Source parameters of Jabalpur earthquake of 22 May 1997

S. N. Bhattacharya, A. K. Ghose, G. Suresh, P. R. Baidya and R. C. Saxena

Seismology Division, India Meteorological Department, Mausam Bhavan, Lodi Road, New Delhi 110 003, India

A moderate earthquake occurred in the morning of 22 May 1997 close to Jabalpur town in Madhya Pradesh. The earthquake records of seismological observatories maintained by India Meteorological Department were analysed to obtain source parameters. Of these, ten observatories in the Indian Peninsula have recently been upgraded with equipment of the standard of Global Seismograph Network. The upgraded observatories recorded ground velocity in broad frequency band and also the ground acceleration in digital mode. The high quality digital data have especially been processed to obtain both kinematic and dynamic source parameters. The basic source parameters are – Origin time: 04 h 21 m 30.8 s (IST), epicentre: 23°.08 N, 80°.06E, focal depth: 35 km, magnitude: 6.0. The focal depth of this earthquake could be clearly obtained using depth phase sPn in filtered waveforms. The first motions of P wave were used to obtain the focal mechanism. The first motion of P waves at the upgraded observatories were obtained through filtering and their amplitudes are also used to evaluate the focal mechanism. The focal mechanism solution was obtained as: Strike direction N80°E, dip 66° and slip angle 66°. This is a thrust type fault with left lateral strike slip component. The study of amplitude spectra of S wave from upgraded observatories gave seismic moment (M_0) of 5.4×10^{24} dyne.cm and radius of circular fault, 3.2 km. These results gave an average dislocation as 37 cm.

In the early morning of 22 May 1997, a moderate earthquake occurred in Jabalpur and adjoining Mandla districts of the Indian Peninsula. It took a toll of 43 human lives and caused damage to a large number of houses in Jabalpur city and neighbourhood. Past history of this area shows that an earthquake of magnitude 6.5 occurred on 27 May 1846. In the recent past, Jabalpur experienced a slight earthquake of magnitude 3.8 on 31 October 1993.

The Indian Peninsula is known as a stable cratonic subcontinent where Precambrian rocks constitute most of the region. As expected in stable continental interiors, the seismicity of the Indian Peninsula is low despite its northward movement and collision with Eurasian Plate[1]. However, two recent intraplate earthquakes, viz. Latur Earthquake of September 1993 and the present Jabalpur earthquake of May 1997 show that earthquake occurrence in stable continental interiors is not yet fully explained. The lithospheric plate in the continental interior has been found with large horizontal comprehensive stress consistent with regional stress field which drives the plates[2,3]. Kanamori and Anderson[4] found. that stress drop for intraplate and interplate earthquakes is respectively 100 bar and 30 bar and is independent of seismic moment. Johnston and his co-workers[2,5] found that intraplate earthquakes have strong association with rifts and extended crust which means passive margins in addition to rifts.

The main tectonic features of this area are shown in Figure 1. The upper Narmada and Son valley areas of Madhya Pradesh and adjoining Uttar Pradesh expose a linear belt trending along WSW-ENE and consisting of meta volcanic and meta sedimentary sequence between 79°E and 83°.5E with an average width of 20 km. This is referred as Mahakoshal greenstone belt which is a typical continental rift set up. The boundary faults of the Mahakoshal belt are named as Son Narmada north fault and Son Narmada south fault[6]. Figure 1 shows that the seismic activity around Jabalpur is mostly confined around these two faults.

Data and hypocentre

India Meteorological Department (IMD) is the nodal agency for instrumental recording of earthquakes by operating seismological observatories since 1898. IMD has now 45 national seismological observatories spread over India. In addition, there are 4 observatories in and around Delhi and 9 observatories in river valley projects in north India (Figure 2). Under World Bank-assisted project, 10 observatories of IMD have been upgraded during 1996–97 to the standards of Global Seismograph Network (GSN) (Figure 2). In these upgraded observatories, high quality broadband digital data of ground velocity and acceleration are being acquired. For sensing ground velocity, a triaxial STS-2 seismometer is used and data is recorded by a Q680LVG acquisition system in digital mode with 24 bit resolution. The time

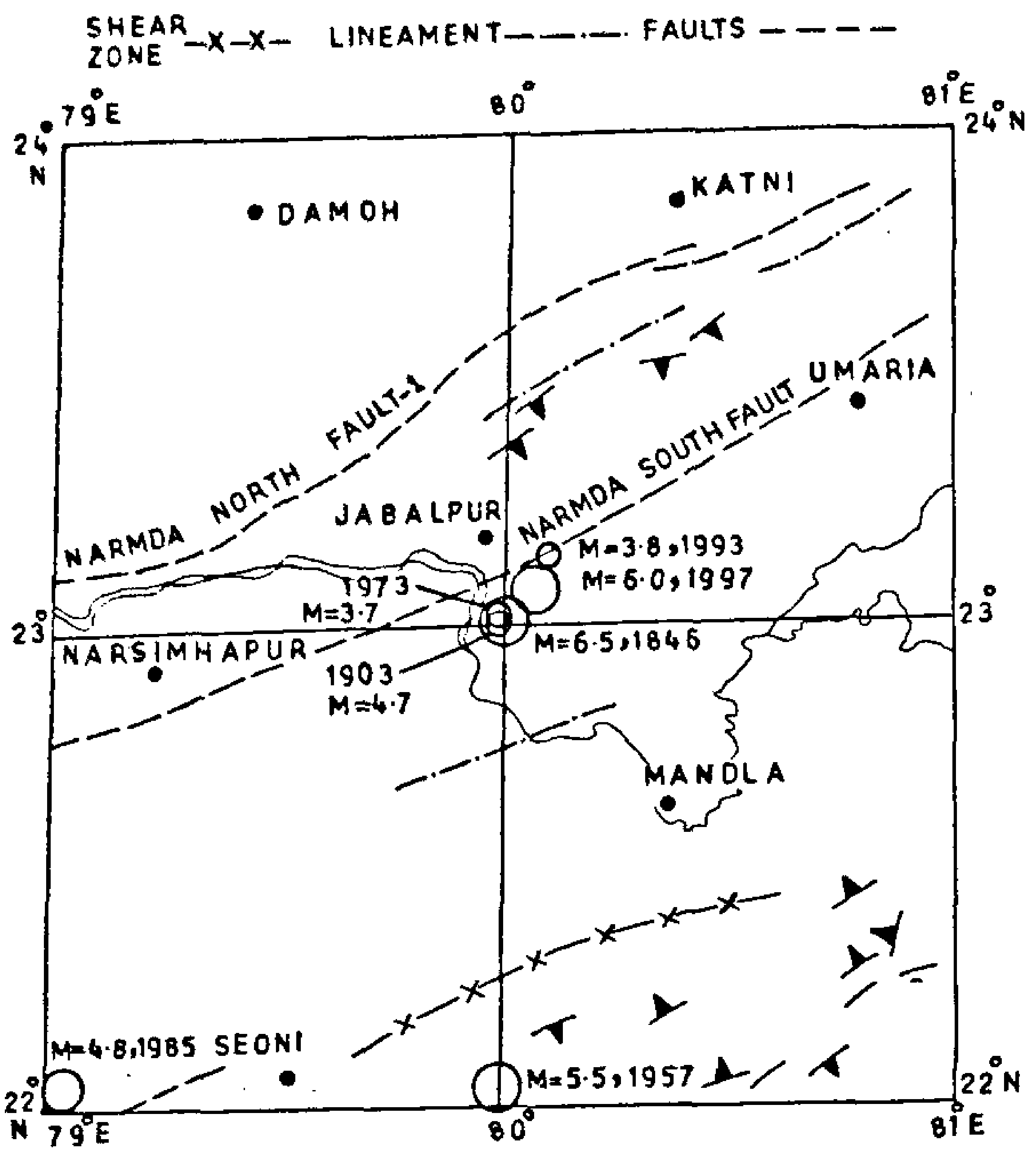


Figure 1. Tectonic features of Jabalpur and its neighbourhood. The locations of the past earthquakes and the earthquake of 22 May 1997 have been shown along with their magnitudes and the years of occurrences.

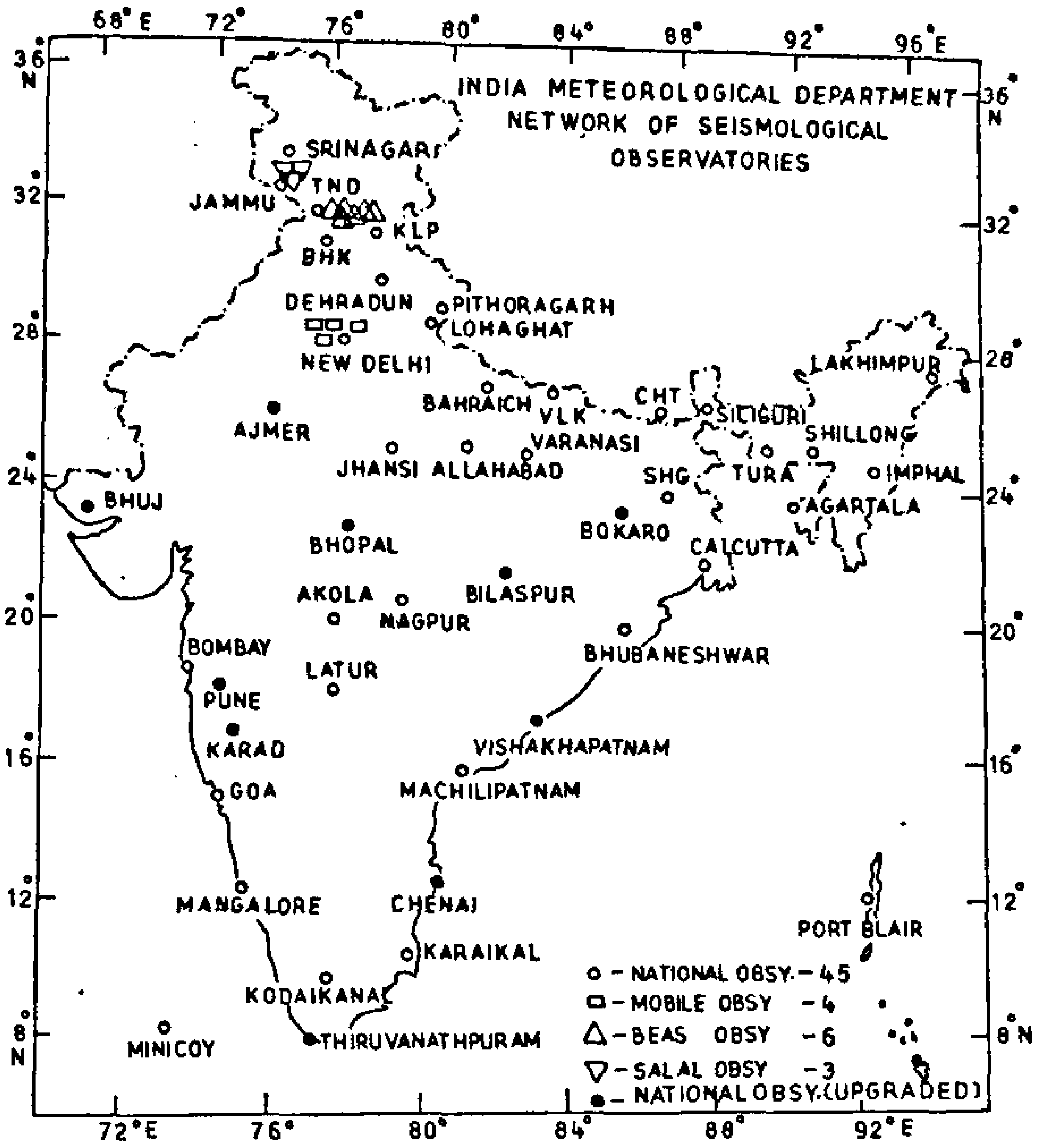


Figure 2. Seismological observatories of India Meteorological Department. The National Seismological Observatories have been shown by circles. Upgraded broadband recording observatories have been shown by solid circles.

is synchronized with Global Positioning System. Q680LVG records 80 samples per second in trigger stream and 20 samples per second in continuous stream. The velocity is recorded in counts and the velocity response curve is nearly flat between 0.008 Hz and 32 Hz for 80 samples per second and between 0.008 Hz and 8 Hz for 20 samples per second. In these upgraded observatories, ground acceleration is also measured by K2 accelerograph.

The digital data which are recorded in vertical, north–south and east–west directions have been converted to ground velocity using the response curve. These recordings of horizontal components are vectorially rotated to obtain ground velocity in vertical, radial and transverse direction at the station from the source. These have been done to obtain some phases clearly particularly to differentiate SV- and SH-waves. Theoretically in an isotropic medium, P wave is not recorded in transverse component which records the SH waves; while radial component records both P and SV waves. The vertical, radial and transverse components for the observatories at Bilaspur and Bhopal are shown in Figure 3. Arrival times of P, S phases and other phases were obtained from these records. Zooming and filtering have been done for this purpose.

In addition to upgraded stations, data of other IMD observatories are also collected. Data from NGRI observatory at Hyderabad was also included. The arrival times of P and S phase of these observatories have been used to determine the hypocentre using the program HYPOCENTRE version 3.2 (ref. 7). This is a computer program for locating earthquakes locally, regionally and globally. It uses the travel time of IASPEI 91. However, if specified, it uses local structure to calculate travel time for the stations which are within a given hypocentral distance.

Nagpur was the nearest observatory to the hypocentre to record P arrival time and the next observatory was at Bilaspur. The epicentral distances of Nagpur and Bilaspur are 231 km and 237 km respectively. Thus the distances are far away from hypocentre to determine reliable focal depth of the earthquake. Attempts were therefore made to determine the focal depth after identification of depth phases.

The surface reflected depth like pP, sP are commonly interpreted at teleseismic distances and their use results in an improved depth determination. The identification of depth phases at local or regional distances is a much more difficult problem than at teleseismic distances, and is practically impossible if only narrow-band data are available. The upgradation of observatories in the Indian

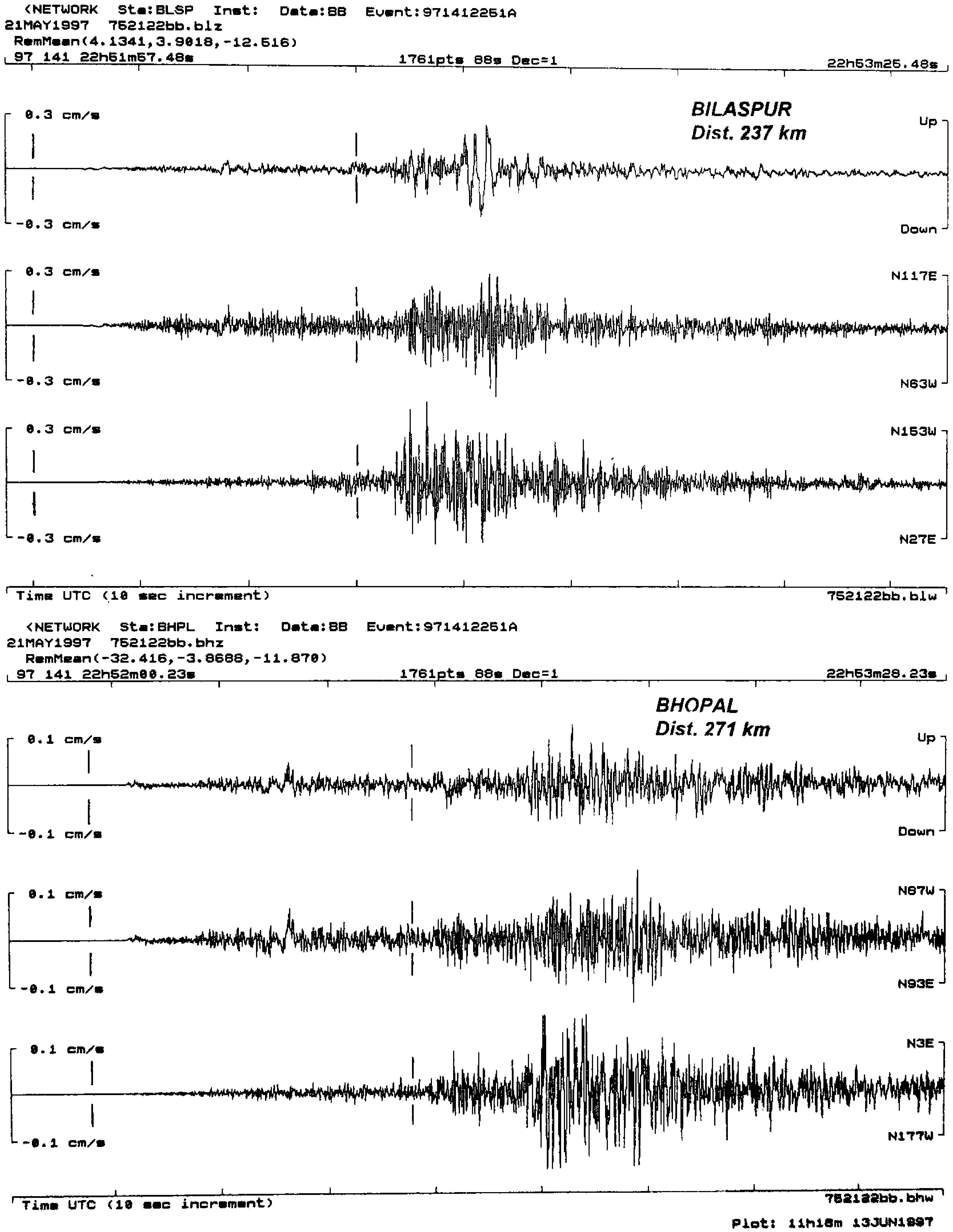


Figure 3. The broad band ground velocity waveform of vertical (top trace), radial (middle trace) and transverse (bottom trace) components of the observatories at Bilaspur and Bhopal. The velocity scale is given in the left and the direction of motion is given in the right. For Bilaspur and Bhopal, the initial 30 s record of the portions marked by two vertical dashed lines have been zoomed and filtered in Figure 4. Here and in the next computer-generated figures, the time indicated corresponds to UTC.

Table 1. Crustal and subcrustal model

	Body wave study[8]			Surface wave study[9]		
Layer no.	Thickness H, km	α km/s	β km/s	Thickness H, km	α km/s	β km/s
1	20.0	5.78	3.42	20.4	5.78	3.53
2	18.7	6.58	3.92	18.3	6.58	3.916
3	–	8.19	4.62	–	8.19	4.603

Peninsula with broad band digital recording opened up a new possibility to identify these surface-reflected depth phases at local or regional distances for determination of focal depth.

The crustal and subcrustal structure of the Indian Peninsula has been studied through body waves[8] and surface waves[9]. These studies show a two-layered crust (Table 1). The ray path of sPn and Pn is shown in Figure 4 when the hypocentre is in the first or in the second layer of the crust. For sPn, the S-wave from the source moving upward is reflected back downward as P by the free surface with sufficient energy. The phase sPn has also been seen in the synthetic seismograms[10]. In the record, Pn comes first and sPn comes later. To calculate their travel time let us assume that α_1, β_1 and H_1 are respectively the P wave, S wave velocities and thickness of the first layer; that α_2, β_2 and H_2 are those of second layer, α_3 and β_3 are respectively the P wave and S wave velocities of the subcrustal region (Figure 3). Using ray theory, the time difference, dt, between the phases sPn and Pn are obtained as

$$\begin{aligned} dt &= h[\surd\{1/\beta_1^2 - 1/\alpha_3^2\} + \surd\{1/\alpha_1^2 - 1/\alpha_3^2\}] \\ &= h(\eta_{\beta_1} + \eta_{\alpha_1}), \end{aligned} \tag{1}$$

where the hypocentre is lying in the first layer and h is the depth of the hypocentre below the free surface, $\eta_{\alpha i}$ and $\eta_{\beta i}$ are vertical slowness of P and S waves in the ith layer with ray parameter = $1/\alpha_3$. If the hypocentre is in the second layer,

$$dt = H_1[\eta_{\beta 1} + \eta_{\alpha 1}] + h[\eta_{\beta 2} + \eta_{\alpha 2}], \tag{2}$$

where h is the depth below the interface between first layer and second layer.

It may be seen from equations (1) and (2) that the time difference dt, between the two phases does not depend on the epicentral distance. In Figure 2, the records of Bilaspur and Bhopal show sPn. Ajmer also recorded this phase. To get a clear picture, the initial 30 seconds of these waveforms are filtered with lowpass filter having high cut at 2 Hz. The filtered waveform shows the sPn clearly (Figure 5). The time differences between the two phases P and sPn are found to be 12.6 s, 12.6 s and 12.3 s respectively in the records of Bilaspur, Bhopal and Ajmer. As expected from equations (1) and (2), the difference is nearly the same at these observatories irrespective of their epicentral distances. The average difference is 12.5 s. The hypocentre is found to be in the second layer. Using equation (2), the focal depth is obtained as 35.1 km using body wave model and 35.6 km using surface wave model (Table 1). The focal depth thus determined is 35 km.

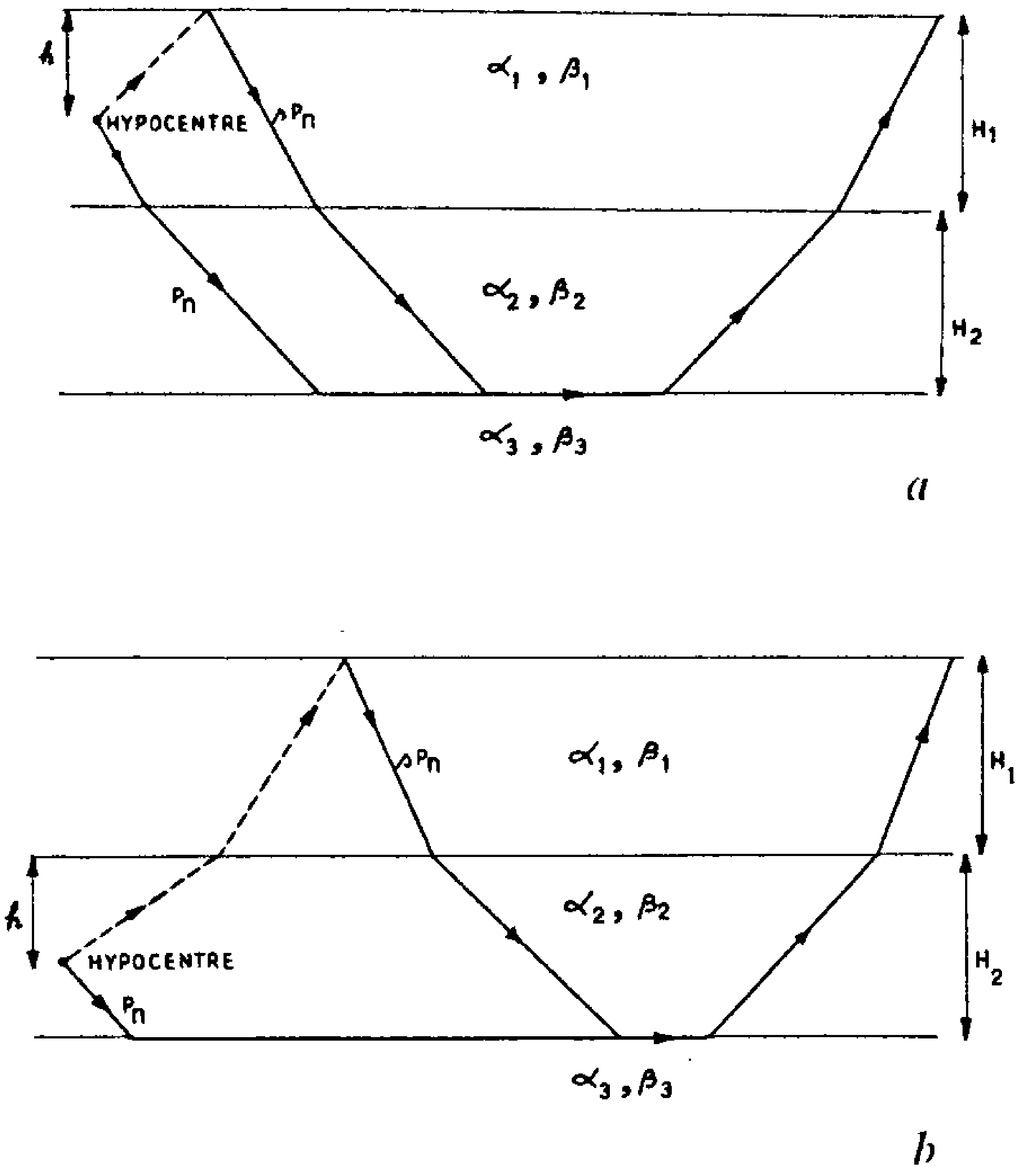


Figure 4. Ray paths of Pn and sPn. *a*, when hypocentre is in the first layer; *b*, when hypocentre is in the second layer.

After focal depth is fixed, the hypocentre is obtained using the program HYPOCENTRE 3.2. The hypocentral parameters are determined as

Date	22 May 1997
Origin time	04 h 21 m 30.8 s (IST)
Epicentre	23°.08N, 80°.06E
Focal length	35 km
Magnitude (M_L)	6.0.

Fault plane mechanism

To evaluate fault plane mechanism, the directions of first P wave motion from Indian observatories are collected. For broad band digital data, a clear direction of P wave motion is obtained by filtering. In some observatories, such as Pune, the first motions of P wave are not so clear in broad band waveform but clarity is obtained only through filtering. These first motions are plotted in

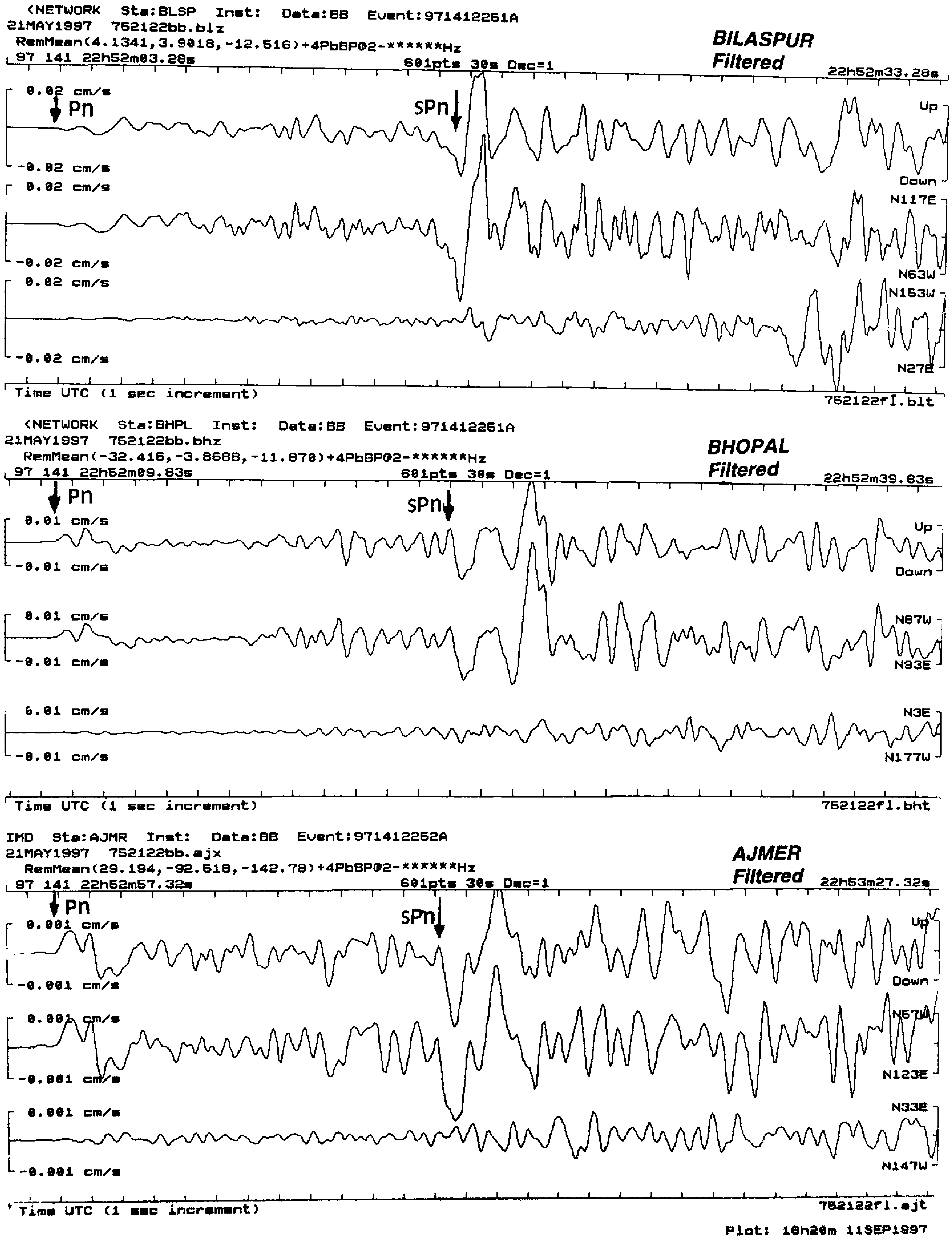


Figure 5. The initial 30 s portion of broad band ground velocity waveforms of Bilaspur, Bhopal and Ajmer have been filtered with low frequency pass filter with cut at 2 Hz. The sPn may be seen in the filtered waveforms.

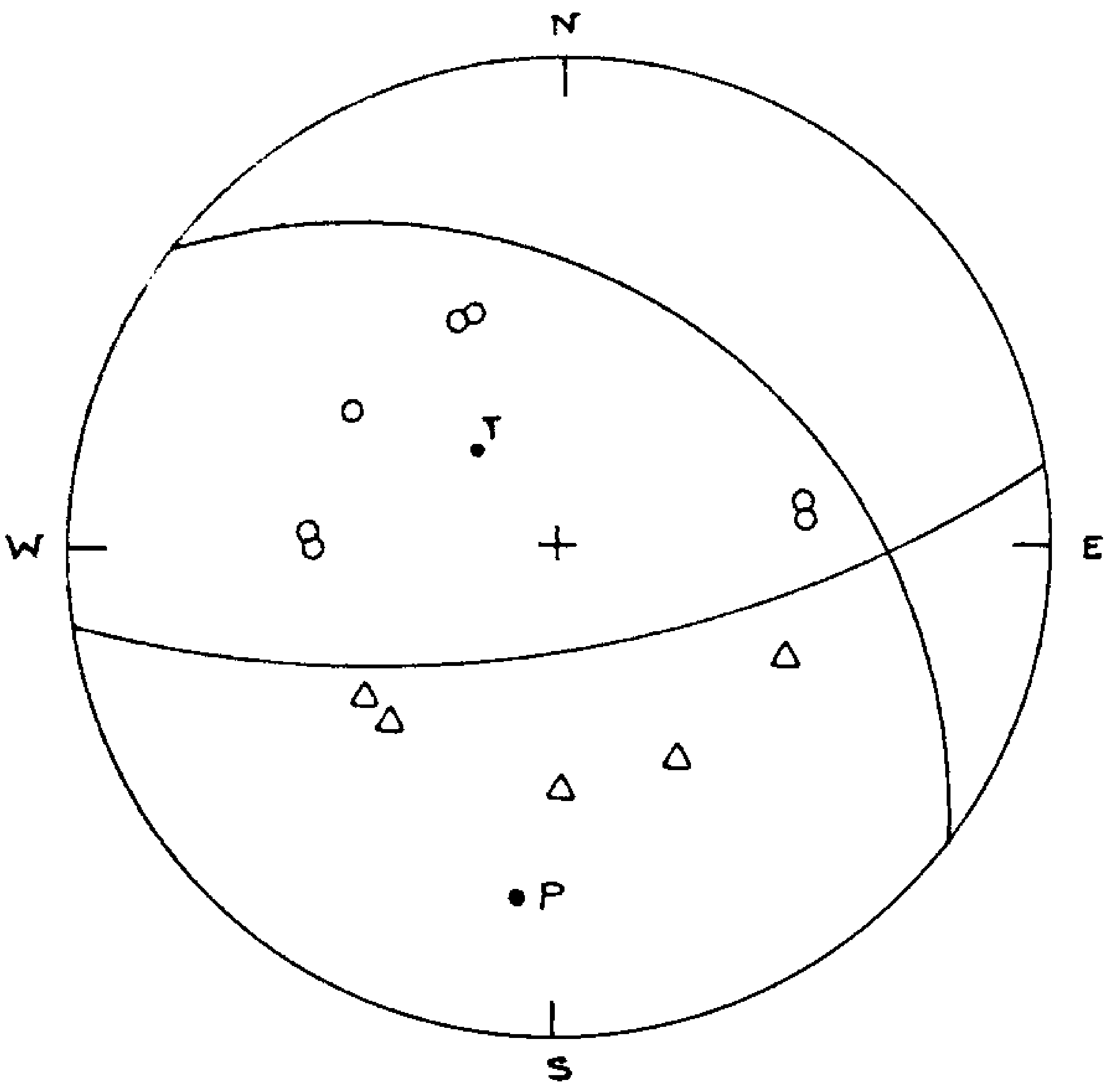


Figure 6. Fault plane solution is shown in an equal area projection of the lower half of the focal sphere. Circles show compression and triangles show dilatation of the first motion of P waves.

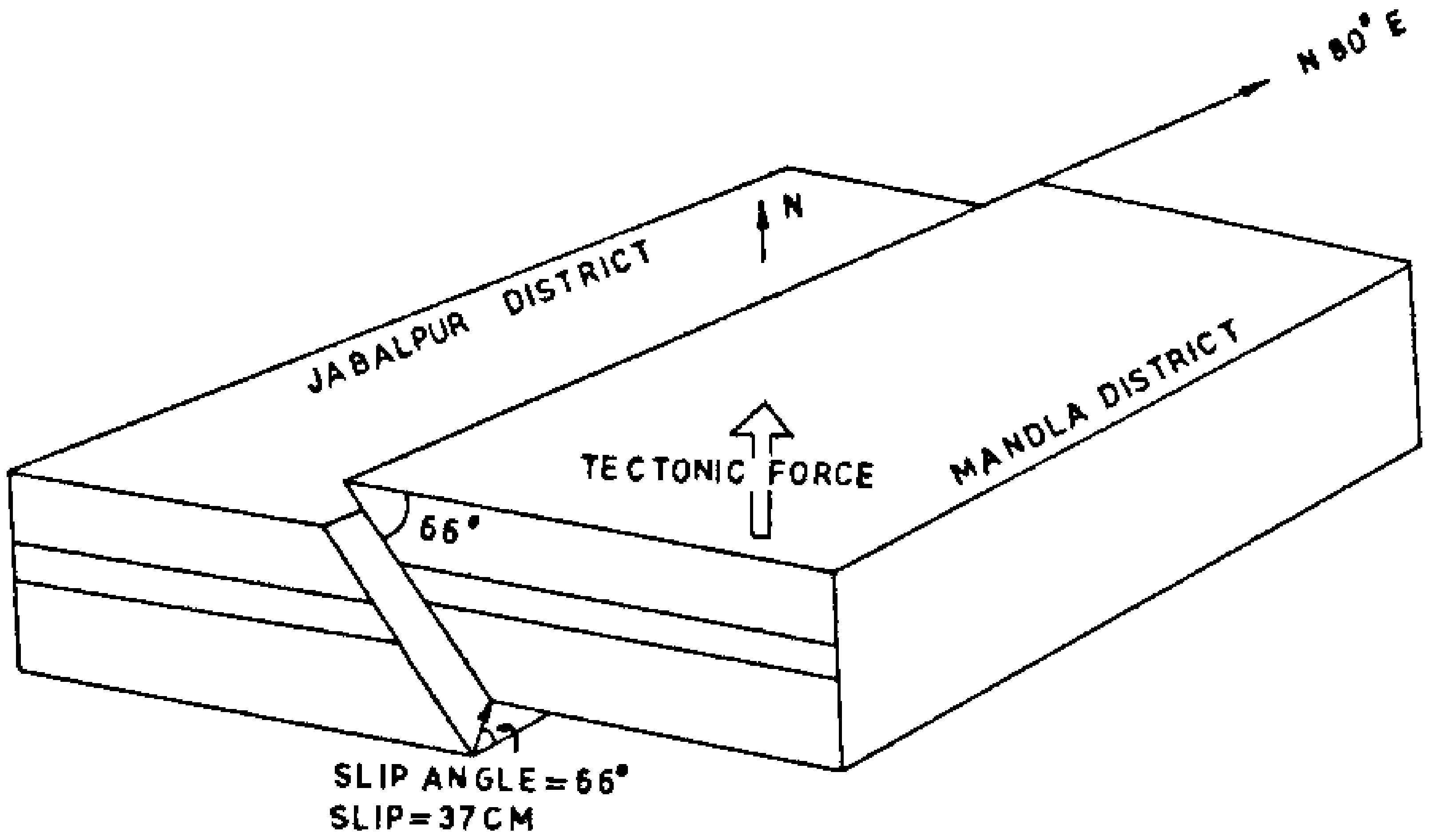


Figure 7. Three-dimensional view of the fault plane solution. The figure shows that southern block (Mandla district side) has moved upward at an angle 66° with the horizontal direction.

an equal area projection of the lower half of focal sphere (Figure 6). To evaluate the mechanism, the amplitudes of P wave at the upgraded observatories have also been used. The solutions thus obtained are as follows.

Double couple solution:

NP1 strike 80°, dip 66°, slip 66°
NP2 strike 307°, dip 33°, slip 133°

Principal axis

T plg. 66°, Az. 317°
N plg. 29°, Az. 90°
P plg. 26°, Az 187°

This is a thrust type fault with some left lateral strike slip component. The major axis of isoseismals based on field observation (personal communication with GSI) also nearly agrees with the above strike direction of nodal plane 1 (NP1). The earthquake appears to be associated with the Son Narmada South fault, whose dip (personal communication with GSI) closely agrees with that of the fault plane solution. A three-dimensional view of fault plane solution has been shown in Figure 7.

Moment, fault area, stress drop and average dislocation

Estimates of seismic moment M_0, source radius r and stress drop are obtained from amplitude spectra of S wave using Brune's[11,12] model on a circular fault. The seismic moment is given by

$$M_0 = \frac{4\pi\rho\beta^3}{R_{\theta\phi}} * R * A_0, \qquad (3)$$

where A_0 is the low frequency spectral amplitude of S wave, R is hypocentral distance, $R_{\theta\phi}$ the radiation pattern of S wave, β the S wave velocity at the source and ρ, density at the source.

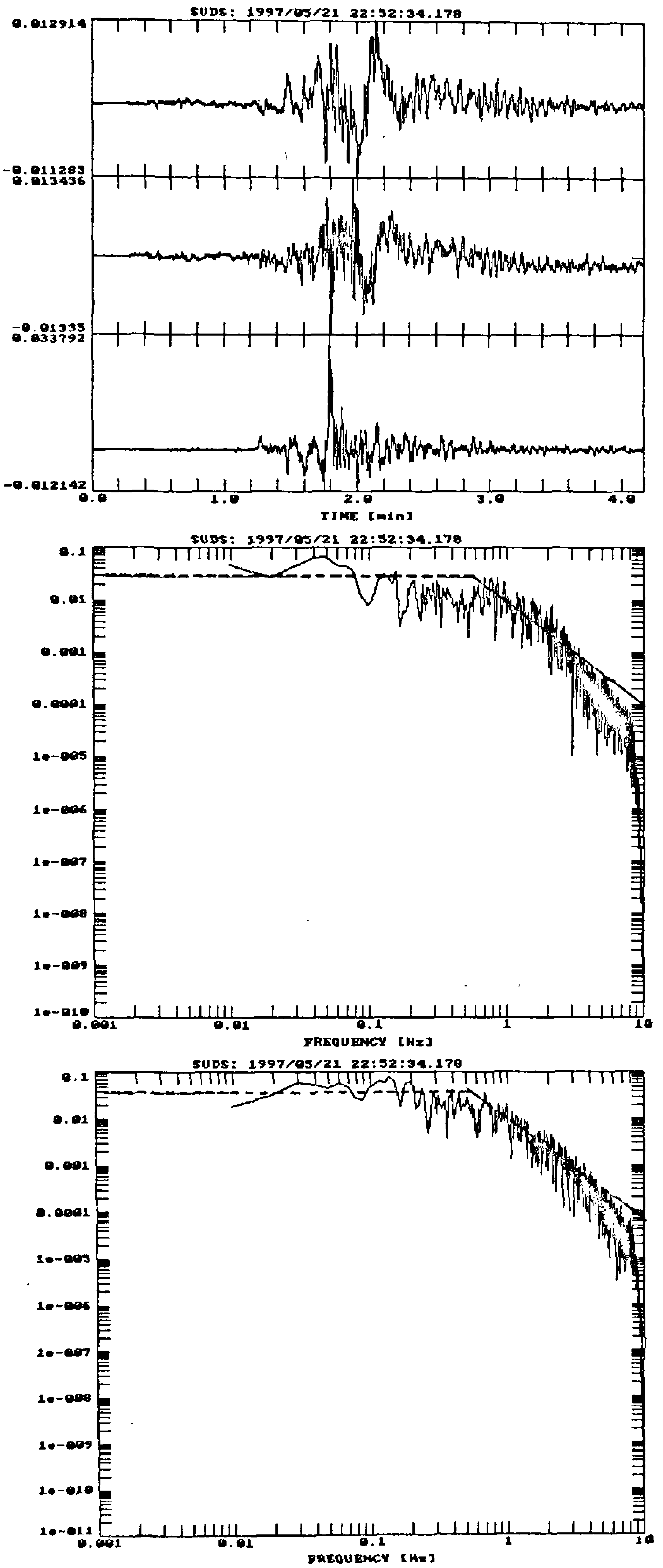
Following Fletcher[13] we have considered $R_{\theta\phi} = 0.85$ which takes care of free surface amplification and average contribution of components. Corner frequency f_c is the frequency at which the low frequency and high frequency asymptotes of amplitude spectra intersect. The corner frequency f_c gives the radius of circular fault r as

$$r = \frac{2.34\beta}{2\pi f_c}.$$

Following the studies conducted in Indian Peninsula (Table 1), $\beta = 3.92$ km/s and $\rho = 3.0$ g/cm^3 have been considered.

However, amplitude spectra are attenuated with distance due to (1) geometrical spreading and (2) internal friction. Geometrical spreading causes decrease of amplitude spectra as $1/R$ with hypocentral distance R. For estimating attenuation due to internal friction, it is seen that Bhopal and Bhuj are nearly in the same direction from the epicentre. When ratio of amplitude spectra of Bhopal and Bhuj is plotted against frequency both for radial and transverse component, it is seen that the attenuation is mainly due to geometrical spreading and the attenuation due to internal friction can be neglected. Recording of S wave in the Indian Peninsula with little attenuation has also been seen earlier[14]. A factor R has already been considered in equation (3) to take care of geometrical spreading.

Figure 8 shows the displacement waveforms of Bokaro obtained by integration of corresponding velocity record. The figure also shows the displacement am-



BOKARO

VERTICAL

RADIAL

TRANSVERSE

Radial
Component

A_0 = 0.03 cm.s

f_c = 0.57 Hz

$M = 4.77 \times$
10^{24}dynes .cm

r = 2.56 km

Transverse component

A_0 = 0.04 cm.s

f_c = 0.55 Hz

$m_0 = 6.36 \times$
10^{24}dyne.cm

r = 2.66 km

Figure 8. Top three traces are vertical, radial and transverse displacement waveforms of Bokaro obtained by integration of corresponding velocity waveforms. The bottom two figures show the displacement amplitude spectra of S wave in the above radial and transverse components. Asymptotes of low frequency and high frequency amplitude spectra have been estimated by two dashed straight lines. These two asymptotes intersect at corner frequency f_c.

Table 2. Results of determination of seismic moment M_0 and radius of circular fault

Station	Epicentral distance (km)	Component	A_0 cm.s	M_0, 10^{24} dyne.cm	f_c hz	r km
Bilaspur	237	Radial	0.060	3.77	0.63	2.32
		Transverse	0.070	4.39	0.85	1.72
Bhopal	271	Radial	0.080	5.85	0.40	3.65
		Transverse	0.090	6.58	0.45	3.25
Bokaro	600	Radial	0.030	4.77	0.57	2.56
		Transverse	0.040	6.36	0.55	2.66
Ajmer	665	Radial	0.025	4.45	0.36	4.06
		Transverse	0.030	5.34	0.60	2.43
Visakhapatnam	684	Radial	0.040	7.30	0.47	3.11
		Transverse	0.030	5.47	0.50	2.92
Pune	820	Radial	0.019	4.18	0.40	3.65
		Transverse	0.028	6.15	0.46	3.18
Karad	886	Radial	0.020	4.75	0.40	3.65
		Transverse	0.020	4.75	0.34	4.30
Bhuj	1066	Radial	0.020	5.70	0.40	3.65
		Transverse	0.025	7.13	0.38	3.84

Average $M_0 = 5.43 \times 10^{24}$ dyne.cm.
Average $r = 3.18$ km

plitude spectra of S wave both for radial component and transverse component. The results of M_0 and r from Bokaro have been indicated in the figure. Similar results have been obtained from seven other observatories close to the hypocentre and are given in Table 2. The average value of seismic moment and radius of fault are respectively

$$M_0 = 5.4 \times 10^{24} \text{ dyne.cm},$$

$$r = 3.2 \text{ km}.$$

Thus, fault area $= \pi r^2 = 31.85$ km^2.

We know stress drop $\Delta\sigma$ is given by

$$\Delta\sigma = \frac{7}{16} \times \frac{M_0}{r^3},$$

and with above values of M_0 and r we get

$$\Delta\sigma = 68 \text{ bar}.$$

The stress drop for a interplate earthquake lies around 30 bar while for a intraplate earthquake it lies around 100 bar[5]. The stress drop obtained here lies close to average stress drop of the two types of earthquakes.

The moment magnitude is given by

$$M_w = (\log M_0 - 16)/1.5 = 5.8.$$

Further, M_0 = radius of rigidity × fault area × average dislocation.

Now modulus of rigidity $= \rho\beta^2$ and values of ρ and β have been described above. Thus the above formula gives

average dislocation = 37 cm.

Discussions

The epicentral location (Figure 1) and the fault plane solution (Figure 7) indicate that the Jabalpur earthquake of 22 May 1997 is associated with Narmada Son South fault. The focal depth was found to be 35 km which shows that the hypocenter is in the lower crust close to crust mantle boundary. As per the *Bulletin of the International Seismological Centre*, other moderate earthquakes in the neighbouring peninsular India such as Ongle earthquake (15°.62N, 80°.16E) had a focal depth 15 km and Bhadrachalam earthquake (17°.81N, 80°.67E) had a focal depth 25 km which was found as 14 km by Biswas and Majumdar[15] on recomputation; Latur earthquake (18°.07N, 76°.62E) had a focal depth of 12 km (ref. 16). Further, the earthquakes in the western coast of the Peninsula have normally focal depth less than 10 km. Thus the present earthquake is relatively at deeper depth than other earthquakes of the Peninsular India occurring during recent years. This shows that the Narmada Son South fault, with which this earthquake is associated, goes deep into the crust close to crust–mantle boundary. The deep nature of both North and South Narmada Son faults is indicated by the presence of ultrabasic and alkaline intrusives along these faults[1]. The faults have been inferred as fundamental faults in the crust since they created volcanism and deposits of Mahakoshal group.

The dip of the fault plane, which is on Son Narmada South fault, has been seen as 66° towards south. It has been seen that the Son Narmada North fault is of thrust type and is heading towards South due to which Mahakoshal Group of rocks are seen overriding the Vindhyan rocks. In Jabalpur–Katni section, the inverted Vindhyan rocks near the fault Zone have 70° to 80° dip towards south. The fault plane solution also shows that Son Narmada South fault has similar feature as that of the North fault.

The principal axis of thrust faulting of Jabalpur earthquake of 22 May 1997 is found nearly along N–S direction. The Latur earthquake of 29 September 1997 was also thrust type with pressure axis along NNE–SSW[16]. Biswas and Majumder[15] found predominance of thrust faulting with more or less N–S pressure axis for earthquakes in the intraplate region of Bay of Bengal and adjoining Indian Peninsula. Thus N–S compression is more prevalent in this region resulting from collisional resistance[17] to North-moving Indian plate by the Eurasian plate at the Himalaya where subduction of Indian Lithosphere in the mantle has ceased now[15]. This has caused the stress to transmit thousands of kilometres towards south. This has further caused the Indian Peninsula and adjoining Bay of Bengal to undergo N–S compressive deformation and to become seismic.

Conclusions

Data from observatories spread in India have been used to locate the hypocentre and determine the focal mechanism. The broadband seismographs installed at 10 upgraded observatories have improved the location of the hypocentre, particularly its focal depth using depth phase sPn. The directions of P wave of all available observatories as well as P wave amplitude of upgraded observatories have shown the focal mechanism of the Jabalpur earthquake as thrust type with some strike slip component. The amplitude spectra of S waves recorded at upgraded observatories have given stress drop as 68 bars and average slip dislocation as 37 cm. Thus with the use of digital broadband seismographs in upgraded observatories, evaluations of a larger number of source parameters have been possible.

1. Chandra, U., *Bull. Seismol. Soc. Am.*, 1977, **67**, 1387–1413.
2. Johnston, A. C. and Kantar, L. R., *Sci. Am.*, 1990, **262**, 68–75.
3. Talwani, P. and Rajendran, K., *Tectonophysics*, 1991, **186**, 19–41.
4. Kanamori, H. and Anderson, D. L., *Bull. Seismol. Soc. Am.*, 1975, **65**, 1073–1095.
5. Johnston, A. C. and Metzer, A. G., Tennessee Earthquake Inf. Cent., 1986, Special report 86-1, I/II.
6. Jain, S. C., Nair, K. K. K. and Yedekar, D. B, *Project Crumansonata*, GSI special publication 10, 1995, pp. 1–154.
7. Lienert, B. R. and Havskov, J., *Seismol. Res. Lett.*, 1995, **66**, No. 5, 26–36.
8. Dube, R. K., Bhayana, J. C. and Chaudhury, H. M., *Pure Appl. Geophys.*, 1979, **109**, 1718–1727.
9. Bhattacharya, S. N., *Bull. Seismol. Soc. Am.*, 1981, **71**, 1489–1501.
10. Zonno, G. and Kind, R., *Bull. Seismol. Soc. Am.*, 1984, **74**, 1645–1659.
11. Brune, J. N., *J. Geophys. Res.*, 1970, **75**, 4997–5009.
12. Brune, J. N., *J. Geophys. Res.*, 1971, **76**, 5002.
13. Fletcher, J. B., *Bull. Seismol. Soc. Am.*, 1980, **70**, 735–755.
14. Tandon, A. N. and Chaudhury, H. M., India Meteorological Department, Scientific Report, no. 59, 1968.
15. Biswas, S. and Majumdar, R. K., *Tectonophysics*, 1997, **269**, 323–336.
16. India Meteorological Dept., *Latur earthquake of 30 September 1993 and its Aftershocks*, A consolidated document, 1994, pp 1–37.
17. Richardson, R. M., *J. Geophys. Res.*, 1992, **97**, 11739–11748.

ACKNOWLEDGEMENTS. We are grateful to Dr V. S. Ramamurthy, Secretary, DST and Dr N. Sen Roy, Director General of Meteorology for their encouragement. We thank Dr S. K. Srivastava, ADGM for helpful discussions. We are also grateful to Shri H. N. Srivastava, ADGM (retd.) for going through the manuscript and for his suggested improvements.

Received 25 June 1997; revised accepted 14 October 1997.