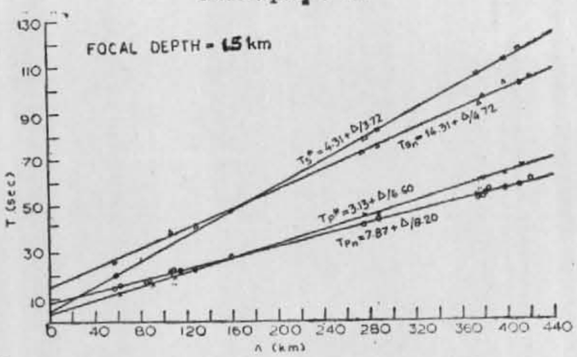


Fig. 5

Travel time curves for P_n, S_n, P^* and S^* for focal depth 15 km

TABLE 3

Preliminary average velocities determined from five main shocks

Phase	Velocity (km/sec)	Intercept time a (sec)
P_n	8·20	8·5
P^*	6·73	3·0
P_g	5·75	—
Sn	4·77	14·5
S^*	3·87	5·0
S_g	3·38	—

Since the epicentres were very close to most of the observatories in the network P_g and S_g travel times were fitted to hyperbolic curves drawn at intervals of depth of five kilometres. Different depths were tried till a good intersection was obtained thus giving minimum residuals. Jwalamukhi and Bhakra being on the same line passing southwards through the aftershock area, gave a check of focal depth by the convergence or divergence of intersection as the depth was increased or decreased. After fixing the epicentre, focal depth etc of the events as described above the epicentral distances were recalculated and fresh travel time analysis was made. These revised travel time curves are given in Figs. 4 and 5.

The magnitudes for the bigger events were determined from the standard Wood-Anderson seismograms. To determine magnitudes of the smaller events which could not be recorded by the Wood-Anderson seismographs, magnification curves for Hagiwara Electromagnetic Seismographs (H.E.S.) for Pong Dam and Jwalamukhi were prepared. The amplitudes read from the seismograms at these stations were reduced to ground amplitude on Wood-Anderson seismograph. The following corrections worked out from about 150 shocks recorded both by Wood-Anderson and H.E.S. were applied to determine the magnitudes of the smaller events.

Magnitude range	*Corr. applied*
2·0—2·9	—0·2
3·0—3·9	—0·3
4·0—4·9	—0·4

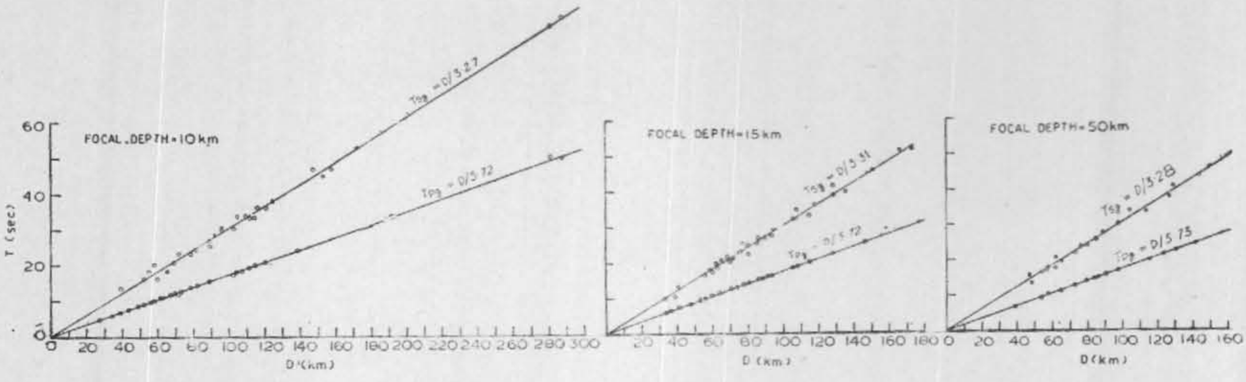


Fig. 6

Transit time curves for *Pg* and *Sg* for focal depth 10, 15, 20km

TABLE 4

Earthquake parameters of main shocks and after shocks

Date	0-Time *h*	0-Time *m*	0-Time *s*	Epicentre Lat. (°N)	Epicentre Long. (°E)	Mag. (M_L)	Focal depth (km)
				1968			
12 Oct	19	06	13·0	32·36	76·82	4·5	25
3 Nov	04	44	48·0	32·64	76·55	1·8	25
4 Nov	00	23	43·2	32·97	76·73	2·4	15
	00	25	51·8	32·79	76·72	2·4	20
	00	36	23·7	32·86	76·71	—	10
	02	17	05·5	32·79	76·77	2·0	10
	03	34	36·1	32·65	76·69	—	15
	17	05	02·8	32·44	76·60	2·5	10
	23	23	13·7	32·38	76·40	4·3	10
5 Nov	00	14	17·2	32·92	76·69	2·1	10
	00	25	14·7	32·40	76·49	—	10
	01	56	13·5	32·49	76·65	1·6	15
	02	02	42·0	32·46	76·51	4·4	10
	02	02	43·8	32·37	76·42	4·7	15
	02	20	02·2	32·51	76·35	2·0	20
	02	52	16·8	32·40	76·54	1·9	20
	03	07	04·7	32·49	76·57	4·3	10
	03	07	08·1	32·36	76·39	4·6	15
	04	35	14·4	32·59	76·55	2·0	20
	05	03	54·7	32·64	76·55	2·1	15
	05	09	40·6	32·48	76·34	2·4	15
	05	22	25·5	32·41	76·45	2·9	15
	05	38	41·5	32·65	76·37	—	15
	06	34	29·4	32·55	76·55	1·8	15
	06	56	42·4	32·59	76·38	1·8	15
	07	44	02·6	32·57	76·48	2·1	25
	07	58	37·3	32·55	76·48	1·8	20
				1969			
23 Jan	20	01	14·8	32·43	76·28	4·3	15
	23	46	21·5	32·40	76·20	4·2	10
				1970			
5 Mar	18	34	21·8	32·38	76·29	4·8	10

TABLE 5

Crustal Constants

Phase	Velocity V (km/sec)	Intercept time a (sec)	Slope b
	Focal depth = 10 km		
P_n	$8{\cdot}24\pm0{\cdot}014$	$8{\cdot}23\pm0{\cdot}10$	0·121
P^*	$6{\cdot}61\pm0{\cdot}030$	$3{\cdot}26\pm0{\cdot}12$	0·151
P_g	$5{\cdot}72\pm0{\cdot}004$	—	—
S_n	$4{\cdot}73\pm0{\cdot}040$	$14{\cdot}55\pm0{\cdot}18$	0·211
S^*	$3{\cdot}74\pm0{\cdot}031$	$5{\cdot}15\pm0{\cdot}34$	0·268
S_g	$3{\cdot}27\pm0{\cdot}032$	—	—
	Focal depth = 15 km		
P_n	$8{\cdot}20\pm0{\cdot}012$	$8{\cdot}01\pm0{\cdot}31$	0·122
P^*	$6{\cdot}60\pm0{\cdot}022$	$3{\cdot}13\pm0{\cdot}24$	0·151
P_g	$5{\cdot}72\pm0{\cdot}002$	—	—
S_n	$4{\cdot}72\pm0{\cdot}054$	$14{\cdot}31\pm0{\cdot}42$	0·212
S^*	$3{\cdot}70\pm0{\cdot}040$	$4{\cdot}31\pm0{\cdot}46$	0·270
S_g	$3{\cdot}31\pm0{\cdot}011$	—	—

TABLE 6

Average crustal thickness (km)

Focal depth (km)	P-Group data		S-Group data	
	H_1	H_2	H_1	H_2
10	24	20	22	21
15	25	19	23	22

A total of 30 well recorded shocks were used for determining the velocities of different phases. The parameters of these shocks are given in Table 4. After assigning the proper depth, the epicentral distances for P_g and S_g were converted into hypocentral distances for fitting the observed points using the least square method. These curves for focal depths of 10, 15 and 20 km are shown in Fig. 6 (a, b and c). The travel time curves for other phases shown in Figs. 4 and 5 were also fitted by least square method. The velocities of different phases determined for focal depths of 10 and 15 km are given in Tables 5 and 6 respectively. The intercept time a and slope b along with the limits of error in a and velocity V are also in given in the same tables.

5. Results and discussions

In analysing the data and drawing the conclusions in the previous sections, a two layered crust has been assumed. There have, however, been a number of studies indicating the presence of sediments over the granitic layer. Since none of the focal parameters were known, the analysis had to be made with a two-layered model. However, the application of Gedney and Buerg's method for the determination of the origin time, which is valid only when there is a single homogeneous layer and the agreement of the results obtained show that the effect of sediments, if any, on the travel times is negligible.

Table 5 shows that the velocities are consistent at different focal depths (10 or 15 km) and are within the limits of error. The negligible limits of error for V_{pg}, over a set of 42 observations, indicates the accuracy in determining the velocity. Though the arrival times of P_g and S_g were available at epicentral distances greater than 400 km, only the near observations of P_g and S_g were taken for fitting the curves more accurately on an enlarged scale.

In the present study no corrections were applied to the travel times for elevation differences in the epicentres and the recording stations because the elevation differences were negligible.

The intercept times of P_g for focal depths of 10 and 15 km were found to be very small (0.051 and 0.004 sec) and hence the lines passed through the origin as expected.

The mean velocities computed are (in km/sec)—

$$P_n=8.22,\ P^*=6.61,\ P_g=5.72,$$

$$S_n=4.73,\ S^*=3.72 \text{ and } S_g=3.29$$

The final average crustal thicknesses computed from the 30 events are listed in Table 6, for different depths of focus. These results gave the mean depths (in km) as $H_1=24$, and $H_2=21$ for the granitic and basaltic layers respectively and the depth of the Mohorovicic discontinuity as 45 km below the surface. All depths are rounded off to the nearest kilometre.

A comparison of the results obtained by the present authors with those of the others is given in Table 7. The average velocities showed good agreement with the results of Tandon (1972) for interior Himalayas. It is evident that the thicknesses of granitic and basaltic layers increase towards the interior Himalayas. The Mohorovicic

TABLE 7

Comparison of average velocities and crustal structure by different workers

Crustal parameters	Present study (Himalayan foothills)	Tandon (1972) (Interior Himalayas)	Tandon (1954) (Assam region)	Chauhan and Singh (1965) (Himalayan region)	Kaila *et al.* (1968) (Himalayan foothills)	Chakravorty and Ghosh (1960) (Himalayan region)
			Average velocities (km/sec)			
V_{Pn}	8·22	8·20	7·91	7·8	8·2	7·7
V_{P*}	6·61	6·50	6·55	6·7	6·9	6·3
V_{Pg}	5·72	5·60	5·58	5·5	6·2	5·3
V_{Sn}	4·73	4·75	4·46	4·4	—	4·4
V_{S*}	3·72	3·75	3·85	3·7	—	3·7
V_{Sg}	3·29	3·30	3·43	3·3	—	3·3
			Crustal structure (km)			
H_o	—	—	—	—	6±1	—
H_1	24	29·5	24·8	25	8±5	16·5
H_2	21	28·5	21·5	25	14±7	21·6
Depth of Moho	45	58	46·3	50	28±8	38.1

discontinuity is dipping towards Anantnag area by about 13 km with an angle of about 5°. This is in agreement with the observations that the crust is thicker in the interior Himalayas than that at the foothills.

Though the velocities of $V_s^*=3.7$ and $V_{sg}=3.3$ km/sec obtained by Chauhan and Singh (1965) agree with the results, the velocities of other phases obtained by them are lower. The thickness of the granitic layer calculated by them is, however, in good agreement. In their study the epicentral distances were such that P_n was the first arrival at all the stations and the epicentres of 15 shocks selected for study were widely distributed in space and time. The thickness of crust in different regions of Himalayas has been computed from individual shocks.

Chakravorty and Ghosh (1960) computed lower values for V_{pn}, V_{p*} and V_{pg}. The values of $V_{s*}=3.7$ and $V_{sg}=3.3$ km/sec agree well with those obtained by us. The thickness of the granitic layer is low but the average thickness of 21.6 km in the southern part of central Himalayas for basaltic layer is in close agreement. The average depth of Moho is about 7 km less. The low value for the thickness of granitic layer obtained by them may be due to lower values of P-phase velocities and correspondingly lesser delay times. In their study most of the shocks were from Tibet, Assam and India-Nepal border region. The computation of velocities and crustal structure is based on individual shocks which in turn requires precise determination of both epicentre and focal depth. The authors admit that most of the desired phases were available from the records of few stations only. The minimum epicentral distance was about 300 km, whereas in the present study the precise determination of epicentres was carried out using the close network of observatories.

Tandon (1954) obtained mean depths of $H_1=24.8$ and $H_2=21.5$ km and the depth of Moho as 46.3 km for Assam region. Even though a mean focal depth of 13 km was assumed by him for calculations of crustal thickness, the results showed good agreement with our study. From the actual analysis of earthquake records he found that most of the foci lay in the upper most layer, *i.e.*, granitic layer and hence he combined the data for all shocks for the purpose of least square analysis. In the present case earthquakes were grouped in accordance with their focal depth and separate least square analysis was carried out in each case. The velocities of various phases in Assam region showed slight variation which may be the characteristic of the region. It may be mentioned that the epicentre of the great Assam earthquake of 15 August 1950 (Mag. 8.5) was located near the foothills of eastern Himalayas. The shocks in the present study also occurred near the foothills of Himalayas.

Although the velocity of P_n=8.2 km/sec calculated by Kaila *et al.* (1968) for foothills agrees with the results of present authors, the velocities of P^* and P_g obtained by them are higher. The thicknesses of granitic and basaltic layers are comparatively low and the depth of Moho (28 $\pm$ 8 km) is also low. Most of the shocks in their study were recorded at one station only. The smallest Δ-value, they could obtain was 150 km whereas in this study the maximum number of observations were available within the epicentral distance of 150 km. Further, the control over the epicentres was poor in the study of Kaila *et al.* due to the scattered network of observatories. In the present study the close network of observatories provided a good control over earthquake parameters. Kaila *et al.* also concluded that most of the normal earthquakes in the Himalayan foothills region have their foci in the sedimentary layer and based their calculations on the above focal depth. As mentioned earlier the shocks studied by them were recorded at distances greater than 150 km by instruments which were not so sensitive as those used now-a-days. The magnitudes of the events therefore were such that it is not known how the energy released by them could be stored in the low velocity sedimentary layer as assumed by them. In the present study we observed that in majority of cases the first arrival at number of stations was unmistakably P_g. Since the epicentres of shocks were very close to the network, the focal depths could be determined with reasonable confidence. P_g and S_g phases were well recognised even when the depth of focus of the events was between 20 to 24 km indicating that the thickness of granitic layer is of the order of 20 km. Table 3 shows that most of the shocks have focal depths greater than 10 km. This fact invariably indicates that the foci of the majority of shocks lay within the granitic layer.

From gravity and seismological data Roy and Jain (1968) obtained 8.24 km/sec as the velocity below the Moho. The velocity agrees with the P_n velocity of 8.22 km/sec obtained in the present study. They calculated normal crustal thickness on the Indian side of Himalayas as 50 km.

The values of Vs^*=3.71 and V_{sg}=3.29 km/sec obtained by Roy (1938) for the Gangetic valley agree with the results obtained. For other phases he obtained slightly lower values.

From the study of dispersion of surface waves Gabriel and Kuo (1966), Chaudhury (1966), Tandon and Chaudhury (1968), Chatterjee (1971) calculated the thickness of the crust as around 40 km for the plains south of the Himalayan mountains. Studies through surface wave dispersion by Tandon and Chaudhury (1963) as well as by Gupta and Narain (1967) clearly showed that the average depth of the Moho under the Himalayan hills is more than 55 km, indicating that the Moho dips under the mountains which thus has a root. From the analysis of dispersion of Rayleigh waves across a number of crossing paths Santo and Sato (1966) have made a division of the earth on the basis of group velocities. This divisioning also clearly shows a rapid increase of the depth of the Moho from the Gangetic plain to the mountains. A similar study by Gupta and Sato (1968) using Love waves confirmed the same. The area of the present investigation in the Himalayan foothills is between the plains of the *Ganga* and the mid-mountains. The depth of 45 km obtained for the Moho seems to fit in with the above picture of the dipping Moho.

6. Conclusions

In summary the study has brought out the following :

(*i*) The foci of majority of shocks lay in the granitic layer.

(*ii*) The mean thicknesses of granitic and basaltic layers are 24 and 21 km respectively. The depth of the Mohorovicic discontinuity in the foothills of Himalayas is about 45 km.

The velocities of different crustal phases for focal depths of 10 and 15 km are consistent and are within the limits of error. The results of the present study showed a close agreement with the body wave, gravity and surface wave studies carried out by different workers in this region.

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