Mausam, (1988), 39, 2, 221-226

550.347.642

P-wave traveltime and crust-upper mantle velocity structure in the Indian region

R. K. DUBE

Central Seismological Observatory, Shillong

(*Received 2 April 1987*)

सार — अमरीका के अन्तरिक्ष भूगर्भ सर्वेक्षण विभाग (ई. डी. आर.-यू. एस. जी. एस.) के भूकम्प आंकड़ा रिपोर्ट में दिए गए विवरण के अनुसार भारतीय क्षेत्र के उथले अभिकेन्द्र (फोकस) वाले भूकम्पों से भी प्रगमन काल और अवशिष्टों के आंकड़ों को एकत्रित किया गया है और उनका विश्लेषण किया गया है। विगतकाल में लिए गए अध्ययनों के आधार पर जैफरीज-बुलेन (जे. बी.) मॉडल की तुलना में और उससे उच्चत्तर पी-तरंग वेगों वाली पर्तों में से प्रत्येक के लिए प्रगमन काल के आंकड़ों को भारतीय मैदानों के लिए चुना गया है। जे. बी. मॉडल में ऊपरी प्रावार से 185 कि. मी. की गहराई तक पहले की तुलना में एक उच्चत्तर पी-तरंग वेग की व्याख्या की गई है। इस गहराई से अधिक गहराई के लिए जे. बी. मॉडल स्वीकार किया गया है।

इस मॉडल का उपयोग कर के 30 दिसम्बर 1984 को कछार में आए भूकम्प के अवकेन्द्र की स्थिति निर्धारित की गई है। यू. एस. जी. एस. और दुबे इत्यादि (1986), दोनों द्वारा ही इन निर्धारणों में काफी समानता पाई गई है।

ABSTRACT. *P*-arrival times and residuals from shallow focus earthquakes of Indian origin, as reported in the *Earthquake Data Report* of the United States Department of the Interior, Geological Survey (EDR-USGS), at seismological stations in India have been collected and analysed. Based on the past studies a thicker two layered crust and higher *P*-wave velocities in each of the two layers compared to a Jeffreys-Bullen model (J-B model), which is in conformity with the traveltime data, has been chosen for the Indian plains. A comparatively higher *P*-wave velocity than in the J-B model in the upper mantle down to a depth of 185 km has been interpreted. J-B model has been accepted beyond this depth.

Hypocentre location of Cachar earthquake on 30 December 1984 has been obtained using this model. This has been found to be in good agreement with both those determinations by USGS and Dube *et al.* (1986).

1. Introduction

Several studies made in the past have established the existence of lateral/regional variation in the crust upper mantle structure in several parts of the world (Jeffreys 1966; Ram & Meeru 1977). Hence, knowledge of a reliable crust-upper mantle structure of a region becomes a pre-requisite for a reasonably accurate determination of hypocentre locations using phase data of *P* and *S*-waves on regional scale and to carry out many other investigations. The International Seismological Centre and United States Department of Interior and Geological Survey still use Jeffreys-Bullen traveltimes for hypocentre locations. This results in large residuals in traveltimes for a particular region and thus, ignores even accurate observations altogether. Some such situations are observed in case of traveltimes of *P*-waves for epicentral distance less than 20 degrees in Indian region from earthquakes of very shallow depth. This, perhaps, reveals for marked difference in the crust-upper mantle structure in the Indian region as compared to Jeffreys-Bullen model.

In this paper an attempt has, therefore, been made to analyse the *P*-traveltimes and residuals from earthquakes of Indian origin having similar depth of foci in the top most layer of the crust recorded at seismological stations in India and seek for a suitable inversion in terms of crust-upper mantle velocity structure.

2. Data

P-wave arrival times and residuals, as reported in the *Earthquake Data Report* of United States Department of the Interior, Geological Survey, America, in respect of twelve earthquakes having depth of foci in the top most layer (granite layer) of the earth's crust, details of which are presented in Table 1 and locations presented in Fig. 1, were collected. Depth of foci in respect of four earthquakes, eventhough reported higher, are confirmed to be in granitic layer of the crust by virtue of P_g and S_g phases having been recorded. Arrival times and corresponding residuals from worldwide network of seismograph stations in India and seismological observatories at Hyderabad, Gauribidnur, where a very good time keeping is expected, were considered for the study. However, arrival times at seismological stations at Bombay, Ajmer and Bokaro were also considered in a few cases wherever these were found to be consistent with other readings.

P-traveltime residuals against corresponding epicentral distances have been plotted in Fig. 2. A perusal

TABLE 1

List of earthquakes

Date	Origin time (GMT)			Location		Depth of focus (km)	Magnitude
	hr	min	sec	Lat. (°N)	Long. (°E)		
29 Jul '80	12	23	12.30	29.331	81.258	34.2	5.7
29 Jul '80	14	58	40.80	29.598	81.092	18	6.1
23 Aug '80	21	36	51.60	32.913	75.633	24.9	5.2
26 Oct '84	20	22	21.83	39.155	71.328	33	6.0
14 Nov '84	11	58	18.30	17.127	73.817	10.0	4.6
21 Nov '84	07	54	06.96	25.417	96.566	33	4.5
28 Nov '84	10	29	21.81	26.697	97.085	17.7	5.9
30 Dec '84	23	33	37.72	24.64	92.89	22.6	5.3
7 Jan '85	16	13	05.19	27.152	91.986	11.8	5.6
12 Oct '85	18	22	35.88	27.133	92.537	9.1	5.3
19 Feb '86	17	34	24.77	25.136	91.184	17.5	5.3
26 Apr '86	07	35	16.10	32.128	76.374	33	5.5

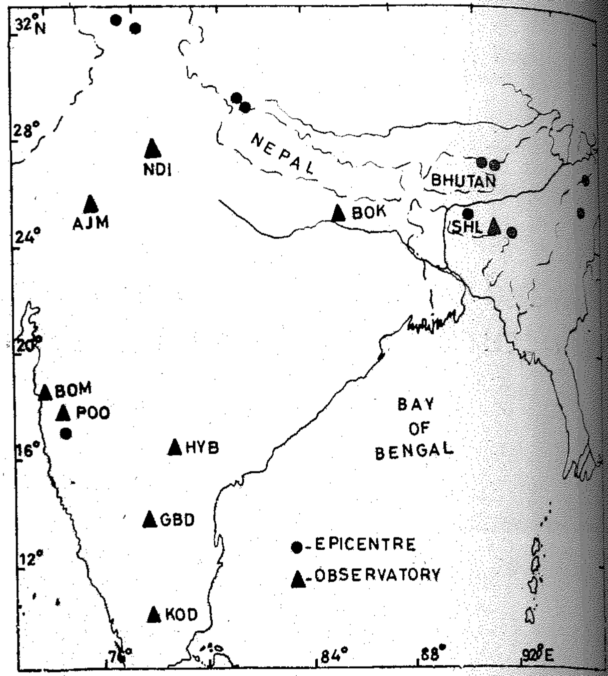

Fig. 1. Location of epicentres and recording stations

of this figure reveals that inspite of large scatter in residuals a systematic trend with respect to epicentral distances is clearly discernible. These residuals are mostly positive for epicentral distances less than and equal to 10 degrees, significantly negative for epicentrals distances between 11 and 16 degrees and both positive and negative between 17 and 20 degrees. In order to test for any relationship of residuals with respect to epicentral distance in the ranges as above, straight line relations using methods of least square have been obtained. These are given below and represented as solid lines in Fig. 2.

$$T_{res} = 0.0277\Delta + 0.675 \quad \text{for } \Delta \leqslant 10° \quad (1)$$

$$T_{res} = 0.1503\Delta - 6.583 \quad \text{for } 11° < \Delta \leqslant 16° \quad (2)$$

$$T_{res} = 0.0241\Delta - 0.4763 \quad \text{for } 17° < \Delta \leqslant 20° \quad (3)$$

Reduced traveltimes against epicentral distance have been plotted in Fig. 3. Taking into consideration the nature of residuals, traveltimes have been arranged into three distinct group, *viz.*, for $\Delta \leqslant 10°$ (predominantly positive), $11° < \Delta \leqslant 16°$ (predominantly negative) and $17° < \Delta \leqslant 20°$ (both positive and negative). Straight line relations ($T = b\,\Delta + a$) using method of least squares have been obtained as given below. These are represented as solid lines in Fig. 3.

$$T = 13.964\,\Delta + 6.00 \quad \text{for } \Delta \leqslant 10° \quad (4)$$

$$T = 13.406\,\Delta + 7.61 \quad ,,\ 11° < \Delta \leqslant 16° \quad (5)$$

$$T = 12.93\,\Delta + 16.85 \quad ,,\ 17° < \Delta \leqslant 20° \quad (6)$$

A look at the reduced traveltime curve in Fig. 3, although, reveals offset in traveltime at epcentral distance of about 11 degrees, it is not apparent at epicentral distance at 16 degrees, as seen in Fig. 2 for traveltime residuals. As such a straight line relation by method of least squares has also been obtained between the traveltimes and epicentral distances for 11 to 20 degrees. It is given below :

$$T = 13.432\,\Delta + 7.28 \quad \text{for } 11° < \Delta \leqslant 20° \quad (7)$$

Standard deviations and standard errors of the constant a and b are given in Table 2.

3. Analysis of traveltimes and residuals

Geologically, Indian subcontinent has been divided into three main regions, *viz.*, Extra-Peninsula, Indo-Gangetic plains and Peninsula, each representing different geological block (Krishnan 1956). Studies made on the crustal structure in these blocks based on body wave data from near earthquakes and explosions (Tandon & Chaudhury 1968, Dube *et al.* 1973, Tandon and Dube 1973, Kamble *et al.* 1974, Dube and Bhayana 1974, Kaila *et al.* 1979, Chaudhury *et al.* 1984) have brought out variations in the velocities and thicknesses of the crustal layers. However, crustal structure of the Indian Peninsula and Indo-Gangetic plains do not show much significant variation and, therefore, an average model based on these studies can be chosen to represent both the regions.

Although, it would have been ideal to take up traveltime studies to obtain crust-upper mantle structure for the three geological blocks representing tectonically disturbed mountainous region, foredeep and shield region separately, but inadequate network of seismological observatories and nonavailability of very good time-keeping (accuracy <0.5° second) at several existing stations in India came in the way. Hence, traveltimes at stations mentioned in the previous section were only considered. With this, an average crust-upper mantle

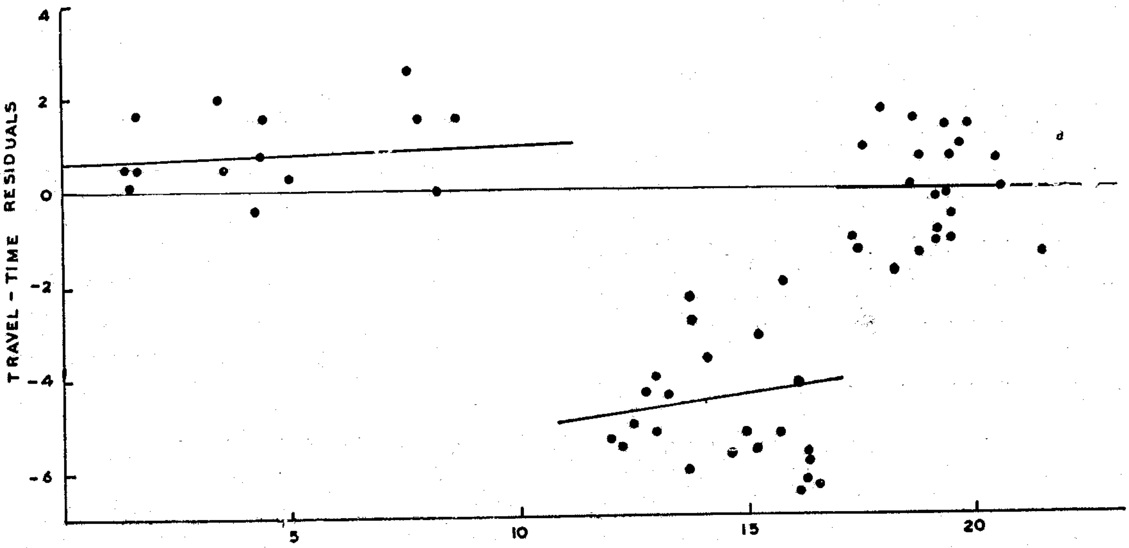

Fig. 2. Traveltime residuals *versus* epicentral distance

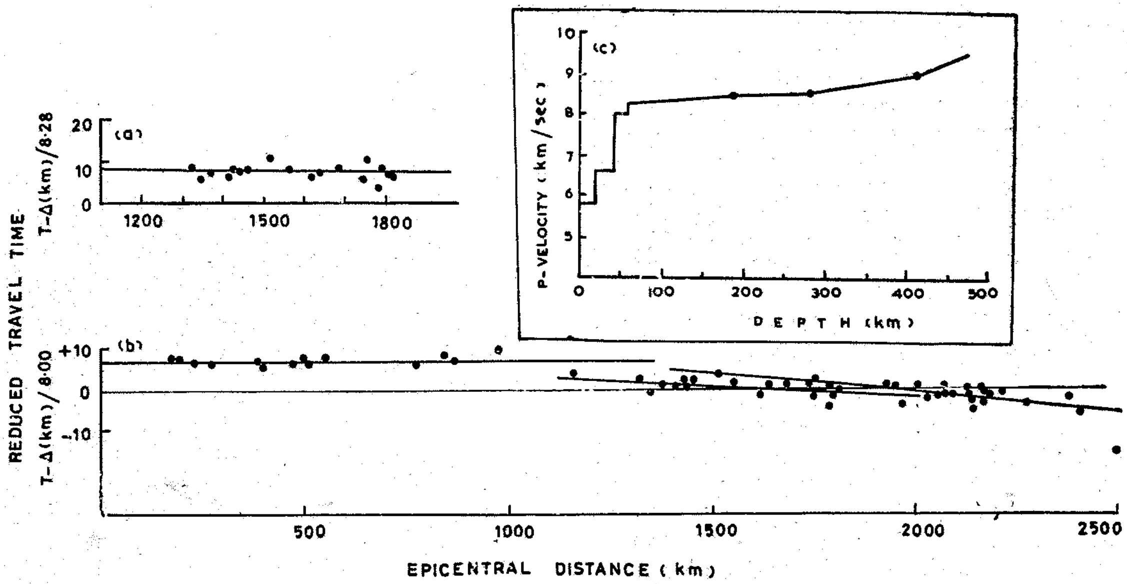

Fig. 3. (a&b) Reduced traveltimes *versus* epicentral distance and (c) Crust-upper mantle *P*-velocity model in the Indian region

TABLE 2

Error parameters of constants '*a*' and '*b*'

Epicentral distance range	Standard deviations *a*	Standard error *a*	Standard deviations *b*	Standard error *b*
0-10°	2.40	±0.665	0.1435	±0.0398
11°-16°	13.83	±3.01	0.20	±0.01
17°-20°	44.10	±10.40	0.5567	±0.13
11°-20°	10.94	±1.80	0.11	±0.02

velocity structure suitable for the Indian region is proposed to be interpreted.

As mentioned earlier, Fig. 2 shows that the traveltime residuals with respect to Jeffreys-Bullen model are significantly positive for epicentral distances less than and equal to 10 degrees. This suggests for a thicker crust or slower *P*-wave velocity in the crust or a combination of both. Slower wave velocity does not seem to be acceptable while a thicker crust appears reasonable in view of the results of many studies made in the past. A chosen crustal model in agreement with the traveltime data will be presented in the next section.

Residuals are predominantly negative for epicentral distances between 11 and 16 degrees suggesting for *P*-wave velocities to be comparatively higher than Jeffreys-Bullen for depths penetrated by rays emerging at these epicentral distances. A comparatively thicker crust in the Indian region than that of J-B model is likely to reduce the negative residuals but it is only of the order of 1 sec with the chosen model in the present study. Thus, a suggestion for higher *P*-velocity than J-B model appears reasonable. However, J-B model appears to satisfy the data for epicentral distances between 17 and 20 degrees owing to both positive and negative random bias for residuals. These residuals are within ± 1.5 seconds.

Velocity discontinuities in the upper-mantle at depths 390 km (corresponding to 18°) and 650 km (corresponding to 23°) seem to be well established in many recent studies (Johnson 1967, Ram and Meeru 1977, Walck 1984). It has been observed that reflections from 390 km discontinuity have been recorded at epicentral distances from about 14 degrees to 17 degrees as sharp second arrivals in *P*-group and thereafter as first arrivals (Walck 1984). It is likely that *P*-arrivals corresponding to traveltime residuals less than and equal to 3 seconds for epicentral distance between 13 and 16 degrees are reflections from 390 km. If these are removed, scatter is minimised and a velocity structure with slight increase with depth appears to emerge. Large scatter at epicentral distance between 17 & 20 degrees, as also evidenced by high values of standard deviations in Table 2, may be the result of triplication in the traveltime curve due to the discontinuity at 390 km. Due to nonavailability of seismograms it has not been possible to distinguish between first and second arrivals which would have helped in reducing scatter in data.

Traveltimes have been grouped into three branches one upto 10 degrees, second from 11 to 16 degrees and third from 17 to 20 degrees as mentioned earlier. Apparent *P*-wave velocities have been determined using method of least squares. These are 7.96 ± 0.0002 km/sec, $8.28\pm\ 0.0002$ km/sec. and 8.58 ± 0.0008 km/sec respectively. Scatter in data as well as its lesser availability at some epicentral distance, as seen in Fig. 3, constrains determination of Ray parameter ($dt/d\triangle$) at frequent intervals as function of epicentral distance and thus restricts use of Herglotz-Weichert method to evaluate velocity structure. Therefore, a flat layered earth model has been accepted. Satisfactory representation of traveltime data by straight lines supports this. It is felt that the effect of curvature of the earth for such short epicentral distance can be neglected. It is, however, added that there is a scope for improvement in the model as and when network of good seismological observatories increase.

4. Crust upper-mantle model

In view of what has been described in the previous section a flat, layered crust-upper mantle velocity models has been chosen for inversion of traveltime data in term of velocity structure. An average crustal model based on studies made in the past (Tandon and Chaudhury 1968, Dube *et al.* 1973, Tandon & Dube 1973, Dube & Bhayana 1974, Kamble *et al.* 1974, Kaila *et al.* 1979, Chaudhury *et al.* 1984), and in conformity with traveltime data, as given below, has been chosen to represent Indo-Gangetic plains and Peninsular India. This model has been chosen because the paths of propagation of seismic waves from earthquake sources to recording stations mainly cover these regions (Fig. 1).

Crustal Model

Depth (km)	*P*-velocity (km/sec)
0	5.78
20	6.58
40	8.00

Based on this crustal model and traveltime *versus* epicentral distance relations obtained in section 2, depth of the discontinuity represented by the second branch of the traveltime curve has been evaluated at 60 km. Depth of foci reported by U.S.G.S. in Table 1 vary from 9 to 24 km but an average depth of focus as 9 km appears to satisfy the traveltime data. Thus has, therefore, been accepted. Thus, *P*-wave velocity shows a jump from 8.00 km/sec just below the Mohorovicic discontinuity to 8.28 km/sec at this depth. Although, a general look at the traveltime data in Fig.3 (a&b) permits it to be represented by a straight line for epicentral distance between 11 & 16 degrees, but a closer look brings out that most of the data points at epicentral distance between 15 & 16 degrees lie below the solid line obtained by least square method. This suggests for a comparatively higher *P*-wave velocity than 8.28 km/sec at depths penetrated by rays emerging at these epicentral range. It has been mentioned earlier that data points above the solid line which is only one, might be reflection from 390 km discontinuity.

Considering a spherical earth with concentric layers, maximum depths penetrated by rays emerging at epicentral distance of 16 degrees has been calculated using a relation given below (Gutenberg 1959).

$$\log r_s = 3.80393 - 0.0024127 \int_0^{\triangle s} q\, d\triangle \quad (8)$$

where r_s is the maximum depth of penetration corresponding to epicentral distance $\triangle s$ and

$$\cosh q = \left(\frac{d\triangle}{dt}\right)_s \Big/ \frac{d\triangle}{dt} \quad (9)$$

TABLE 3

***P*-velocity crust-upper mantle model in the Indian region**

Depth (km)	*P*-wave velocity (km/sec)	Depth	*P*-wave velocity (km/sec)
0.0	5.78	185	8.47
20.0	6.58	280	8.54
40.0	8.00	410	8.97
60.0	8.28	475	9.50

TABLE 4

Located by	Origin time (GMT) hr	min	sec	Hypocentre location Lat. (°N)	Long. (°E)	Depth of focus (km)	Error
Present study	23	33	37.11	24° 34.78′	92° 51.42′	22.25	Rms=0.79 ERH=6.6 km ERZ=7.1 km
Dube *et al.* (1986)	23	33	35.7	24° 41.18′	92° 52.68′	5	
U.S.G.S.	23	33	37.7	24° 38.40′	92° 53.4′	22.6	

TABLE 5

Earthquake occurred on date	Station	Epi-central dis-tance	Origin time based on present study *P*-wave hr	min	sec	*S*-wave hr	min	sec	U.S.G.S hr	min	sec
29 July '80	Pune	12.85	14	58	41.5		—		14	58	40.80±0.07
	Hyderabad	12.35	14	58	40.4	14	58	42.8			
7 Jan '85	Delhi	13.15	16	13	06.2	16	13	6.10	16	13	05.19±0.87
	Hyderabad	15.75	16	13	7.7		—				—
12 Oct '85	Hyderabad	16.14	18	22	36.5		—		18	22	35.88±0.15
	Ajmer	16.24	18	22	36.6	18	22	36.7			—
19 Feb '86	Delhi	12.95	17	34	24.2	17	34	25.1	17	34	24.77±1.21
	Hyderabad	14.05	17	34	25.6	17	34	24.5			

The maximum depth corresponding to epicentral distance 16 degrees has been obtained as 185 km and *P*-wave velocity at this depth as 8.47 km/sec. J.B. model has been accepted to hold good below this depth as mentioned earlier. Thus, an average crust-upper mantle model representing Indian region has been presented in Table 3 and shown in Fig 3 (c). It is, thus, observed that *P*-wave velocities in the crust and upper mantle of the Indian region are higher compared to J.B. model down to a depth of about 185 km.

Assuming Poissions ratio to be 0.25, *S*-wave traveltime *versus* epicentral distance relations have been calculated for the accepted crust-upper mantle model in the Indian region. The relations are as given below :

$$T=24.026\Delta+9.72 \quad \text{for } \Delta\leqslant 10^\circ \qquad (10)$$

$$T=23.173\Delta+12.80 \quad \text{for } 11^\circ<\Delta\leqslant 16^\circ \qquad (11)$$

5. Hypocentre location

In order to test the validity of the crust-upper mantle model accepted in this study, hypocentre location of Cachar earthquake of 30 December 1984 has been obtained using Hypo-71 Program and *P* and *S*-phase data of local and regional stations in India. This earthquake was also located by United States Geological Survey (U.S.G.S.) using teleseismic data and Dube *et al.* (1986) using *P* and *S*-phase data from local network of observatories and local crustal model. These locations are given in Table 4 for comparison. It is seen that a good agreement exists between these three locations. *P*-traveltime residuals as obtained are also within ±1 second for epicentral distance upto 2200 km.

It is mentioned here that India Meteorological Department during its routine determination of the location of epicentre had located the Cachar earthquake at 25° N and 92° E. Here, they had used the origin time (23^h 33^m 45^s GMT) based on arrival on time of *P* and *S*-waves at Delhi observatory using J.B. tables. As Delhi is 14.58 degrees away from the epicentre (the region where residuals are predominantly negative), the origin time determined showed higher value and thus the epicentre was shifted towards west from the actual place of occurrence. However, origin time determined on the basis of local crustal model and *P* and *S*-phase data at seismological observatories in northeastern India has improved the result.

To know the suitability of the traveltime-epicentral distance relations obtained, origin time of all the twelve earthquakes were determined from P and S arrival times at Delhi, Pune, Hyderabad and Ajmer seismological observatories. These were found to be in good agreement with those from United States Geological Survey. Origin times of few earthquakes, selected randomly, are presented in Table 5. It is, therefore, recommended that the crust-upper mantle model suggested in this study and traveltime-epicentral distance relations obtained may be adopted for hypocentre locations using regional stations data.

6. Conclusions

From what has been described in the foregoing, following conclusions are drawn :

(*i*) A thicker crust with higher P-wave velocity than the J.B. model appears to represent Indian plains. The crust of 40 km thickness having two layers, *viz.*, granitic and basaltic, each 20 km thick with P-wave velocities as 5.78 and 6.58 km/sec respectively has been chosen for Indian plains based on past studies.

(*ii*) P-wave velocities continue to be higher than the J.B. model upto 185 km depth beyond which the correspondence may be acceptable.

(*iii*) Hypocentre location determined for Cachar earthquake of 30 December 1984 from P and S-phase data from regional and local stations in India using crust-upper mantle model of this study, is in good agreement with those determined by U.S.G.S. and Dube *et al.* (1986).

(iv) The general use of crust-upper mantle model suggested here is expected to yield improved locations.

References

Dube, R.K., Bhayana, J.C. and Chaudhury, H.M., 1973, Crustal structure of the Peninsular India, *Pur. appl. Geophys.*, pp. 1717-1727.

Dube, R. K. and Bhayana, J.C., 1974, Crustal structure in the Gangetic plains of the Indian subcontinent from Body waves, *Bull. seism. Soc. Am.*, **64**, pp. 571-579.

Dube, R.K., Dattatrayam, R.S., Mathura Singh and Srivastava, H.N., 1986, Seismicity of northeast India with reference to Cachar earthquake of 30 December 1984, Interm. Symp. Neotectonics in Southesast Asia, Dehradun, India, 18-21, Feb., 395 pp.

Chaudhury, H.M., Srivastava, H.N., Kamble, V.P., Dube, R.K., Verma, R.K. and Varma, G.S., 1984, Crustal investigations from explosion data along Kavali–Udipi section of Peninsular India, *Mausam*, **35**, pp. 157-164.

Gutenberg, B., 1959, *Physics of the Earth's Interior*, Academic Press, p. 15.

Johnson, L.R., 1967, Array measurements of P-velocities in the upper mantle, *J. geophys. Res.*, **72**, pp. 6309-6325.

Jeffreys, H., 1966, Revisions of traveltimes, *Geophys. J. Roy. astr. Soc.*, **11**, pp. 5-12.

Jeffreys, H., 1962, *The Earth*, Cambridge University Press, p. 122.

Kaila, K.L., Reddy, P.R., Murthy, P.R.K. and Tripathi, K.M., 1979, Technical Report on Deep Seismic Sounding Studies along Koyna I and Koyna II profiles—Deccan Trap Covered Area, Maharashtra State, India, NGRI, Hyderabad, India.

Kamble, V.P., Verma, R.K. and Chaudhury, H.M., 1974, Crustal structure in the Mandi section-Himachal Himalayas, *Indian J. Met. Geophys.*, **25**, pp. 229-233.

Krishnan, M.S., 1956, *Geology of India and Burma*, Higgin Brothers Pvt. Ltd.

Ram, A. and Meeru, R.F., 1977, Lateral variations in upper mantle structure around India as obtained from Gauribidnur Seismic Array data, *Geophys. J. Roy. astr. Soc.*, **49**, pp. 87-113.

Tandon, A.N. and Dube, R.K., 1973, A study of the crustal structure beneath the Himalayas from Body waves, *Pur. appl. Geophys.*, **111**, pp. 2205-2215.

Tandon, A.N. and Chaudhury, H.M., 1968, Koyna earthquake of December 10, 1967, India Met. Dep. Sci. Rep. No. 59, 12 pp.

Walck, Harianne. C., 1984, The P-wave upper mantle structure beneath an active spreading centre : The Gulf of California, *Geophys. J. Roy. astr. Soc.*, **76**, pp. 697-723.