TRAVEL TIMES OF *P*-WAVES IN NORTH-EAST INDIA

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Summary: *Based on 90 accurately localized earthquakes in and around North-East India and the local crustal velocity model of Gupta et al. [4], the travel times of P-waves have been determined from the foci of these earthquakes at arbitrarily selected depths of 5, 13, 25, 41 and 50 km to the sites of the seismic stations operated by the Regional Research Laboratory, Jorhat and the National Geophysical Research Institute, Hyderabad, and also to the sites of the Shillong and Tura seismic stations run by the India Meteorological Department, New Delhi. The travel times of P-waves fit a straight line very well with velocities of 5·97 ± 0·31, 6·18 ± 0·01, 6·41 ± 0·03, 7·82 ± 0·07 and 7·95 ± 0·01 km/sec at each of the depths under study. Similar investigations of P* and Pg-waves of 16 earthquakes at a depth of 10 km have revealed velocities of 6·53 ± 0·31 and 5·64 ± 0·34 km/sec, respectively. A simplified two-layered crustal model consisting of an average crustal thickness of 41·5 km with 22·2 and 19·3 km thick layers has been obtained.*

1. INTRODUCTION

Travel times of *P*-waves are of great importance for the physics of the earth's interior as well as for seismology. These times are the main source of the data for computing hypocentral parameters. On the other hand, as far as near earthquakes are concerned, an accurate determination of these times can contribute to the knowledge of the regional crustal structure and upper mantle structure immediately below the Mohorovičić (also known as Moho) discontinuity.

Attempts to determine the crustal velocity structure beneath North-East India have been made by some scientists. For example, Tandon [11], Saha et al. [10] Gupta et al. [4] have reported the crustal velocity structure in connection with the computation of the hypocentral parameters of micro-earthquakes that occurred in the region. With a view to the micro-earthquake investigations undertaken in the year 1979, the Regional Research Laboratory, Jorhat (RRL-J) jointly with the National Geophysical Research Institute, Hyderabad (NGRI) initiated the programme of the establishment of a close network of seismic stations in Northeastern India. During the period 1981—82, the group established seven seismic stations comprising two 3-component and five vertical component (mainly short period) seismic stations. The stations are situated at Guwahati (GWH), Jorhat (JHI) and Kaziranga (KZI) in Assam; Itanagar (INR) and Khonsa (KOI) in Arunachal Pradesh; and Kohima (KHM) and Yaongyimsen (YYI) in Nagaland. The present study makes use of *P*-wave arrival times in addition to those at the seismic stations located at Shillong (SHL) and Tura (TUR) in Meghalaya state, operated by the India Meteorological Department, New Delhi (IMD) for the relatively accurate localization of shallow earthquakes in order to analyse the *P*-wave travel times.

2. THE DATA

About 180 arrival times of *P*-waves were used to compute the travel times from the locations of about 90 earthquakes (of magnitude 3·5 – 5·5) that occurred in North-eastern India during the years 1981 – 82 at depths of 5, 13, 25, 41 and 50 km. These

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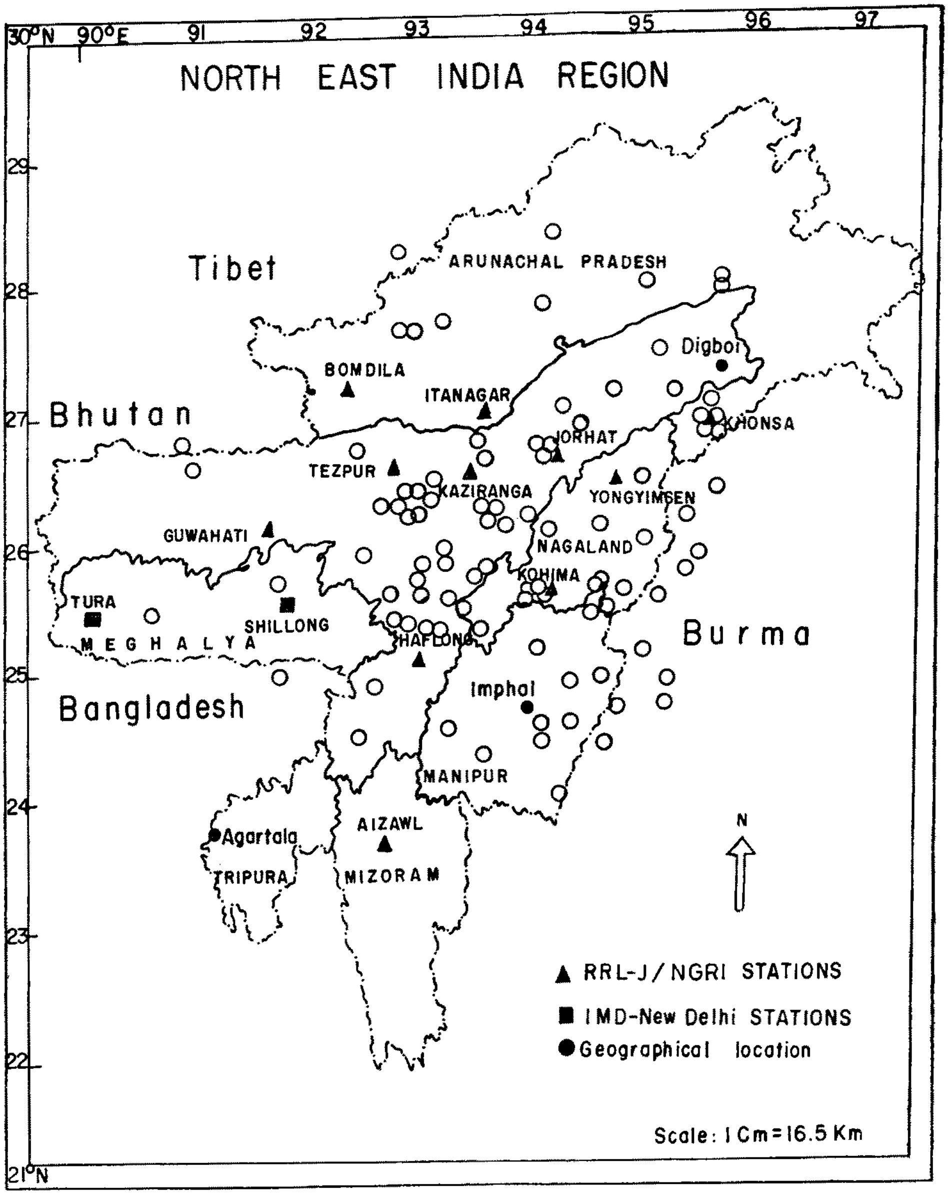

Fig. 1. Map showing the epicentres (denoted by white circles) of microearthquakes considered in the present study.

depths (arbitrarily selected) are the mean estimates of the focal depths considered within ± 3 km. *P*-wave times were obtained from the seismograms at the RRL-J/NGRI seismic stations namely GWH, JHI, KZI, INR, KOI, KHM, YYI

Table 1. Information on the seismic stations.

Station Code	Station	Lat. N	Long. E	Height mts. (M. S. L.)	Rock Formation	Equipment	Component	Magnification	Speed mm/min.	Recording type
GWH	Guwahati, Assam	26°9′*	91°43′.8*		Granite	Seismometer S-13, Analog Amplifier 42·21, Helicorder Amplifier AR-320, Timing System TG-120, Helicorder RV-310B	*ZNE*	66 db (*Z* & *NS*) 96 db (*EW*)	60	Ink pen
INR	Itanagar, Arunachal Pradesh	27°4′.8*	93°36′*		Sandstone	Seismometer S-500, Portacorder RV-320, Filter setting 5—12·5 Hz	*Z*	60 db	60	Smoked paper
JHI	Jorhat, Assam	26°44′	94°10′	84	Alluvium	Same as above	*Z*	60 db	60	Smoked paper
KHM	Kohima, Nagaland	25°39′47″	94°04′34″	1630*	Sandstone	Same as above	*Z*	72 db	60	Smoked paper
KOI	Khonsa, Arunachal Pradesh	26°59′	95°30′	785	Hard shale	Johnson-Matheson Seismometer, $T_s = 1·25$ sec., $T_g = 0·75$ sec., Timing system TG-120	*Z*	50 000	30	Galvanometric photograph.

KZI	Kaziranga, Assam	26°34′.6	93°24′.5	130	Granite	Seismometer S-13, Analog Amplifier 42·21, Helicorder Amplifier AR-320, Timing system TG-120, Helicorder RV-301B	*ZNE*	96 db	60	Ink pen
SHL**	Shillong, Meghalaya	25°34′.2	91°52′.8	1600		Benioff Seismometer, $T_s = 1{\cdot}0$ sec., $T_g = 0{\cdot}76$ sec.,	*ZNE*	200 000	60	Galvano-metric photo-graph.
						Press-Ewing Seismometers, $T_s = 15$ sec. $T_g = 100$ sec.	*ZNE*	3000	15	
TUR**	Tura, Meghalaya	25°33′	90°20′	305		Electromagnetic Seismometer, $T_s = 1{\cdot}5$ sec. $T_g = 0{\cdot}5$ sec.	*Z*	1000	60	
YYI	Yaongyim-sen, Nagaland	26°34′	94°41′	707	Sandstone	Johnson-Matheson Seismometer, $T_s = 1{\cdot}25$ sec., $T_g = 0{\cdot}75$ sec., Timing system TG-120	*Z*	50 000	60	Galvano-metric photo-graph.

Abbreviations: Lat — Latitude; Long-Longitude; mts — Metres; M. S. L. — Mean Sea Level; mm/min — Millimeters per minute; db — Decibels; *ZNE* — Vertical, North-South and East-West components; * — Approximate; ** — Seismic station operated by I. M. D., New Delhi; T_s, T_g — periods of seismometer and galvanometer, respectively.

and also at the IMD stations namely SHL and TUR. The epicentres of the earthquakes confined to the states of Assam, Nagaland, Manipur, Arunachal Pradesh, Meghalaya, and also to the Indo-Burma and Indo-Bangladesh borders are shown in Fig. 1. Further, in order to obtain P^* and Pg-wave travel times, these wave types were initially identified on the seismograms using the Jeffreys-Bullen [5] travel time table for near earthquake phases of 16 earthquakes (magnitudes 3·5 – 5·5) that occurred in the region during 1981 – 82 at a depth of 10 km. The depth (arbitrarily selected) is, again, the mean estimate of the depths considered within ± 3 km. Later, arrival times for these wave types were measured. All times are accurate to $\pm 0{\cdot}1$ sec.

3. SEISMIC STATIONS

The seismic stations namely INR, JHI and KHM are equipped with S-500 Teledyne Geotech (TG) model short period vertical component seismometers and TG model RV-320 portacorders with builtin crystal controlled chronometers. Whereas the stations at GWH and KZI are equipped with 3-Component TG model S-13 short-period seismometers with helicorder recording systems and TG-120 model crystal controlled chronometers. On the other hand, the stations at KOI and YYI are equipped with Johnson-Matheson short-period vertical component seismometers with galvanometric photographic recording systems, the time being obtained from TG-120 chronometers. The locations of these stations, particulars of the seismic equipment and other related information are given in Table 1. Similar information for the IMD stations (namely SHL and TUR) is also given in the table. At all these stations the time signals received are from the National Physical Laboratory, New Delhi and are used as the reference of Standard Time.

4. HYPOCENTRAL PARAMETERS

P-wave arrival times are fed to a VAX 11/750 computer at NGRI, Hyderabad for the computation of the hypocentral parameters of the earthquakes under study using the modified version based on the HYPO-71 programme of Lee and Lahr [6]. The crustal velocity model (Table 2), employed in these computations, is that of

Table 2. Crustal velocity model proposed by Gupta et al. [4].

P velocity km/sec	Thickness km	Depth km
4·0	1·0	0·0
6·0	24·0	1·0
6·7	20·0	25·0
8·1	20·0	45·0
8·3	∞	65·0

Gupta et al [4] for a P-wave to S-wave velocity ratio of 1·75. The hypocentral parameters obtained are accurate to $\pm$ 10 km.

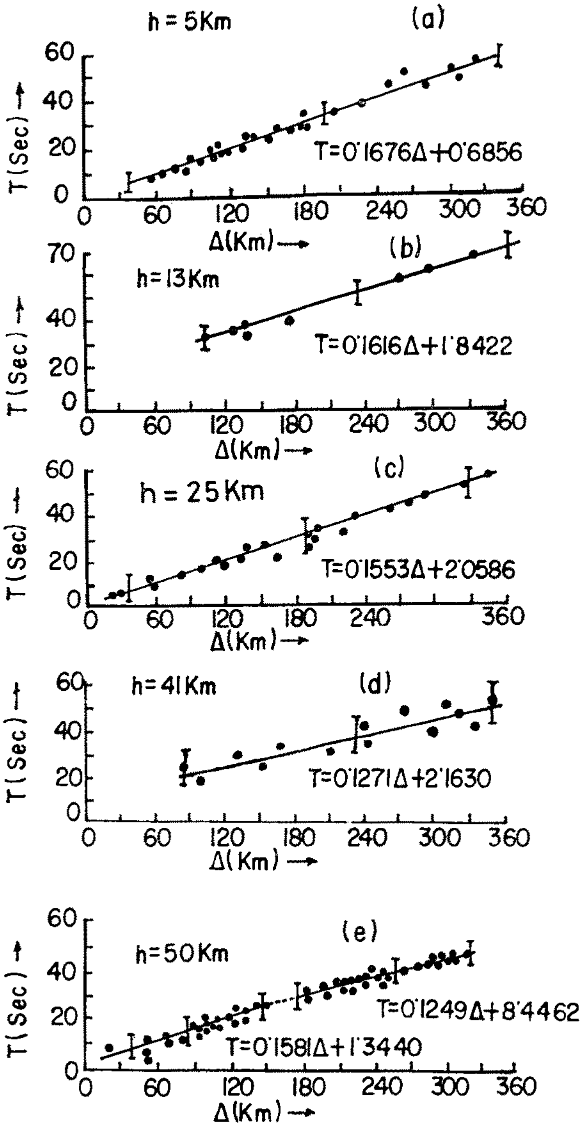

Fig. 2. Travel time (T) versus epicentral distance (Δ) plots for P-wave for each of the depths 5, 13, 25, 41 and 50 km (a to e). The linear relations of the form $T = \Delta / V + I$ (V and I are P-wave velocity and intercept, respectively) are also shown along with the ninety-five per cent confidence limits (denoted by short lines).

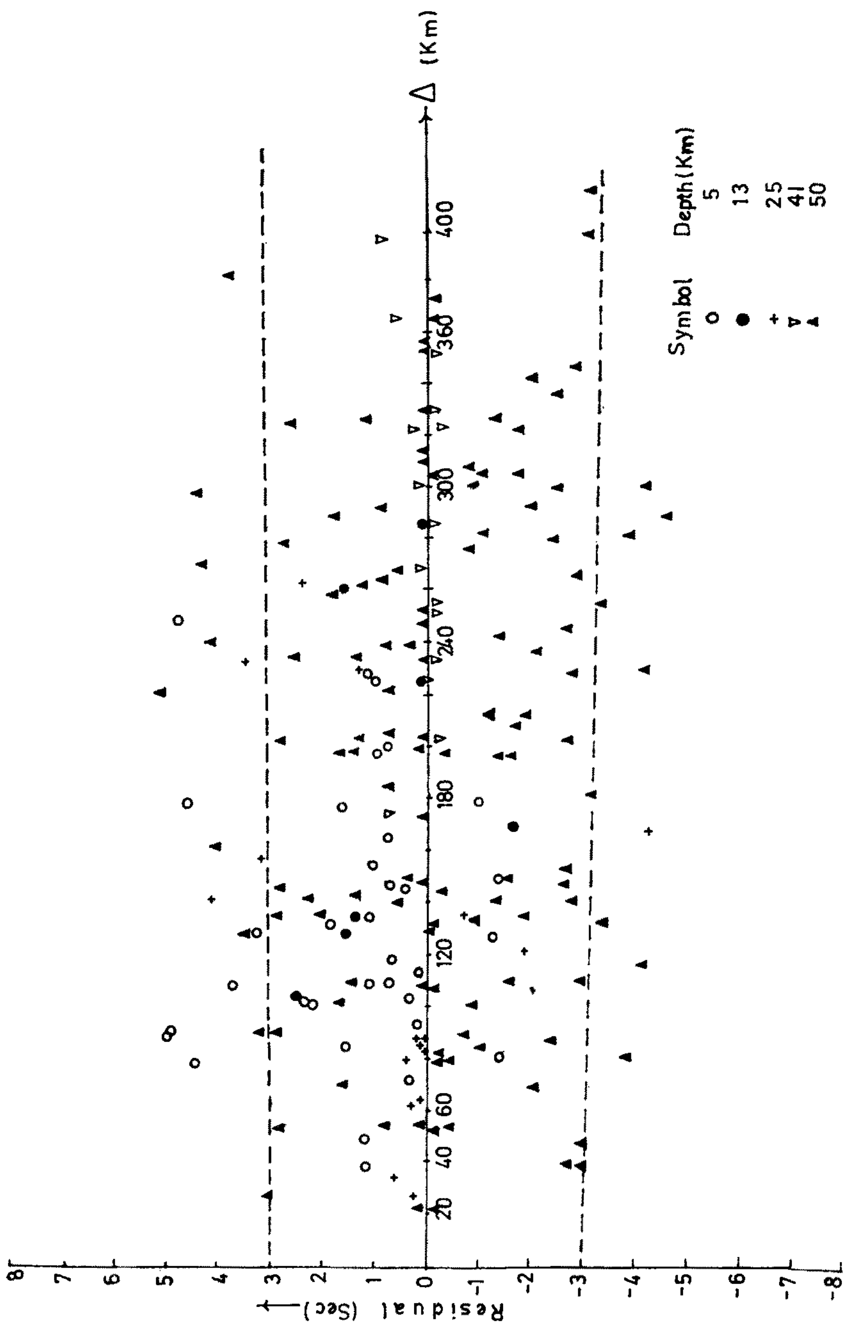

Fig. 3. *P*-wave travel-time residuals versus epicentral distance (*Δ*) for depths of 5, 13, 25, 41 and 50 km. Dashed lines represent the limits of residuals within which arrival time data were considered for obtaining the *P*-travel times.

5. TRAVEL-TIME CURVES OF *P*-WAVES

Using the geographic coordinates of the seismic stations, the epicentres and ellipticity correction (Richter, [8]), the epicentral distances were computed with the help of a mini-computer at the Regional Research Laboratory, Jorhat following the relations of Turner [12] as described by Bullen [1]. By subtracting the origin times (obtained from the computer output for the hypocentral parameters) from the

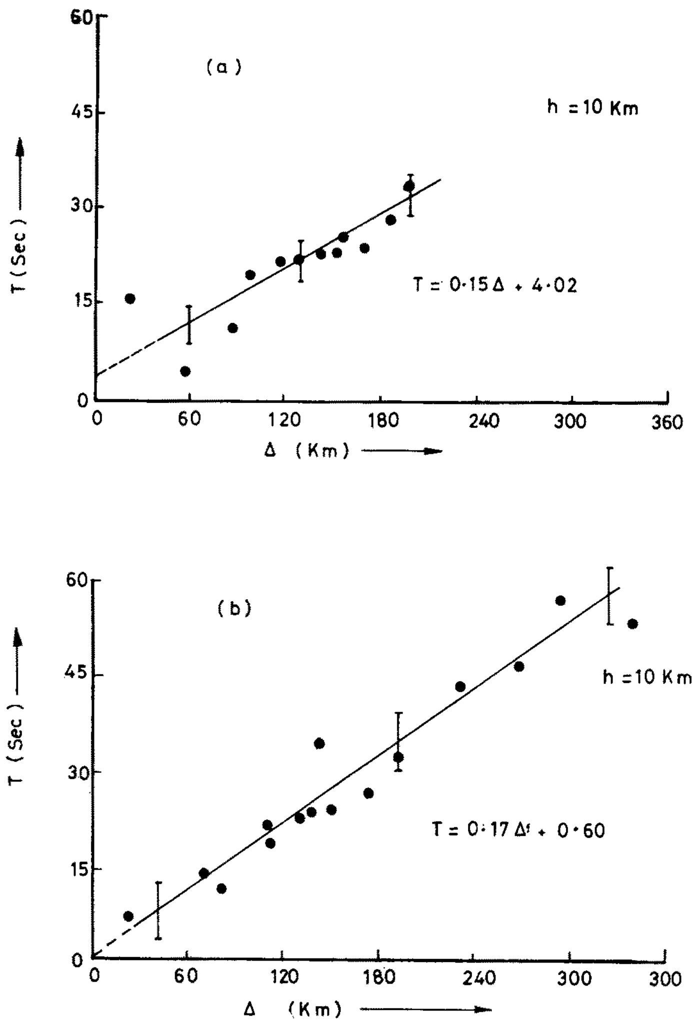

Fig. 4. Travel time (T) versus epicentral distance (Δ) plots (a and b) for P^* and Pg-waves for the depth 10 km. The linear relations of the form $T = \Delta/V + I$ (V and I are velocity and intercept, respectively) are also shown along with the ninety-five per cent confidence limits (denoted by short lines).

corresponding arrival times of the P-waves, the travel times from the foci of each of the seismic stations are obtained. Plots of the travel times (Fig. 2) as a function of distance have been made for P-waves at each of the depths 5, 13, 25, 41 and 50 km. It has been observed that in each of these plots the data points fit a straight line very well. However, it may be noted that the P-wave arrival times at each of the stations, for which the P-residuals exceed ± 3 sec, were not considered. Further, the distribution of P-residuals as a function of epicentral distance can be seen in Fig. 3. Similarly, the travel-time plots for P^* and Pg-waves are made in Fig. 4 for a depth of 10 km, in which straight line fits are also shown.

6. RESULTS

The travel time data points in Fig. 2 for P-waves fit a linear relation of the form $T = \Delta / V + I$, in which T, Δ, V, and I are P-travel time (sec), epicentral distance (km), wave velocity (km/sec) and intercept time (sec), respectively. Table 3 gives such relations for the P-travel times at each of the depths under consideration. The inferred P-wave velocities are $5{\cdot}97 \pm 0{\cdot}31$, $6{\cdot}18 \pm 0{\cdot}01$, $6{\cdot}41 \pm 0{\cdot}03$, $7{\cdot}82 \pm 0{\cdot}07$ and $7{\cdot}95 \pm 0{\cdot}01$ km/sec for depths of 5, 13, 25, 41 and 50 km, respectively. Further, the relation $T = 0{\cdot}13\Delta + 8{\cdot}45$ given in Table 3 for the depth of 50 km was derived using the observations in the distance interval 150 – 300 km. Correspondingly, the P-wave velocity is $7{\cdot}95 \pm 0{\cdot}01$ km/sec. Similarly, the relations $T = 0{\cdot}15\Delta + 4{\cdot}02$ and $T = 0{\cdot}17\Delta + 0{\cdot}60$ fit the data points in Fig. 4 for P^* and Pg-waves, respectively, for the depth of 10 km. Thus, the velocities obtained from these relations are $6{\cdot}53 \pm$ $\pm 0{\cdot}31$ and $5{\cdot}64 \pm 0{\cdot}34$ km/sec.

Table 3. Linear relations for the straight-line fits made to the observation points of P-wave travel times (T) against epicentral distance (Δ) for each of the depths 5, 13, 25, 41 and 50 km.

Linear relation involving travel time (T) and distance (Δ)	Depth km
$T = 0{\cdot}1676\Delta + 0{\cdot}6856$	5
$T = 0{\cdot}1616\Delta + 1{\cdot}8422$	13
$T = 0{\cdot}1553\Delta + 2{\cdot}0586$	25
$T = 0{\cdot}1271\Delta + 2{\cdot}1630$	41
$T = 0{\cdot}1249\Delta + 8{\cdot}4462$	50

7. CRUSTAL STRUCTURE

Assuming a simplified two-layered model with a horizontal layer of isotropic media without velocity inversion, an attempt has been made to determine the regional crustal structure using the velocities of Pn, P^* and Pg-waves and also the corresponding intercept times especially for *Pn* and *P**-waves on the basis of the following relations:

$$t^* = 2H_g[(V_b)^2 - (V_g)^2]/V_b V_g \qquad (1)$$

and

$$t_n = 2H_b[(V_m)^2 - (V_b)^2]/V_m V_b + 2H_g[(V_m)^2 - (V_g)^2]/V_m V_g \qquad (2)$$

where t^* = intercept time of P^*, t_n = intercept time of *Pn*, H_g = thickness of upper crust, H_b = thickness of lower crust, V_b = velocity of *P**-wave, V_g = velocity of *Pg*-wave and V_m = velocity of *Pn*-wave. The thickness of the upper crust was initially found to be 22·2 km according to the relation (1) using *Pg* and *P** velocities (5·64 and 6·53 km/sec) and also the intercept time (4·02 sec) of the travel time relation for *P**-wave. The average thickness of the sedimentary layer beneath the recording stations (GWH, INR, JHI, KHM, KOI, KZI, SHL, TUR and YYI) is assumed to be 2 km. Mathur and Evans [7] have obtained 3 km as the maximum thickness of sedimentary layer in their attempt to map the subsurface structure in the vicinity of an oil field at Digboi in Assam state. Whereas, Evans [2] found that the thickness of the sedimentary layer in the region between the large scale thrusts in the northwest (Himalaya) and southeast (Naga Hills) is of the order of 4 km. Thus, excluding the thickness of the sedimentary layer, the thickness of the upper crust (20·2 km), *P*-wave intercept time (8·45 sec) and *Pn*, *P** and *Pg* velocities (7·95, 6·53 and 5·64 km/sec) are used in relation (2) for obtaining an estimate of the lower crust thickness as 19·3 km. Hence, the depth of the Moho was found to be 41·5 km.

In connection with the evaluation of the crustal *P*-velocity structure, the *P*-wave velocity estimate 4·0 km/sec as observed by Gupta et al. [4] for the depth of 0 km is used as the mean *P*-velocity in the 2-km thick sedimentary layer. The present estimates of *P* velocities (5·97 km/sec and 6·53 km/sec) for the depths of 5 km and 10 km are considered to be the mean *P*-velocity estimates in the 20-km and 19-km thick upper and lower crustal layers, respectively. The present estimate of the *P* velocity of 7·82 km/sec for the depth of 41 km is also used in the crustal velocity model, deduced and shown in Table 5. The upper mantle velocity of 8·3 km/sec, as given by Gupta et al. [4], for the depth of 65 km is also used to derive the present crustal model.

8. VARIATION OF *P*-WAVE VELOCITY WITH DEPTH

The observation points in Fig. 5 showing *P*-velocities of 5·97 ± 0·31, 6·18 ± 0·01 and 6·41 ± 0·03 km/sec for depths of 5, 13 and 25 km indicate a linear relation, $V = 0{\cdot}02h + 5{\cdot}91$, in which V and h are the *P* velocity and depth, respectively. The remaining two points in the figure, showing the velocities 7·82 ± 0·07 and 7·95 ± 0·01 km/sec for the depths of 41 and 50 km, seem to fit another straight line. It appears that there is a transition zone in the depth interval of 35–40 km.

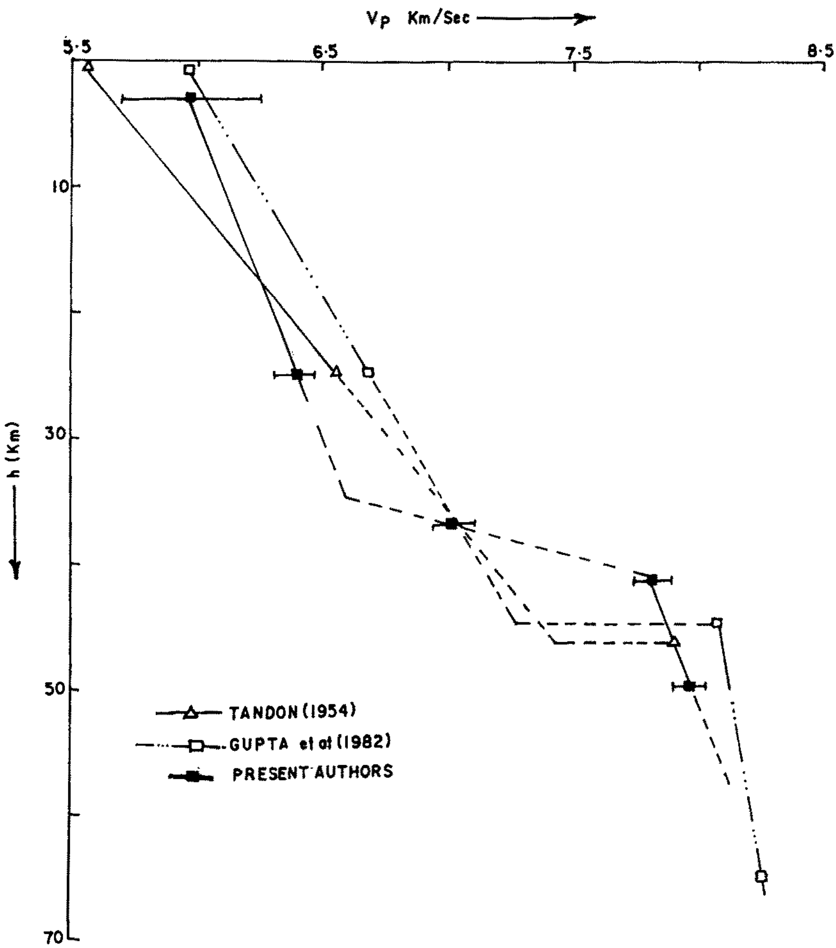

Fig. 5. Graph showing P-wave velocity (V_p) versus (h) curves obtained by Tandon [11], Gupta et al. [4] and present authors. The ninety-five per cent confidence limits (denoted by short lines) are shown for the present V_p versus h curve. Dashed line represent the possible trend of the line.

9. DISCUSSION

Table 4 gives the comparison of the P-wave velocity estimates obtained by Tandon [11], Saha et al. [10], Gupta et al. [4] and the present authors for the depths 5, 13, 25, 41 and 50 km. Saha et al. [10] reported P velocities (Table 4) from their micro-earthquake investigations for North-East India. Further, Gupta et al. [4] initially applied the crustal model of Tandon [11] to the P-wave arrival time at the RRL-J/NGRI seismic stations and also some of the stations operated by the IMD. Later, they modified the crustal model for a P-wave to S-wave velocity ratio of 1·75 and used it to determine the hypocentral parameters so as to yield least errors.

Table 4. *P*-wave velocity estimates obtained in the present study and also by Tandon [11], Saha et al. [10] and Gupta et al. [4].

Wave type			*P*		
Depth (km)	5	13	25	45	50
INVESTIGATORS					
Tandon [11]	5·58		6·55	7·91	
Saha et al. [10]	6·0		6·7	8·1	
Gupta et al. [4]	6·0		6·7	8·1	
Present authors	5·97 ± 0·31	6·18 ± 0·01	6·41 ± 0·03	7·82* ± 0·07	7·95 ± 0·01

* — Velocity estimate derived for the depth 41 km.

The *P*-wave velocity of 5·97 ± 0·31 km/sec as observed in the present study for the depth of 5 km is comparable with the corresponding estimates reported by Saha et al. [10] and Gupta et al. [4]. Whereas, the present *P*-velocity estimates of 6·41 ± 0·03 km/sec and 7·82 ± 0·07 km/sec for depths of 25 and 41 km are significantly lower as compared to those of Saha et al. [10] and Gupta et al. [4]. But, these estimates are almost comparable with those of Tandon. Further, the present *P*-velocity estimate of 7·82 ± 0·07 km/sec for the depth of 41 km is in agreement with that of Roy [9] who arrived at 7·80 km/sec by analysing the travel time versus distance plots for the Bihar-Nepal earthquake of January 15, 1934 and its aftershocks. Even, the P^* and Pg velocities (6·53 ± 0·31 and 5·64 ± 0·34 km/sec) are close to those of Tandon (6·55 and 5·58 km/sec).

Table 5. Crustal velocity model derived in the present study.

P-wave velocity km/sec.	Thickness km	Depth km
4·00	2	0
5·97	20	2
6·53	19	22
7·82	24	41
8·30	∞	65

Fig. 5 depicts the comparison of the *P* velocity versus the depth curves of Tandon [11], Gupta et al. [4] and the present authors. It is evident from the figure that the present curve differs from the others, and this may be due to the differences in the treatment of the data. However, the present curve shows that the depth of the Moho lies in the interval of 35—40 km. But the aforementioned derivation for the crustal structure reveals the depth of Moho to be 41 km and the thickness of the upper and lower crustal layers as 22·2 km and 19·3 km. Evans and Crompton [3] determined the Moho depth at 40 km from their study of the gravity profile along the 24 °N latitude for Burma and India. Verma and Gupta [13] also found the Moho depth to be 40 km while interpreting the gravity data compiled from the Bouguer, Hayford and Airy isostatic anomaly maps in terms of the tectonics of the Assam region. The thickness of the upper and lower crustal layers and the depth of the Moho obtained in the present study are listed in Table 6 along with those of Roy [9] and

Table 6. Estimates of the thicknesses of the crustal layers and the depth of Moho, derived in the present study and also by other investigators.

Investigators	Thickness of upper crust km	Thickness of lower crust km	Moho depth km	Region
Roy [9]	14·8	25·4	40·2	Bihar
Tandon [11]	24·8	21·5	46·3	North-East India
Present authors	22·2	19·3	41·5	North-East India

Tandon [11]. Using the arrival times of the *Pn*, *P** and *Pg*-waves, recorded by the seismic stations at Alipore, Agra, Dehra Dun, Colaba, Orgaum, Kodaikanal and Colombo for the Bihar-Nepal earthquake of January 15, 1934 and also for the aftershock of January 19, 1934, Roy [9] plotted the time-distance curves and inferred the thicknesses of the upper and lower crustal layers and the depth of the Moho as 14·8, 25·4 and 40·2 km beneath Bihar. However, Tandom [11] obtained a crustal thickness of 46·3 km with a 24·8-km thick upper crust and 21·5-km thick lower crust below the northeastern region of India from his study of surface waves of the Great Assam earthquake of August 15, 1950 and its aftershocks.

10. CONCLUSION

The *P*-wave travel times for the depths 5, 13, 25, 41 and 50 km were obtained with reference to Gupta's et al. [4] crustal velocity model using the *P*-wave arrival times at RRL-J/NGRI seismic stations and also at the Shillong and Tura stations of the IMD in North-East India. The analyses of these travel times have yielded *P* velocities of $5{\cdot}97 \pm 0{\cdot}31$, $6{\cdot}18 \pm 0{\cdot}01$, $6{\cdot}41 \pm 0{\cdot}03$, $7{\cdot}82 \pm 0{\cdot}07$ and $7{\cdot}95 \pm$ $\pm\ 0{\cdot}01$ km/sec for each of the depths under study. Further, a similar investigation of travel-time curves for the P^* and *Pg*-waves has enabled velocities of $6{\cdot}53 \pm 0{\cdot}31$ and $5{\cdot}64 \pm 0{\cdot}34$ km/sec, respectively, to be inferred for the depth of 10 km. The *P*-wave velocity (V) appears to vary with depth (h) linearly in the depth intervals of 5–25 km and 40–50 km. In particular the relation $V = 0{\cdot}02h + 5{\cdot}91$ seems to hold for the depth interval of 5–25 km. Moreover, a simplified two-layered crustal model consisting of a 22·2-km thick upper crust (including the thickness of the sedimentary layer) and a 19·3-km thick lower crust was obtained indicating the depth of the Moho at 41·5 km. A crustal velocity model was also derived; it is given in Table 5.

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