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On the crustal structure of the eastern Himalayas adjoining Tibetan Plateau and Chinese mountains

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ABSTRACT. The crustal structure of the eastern Himalayas, adjoining Tibetan Plateau and Chinese mountains has been investigated from body wave data of near earthquakes. A three layered crustal model consisting of two granitic layers (granite I and II) and one basaltic layer has been interpreted. Wave velocities for Pg_1, Pg_2, P^* and Pn phases have been observed to be as 5·65, 6·03, 6·49 and 7·97 km/sec and for Sg_1, Sg_2, S^*, and Sn phases to be as 3·42, 3·60, 3·90 and 4·53 km/sec respectively. It has also been observed that the wave velocity increases with depth in the granite I layer. The average thicknessess of the crustal layers for granite I are found to be as 22·0 km, for granite II as 12·3 km and for basaltic layer as 16·1 km. The average depth of the M-discontinuity in the region has been interpreted as 50·4 km. It has also been observed that the crust-mantle boundary dips at an angle of about 30′ from south to north along Long. 103°E. A general thickening of the crust has also been observed in the eastern Himalayas from Kunming towards Lhasa.

Introduction

The triangular piece of area with its vertex near the Pamir Plateau and the sides extending northeast wards and southeast wards to the region of Szechuan and Yunan in the east, constitutes the biggest and the highest elevated land mass on the earth. It has been classified by Gutenberg and Richter (1949) as the 'Chinese active area of Non-Alpide Asia'. It lies immediately to the north of the Himalayan Alpide belt and includes the Tibetan Plateau, the Kunlun, Altyn Tagh and Nanshan range and the regions of Szechuan and Yunan. The average height of this land mass exceeds 16,000 ft. Except for parts of the Tibetan Plateau and the area lying between Kunlun and Altyn Tagh and Nanshan ranges, the whole block is seismically very active. Two very great earthquakes occurred in Kaueu in 1920 and 1927. A study of the earth's crust below this region is therefore of great interest.

According to the principle of isostacy the earth's crust should be thicker under the mountains than under the plains or oceanic areas. Studies of the earth's crust in different parts of the world based either on earthquake data or on the data obtained from explosions have in general supported this view (*cf.* Gutenberg 1933, Byerly 1938, 1956, Caloi 1958, James and Steinhert 1965 and Kosminskaya and Riznichenko 1964). Contrary to this view Tatel *et al.* (1957) found evidence that there is no direct correlation between the high land areas and concentration of more matter in the crust. It is, however, generally accepted that there are distinct regional variations with regard to the elastic and physical properties of the crustal and subcrustal layers. The present investigation has been undertaken with a view to study the structure of the crust under this elevated area and to find out if the depth of Mohorovicic discontinuity changes from place to place in the region. In an earlier paper Tandon and Dube (1973) had made a study of the crustal structure of the great Himalayas and adjoining mountains region using data of the network of Russian and Chinese Observatories. In the present investigation a study of the earth's crust in the eastern region and a small section of the eastern Himalayas has been undertaken using data provided by earthquakes occurring within the region and recorded by the close network of Chinese stations. Fig. 1 gives the spatial distribution of the epicentres and observatories.

2. Materials used

Relevant published data of all earthquakes in the bounded region (Fig. 1) has been collected from International Seismological Summary (I.S.S.) (1956-65) and International Seismological

TABLE 1

Date	Location of epicentre		Origin time (GMT)			Depth of focus (km)
	Lat. (°N)	Long. (°E)	*h*	*m*	*s*	
4 Dec 1957	45·21	99·24	03	37	48	0
4 Dec 1957	45·04	101·37	13	20	08	0
7 Dec 1957	43·19	100·26	14	11	13	0
7 Feb 1958	31·54	103·87	23	23	33	0
24 Feb 1958	45·13	99·58	12	27	19	0
30 Apr 1958	38·52	103·99	13	54	46	0
14 Feb 1959	27·58	96·57	22	10	42	0
14 Feb 1959	27·58	96·48	22	25	48	0
22 Feb 1959	28·92	91·85	03	30	40	0
11 Mar 1959	28·23	103·89	02	59	54	0
9 Apr 1959	25·7	94·76	17	08	33	0
26 Apr 1959	26·16	100·61	12	34	57	0
27 Apr 1959	33·23	92·68	13	09	21	0
4 May 1959	28·86	92·07	17	18	32	0
22 May 1959	25·38	96·23	08	31	07	0
13 Jun 1959	38·52	103·92	16	04	10	0
27 Aug 1959	25·12	96·17	23	53	11	0
10 Nov 1959	36·14	88·67	20	56	13	0
24 Apr 1960	39·06	101·27	21	27	14	0
3 May 1960	29·85	99·58	07	55	11	0
26 May 1960	26·82	92·68	20	05	07	0
9 Nov 1960	32·85	103·54	10	43	40	0
3 Dec 1960	43·18	104·46	04	24	44	0
11 Jun 1961	25·13	98·56	17	15	30	0
4 Dec 1961	33·39	95·25	12	38	09	0
8 Dec 1961	30·92	87·20	10	19	50	0
20 Feb 1962	26·13	96·94	22	02	35	0
21 May 1962	37·11	95·83	12	02	49	0
1 Aug 1962	39·33	98·57	15	47	43	0
22 Sep 1962	26·48	96·82	06	51	28	0
7 Dec 1962	38·20	106·26	09	35	58	0
17 Dec 1962	37·97	106·25	17	25	36	0
11 Jun 1963	30·93	87·27	18	07	19	0
11 Apr 1965	29·37	104·85	14	27	40·0	0
	±·043	±·044			±0·22	
23 May 1965	24·28	102·47	16	05	29·3	0
	±·084	±·054			±0·33	
14 May 1966	27·39	92·4	04	11	26	
	±·098	±·190			±1·2	0

Centre (I.S.C.) (1966-1969) for a period of 14 years. 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 atleast a few observatories. Table 1 gives the earthquake parameters of 36 selected earthquakes. The arrival times of the seismic waves as picked up and reported by the observatories located well within the bounded region (Fig. 1) were collected and used without modification.

As a first step, the travel-times of various phases were plotted against the epicentral distances (upto 10 degrees) in Fig. 2. A perusal of the plotted points showed that while the points corresponding to P_n, S_n and P^*, S^* fell along distinct lines, the points corresponding to P_g and S_g arranged themselves along two distinct branches. These have been designated as P_{g1}, P_{g2} and S_{g1}, S_{g2} respectively. This is suggestive of the existence of an additional layer, between the conventional granitic and basaltic layers and is responsible for transmission of an additional refracted pulse for each P and S waves.

3. Calculation of velocities and thickness of layer

3·1 Having assigned the observed points to different wave groups the problem reduced to find out the best straight line fit for the time of arrival of each pulse at varying distances using the method of least squares. If T denotes the observed arrival at an epicentral distance $\triangle$, we have to determine a and v so as to make $[\Sigma\ T - a - (\triangle/v)]^2$ as small as possible. Here v is the velocity and a a constant which is called 'the apparent delay of starting'. To solve the equation a preliminary approximate value of v is chosen, say w, then the values of b are computed to the nearest tenth of a second.

Let

$$\frac{1}{v} - \frac{1}{w} = b \tag{1}$$

then the equation of condition becomes

$$a + b \triangle_r = T_r - \triangle_r/w = C_r \tag{2}$$

For a suitable choice of w the quantities C_r are nearly equal. For n observatories the normal equations are :

$$n\,a + b\,\Sigma \triangle_r = C_r \tag{3}$$

$$a\,\Sigma \triangle_r + b\,(\Sigma \triangle_r^2) = \Sigma C_r \triangle_r \tag{4}$$

which can be solved for a and b and the value of v determined from (1).

In order to find out the accuracy of the solution the series of residuals after using computed values of a and b can be found out.

$$C_r' = T_r - a - (\triangle_r/v) \tag{5}$$

The mean square residual σ is given by

$$n\,\sigma^2 = \Sigma\, {C'}_r^{\,2}$$

and the standard deviations of a and b can be expressed as (Jeffreys 1971)

$$\sigma_a^2 = \frac{\Sigma \triangle_r^2}{n\,\Sigma \triangle_r^2 - (\Sigma \triangle_r)^2}\ \frac{\Sigma {C'}_r^2}{n-2} \tag{6}$$

$$\sigma_b^2 = \frac{n}{n\,\Sigma \triangle_r^2 - (\Sigma \triangle_r)^2}\ \frac{\Sigma {C'}_r^2}{n-2} \tag{7}$$

For large n, the posterior probability of different values of a and b is governed by normal law. Thus for a, the probability that the computed value is wrong by $0{\cdot}674\ a$ or more is 1/2. If the computations have been done correctly and there is no error in data, we should have

$$\Sigma\, C_r' = 0\ ;\ \Sigma \triangle_r C_r' = 0 \tag{8}$$

This criteria serves as a check to the computations.

3.2. *Thickness of crustal layers*

From the ray theory it can readily be deduced that for the m^{th} layer (layers considered to be horizontal and homogeneous)

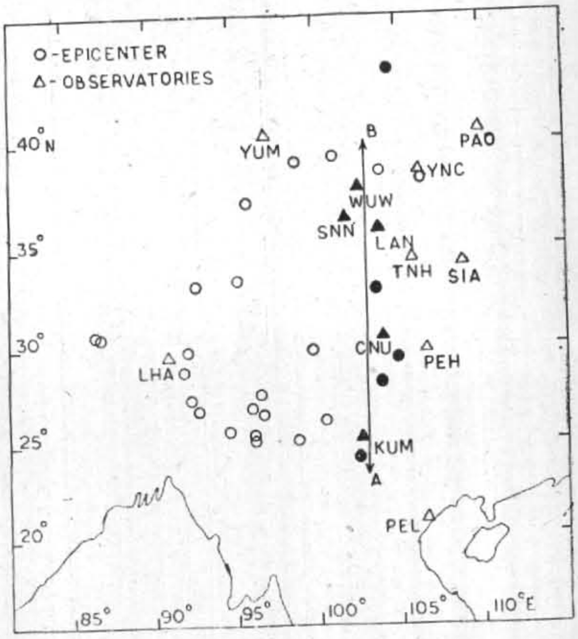

Fig. 1

Index map showing locations of epicentres and observatories. Solid triangles and circles are the observatories and epicentres respectively that lie along the N—S profiles (A B)

$$C_m = (2\,H_1 - h)\ \left(\frac{1}{v_1^2} - \frac{1}{v_m^2}\right)^{\frac{1}{2}} + \sum_{p=2}^{m-1} 2H_p \left(\frac{1}{v_p^2} - \frac{1}{v_m^2}\right)^{\frac{1}{2}} \tag{9}$$

where C_m is the delay time or intercept time on the T axis and is dependent on the thickness and velocities of waves through different layers, but independent of $\triangle$, v_p and H_p are the velocity and thickness of the m^{th} layer and h is the focal depth. For a three layered crust we deduce from (9)

$$H_1 = C_2\, v_2\, v_1 \,/\, \{2 \sqrt{(v_2^2 - v_1^2)}\}$$

$$H_2 = \frac{[C_3 - 2\,H_1 \sqrt{(v_3^2 - v_1^2)}\,/\,v_2 v_1]\ v_3\, v_2}{2\sqrt{(v_3^2 - v_2^2)}}$$

$$H_3 = [C_4 - 2\,H_1 \sqrt{(v_4^2 - v_1^2)}\,/\,v_4 v_1 - 2\,H_2 \sqrt{(v_4^2 - v_2^2)}\,/\,v_4 v_2]\ v_4 v_3 \,/\, \{2\sqrt{(v_4^2 - v_3^2)}\} \tag{10}$$

Having determined the values of the delay times and velocities of P and S waves through the different layers, the thickness of each layers can be calculated separately.

4. Results

4.1. *Velocities*

Based on the method of least squares as outlined in Sec. 3 and the observed travel times of different

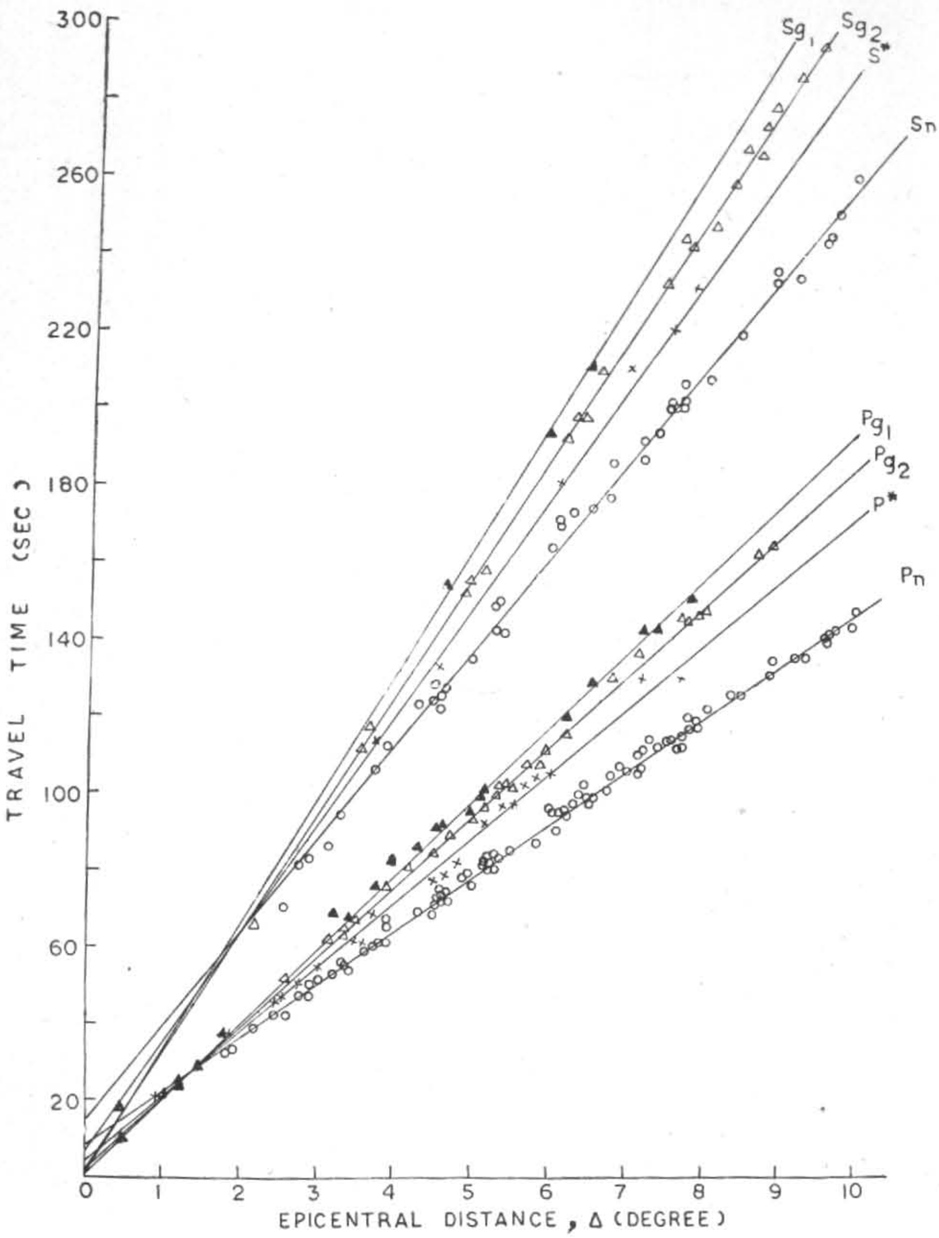

Fig.
Travel-time curves for crustal and subcrustal phases

TABLE 2

	Pg_1	Pg_2	P^*	P_n	Sg_1	Sg_2	S^*	S_n
b	19·633	18·407	17·111	13·919	32·456	30.789	28·446	24·512
$\sigma'b$	0·269	0·142	0·291	0·089	—	0·254	0·966	0·269
S.E.	±0·065	±0·030	±0·072	±0·009	—	±0·073	±0·291	±0·040
a	1·618	2·373	4·324	9·404	2·000	2·759	7·665	15·418
$\sigma'a$	3·513	3·800	4·480	5·402	—	5·722	19·400	11·86
S.E.	±0·857	±0·808	±1·12	±0·560	—	±1·364	±5·880	±1·77

seismic phases for different epicentral distances, the wave velocities and thicknesses were calculated with the help of an IBM 360/44 computer. The programme was made for a double precision accuracy. Because of the small distances of the observatories with respect to the epicentres the curvature of the earth's surface was neglected. The slopes, velocities as well as the values of the constants thus determined are given in Table 2 along with the standard deviations of the slopes and the intercept times. The values of the velocities observed by various workers for different parts of the Indian subcontinent are given in Table 3 for the sake of comparison.

It can be seen from Table 3 that the velocities of body waves through different crustal layers are of the same order as that of the other parts of the Indian subcontinent except for P_n and S_n phases which are slightly lower. This can be attributed to the tectonically disturbed geological condition of this region. Lower sub-crustal velocities have also been observed in other parts of the world (Gutenberg 1959, Roller *et al.* 1966, Tandon and Dube 1973). Explosions studies in Eurasian subcontinents by Kosminspaya and Riznichenko (1964) also support a lower sub-crustal velocities in tectonically disturbed regions as compared to those of basin and shield areas. Lower sub-crustal velocities have also been reported for the tectonically disturbed Japan region by research group on explosion seismology (1966).

It is also seen from Table 3 that the crustal velocities in the granite II and basaltic layers for both P and S waves are in close agreement to those obtained by Tandon (1972), Tandon and Dube (1973), but the velocities in the granite I layer are comparatively higher. A close look at Fig. 2 indicates that most of the observed points of P_{g1} phase within an epicentral distances of 5 degrees fall above the computed line while the same lie on or below the curve at greater epicentral distances. This suggests an increase of velocity with depth in the granite I layer. However, to confirm this interpretation a straight line relation ($T=b\triangle+a$) was fitted to the observed travel-times within epicentral distances of 5 degrees by the method of least squares and the following relation was obtained :

$$T = (20.29 \pm 0.10) \triangle + 0.23 \pm 0.37 \qquad (11)$$

which gives a velocity of 5.5 km/sec in the upper part of the granite I layer — a value comparatively lower than the average of the whole layer. This value is also in better agreement to those obtained by Tandon and Dube (1973). A similar interpretation for the S_{g1} phase does not appear feasible due to inadequate data.

4.2. *Thickness of layers*

Even though the I.S.S. and I.S.C. reported zero depth of focus for all the earthquakes considered (Table 1), a check of the depth of focus was considered necessary since it has a pronounced effect on the computation of the thicknesses of layers. Determination of the depth of focus of each earthquake from the travel times of P_g and S_g phases was not possible due to non availability of data for distances less than one degree. However, an average depth of focus for all the earthquakes considered has been computed from the (P_g-P_n) interval. This gave value of 10 km for the depth of focus which has been used for calculation of the thickness of layers. The layer thickness as well as the depth of M-discontinuity were calculated independently from P and S wave travel time curves by the formula given in (10). The values obtained are given in Table 4. The average thickness of the crust in the region works out to be about 50 km consisting of two layers of granite of thickness 34 km resting on a layer of basalt 16 km thick.

It is interesting to note that contrary to the conventional two layered crust, a three layered crust has been interpreted for this region. Evidences regarding formation of three layered crust having two granitic layers (with different velocities) have also been found for other regions in the world (*cf.* Stewart 1968; Balavadze and Tvaltvadze 1957; Tandon and Dube 1973). The average thickness of the crust is higher than the value obtained for the Indian plains. This same result was obtained for the great Himalayas and adjoining mountain region by Tandon and Dube (1973). Evidences for higher crustal thickness in mountainous regions have also been put forward by many other workers. Table 5 taken from Fernadez and Careaga (1968) summarises these results.

4·3 *Dipping of the Mohorovicic discontinuity*

It can be seen from Fig. 1 that a number of earthquake epicentres (solid circles) and recording stations (solid triangles) lie in a narrow belt along the line AB forming almost north-south profile. During the course of investigation it was observed that consistently positive and negative residuals of P_n and S_n phases were reported from the observatories situated south and north of epicentres in this belt. Such type of orientation of the observatories and epicentres enabled us to study the variations in the depth of the M-discontinuity along the line AB by studying the travel times of P_n and S_n waves travelling from north to south and in the reverse direction, *i.e.*, from south to north.

These have been designated as D(1) and D(2) respectively and plotted in Fig. 3. The slopes

TABLE 3

Wave veclocities of the various crustal and subcrustal phases

	Pg_1 or Pg	Pg_2	P^*	Pn	Sg_1 or Sg	Sg_2	S^*	Sn
Tandon (1954) (N.E. India)	5·58 ±0·01	—	6·55 ±0·02	7·91 ±0·02	3·43 ±0·01	—	3·85 ±0·01	4·45 ±0·01
Tondon and Chaudhury (1968) (Deccan Shield)	5·67	—	6·44	8·24	—	—	—	4·73
Arora (1971) (Gauribinder)	5·67	—	6·51	7·98	3·46	—	3·96	4·61
Dube and Tandon (1973) (Himalaya)	5·48 ±0·02	6·00 ±0·06	6·45 ±0·02	8·07 ±0·005	3·33 ±0·012	3·56 ±0·02	3·90 ±0·02	4·57 ±0·01
Tandon (1972) (Kashmir valley)	5·6	—	6·5	8·2	3·3	—	3·75	4·75
Present study	5·65	6·03	6·49	7·97	3·42	3·60	3·90	4·53

TABLE 4

Thicknesses of the crustal layers

Layer	Thickness (P wave group) (km)	Thickness (S wave group) (km)	Average (km)
Granite I	24	19.9	22.0
Granite II	8.4	16.3	12.3
Basalt	15.9	16.2	16.1
Depth of the M-discontinuity	48.3	52.4	50.4

TABLE 5

High values of the thickness of the crust related with high altitudes (Fernadaz and Careaga 1968)

Author	Thickness (km)	Region	Mountain
Ryaboy (1966)	48.50	N-Afganistan	Ala-Dagh, Indo Kush
Sung Ali (1964)	58.67	S.E. Tibet	Himalayas
Ting Yumyu (1965)	71	China	Himalayas
Sorsky, Ali (1966)	55.65	Caucsus	U. S. S. R.
Kosminskaya (1958)	72	Academy Sc. Mts.	Pamir-Alai
Chaudhury (1956)	73	Afganistan	Hindu Kush

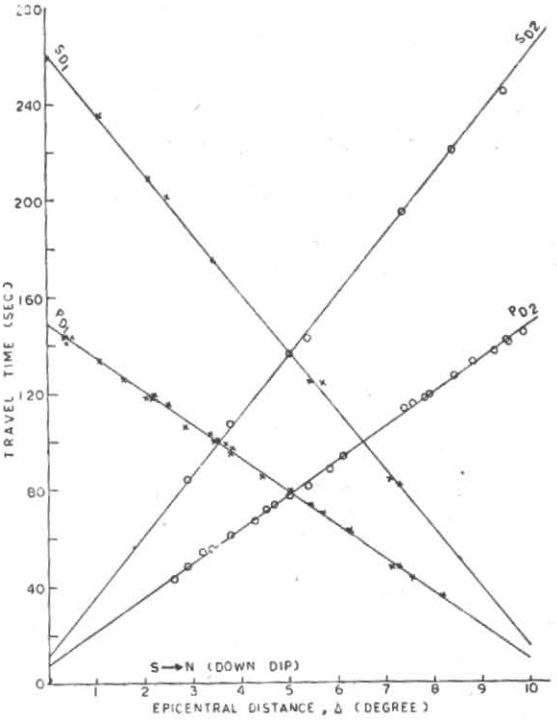

Fig. 3

Travel-time curves for subcrustal phases in the downdip and up dip direction along long. 103° E

intercept time and velocities together with their standard deviations and standard errors for both P_n and S_n waves have been calculated for the best straight line fit by the method of least squares and given in Table 6. It can be seen from the table that the intercept times obtained for the data of group D (1) for both P and S waves are higher as compared to those of D(2). This shows that the M-discontinuity dips from south to north in the region. The dipping angle 'a' of the M-discontinuity, assuming that except for the M-discontinuity the other discontinuities are horizontal, can

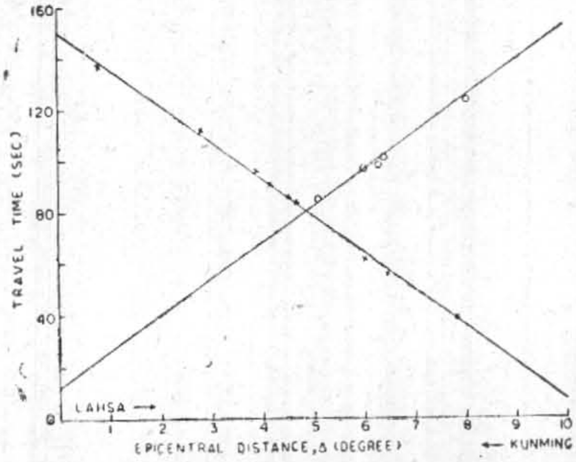

Fig. 4

Travel time curves for subcrustal phases in the direction Kunming-Lhasa and *vice versa*

TABLE 6

	b	$\sigma'b$	S.E.	a	$\sigma'a$	S.E	X	
							P	S
$P(D_1)$	13·925	0·11	±0·02	9·51	3·90	±0·702	28·7	31·7
$P(D_2)$	14·059	0·10	±0·02	7·29	3·06	±0·65	—	—
$S(D_1)$	24·627	0·232	±·008	16·10	4·273	±1·42	—	—
$S(D_2)$	24·885	0·348	±·011	10·43	6·26	±1·39	—	—

be calculated from the following relations.

$$m_d = \frac{1}{v_3} \sin (i_c + a) \tag{12}$$

$$m_u = \frac{1}{v_3} \sin (i_c - a) \tag{13}$$

where, m_d and m_u are the slopes of the travel-time curves for the down dip and up dip of the ray paths. The dipping angle has been calculated separately from the data of P_n and S_n phases and given in column S of Table 6. The average value of a comes to about 30′. This implies that the depth of the M-discontinuity increases by about 9 km for a change of latitude of 9 degrees from south towards north. The thickness of the crust at latitudes 25°N and 35°N comes out to be 44 km and 53 km respectively.

It can also be seen from Fig. 1 that a few epicentres in the eastern Himalayas align themselves along a profile between the observatories at Lhasa and Kunming. This again enabled us to study the variation in the depth of the M-discontinuity in the direction from Kunming towards Lhasa. In Fig. 4 the travel-times of the P_n waves as recorded at these two observatories have been plotted separately. The slopes, intercept times were determined by fitting a straight line. Even though the number of observations are small, a higher intercept time is clearly descernible for the observation recorded at Lhasa, indicating that the depth to the M-discontinuity increases in the direction from Kunming to Lhasa.

5. Conclusions

Based on the results obtained in the preceding pages the following conclusions can be drawn.

(*i*) Contrary to the general view of a two layer crust the existence of an additional granitic layer overlying another with slightly different physical properties has been obtained.

(*ii*) The velocities of the P wave in the granite (I and II), basaltic and the substratum have been found to be 5·65, 6·03, 6·49 and 7·97 km/sec respectively. The velocity increases with depth in the granite I layer.

(*iii*) The velocities of S wave through the granite (I and II) basaltic and subcrustal layers are 3·42, 3·60, 3·90 and 4·53 km/sec respectively.

(*iv*) The velocities of seismic waves in the subcrustal layers are comparatively lower than that of other type of geological blocks. This may be due to the tectonically disturbed state of the region.

(*v*) The average thickness of the granitic (I and II), basaltic layers calculated from both P and S waves are 22·0, 12·3 and 16·1 km respectively Thus the average depth to the M-discontinuity is 50 km.

(*vi*) The crust-mantle boundary dips at an angle of about 30′ along longitude 103°E from south to north. A general thickening of the crust from Kunming towards Lhasa has also been observed in the eastern Himalayas.

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