CRUSTAL AND UPPER MANTLE VELOCITY STRUCTURE OF INDIA FROM SURFACE WAVE DISPERSION

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ABSTRACT –*The dispersion seismic surface waves have widely been used to obtain P-wave velocity, S-wave velocity and density of the crust and upper mantle of India. The dispersion data consist of phase and group velocities as a function of period for multimode Rayleigh and Love waves. India is divided into three regions: ■ the Himalaya, ■ the Indo-Gangetic plain and ■ the Indian Peninsula or Shield. The surface wave dispersion across each of these regions investigated during the last three decades are briefly presented. Inversion of these data gives the crustal and upper mantle structure of each region. The thickness of crust increases northward; it is being 38·7 km in the Indian Peninsula, 43 km in the Indo-Gangetic Plain and 55 km in Himalaya. The mantle of Indo-Gangetic plain is the same as that of the Indian Peninsula.*

INTRODUCTION

The seismic surface waves form the most prominent part of a long period seismogram. For example, figure 1 shows vertical, north-south and east-west components of seismograms. When the source is known we can find out the direction of propagation. So using north-south and east-west components we obtain a component of seismogram in the direction of propagation (radial component) and another component of seismogram perpendicular to the direction of propagation (transverse component) (figure 2). There are mainly two types of surface waves: ■ Rayleigh waves (LR) and ■ Love Waves (LQ). LR is recorded in vertical and radial components and LQ in transverse component. Normally the velocity of LQ is higher than that of LR. However, velocity of each type depends on the period of waves as these waves are dispersive. Further, each type can propagate in different modes. We shall use the following notations:

LR0: Fundamental mode Rayleigh wave
LR1: First higher mode Rayleigh wave
LQ0: Fundamental mode Love wave
LQ1: First higher mode Love wave

METHODS OF DATA COLLECTION

The dispersion data consist of group velocity (U) and phase velocity (C) as a function of period (T). Large data have been collected for different paths in India; paths considered here have been shown in figure 3.

In the 1960s, group velocity was measured by plotting arrival times of peaks and troughs; a smooth curve through these points is drawn[1]. At an arrival time slope of this curve gives the period T. Thus at that period T, group velocity U from epicentre to the recording station is obtained by dividing epicentral distance by travel time. Group velocity between two stations can be obtained from earthquakes lying on the great circle passing through the stations; here group velocity is obtained by dividing the difference of epicentral distances by the difference of arrival times. Since the 1970s the arrival time of surface waves of a certain period is obtained by frequency time analysis or FTAN[2,3,4]. Here time domain record (such as figure 2) is changed to frequency domain by Fourier transformation. This is then multiplied with a narrow filter around a frequency f and brought back to time domain by inverse Fourier transformation; the time of peak

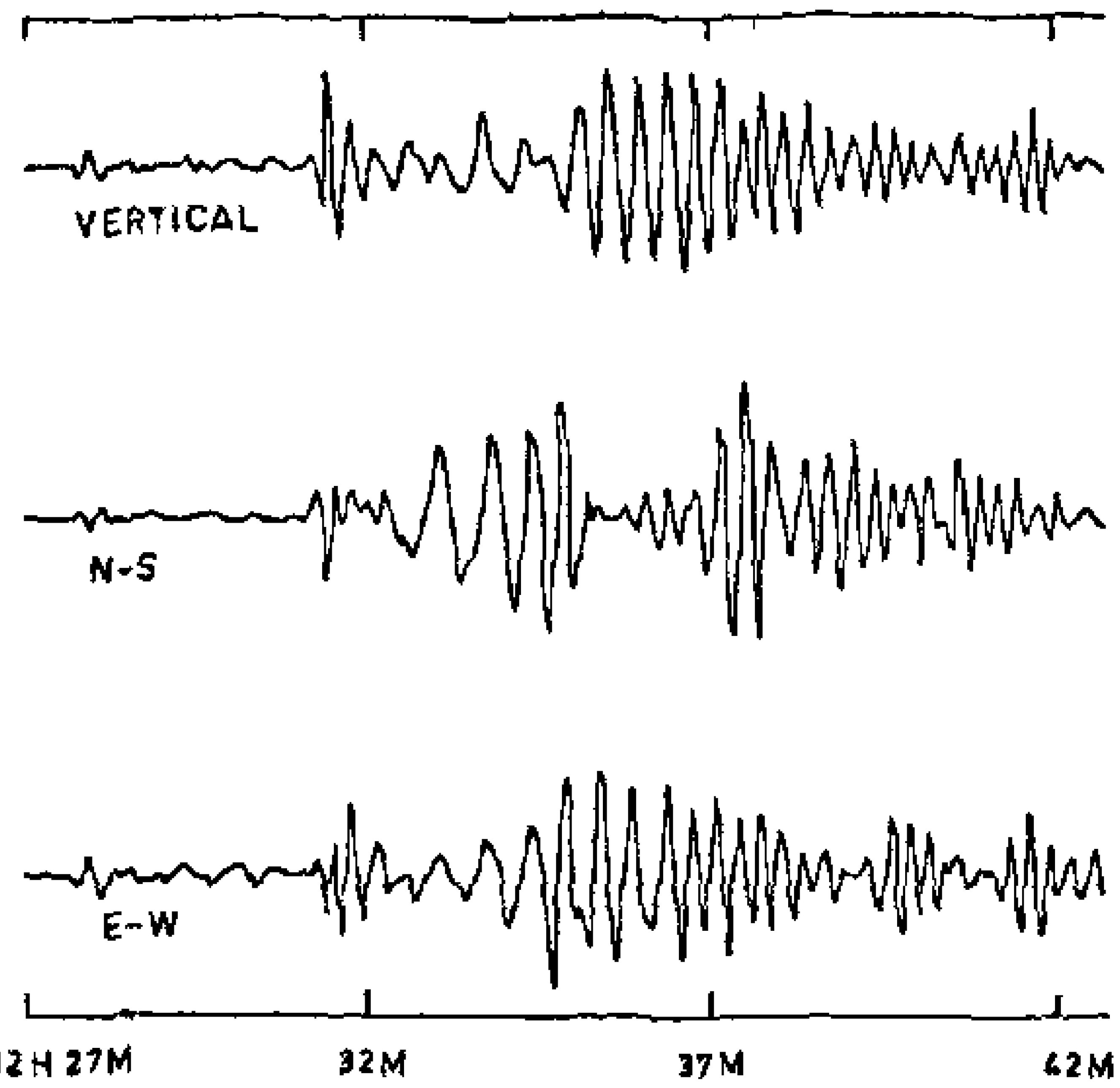

FIGURE 1 Vertical (top), north-south (middle) and east-west (bottom) components of long period SRO seismograms at Cheng Mai (CHG), Thailand from an earthquake on July 29 1980 at 12h 23m 07·7s in western Nepal (29°.34N, 81°.21E), Epicentral distance 2144 km.

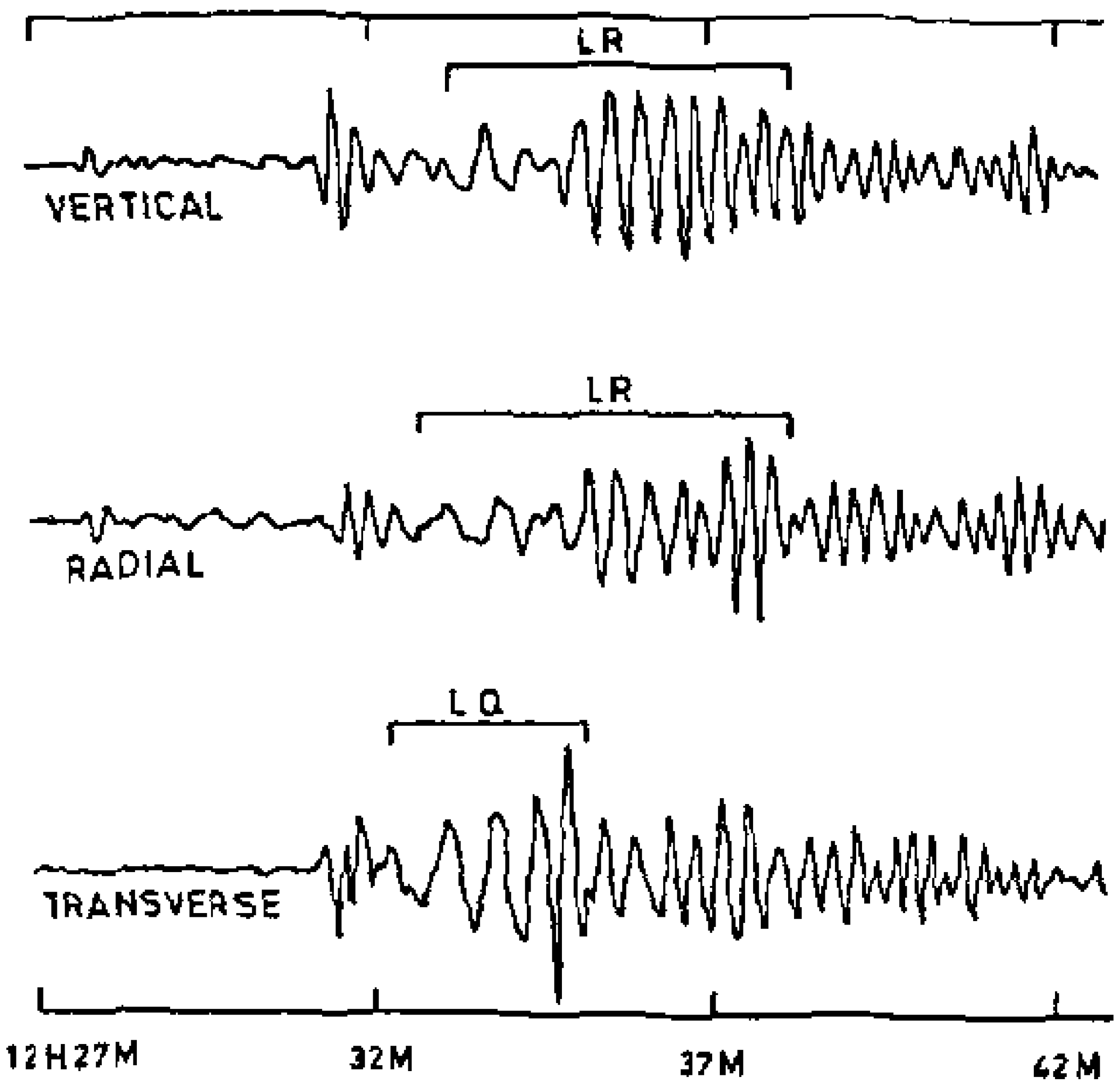

FIGURE 2 Using the azimuth of wave path at CHG we obtain vertical (top, same as figure 1), radial (middle) and transverse (bottom) components of seismograms from figure 1. Rayleigh waves (LR) and Love waves (LQ) are marked on seismograms.

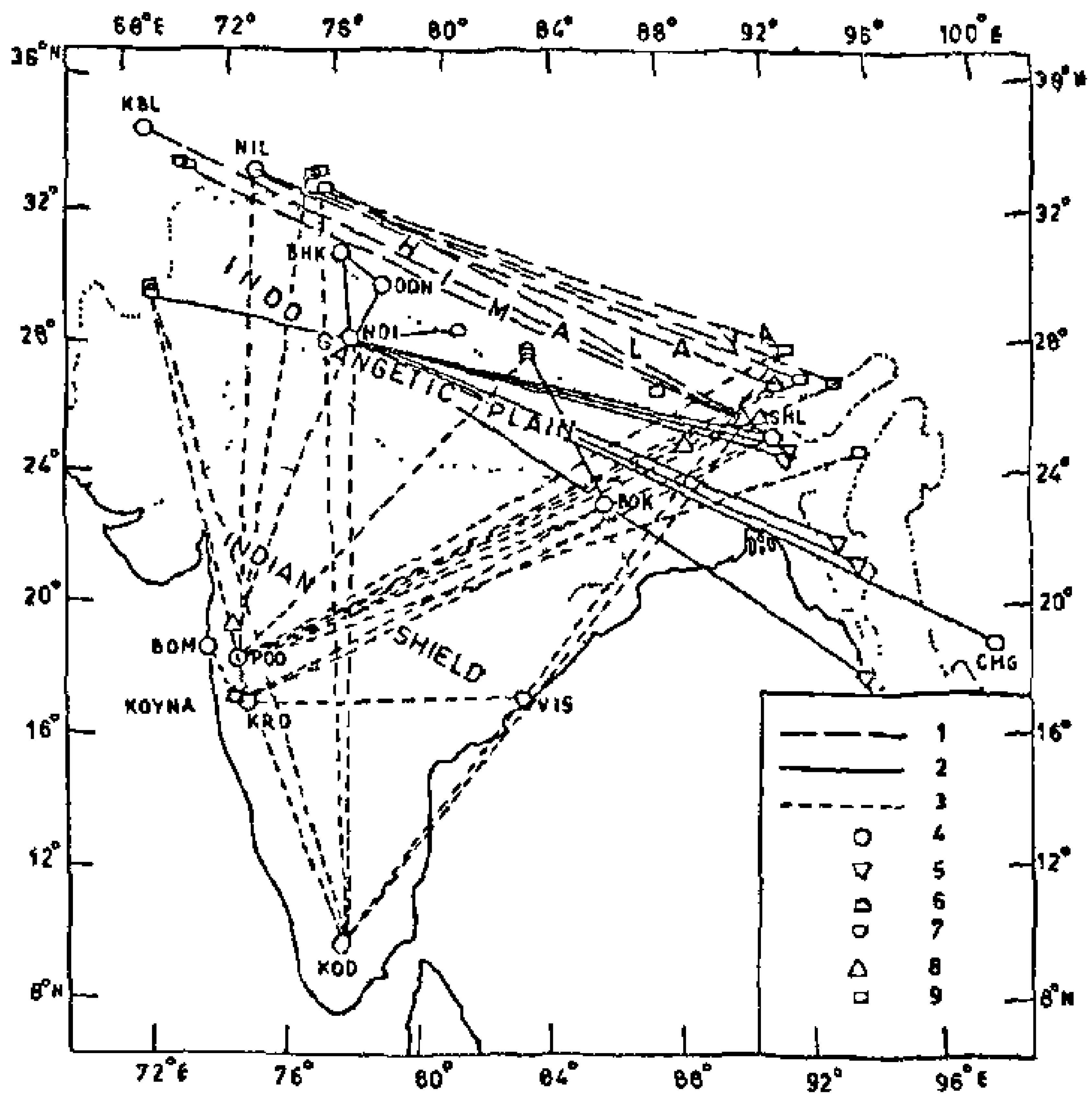

FIGURE 3 Surface wave paths mainly in (1) the Himalaya, (2) the Indo-Gangetic plain and (3) the Indian Peninsula, (4) Station locations: BHK (Bhakra), BOK (Bokaro), BOM (Bombay), CHG (Cheng Mai), DDN (Dehradun), KBL (Kabul), KOD (Kodaikanal), KRD (Karad), NDI (New Delhi), NIL (Nilore), POO (Poona), SHL (Shillong), VIS (Visakhapatnam). Earthquakes used by (5) Chaudhury[6], (6) Chaudhury[10,11], (7) Tandon[19] and Bhattacharya and Srivastava[18] (8) Bhattacharya[3,16] (9) Hwang and Mitchell[9]. Paths between stations are: SHL-NDI[1], NDI-DDN, DDN-BHK, BHK-NDI[5], NDI-KOD[9,14,15], CHG-NDI[2], KBL-SHL, NIL-SHL, SHL-POO, POO-KOD[9].

amplitude gives the arrival time of the surface waves with period T = 1/f. FTAN is useful if surface waves are disturbed by other waves arriving at the same time or by noises; it is also useful for separation of modes.

Phase velocity is measured by correlation of phases between stations[5]; here the stations should be nearby and preferably within one wave length (= T.C) of surface waves. Phase velocity from epicentre to recording station is also obtained with proper initial phase due to source[6]. FTAN described in the previous paragraph also estimates phase which is used to find phase velocity either from epicentre to station or between a pair of stations[2].

DETERMINATION OF STRUCTURE

The dispersions of LR and LQ depend on the medium through which they travel. The medium parameters on which dispersion depend are P-wave velocity, S-wave velocity and density. So dispersion data are useful in obtaining these parameters of the medium through which the waves travel. However, the dispersions largely depend on S-wave velocity and LQ does not depend on P-wave velocity; thus S-wave velocity is determined well by the inversion of dispersion data. The depth covered by surface waves increases with increase of period; further higher modes cover deep structure. Fundamental mode surface wave of period upto 40 s is affected most by the crust. With same period, LR covers a little deeper part than LQ does.

There are many numerical techniques for inversion of dispersion data. Broadly, inferred structure is the one for which theoretical dispersion curves fit the data. A non-uniqueness often arises in finding the structure. This is avoided by using both LR0 and LQ0 and if possible by higher modes. Other geophysical data, if any, are also considered during inversion.

During inversion it is generally assumed that the medium is laterally homogeneous. As such the data should belong to a uniform region. We divide India into three such regions: ■ the Himalaya, ■ the Indo-Gangetic plain and ■ the Indian Peninsula or Shield. The regions are shown in figure 3. Wave paths in this figure lie approximately along each of the regions only and later figures include dispersion data for these wave paths and their inversion.

HIMALAYA

The Himalaya is the world's highest mountain system. It extends from Kashmir to Arunachal Pradesh. There are two sharp bends of the Himalayan chain of mountains: one on the west near Nanga Parbat where Indus takes a turn, and the other on the east near Mishmi Hills where Brahmaputra takes a turn. Gupta and Narain[7] determined group velocities of LR0 and LQ0 across Himalaya and Tibet Plateau. From an inversion of these data, they inferred that the crustal thickness in Himalaya and Tibet plateau is 65 to 70 km. The surface wave studies of this region have been reviewed by Gupta and Bhatia[8]. Rayleigh wave dispersion data accross Himalaya were obtained by Hwang and Mitchell[9] and their mean data are shown in figure 4. The phase velocities of LR0 at periods from 20 to 50 s were obtained between the stations KBL-SHL and NIL-SHL. Group velocities of LR0 at periods from 4 to 40 s were determined between these stations and also from a few epicentres to these stations (figure 3). Group velocities of LR1 at periods from 5 to 16 s were also obtained from some of these epicentres to these stations. Group velocity data show a large scatter particularly at low periods.

As the dispersion depends largely on S-wave velocity, Hwang and Mitchell[9] inferred this velocity structure (figure 5) keeping P-wave velocity and density as in a tectonically active region. The result (figure 5) indicate that the Himalayan crust is about 55 km thick, consisting of a 30 km thick upper crust and 25 km thick lower crust. The S-wave velocity just below the crust is about 4.4km/s. Here upper mantle low velocity layer is between 100 and 110km where S-wave velocity is about 4.0km/s.

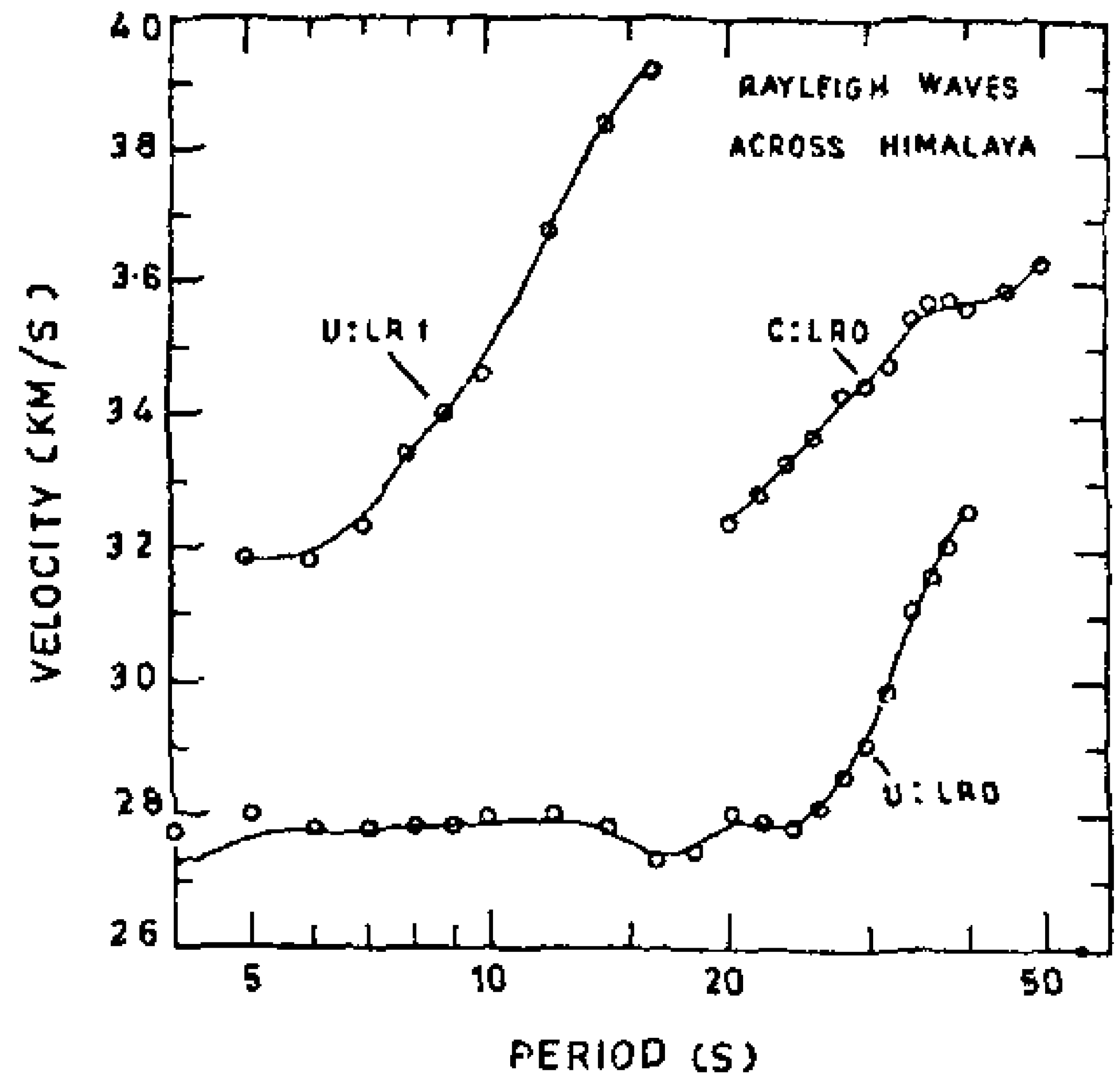

FIGURE 4 Phase velocity (C) and group velocity (U) of Rayleigh waves across Himalayas[9]. The theoretical curves correspond to the model shown in figure 5.

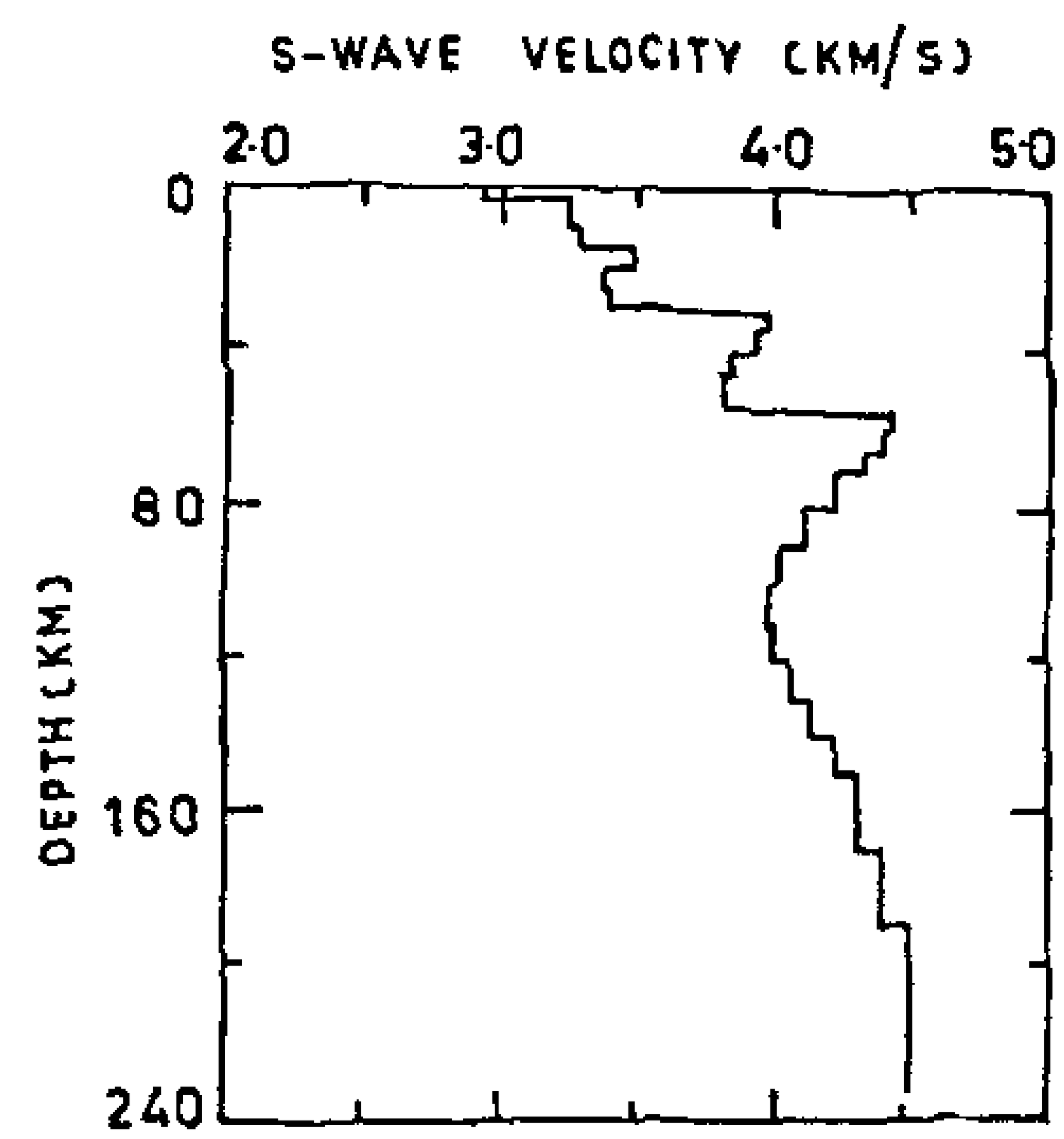

FIGURE 5 S-wave velocity model in Himalaya (based on Hwang and Mitchell[9]).

INDO-GANGETIC PLAIN

Between the Himalaya and Peninsula lies the Indo-Gangetic plain – built up of recent alluvium through the rivers that flow sluggishly towards the seas. It varies in width from 200 km in the east to about 400 km in the west. Tandon and Chaudhury[1] obtained group velocities of surface waves between SHL and NDI; the period of LR0 is between 16 and 70 s and that of LQ0 is between 18 and 100 s. They found that crustal thickness of Gangetic basin is between 40 and 45 km. Chaudhury[6] used surface wave record of NDI from earthquakes in and around northeast India; phase and group velocities of LR0 were obtained at periods ranging from 18 to 60s; group velocities of LR1 at periods from 5 to 15s were also obtained. For Love waves Chaudhury[6] determined group velocities of LQ0 at periods between 18 and 65s, phase velocities of LQ0 at periods between 17 and 50s and group velocities of LQ1 at periods between 6 and 14s. From these data Chaudhury[6] inferred 40km thick crust including 3km sediments at the top.

Tandon and Chaudhury[5] obtained phase velocities of LR0 at periods between 17 and 50s across the stations NDI-DDN, DDN-BHK and BHK-NDI using phase correlation. DDN-BHK path is in Himalaya nearly along the border with Indo-Gangetic plain; the phase velocities along this path are approximately the same as those along NDI-DDN and BHK-NDI. It appears that the structure of Indo-Gangetic plain continues in this bordering regions of Himalaya. Tandon and Chaudhury[5] found that the crustal thickness is about 40km including 5 to 6km of sediments. Gupta *et al.*[2] obtained phase velocities of LR0 and LQ0 between the station CHG-NDI for periods extending to 200s. They noted shield like upper mantle structure beneath the Indo-Gangetic plain.

Fundamental mode surface waves for short periods were also observed in Indo-Gangetic plain. Chaudhury[10] obtained group velocities of LR0 at periods from 5 to 15s across Gangetic plain and found 4 to 6km of sediment with S-wave velocity 2·0km/s. However large parts of some of these paths were in Himalaya. We consider only three paths (figure 3) which are mainly along Gangetic plain; these are from two earthquakes at (28°·5N, 80°·9E) to NDI and from an earthquake at (28°·5N, 83°·2E) to BOK. Chaudhury[11] obtained group velocities of LR0 and

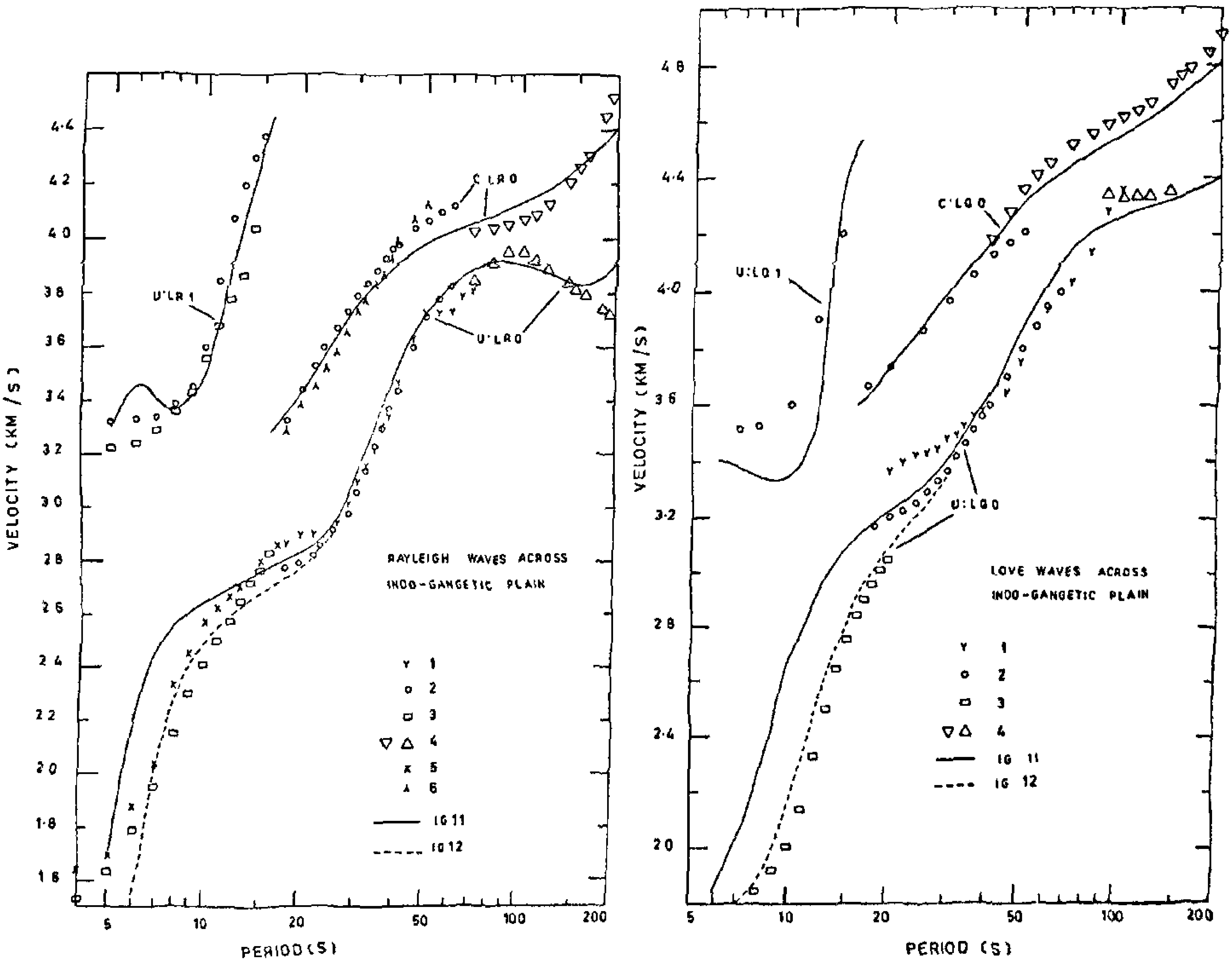

Figure 6 Rayleigh (a) and Love (b) waves dispersion data across Indo-Gangetic plain: (1) Tandon and Chaudhury[1], (2) Chaudhury[6], (3) Chaudhury[11], (4) Gupta *et al.*[2], (5) Chaudhury[10], (6) Tandon and Chaudhury[5]. Theoretical dispersion curves are drawn for the models IG11 and IG12 (table 1).

LQ0 at periods between 5 and 20s across paths from *earthquakes in Sulaiman range (Pakistan) to NDI.* It is inferred that sediments overlying the granitic basement are about 5km. Chaudhury[11] also obtained group velocities of LR1 along these paths at periods ranging from 4 to 14s.

The dispersion data of Indo-Gangetic plain for each of the above investigations are plotted in figure 6. In an investigation if data are many, a smooth curve is drawn through the original data set; the data from this smooth curve are shown in figure 6.

Chun and Yoshi[12] reinterpreted the group velocity data of LR0 and LQ0 obtained by Chaudhury[6] and inferred a model for the Gangetic plain. As shown in figure 6. dispersion curves for the model IG11 (table 1) satisfy the dispersion data of the Indo-Gangetic plain except data of fundamental mode at short period range. The model IG11 has the same crust as found by Chun and Yoshi[12] and the same mantle as that in the model IP11 (table 2) which has been obtained for the Indian Peninsula. In the model IG11 thickness of sediments is 3.5km. The short period fundamental mode surface wave dispersion data are satisfied with the dispersion curves for the model IG12 (table 1); this model is the same as IG11 except that the sedimentary layer thickness is 4·5km. It appears that average sedimentary layer thickness is 3·5km across the long surface wave paths in Indo-Gangetic plain. However, along the short wave paths, across which short period surface waves were observed, is a sedimentary layer thickness of 4·5 km. Gabriel and Kuo[13] determined phase velocities of LR0 along a profile between NDI and Lahore, Pakistan at periods between 14 and 45s. Although these data agree with those in figure 6 between 35 and 45s but remain higher than those given in this figure at lower periods and the difference becomes about 0·2 km/s at 20s period. These data may be explained by decreasing the sedimentary layer thickness of IG11 along this profile. Gupta *et al.* (1977) suggested a sedimentary layer of thickness 0·4km for this profile.

TABLE 1. Models of crust and upper mantle of Indo-Gangetic Plain.

Model	Depth of top of layer (km)	Thickness of layer (km)	P-wave velocity (km/s)	S-wave velocity (km/s)	Density (gm/cm^3)
IG11	0.0	3.5	3.40	2.00	2.00
	3 5	16.5	6.15	3.55	2 60
	20.0	23.0	6.58	3.80	3.00
	43.0	57.0	8.19	4 603	3.30
	100.0	20.0	8.30	4.603	3.30
	120 0	20.0	8.30	4.603	3.40
	140.0	80.0	8.40	4.57	3 40
	220.0	60.0	8.40	4.55	3.50
	280.0	60.0	8.50	4.55	3.50
	340.0	20 0	8.50	4.70	3.60
	360.0	40.0	8.60	4.70	3.60
	400 0	∞	9.10	5.30	3 70
IG12	0.0	4.5	3.40	2.00	2 00
	4.5	15.5	6.15	3.55	2.60
	20.0	∞	As in IG11		

TABLE 2. Models of crust and upper mantle of Indian Peninsula.

Model	Depth of top of layer (km)	Thickness of layer (km)	P-wave velocity (km/s)	S-wave velocity (km/s)	Density (gm/cm^3)
IP11	0.0	20.4	5.78	3.530	2.60
	20 4	18 3	6.58	3.916	3.01
	38.7	61.3	8.19	4 603	3.30
	100.0	20.0	8.30	4.603	3.30
	120.0	20.0	8.30	4 603	3.40
	140.0	80.0	8.40	4.57	3.40
	220.0	60.0	8.40	4.55	3.50
	280.0	60.0	8.50	4.55	3.50
	340.0	20.0	8.50	4.70	3.60
	360.0	40.0	8.60	4.70	3.60
	400.0	∞	9.10	5.30	3.70
IP12	0.0	1.0	4.80	2.65	2.40
	1.0	19.4	5.80	3.56	2.60
	20.4	∞	As in IP11		

INDIAN PENINSULA

The Indian Peninsula is a shield region which has maintained its continental structure since Precambrian times and is also known as Indian Shield. Group velocities of LR0 and LQ0 for period extending upto 100 s were obtained by Bhattacharya[14,15] along north south profiles across this region. Bhattacharya[3] obtained group velocities of LR0, LR1 and LQ0 at periods ranging respectively from 5 to 56s, from 5 to 14s and 5 to 43s along east-west profiles in central India and inferred the crust-mantle model *IP11 (table 2).* Bhattacharya[16] obtained group velocities of LR0 and LQ0 at periods ranging respectively from 7 to 46s and 5 to 46s across northwestern part of the Indian Peninsula and noted that data are nearly same as those in central India; it is inferred that the model IP11 continues in the northwestern part of the Peninsula. Hwang and Mitchell[9] obtained phase velocities of LR0 at periods from 20 to 50s, group velocities of LR0 at periods from 4 to 40s and group velocities of LR1 at periods from 5 to 16s along various paths of this region (figure 3); they obtained crust-mantle model which is similar to that of IP11, but has velocity jumps across discontinuities and contains gentle velocity gradients between the discontinuities.

The mean values of dispersion data obtained at each of

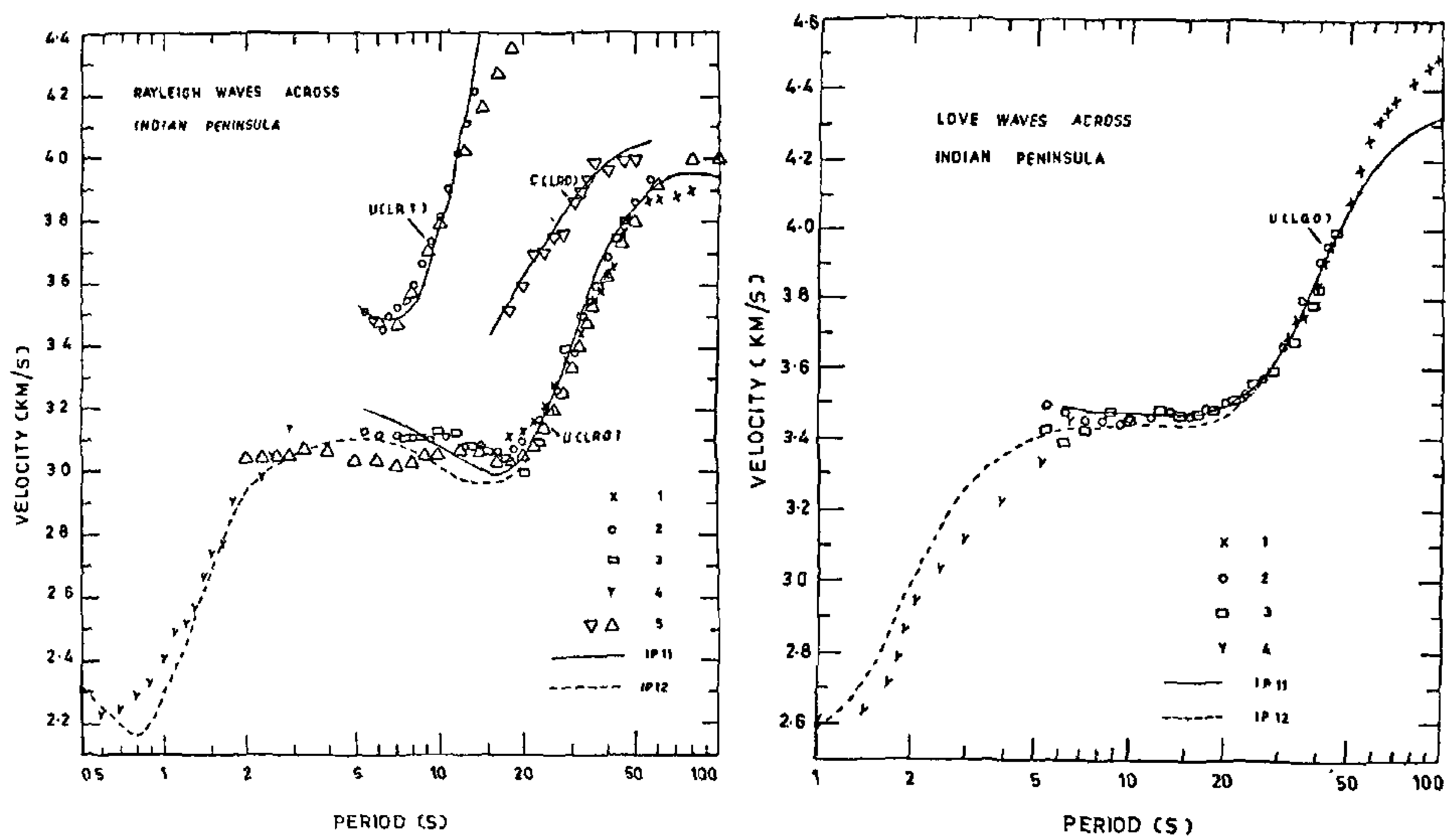

FIGURE 7 Rayleigh (a) and Love (b) waves dispersion data across the Indian Peninsula: (1) Bhattacharya[14,15] along NDI-KOD, (2) Bhattacharya[3], (3) Bhattacharya[16], (4) Tandon[19] and Bhattacharya and Srivastava[18], (5) Hwang and Mitchell[9]. Theoretical dispersion curves are drawn for the models IP11 and IP12 (table 2).

the investigations mentioned above are shown in figure 7. The mean values of Bhattacharya[3] for central India are modified with the inclusion of data of two paths from Koyna to VIS used by Bhattacharya[16]. Mean values of Bhattacharya[16] in figure 7 includes only the data along paths across northwestern part of the Peninsula. The figure 7 shows that the theoretical dispersion curves for the model IP11 satisfies the observed data obtained in various investigations. At long periods observed group velocity of LQ0 is higher than the theoretical curve of IP11. Bhattacharya[15] interpreted this by considering that the mantle between 60 and 160 km is anisotropic and SH-wave velocity (which affects Love wave) about 5% higher than SV- wave velocity (which affects Rayleigh wave). We may note that in an isotropic medium SH-wave velocity is equal to SV-wave velocity and commonly called as S-wave velocity. Singh[17] determined dispersion data of fundamental mode surface waves along a few paths; but deviations for different paths were large.

Group velocities of very short period (0·6 to 2·8 s) LR0 from Kirkee (3·6 km from POO) to KRD were obtained by Bhattacharya and Srivastava[18]. Group velocities of short period (1·0 to 6·4 s) LQ0 from Koyna to BOM were obtained by Tandon[19]. These short period surface waves pass through the Deccan Trap. Bhattacharya and Srivastava[18] and Tandon[19] found thickness of this trap as 1·25 and 1·15 km respectively. These data are shown in figure 7. Here we tried to fit this data by dispersion curves of a model with a Deccan Trap layer overlying a structure similar to IP11 and found the model IP12 (table 2) to satisfy the data. The model IP12 is the same as IP11 except that the top 1 km is Deccan Trap and velocities of granitic layer is slightly increased.

CONCLUSIONS

■ India is divided into three regions ■ the Himalaya ■ the Indo-Gangetic plain and ■ the Indian Peninsula or Shield. The dispersion data of various investigations across each of these regions are presented. The data extend over a wide range of period. The crust-mantle models obtained through inversion of the observed dispersion data are also presented.

■ The crust-mantle model of Himalaya is shown in figure 5.

■ The crust-mantle model of Indo-Gangetic plain is given by IG11 (table 1) which includes 3·5 km sedimentary layer. However, many areas in this plain have a sedimentary layer of thickness 4·5 km (model IG12, table 1).

■ The crust-mantle model of the Indian Peninsula or Shield is given by IP11 (table 2). Koyna-POO-BOM area has a Deccan Trap of thickness 1 km at the top (model IP12, table 2).

■ The mantle of Indo-Gangetic plain is the same as that of Indian Shield. It is wellknown that Indo-Gangetic plain forms a foredeep in the process of the collision of Indian plate with Eurasian plate across Himalaya. Thus the basement of the Indo-Gangetic plain being the same as that of the Indian Shield is in agreement with the evolution of the plain.

■ The thickness of crust increases northward. It is being 38·7 km in the Indian Peninsula, 43 km in the Indo-Gangetic plain and 55 km in the Himalaya.

REFERENCES

1. Tandon, A. N., *Indian J. Meteorol. Geophys.*, 1964, **15**, 467–474.
2. Gupta, H. K., Nyman, D. C. and Landisman, M., *Earth Planet Sci. Lett.*, 1977, **34**, 51–55.
3. Bhattacharya, S. N., *Bull. Seismol. Soc. Am.*, 1981, **71**, 1489–1501.
4. Bhattacharya, S. N., *Bull. Seismol. Soc. Am.*, 1983, **73**, 1395–1406.
5. Tandon, A. N. and Chaudhury, H. M., *Indian J. Meteorol. Geophys.*, 1968, **19**, 431–434.
6. Chaudhury, H. M., *Indian J. Meteorol. Geophys.*, 1966, **17**, 385–394.
7. Gupta, H. K. and Narain, H., *Bull. Seismol. Soc. Am.*, 1967, **57**, 235–248.
8. Gupta, H. K. and Bhatia, S. C., *Zagros, Hindukush, Himalaya; Geodynamic evolution*, (ed. Gupta, H. K. and Delany, F. M.) Am. Geophys. Un., Geodyn. Ser., 1981, pp. 294–306.
9. Hwang, H. G. and Mitchell, B. J., *Geophys. J. R. Astron. Soc.*, 1987, **90**, 575–613
10. Chaudhury, H. M., *Indian J. Meteorol. Geophys.*, 1967, **18**, 273–278.
11. Chaudhury, H. M., *Indian J. Meteorol. Geophys.*, 1969, **20**, 227–234.
12. Chun, K. Y. and Yoshi, T., *Bull. Seismol. Soc. Am.*, 1977, **67**, 735–750.
13. Gabrial, V. G. and Kuo, J. T., *Bull. Seismol. Soc. Am.*, 1966, **56**, 1137–1145.
14. Bhattacharya, S. N., *Indian J. Meteorol. Geophys.*, 1971, **22**, 179–186.
15. Bhattacharya, S. N., *Geophys. J. R. Astron. Soc.*, 1974, **36**, 273–283.
16. Bhattacharya, S. N., *Pure Appl. Geophys.*, 1991, **135**, 53–65.
17. Singh, D. D., *Tectonophysics*, 1987, **139**, 187–203.
18. Bhattacharya, S. N. and Srivastava, H. N., *Bull. Seismol. Soc. Am.*, 1973, **63**, 2197–2199.
19. Tandon, A. N., *Pure Appl. Geophys.*, 1973, **109**, 1693–1699.

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