Mausam, (1992), **43**, 1, 51-58

550.344.5:551.14(1-925.62)

Similarity of lithospheric structure of central and northwestern part of the Indian Peninsula inferred from observed surface wave forms

S. N. BHATTACHARYA

India Meteorological Department, New Delhi

(*Received 4 October 1990*)

सार — भारतीय प्रायद्वीप के केन्द्रीय भाग और प्रायद्वीप के उत्तर-पश्चिम भाग के पार बनने वाले प्रेक्षित सतह तरंग पर विचार किया गया। पूर्ववर्ती कार्य में, पूर्वो लिखित क्षेत्र के पार सतह तरंगों के समूह वेग का प्रयोग करते हुए निदर्श स्थलमंडल आईपी 11 का पता चला है। इन दो क्षेत्रों के पार बनने वाले प्रेक्षित सतह तरंग की तुलना निदर्श आईपी 11 का प्रयोग करते हुए संश्लेषित भूकम्प लेखियों के साथ की गई है। प्रेक्षित तरंग रूप संश्लेषित (सिन्थेटिक) के साथ परस्पर मेल खाते हुए पाए गए हैं। इससे पता चलता है कि भारतीय प्रायद्वीप के मध्य और उत्तर पश्चिम भागों की औसत स्थलमंडलीय संरचना एक समान है और स्थलमंडलीय निदर्श आई पी 11 की स्थिति इस संरचना के निकट है।

ABSTRACT. Observed surface wave forms across the central part of the Indian Peninsula and across northwestern part of the Peninsula have been considered. In a previous work, using group velocity of surface waves across former region revealed model lithosphere IP 11. Observed surface wave forms across these two regions have been compared with synthetic seismograms using model IP11. Observed wave forms are found to agree with synthetic ones. This suggests that the average lithospheric structure of central and northwestern parts of the Indian Peninsula is similar and the lithospheric model IP11 is an approximation to it.

Key words — Lithospheric structure, Synthetic seismograms, Rayleigh wave, Love wave.

1. Introduction

The Indian Peninsula has maintained its continental structure since Precambrian times. It is important to investigate the internal structure of this old block. Deep seismic sounding (DSS) experiments in the present study area have been conducted in some limited regions by inversion of body waves (Srivastava *et al.* 1983, Srivastava *et al.* 1984, Mittal *et al.* 1990). However, inversion of surface waves gives an average structure over a wide area; further it gives shear wave velocity structure with more confidence. Lithospheric structure across the plateau region along east-west profiles in the central part of the Indian Peninsula was investigated earlier (Bhattacharya 1981) by measuring group velocities of surface waves and on that basis model IP11 (Fig. 1) was proposed. The model IP11 is very similar to the crustal and upper mantle structure obtained by Hwang and Mitchell (1987) for Indian Peninsula through the inversion of Rayleigh wave group velocity data. The crustal structure of IP11 has been compared with the results of DSS in Table 1. The crustal structure of the model IP11 is very similar to that obtained by deep seismic sounding in Koyna region (Srivastava *et al.* 1984).

The northwestern part of the Indian peninsula consists of the central highlands. It is a wide belt of hilly country bordered on the west by the Aravalli range and on the south by the Satpura range. The great plain lies to the north of this region. The boundaries of the central highlands and plateau region of the Indian Peninsula are shown in Fig.2. Both the central highlands and the plateau region form the Indian Peninsula which has maintained its continental structure since Precambrian times and is known as Indian shield. Auden (1949) divided Indian shield into northern and southern parts partitioned by Satpura range and called central highland as northern shield.

In the past two decades, our understanding of earthquakes and earth structure has increased significantly because of improved ability to interpret a seismogram by comparing it with the corresponding synthetic seismogram. Comparison of surface waves on observed seismogram with those on synthetic seismogram at an epicentral distance up to 20° has been seen to be successful in evaluating lithospheric structure (*e.g.*, Mitchell and Herrmann 1979). The purpose of this work is to verify the model lithosphere IP11 for central India through comparison of the wave form of observed surface waves with synthetic ones. With a similar comparison it is also investigated whether the mode lithosphere IP11 continues in the northwestern part of the Peninsula.

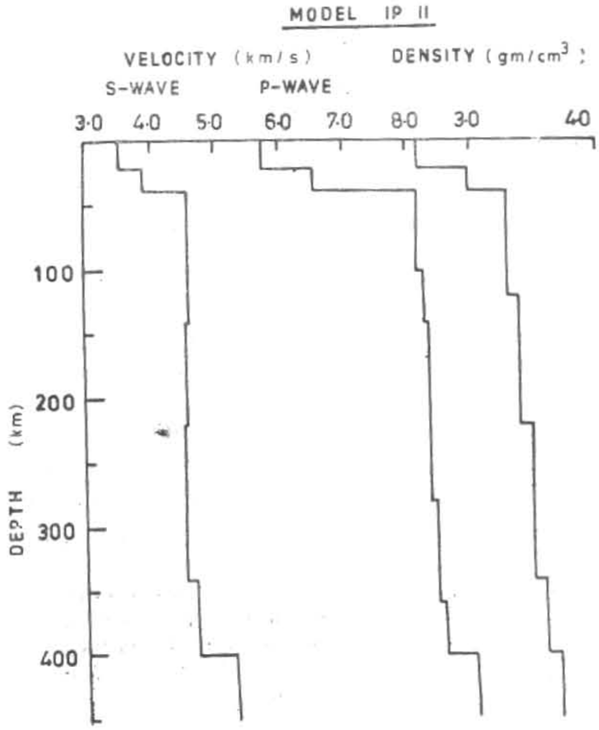

Fig. 1. Compressional (*P*) wave and shear (*S*) wave-velocity and density in model IP11

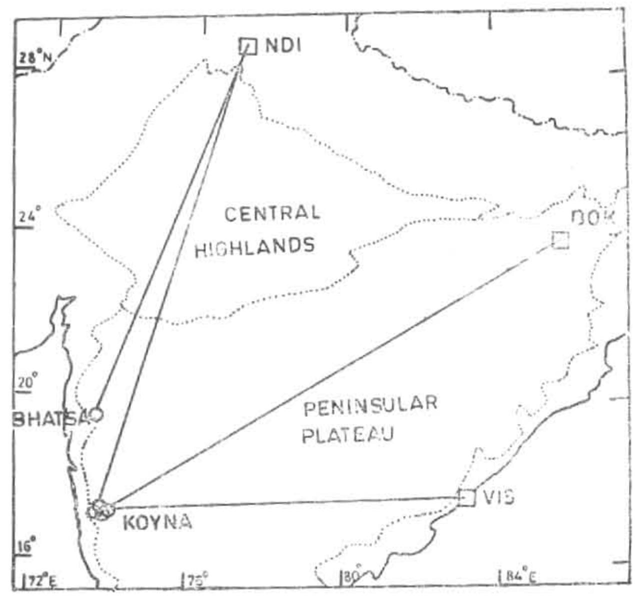

Fig. 2. Wave paths used in the present study

TABLE 1

Comparison of crustal structure of IP11 with DSS results

Region	*P*-wave velocity (km/s)			*S*-wave velocity (km/s)			Layer thickness (km)			Ref.*
	P_g	P^*	P_n	S_g	S^*	S_n	H_1	H_2	Total	
Indian Peninsula (IP11)	5.78	6.58	8.19	3.53	3.92	4.60	20.4	18.3	38.7	A
Koyna region	5.82	6.61	8.23	3.41	4.09	4.60	17.6	18.7	36.3	B
Indore-Khandwa	6.01	6.69	8.03	3.63	—	4.77	18.0	19.9	37.9	C
Jabalpur-Mandla	5.94	6.65	8.19	3.54	—	4.73	23.0	16.0	39.0	D

* A : Bhattacharya (1981), B : Srivastava *et al.* (1984),
C : Srivastava *et al.* (1983), D : Mittal *et al.* (1990).

2. Computation of synthetic seismograms

A synthetic seismogram is a theoretical simulation of a wave train as recorded by a seismograph. For this we take account of the entire process whereby the seismic waves progress from the source to the output of the receiver. This may be separated into three major elements: (*i*) the generation of waves by the source, (*ii*) the passage of the waves through the earth, and (*iii*) detection and recording by the receiver. There are many methods available for computation of synthetic seismograms. We shall use the wave number or slowness integration method following Kind (1979), Wang and Herrmann (1980), Herrmann and Wang (1985) and Müller (1985). This method is also known as reflectivity method.

We may represent the vertical component (upward) seismogram containing Rayleigh waves at an epicentral distance $\triangle$ due to a point shear dislocation as

$$\begin{aligned} u_z(\triangle,t) = {} & \mathrm{ZDD}\,[\sin\lambda \sin 2\delta] \\ & + \mathrm{ZDS}\,[-\cos\lambda \cos\delta \cos\varphi + \sin\lambda \cos 2\delta \sin\varphi] \\ & + \mathrm{ZSS}\,[\tfrac{1}{2}\sin\lambda \sin 2\delta \cos 2\varphi + \cos\lambda \sin\delta \sin 2\varphi] \end{aligned} \quad (1)$$

where λ is slip angle, δ is dip angle and φ is azimuth of the recording station measured clockwise from strike direction of the shear dislocation. Also

$$\mathrm{ZDD} = \frac{1}{2\pi}\int_{-\infty}^{\infty} S(\omega)\, I(\omega) d\omega \int_{0}^{\infty} F_1(k,\omega)\, J_0(k\triangle)\, dk$$

$$\mathrm{ZDS} = \frac{1}{2\pi}\int_{-\infty}^{\infty} S(\omega)\, I(\omega) d\omega \int_{0}^{\infty} F_3(k,\omega)\, J_1(k\triangle)\, dk$$

$$\mathrm{ZSS} = \frac{1}{2\pi}\int_{-\infty}^{\infty} S(\omega)\, I(\omega) d\omega \int_{0}^{\infty} F_5(k,\omega)\, J_2(k\triangle)\, dk$$

where, $S(\omega)$ is Fourier transform of source time function $s(t)$ and $I(\omega)$ is seismograph response; F_1, F_3, F_5, are Greens functions required to describe the wave field due to an arbitrary point shear dislocation source in a plane layered elastic medium and are given in Wang and Herrmann (1980); $J_0(k\triangle)$, $J_1(k\triangle)$ and $J_2(k\triangle)$ are Bessel functions. As we are interested in generating synthetic seismograms at large epicentral distances compared to wave length, we have used approximation of Bessel function, for large arguments. It may be noted that (*i*) ZDD is a seismogram with $\lambda=90°$, $\delta=45°$, and $\varphi=45°$, (*ii*) ZDS corresponds to $\lambda=90°$, $\delta=90°$ and $\varphi=90°$, and (*iii*) ZSS corresponds to $\lambda=0°$, $\delta=90°$ and $\varphi=45°$.

The seismogram in the radial direction can be obtained similarly.

The corresponding transverse component (clockwise) seismogram containing Love wave is given by :

$$\begin{aligned} u_\varphi(\triangle,t) = {} & \mathrm{TDS}\,[\sin\lambda \cos 2\delta \cos\varphi + \cos\lambda \cos\delta \sin\varphi] \\ & + \mathrm{TSS}\,[\cos\lambda \sin\delta \cos 2\varphi - \tfrac{1}{2}\sin\lambda \sin 2\delta \sin 2\varphi] \end{aligned} \quad (2)$$

where,

$$\mathrm{TDS} = \frac{1}{2\pi}\int_{-\infty}^{\infty} S(\omega)\, I(\omega) d\omega \int_{0}^{\infty} F_9(k,\omega)\, J_0(k\triangle)\, k\, dk$$

$$\mathrm{TSS} = \frac{1}{2\pi}\int_{-\infty}^{\infty} S(\omega)\, I(\omega) d\omega \int_{0}^{\infty} F_{10}(k,\omega)\, J_1(k\triangle)\, k\, dk;$$

here we have ignored terms with $1/\triangle$ as we are interested in generating synthetic seismograms at large distance. F_9 and F_{10} are given by Wang and Herrmann (1980). We note that (*i*) TDS is seismogram with $\lambda=-90°$, $\delta=90°$ and $\varphi=0°$, and (*ii*) TSS is seismogram with $\lambda=0°$, $\delta=90°$ and $\varphi=0°$.

Two computer programs are written : one to compute ZDD, ZDS and ZSS; other to compute TDS and TSS. The results of the programs are verified with synthetic seismograms given by Herrmann and Wang (1985) at an epicentral distance 75 km and those of Müller (1985) at epicentral distances 1000 km and 1500 km.

ZDD, ZDS and ZSS at an epicentral distance of 1432 km for the model IP11 are shown in Fig. 3. The model has a crust of thickness 38.7 km. To consider attenuation we have taken $Q_\alpha = 1000$ and $Q_\beta = 500$ in the crust and $Q_\alpha = 500$ and $Q_\beta = 250$ in the layers below the crust. The seismograph response of a long period electromagnetic seismograph with $T_0 = 15$ s and $T_g = 100$ s with peak magnification $V_{max} = 1500$ has been considered. The source time function has been taken as (Wang and Herrmann 1980).

$$2Ts'(t) = \begin{cases} 0 & , \; t \leqslant 0 \\ \frac{1}{2}(t/T)^2 & , \; 0 < t \leqslant T \\ -\frac{1}{2}(t/T)^2 + 2(t/T) - 1 & , \; T < t \leqslant 3T \\ \frac{1}{2}(t/T)^2 - 4(t/T) + 8 & , \; 3T < t \leqslant 4T \\ 0 & , \; 4T < t \end{cases}$$

Here $4T$ is the rise time. We have chosen $T = 1$s.

The corresponding TDS and TSS at and epicentral distance 1299 km are shown in Fig. 4.

3. Data used

Surface waves recorded by long period seismograph ($T_o = 15$ s and $T_g = 100$ s) at Bokaro (BOK), Visakhapatnam (VIS) and New Delhi (NDI) from earthquakes occurring in the Koyna and Bhatsa regions on the west coast of India are considered. The parameters of earthquakes are given in Table 2. Focal depths of the earthquakes in the Koyna region are found to be around 5 km using data of local observatories (Gupta *et al.* 1980, Rastogi & Talwani 1980). As such we have considered focal depths as 5 km for all the Koyna earthquakes considered here. With such focal depth synthetic wave form agrees better with observed one than with any other focal depths. Fig. 2 shows the wave paths from Koyna to BOK and VIS across central part of the peninsula and those from Koyna and Bhatsa to NDI across nothwestern part of the Peninsula.

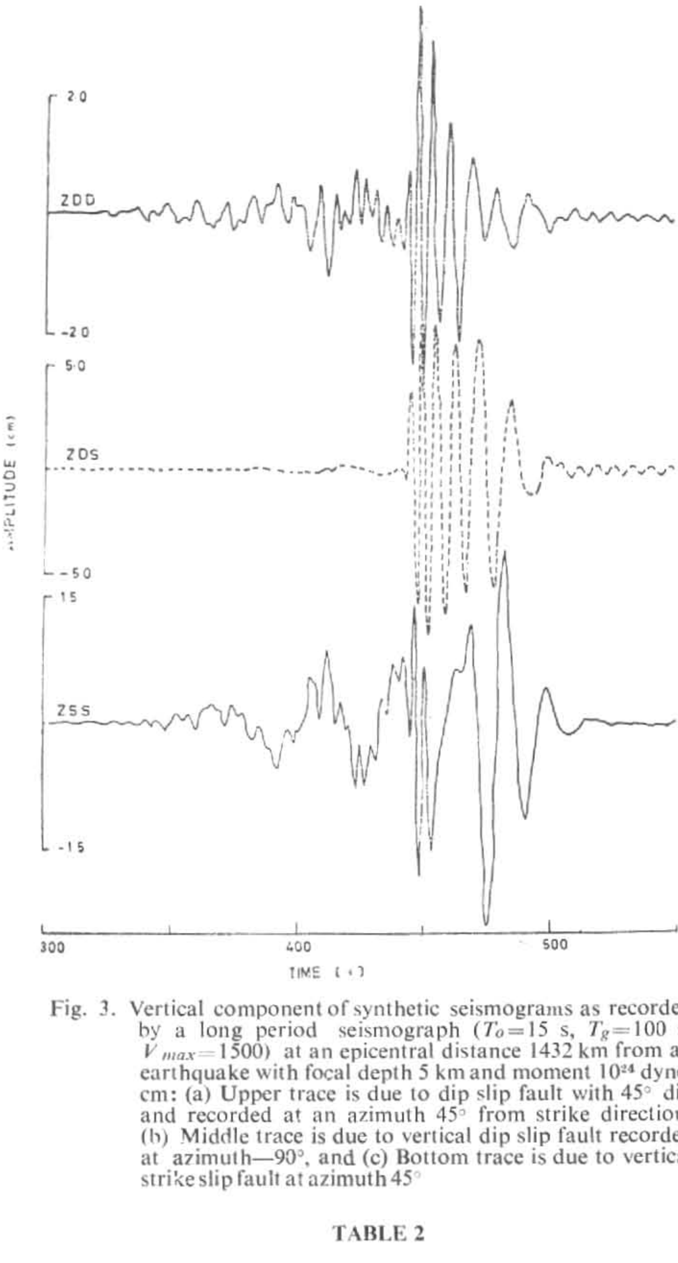

Fig. 3. Vertical component of synthetic seismograms as recorded by a long period seismograph (T_o=15 s, T_g=100 s, V_{max}=1500) at an epicentral distance 1432 km from an earthquake with focal depth 5 km and moment 10^{24} dyne-cm: (a) Upper trace is due to dip slip fault with 45° dip and recorded at an azimuth 45° from strike direction, (b) Middle trace is due to vertical dip slip fault recorded at azimuth—90°, and (c) Bottom trace is due to vertical strike slip fault at azimuth 45°

TABLE 2

Earthquakes used in this study

Date	Origin time			Epicentre		Depth (km)	Mag	Source **	Station used for comparison
	h	m	s	Lat. (°N)	Long. (°E)				
1967SEP13	06	48	25	17.4	73.4	4.0	5.0	IMD	NDI
1967DEC12	15	48	55.0	17.33	73.91	27.0	5.1	ISC	BOK
1969NOV03	23	22	10.0	17.40	73.71	5.0	4.5	RT	BOK
1973OCT17	15	24	49.3	17.40	73.71	5.9	5.2	RT	NDI
1980SEP20	07	28	58.0	17.24	73.87	33	4.8	ISC	VIS
1983SEP14	21	53	41.2	19.64	73.54	5*	4.3	ISC	NDI

** IMD : India Meteorological Department, ISC : International Seismological Centre, RT : Rastogi and Talwani (1980),
* From Rastogi *et al.* (1986).

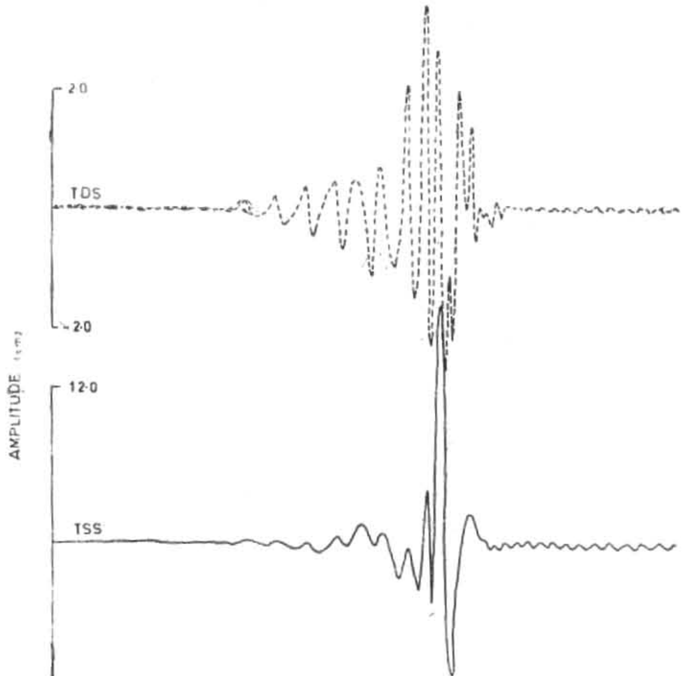

Fig. 4. Transverse component of synthetic seismograms as recorded by a long period seismograph ($T_o = 15$ s, $T_g = 100$ s, $V_{max} = 1500$) at an epicentral distance 1299 km from an earthquake with focal depth 5 km and moment 10^{24} dyne-cm: (a) Upper trace is due to vertical dip slip source and recorded in the strike direction, and (b) Lower trace is due to vertical strike slip source and recorded in the strike direction

The focal mechanism of main Koyna earthquake of 1967 DEC 10 has been inferred to be left lateral strike slip with strike along N 26° E with dip 66° in NW direction (Tandon and Chaudhury 1968). However, for the same earthquake Chandra (1976) obtained same result but with dip 90°. For Koyna earthquake of 1967 SEP 13, Langston (1981) obtained left lateral faulting on a plane with strike N 20° E, dip 90° and slip angle 0°. For Koyna earthquakes of 1968 OCT 29, 1969 NOV 03 and 1973 OCT 17, Gupta *et al.* (1980) and Rastogi and Talwani (1980) obtained north to northeast strike direction with left lateral strike slip and dip of about 80°. It may be noted that from strike direction, the azimuth φ of NDI is around 0°, and that of BOK and VIS is around 45°. Since the faulting in Koyna earthquakes are left lateral strike slip ($\lambda = 0$) on a vertical fault plane, at NDI Love waves were recorded well but Rayleigh waves were recorded poorly; on the other hand, BOK and VIS recorded Rayleigh waves well but Love waves were poorly recorded. This is in accordance with Eqns. (1) and (2). Hence we have used Rayleigh waves at BOK and VIS and Love waves at NDI. For Rayleigh waves vertical component is used. NDI is located nearly in north direction from Koyna and Bhatsa; so for Love waves we have considered east-west component which is approximately transverse to the direction of propagation of the waves.

4. Results

4.1. *Rayleigh waves at BOK and VIS across central par tof the peninsula*

Eqn. (1) shows that vertical component of synthetic seismogram is a linear combination of ZDD. ZDS and ZSS. The average epicentral distance from Koyna to BOK is 1432 km; for this distance ZDD. ZDS and ZSS are shown in Fig. 3. It may be seen that in ZDD and ZDS, Rayleigh waves mainly consist of inversely dispersed R_g waves. Regularly dispersed long period Rayleigh waves with significant amplitude is seen only in ZSS; this is insignificant in ZDD and nearly absent in ZDS. As Koyna earthquakes are approximately vertical strike slip, the main contribution in synthetic seismogram will be from ZSS. However, for a slight variation from vertical strike slip ZDD and ZDS will also have contribution on synthetic seismogram. However, such contribution will affect the wave form of synthetic seismogram from the time where R_g begins (beginning is clearly seen in ZDS of Fig. 3). Thus regularly dispersed long period Rayleigh wave is not much dependent on the exact source mechanism. The comparison of the observed seismogram with synthetic ones is shown in Fig. 5. The synthetic seismograms have been obtained by taking the source as vertical strike slip; so that synthetic seismograms corresponds to ZSS. The agreement of long period wave form along with their time of arrival is clear from the figure. As expected, the later parts which mainly consist of R_g waves, do not agree because they depend largely on exact source mechanism. The agreement gives further qualitative confirmation of the model IP11 for the central part of the peninsula.

4.2. *Love waves at NDI across northwestern part of the peninsula*

Eqn. (2) shows that Love wave motion u_ϕ is linear combination of TDS and TSS only. The average epicentral distance from Koyna to NDI is 1299 km; for this distance TDS and TSS are shown in Fig. 4. TDS mainly consists of higher modes Love waves. TSS contains mainly fundamental mode with a sharp pulse; amplitude of higher mode in TSS is very small compared to the amplitude of fundamental mode. For comparison with observed one in Fig. 6 we obtained synthetic seismogram considering the source as vertical strike slip; so that synthetic seismogram corresponds to TSS. Fig. 4 shows that the amplitude of TSS is one order of magnitude larger than TDS. Thus the wave form of Love waves is dominated by TSS and insignificantly depends on the source mechanism. Thus slight difference from vertical strike slip source will not change the synthetic seismograms in Fig. 6. However, wave form significantly depends on the structure through which wave passes. Thus the Love wave is idealy suited to evaluate the lithospheric structure. The comparison of observed and synthetic seismograms is shown in Fig. 6. The agreement is clear along with the arrival times of the wave forms. It may be mentioned that we have considered Bhatsa earthquake of 1983 SEP 14 as vertical strike slip source and corresponding synthetic seismogram agreed well with observed one; as mentioned before a

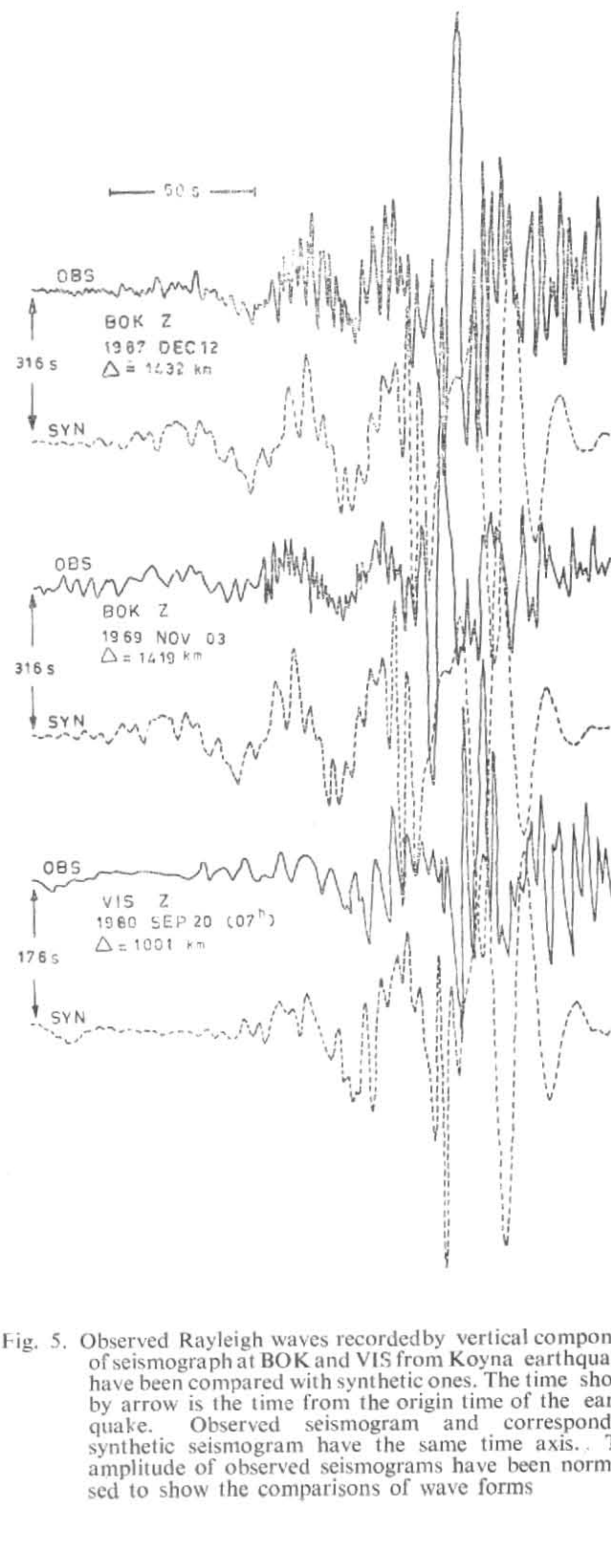

Fig. 5. Observed Rayleigh waves recordedby vertical component of seismograph at BOK and VIS from Koyna earthquakes have been compared with synthetic ones. The time shown by arrow is the time from the origin time of the earthquake. Observed seismogram and corresponding synthetic seismogram have the same time axis. The amplitude of observed seismograms have been normalised to show the comparisons of wave forms

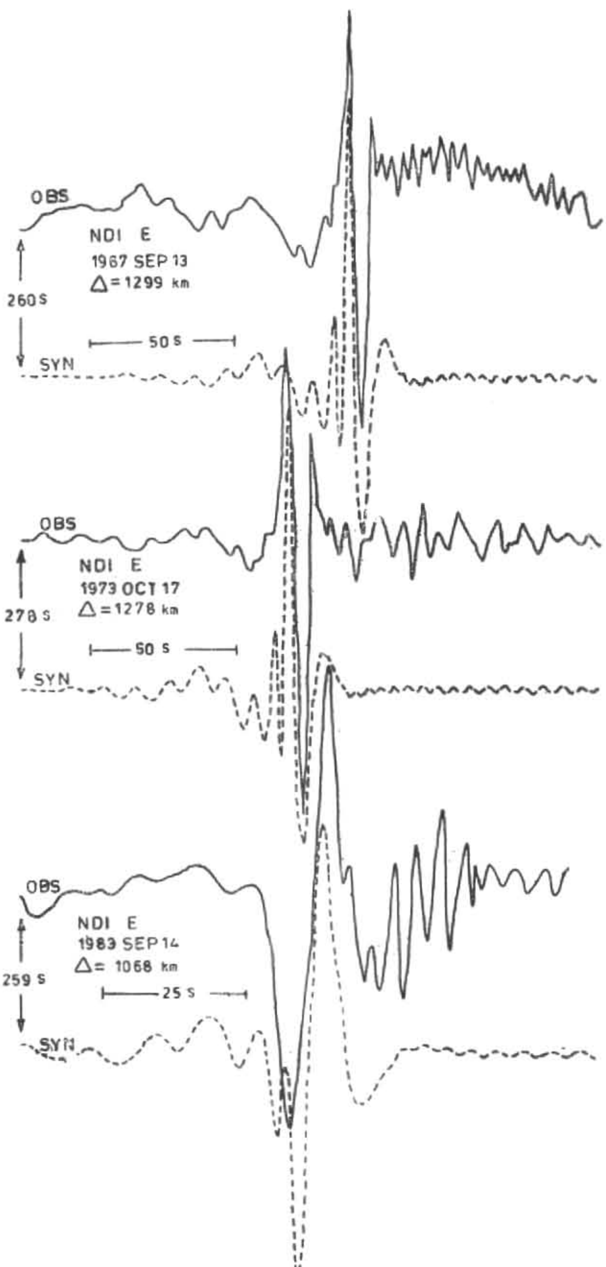

Fig. 6. Observed Love waves recorded by east-west component of seismograph at NDI from Koyna and Bhatsa earthquakes have been compared with synthetic ones. The time shown by arrow is the time from the origin time. Observed and corresponding synthetic seismograms have the same time axis. The amplitudes of observed seismograms have been normalised to show the comparison of wave forms

slight difference of source mechanism will not change the wave pattern significantly. The agreement of the observed Love wave with synthetic seismogram in Fig. 6 shows the continuation of the same lithospheric structure IP11 under the northwestern part of the peninsula.

5. Conclusions

(*i*) Observed Rayleigh waves recorded at BOK and VIS from Koyna earthquakes across central part of the peninsula have been compared with synthetic seismograms in Fig. 5. The qualitative agreement between them lends further support to the lithospheric model IP11 (Fig. 1) obtained earlier for this region (Bhattacharya 1981).

(*ii*) Observed Love waves recorded at NDI from Koyna and Bhatsa earthquakes clearly agrees with synthetic seimsograms in Fig. 6. This suggests that the lithospheric model IP11 may continue in the northwestern part of the peninsula.

(*iii*) The average lithospheric structure of central and northwestern parts of the Indian Peninsula is suggested to be similar and lithospheric model IP11 is an approximation to it.

Acknowledgement

Synthetic seismograms were generated using the VAX8810 computers of the National Centre for Medium Range Weather Forecasting, New Delhi.

References

Auden, J.B., 1949, "A geological discussion of the Satpura hypothesis and Garo-Rajmahal gap", *Trans. Nat. Inst. Sci.*, **15**, 315-350.

Bhattacharya, S.N., 1981, "Observation and inversion of surface wave group velocities across central India", *Bull.seism. Soc. Am.*, **71**, 1489-1501.

Chandra, U., 1976, "Focal mechanism of the Koyna, India earthquake of 1967, December 10", *Geophys. J.*, **47**, 247-251.

Gupta,H.K., Rao, C.V.R.K., Rastogi, B.K. and Bhatia, S.C., 1980, "An investigation of earthquake in Koyna region, Maharashtra, for the period October 1973 through December 1976", *Bull. seism. Soc. Am.*, **70**, 1833-1847.

Herrmann, R. B. and Wang, C. Y., 1985, "A comparison of synthetic seimsograms", *Bull. seism. Soc. Am.*, **75**, 41-56.

Hwang, H. and Mitchell, B.J., 1987, "Shear velocities, $Q\beta$ and the frequency dependence of $Q\beta$ in stable and tectonically active regions from surface wave observations", *Geophys. J.*, **90**, 575-613.

Kind, R., 1979, "Extension of the reflectivity method", *J. Geophys.*, **45**, 373-380.

Langston, C.A., 1981, "Source inversion of seismic waveforms, the Koyna, India earthquakes of 13 September 1967", *Bull. seism. Soc. Am.*, **71**, 1-24.

Mitchell, B.J. and Herrmann, R.B., 1979, "Shear velocity structure in the eastern united states from the inversion of surface wave group and phase velocities", *Bull. seism. Soc. Am.*, **69**, 1133-1148.

Mittal, V.K., Bhattacharya, S.N. and Srivastava, H.N., 1990, "Crustal investigations and microearthquake survey along Hirpur, Jabalpur, Mandla profile using deep seismic sounding explosion data", *Mausam*, **41**, 49-64.

Müller, G., 1985, "The reflectivity method : a tutorial", *J. Geophys.*, **58**, 153-174.

Rastogi, B.K. and Talwani, P., 1980, "Relocation of Koyna earthquakes", *Bull. seism. Soc. Am.*, **70**, 1849-1869.

Rastogi, B.K., Chadha, R.K. and Raju, I.P, 1986, "Seismicity near Bhatsa reservoir, Maharashtra, India", *Phys. Earth Plant. Int.*, **44**, 179-199.

Srivastava, H.N., Verma, R.K. and Verma, G.S., 1983, "Crustal studies along Indore-Khandwa section of Narmada basin by deep seismic sounding", *Mausam*, **34**, pp. 267-274.

Srivastava, H.N., Verma, R.K., Verma, G.S. and Chaudhury, H.M., 1984, "Crustal structure of the Koyna region using explosion data from deep seismic sounding", *Tectonophys.*, **110**, 61-72.

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

Wang C.Y. and Herrmann, R.B., 1980, "A numerical study of P, SV and SH-wave generation in a plane layered medium", *Bull. seism. Soc. Am.*, **70**, 1015-1036.