Estimation of source parameters of the 8 October 2005 Kashmir earthquake of M_w 7.6

Prantik Mandal*, R. K. Chadha, N. Kumar, I. P. Raju and C. Satyamurty

National Geophysical Research Institute, Hyderabad 500 007, India

Aiming at mainly recording aftershock activity of the 2001 Bhuj earthquake of M_w 7.7, a semi-permanent network of five broadband seismographs has been in operation since last six years in the Kachchh area, Gujarat, India. The 8 October 2005 Kashmir earthquake of M_w 7.6 and its aftershocks have been well recorded by this network as well as by the Hyderabad Geoscope station. These data enabled us to estimate the group velocity dispersion characteristics and one-dimensional regional shear velocity structure of peninsular India. First, we measured Rayleigh- and Love-wave group velocity dispersion curves in the period range of 8 s to 35 s and inverted these curves to estimate the crustal and upper mantle structure below peninsular India. Our best model suggested a two-layer crust; 13.8 km thick upper crust with a shear velocity (V_s) of 3.2 km/s and a 24.9 km thick lower crust with V_s 3.7 km/s. V_s for the upper mantle was found to be 4.65 km/s. Based on this structure, we then performed a moment tensor inversion of the bandpass (0.05–0.02 Hz) filtered seismograms of the 2005 Kashmir earthquake. The best fit was obtained for a source located at a depth of 30 km, with a seismic moment M_0, of 1.6×10^{27} dyne-cm, and a focal mechanism with strike 19.5°, dip 42° and rake 167°. The long-period magnitude ($M_A \sim M_w$) of this earthquake was estimated to be 7.31. Analysis of well-developed sP_n and sS_n regional crustal phases from the bandpassed (0.02–0.25 Hz) seismograms of this earthquake at four stations in Kachchh suggested a focal depth of 30.8 km.

Keywords: Aftershock activity, broadband seismographs, Kashmir earthquake, source parameters.

THE Himalayan ranges are considered to be the world's youngest fold mountain ranges, which are geologically active due to active continent–continent collision of the Indian and Eurasian plates, and are most vulnerable to earthquakes[1–4]. India is divided into four zones on the basis of seismicity[5]. Most of the Himalayan States, particularly the northeastern states and the western part of the country are in seismic zone V, the highest degree of vulnerability for earthquakes. During the 53-year period, from 1897 to 1950, four great earthquakes of magnitude 8+ occurred (Shillong 1897, Assam 1950, Kangra 1905 and Bihar 1934), but none such in the last 50 years[1,6]. Along the Himalayan arc, two major thrusts about 2400 km long exist from Kashmir to Assam. These are the Main Central Thrust (MCT) that demarcates High Himalayas in the north and the Main Boundary Thrust (MBT) that delimits the Himalayas to the south. These two major thrusts appear to be relentlessly overriding the Ganga plains, creating every 200 years or so, a series of great earthquakes that sequentially cover the entire 2400 km long arc by 200–300 km long ruptures[1,7]. Rastogi[6] and Bilham[7] suggest that about ten or so great earthquakes can occur every 200 years in the Himalayan area. GPS measurements in Kumaon, Nepal and Ladakh indicate about 2-cm/yr convergence[7]. This means that a 2 m strain can accumulate every 100 years or a 4 m strain every 200 years capable of causing great earthquakes.

The Himalayas was rocked on 8 October 2005 by an M_w 7.6 inter-plate earthquake that claimed a death toll of around 80,000. However, the epicentre of this earthquake was found to be in the frontal belt of the western (near Muzaffarabad, Kashmir-Pakistan) Himalayan Syntaxis (03:50:38 UTC; location 34.493°N, 73.629°E; depth 26 km). This earthquake took place along the earlier mapped north-dipping (~39°) Balakote–Bagh offshoots of the MBT and ruptured[7–10] a length of 65 km. This region lies in the area where the Eurasian and Indian tectonic plates are colliding. Due to this collision[11], the Himalayas began to rise 50 million years ago, and continues to rise by about 5 mm/yr. It is inferred that this could be a causal factor for the occurrence of the 8 October 2005 Kashmir earthquake.

In this article, we determine the average crustal and upper mantle structure of the Indian peninsula from the inversion of dispersion curves of Rayleigh and Love waves. These dispersion curves were estimated from the analysis of data from four broadband stations in Kachchh, along with very broadband seismograms recorded at the Hyderabad Geoscope station. After obtaining the 1D regional velocity structure, we performed moment tensor inversion of the bandpassed (0.05–0.02 Hz) seismograms of the Kashmir earthquake recorded at the four stations in Kachchh and the Hyderabad Geoscope station. We estimated the long-period magnitude ($\sim M_w$) of this earthquake using bandpassed (0.03–0.08 Hz) broadband seismograms. We also calculated the focal depth of this earthquake using sP_n and sS_n regional crustal phases.

*For correspondence. (e-mail: prantikmandal@yahoo.com)

Data and seismological network

The National Geophysical Research Institute (NGRI), Hyderabad installed a close digital network consisting of ten strong-motion accelerographs and five broadband seismographs in the Kachchh region in August 2002, under a DST-sponsored project (Figure 1). Four broadband seismograph stations (i.e. Gadhada (GDD), Kavada (KVD), Vajepar (VJP), and Tapar (TPR)) of the local seismological network at NGRI and two more broadband observatories of NGRI in the Indian shield (e.g. Hyderabad (HYD) and Cuddapah (CUD)) recorded the 8 October 2005 earthquake and its aftershocks (Figure 1). Travel paths of the surface waves cover half of peninsular India. One M 6.4, 49 M 5–5.9 and 232 M 4–4.9 and several thousand $M < 4.0$ aftershocks were recorded till 15 November 2005. The P_n and S_n marked broadband seismograms of the main shock and its largest aftershock are shown in Figures 2 and 3 respectively.

Crustal and upper mantle structure of peninsular India

Prior investigations of the south Indian shield suggested a large variation in the estimated thickness of the upper granitic crust and lower basaltic crust[12,13]. Travel time analysis of crustal phases of aftershocks of the 1967 Koyna event revealed a 20 km thick upper granitic crust

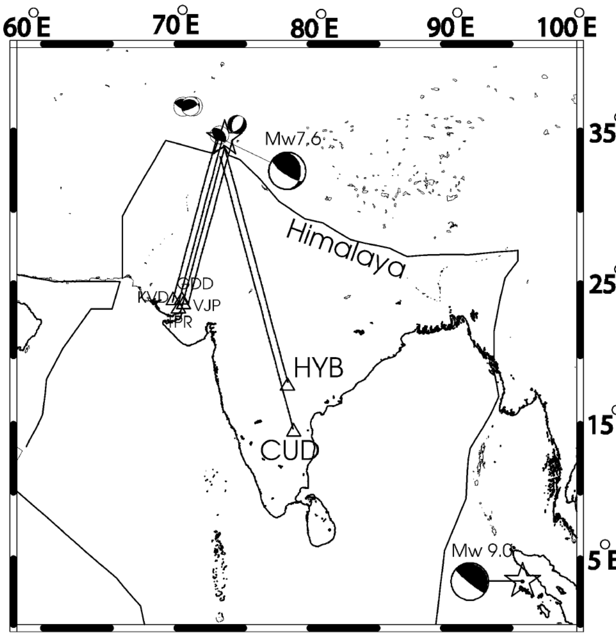


Figure 1. Plot showing locations of the four broadband stations in Kachchh, very broadbrand station at Hyderabad and a broadband station at Cuddapah. Lines show the paths of surface waves, which were used to delineate the regional average 1D velocity structure beneath peninsular India.

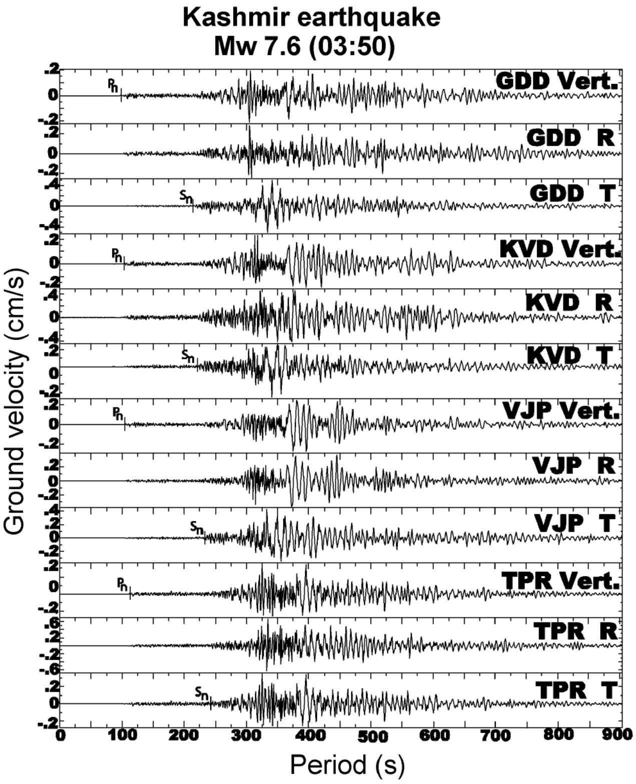


Figure 2. Broadband seismograms of the 2005 Kashmir earthquake of M_w 7.6 recorded at four stations in Kachchh.

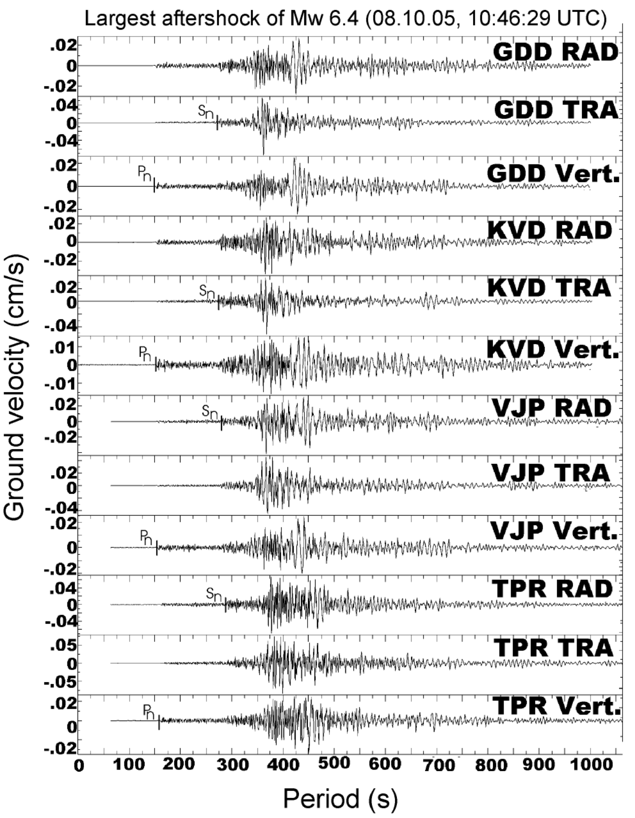


Figure 3. Broadband seismograms of the largest aftershock (M_w 6.4) of the 2005 Kashmir earthquake recorded at four stations in Kachchh.

and a 18.7 km thick lower basaltic crust overlying an upper mantle characterized by P_n and S_n velocities of 8.19 and 4.62 km/s respectively, in the region[12]. Refraction study along the Kavili–Udipi profile showed an upper crust with V_p of 6.4 km/s, a Moho depth ranging from 34 to 41 km, and an upper mantle[13] characterized by higher P_n velocities of 8.4–8.6 km/s. The study[14] of group velocity using mine tremors delineated a Moho depth beneath Gauribidanur to be 34–36 km. Receiver function (RF) analysis[15] of teleseismic P-waves revealed a two-layered crust beneath Hyderabad; a 10 km thick upper crust (shear velocity V_s: 3.54 km/s) and a 26 km thick lower crust with V_s varying at 0.02 s^{-1} gradient. However, a more recent RF study using digital dataset showed a crust with a shallow Moho at 33 km beneath Hyderabad[16].

Few surface wave dispersion studies have been carried out to delineate the crustal structure beneath peninsular India and the Himalayas in general, and the South Indian shield, in particular. In 1964, Tandon and Choudhury[17] estimated crustal thickness of the order of 40–45 km beneath the Indo-Gangetic Plains using the surface wave group velocity dispersion study. The thickness of the crust beneath peninsular India was found to be 38–39 km using surface wave dispersion studies[18–20]. Crustal thickness beneath the Himalayas was estimated to be 65–70 km using a surface wave dispersion study[21]. Recently, Rai *et al.*[22] used the surface wave phase velocity dispersion and delineated a two-layered crust with a crustal thickness of 35 km beneath the South Indian shield.

Data analysis and results

Surface wave group velocity dispersion

Conventional frequency–time analysis of regional seismograms recorded at two broadband stations (Hyderabad and Cuddapah) of the seismological network of NGRI in the South Indian shield was performed to estimate group velocity dispersion of Rayleigh and Love waves. Locations of the stations are shown in Figure 1. A stacking technique was applied in frequency–time domain to measure group velocities of the fundamental mode Rayleigh as well as Love waves[23–25]. The rapid fall of the amplitude spectra at long periods leads to a systematic error in the frequency–time analysis, which was corrected using a procedure by Shapiro and Singh[26]. As we were interested in estimating an average dispersion curve, a logarithmic stacking in the period-group velocity domain was used. This permits an estimation of the average dispersion curves (Figure 4 *a* and *b*). We estimated the average dispersion curves using data of the main shock and its five aftershocks of $M_w \geq 5.5$ from the four broadband stations in Kachchh, a very broadband station at Hyderabad, and a broadband station at Cuddapah.

Inversion of group velocity dispersion

The resulting dispersion curves for Rayleigh and Love waves were inverted for the average 1D velocity structure using a linearized inversion[27]. The initial velocity model was designed based on previously published data on the velocity structure of the Indian crust[12,19,20]. The velocity model consists of two crustal layers with a total thickness of 38.7 km overlying a half space (Moho) with V_s of 4.49 km/s and V_p of 8.05 km/s. The upper crust has a thickness of 13.8 km with velocities of 6.2 and 3.55 km/s for P and S waves respectively (Figure 4 *c*). The lower crustal layer has a P-wave velocity of 6.4 km/s and S-wave velocity of 3.75 km/s. Inversion was performed for the S-wave velocity in each layer and for the depth of the interfaces. Density and Poisson ratio were kept fixed in each layer. For each station, we tested ten models and found eight models whose dispersion curves were within the standard deviation bars. Synthetic dispersion curves were calculated for all successful models, which suggests good agreement with the observed dispersion curves. For each new model, we calculated group velocities of the fundamental mode of the Rayleigh and Love waves using Hermann's[27] subroutines.

Average dispersion curves for peninsular India

Figure 4 *a* and *b* shows the stacked dispersion curves for Rayleigh and Love wave group velocities respectively, estimated using events from Pakistan-Kashmir Himalayas

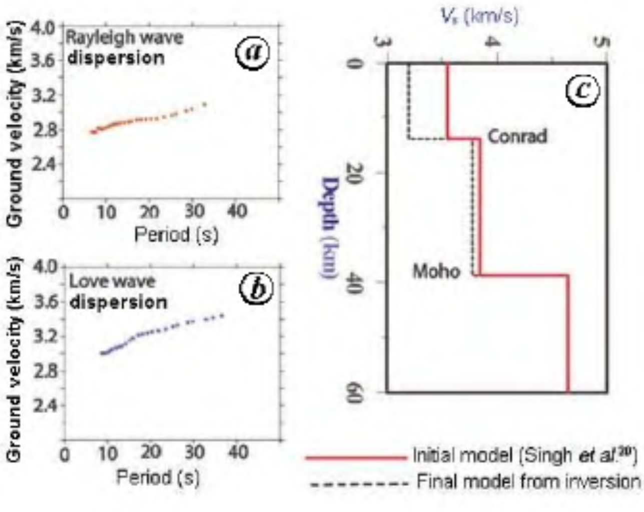


Figure 4. Average stacked dispersion curves obtained using data of mainshock and its five aftershocks from four broadband stations in Kachchh, a VBB station at Hyderabad and a broadband station at Cuddapah (***a***) for Rayleigh waves, and (***b***) for Love waves. ***c***, Average regional 1D shear wave velocity structure for peninsular India obtained from linearized inversion of average stacked dispersion curves. The solid thick red line represents the initial model used for inversion (Singh *et al.*[20]). The dotted line marks the final velocity model from inversion.

recorded at four stations in Kachchh, a VBB station at Hyderabad and a broadband station at Cuddapah. The figure suggests a stable dispersion curve between 7 and 35 s for Rayleigh as well as 7 and 38 s for Love waves. The group velocities for Rayleigh waves show (i) a gradual increase from 2.80 to 2.95 km/s at 7–20 s, and (ii) a relatively sharp increase from 2.95 to 3.15 km/s at longer periods 20–35 s (Figure 4 *a*). The group velocities for Love waves suggest (i) a maximum change from 3.0 to 3.3 km/s at 7–18 s, and (ii) a gradual increase from 3.30 to 3.45 km/s at longer periods 18–38 s (Figure 4 *b*). Thus, the surface wave group velocity dispersion characteristics in peninsular India suggest a crust with increasing shear velocity with depth (Figure 4 *c*).

Average crustal structure in peninsular India

The average shear wave velocity structure for the Indian peninsula was obtained by inverting the stacked Rayleigh and Love wave group velocity dispersion curves estimated at two broadband stations (Hyderabad and Cuddapah) in peninsular India, using the Kashmir main shock and its five aftershocks ($M_w > 5.5$). The obtained crustal structure suggested a two-layer crust, a 13.8 km thick upper crust with V_s of 3.20 km/s and a 24.9 km thick lower crust with V_s of 3.70 km/s (Figure 4 *c*). V_s in upper mantle beneath peninsular India was found to be 4.65 km/s. From Figure 4, we note that our best fitting model was similar to the thicknesses of the crustal layers of the model of Singh *et al.*[20]. However, we obtained a bit shallower Moho, i.e.

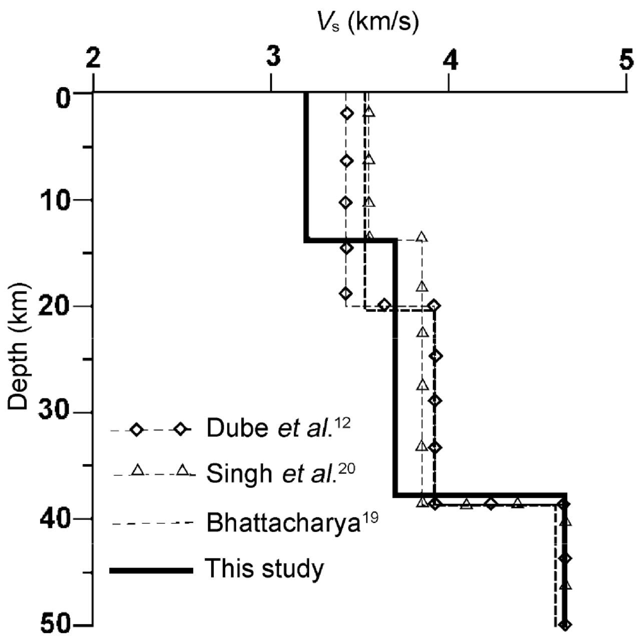


Figure 5. A comparison of the shear wave velocity models for peninsular India obtained by different investigators. Thick line shows our best model. Dashed lines represent other models.

38.7 km in comparison to that obtained by Singh *et al.*[20]. The major differences were slower shear wave velocities for the crustal and upper Mantle layers. In our model, shear wave velocities in upper crust and lower crust were 3.2 and 3.7 km/s respectively, compared to 3.55 and 3.85 km/s in the model of Singh *et al.*[20]. We also found a slower upper mantle beneath peninsular India (i.e. V_s = 4.36 km/s) compared to 4.65 km/s in the model of Singh *et al.*[20]. Figure 5 shows a comparison between the existing 1D average shear velocity models for peninsular India[12,19,20] and our model. We found that our model suggests a slower crustal velocity in comparison to all other models for peninsular India[12,19,20], which could be attributed to the different propagation paths of surface waves used in our study. Further, the surface wave propagation paths considered in this study also cover some part of the Himalayan region, which are characterized by deeper Moho[21]. Hence, as we covered only a narrow western part of peninsular India in our study, our shear velocity model might not be a proper representative of the whole region.

Source parameters of the 2005 Kashmir earthquake

The 8 October 2005 (M_w 7.6) inter-plate earthquake had its epicentre in western (Muzaffarabad, Kashmir-Pakistan) Himalayas (USGS; location 34.493°N, 73.629°E; depth 26 km). The Harvard CMT solution for this earthquake gave a thrust fault (strike 333°, dip 39° and rake 121°) with a seismic moment 2.9×10^{27} dyne-cm, M_w 7.6, and a focal depth of 12 km. However, the NEIC (USGS) CMT solution for this earthquake suggested best fit for a source at 20 km depth with a thrust mechanism (strike 358°, dip 29°, and rake 140°) and seismic moment 1.0×10^{27} dyne-cm, M_w 7.3 (Figure 1). Thus, there is a large variation in the reported source parameters for this earthquake.

Moment tensor solution from regional broadband seismograms

We estimated the moment tensor (MT) solution of the earthquake by inverting the filtered broadband seismograms (sampling rate 20 Hz). We followed the procedure of Randall *et al.*[28] that uses a time-domain MT inversion scheme described by Langston[29]. Inversion was performed over a time window that began with the *P*-wave and included surface waves. In this method, complete synthetic seismograms were computed, using the reflection matrix methods of Kennett[30] and Randall[31]. Surface waves were the predominant feature of the seismograms. In order to minimize the dependence of inversion on the origin time, event location and velocity structure, we aligned the theoretical *P*-wave arrivals with the observed ones. The centroid depth was obtained through a grid search. We estimated MT solutions at various depths. The best centroid depth may be taken as that which gives the lowest rms residual between observed and synthetic seismograms and a low ratio of compensated linear vector dipole (CLVD) component to double-couple (DC) component (Figure 6 *a*).

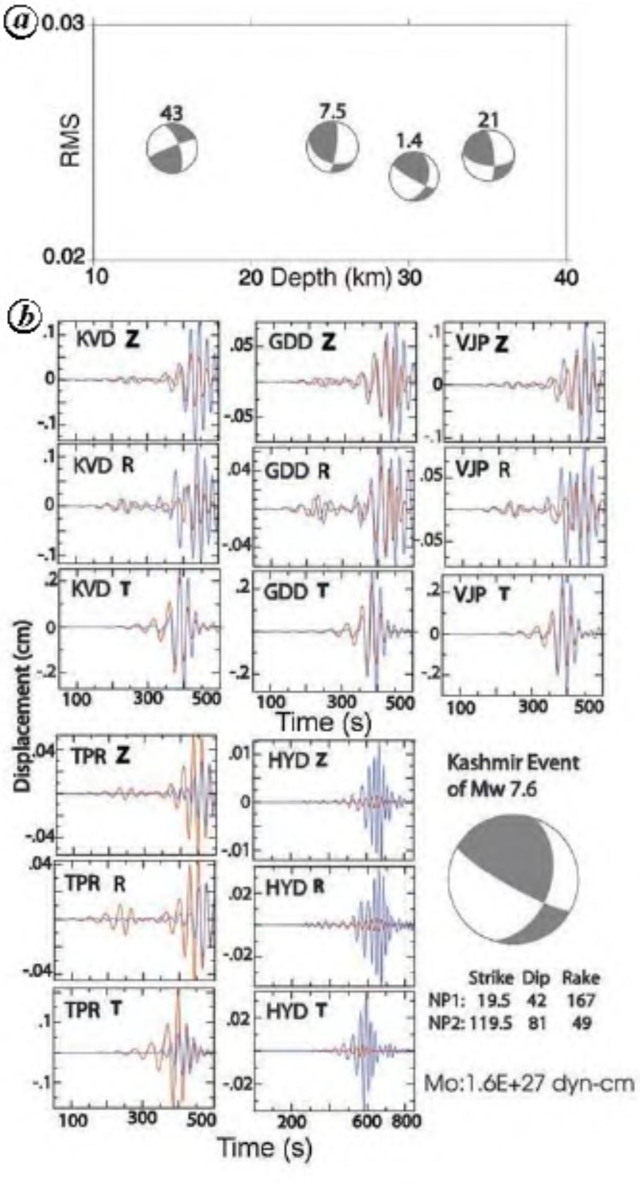


Figure 6. ***a***, RMS error as a function of depth of source, obtained in moment tensor inversion of bandpass filtered (0.02–0.05 Hz) seismograms of the 2005 M_w 7.6 Kashmir earthquake. The number above the focal mechanism gives the percentage of CLVD to DC component. Note that there is little change in the focal mechanism solution (thrust) for sources at 25, 30 and 35 km depths. However, the focal mechanism solution for source at 15 km depth shows a completely different solution (strike–slip). ***b***, Bandpass-filtered (0.02–0.05 Hz) observed (blue lines) and synthetic (red lines) three-component (vertical, radial and transverse) seismograms of the 2005 Kashmir mainshock at four stations in Kachchh (i.e. Gadhada, Kavada, Vajepar and Tapar) and VBB station at Hyderabad.

In 1999, Singh *et al.*[20] suggested that the 20–50 s long period band will give better results for MT inversion of peninsular Indian earthquakes. However, they also cautioned that the depth resolution may be poorer. Following their suggestion, inversion was performed on the filtered displacement seismograms bandpassed between 20 s and 50 s. The records of all stations were initially given only half weight. The misfit between observed and synthetic seismograms was examined and depending on the misfit, the weight of each component was adjusted (Figure 6 *b*).

Figure 6 *a* shows a plot of rms as a function of depth. The lowest rms was obtained for the source at 30 km depth. However, there was significant variance reduction between 15 and 35 km depths. It is well known that there is relative insensitivity of the synthetics to depth at long periods. A significant change in the focal mechanism was obtained at 15 km depth, suggesting a pure strike–slip mechanism. However, there was little change in focal mechanism at 25, 30 and 35 km depths, showing a typical thrust mechanism along a NE-dipping plane (Figure 6 *a*). At 30 km depth, the ratio between CLVD and DC component was estimated to be 1.4%; the double couple mechanism was strike = 19.5°, dip = 42° and rake = 167°, and M_0 is 1.6×10^{27} dyne-cm. Observed and synthetic seismograms corresponding to H = 30 km are shown in Figure 6 *b*. In general, the waveforms of Pnl (the phases arriving between *P*- and *S*-waves) and Rayleigh and Love waves were well modelled. In some cases, however, the arrival times of synthetic and observed seismograms did not coincide (e.g. Hyderabad and Cuddapah stations). This could be attributed to the difference in the crustal structure to each individual path and the average crustal structure derived from the dispersion curves. Figure 6 *b* does not include Cuddapah station due to poor match between the synthetic and observed seismograms. The poor agreement observed for Hyderabad and Cuddapah stations suggests that our shear velocity structure might not be the proper representative of peninsular India. The thrust source mechanism obtained from this study suggests a similar dip as that reported in the Harvard CMT solution. However, a major difference was noticed in the estimated strike, which, in our case, was 19.5° compared to 133° in the mechanism of the Harvard CMT solution. It would be important to note that the azimuthal coverage of our station distribution was quite narrow. Thus, it would be advisable to constrain the MT solution using data from stations covering the other azimuths.

Estimation of long-period magnitude

We have estimated M_w for the main shock using the long-period magnitude estimation procedure by Singh and Pacheco[32].

The procedure for estimating the magnitude $M_A \sim M_w$ is as follows.

- Filter the broadband seismograms between 12.5 and 30 s (0.03–0.08 Hz; Figure 7).
- Estimate amplitude, $V_r = \text{sqrt}(A_E^2 + A_N^2 + A_Z^2)$, where A_Z, A_E and A_N are the maximum amplitude in cm/s, measured on vertical, north-south and east-west components respectively.
- Estimate epicentral distance (R) from locations of epicentre and station.
- Read the value of the amplitude (V_{ref}) from the standard curve corresponding to the epicentral distance (Figure 8)

$$V_{ref}\ (\text{cm/s}) = -2.2 * 10^{-6} R\ (\text{km}) + 0.00564 \qquad (1)$$

- Compute M_0 from the relation

$$M_A = (V_r/V_{ref}) * 10^{25}\ \text{dyne-cm}. \qquad (2)$$

- Compute the magnitude $M_A \sim M_w$ using the following relation:

$$M_w = (\log_{10}(M_0) - 16.1)/1.5. \qquad (3)$$

Moment magnitude estimation of the 2005 Kashmir main shock

The following equation to estimate M_0 was obtained by considering a $M6$ earthquake as reference:

$$M_0 = (V_r/V_{ref})*1.0E + 25\ \text{dyne-cm}. \qquad (4)$$

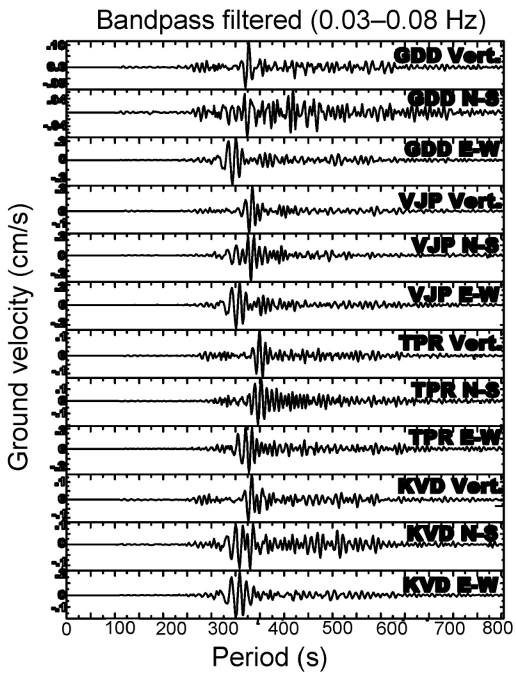


Figure 7. Bandpass-filtered (0.03–0.08 Hz) broadband seismograms for the 2005 M_w 7.6 Kashmir earthquake at four stations in Kachchh, used to estimate the long period magnitude for this earthquake.

After calculating V_r and epicentral distance from the earthquake information, V_{ref} for an earthquake can be estimated from the already obtained standard curve for $M \geq 5$ Indian earthquakes as shown in Figure 8, which gives the relation to estimate V_{ref} as:

$$V_{ref}\ (\text{cm/s}) = -2.2 * 10^{-6} R\ (\text{km}) + 0.00564. \qquad (5)$$

From the bandpass-filtered broadband seismograms of the Kashmir main shock at different stations (Figure 7), V_r was obtained. The estimated parameters for calculating long-period magnitudes at four broadband stations in Kachchh are listed in Table 1.

Average M_w for the 2005 Kashmir earthquake estimated using the above-mentioned four stations was:

$$(M_w)_{avg} = 7.31 \pm 0.064. \qquad (6)$$

The bandpass-filtered (0.03–0.08) broadband seismograms clearly brings out the well-developed surface wave components at all four stations, as shown in Figure 7.

Robust estimation of focal depths from detailed analysis of regional crustal phases (sP and sS_n)

The method for estimating focal depth of an earthquake from the crustal regional phases (sP and sS_n) is shown in Figures 9 and 10. From Figure 9, we know that the focal depth for an earthquake can be estimated using the relations:

$$\Delta t_{sS_n} = 2h\eta_\beta, \qquad (7)$$

and

$$\Delta t_{sP} = 2h\ (\eta_\alpha + \eta_\beta), \qquad (8)$$

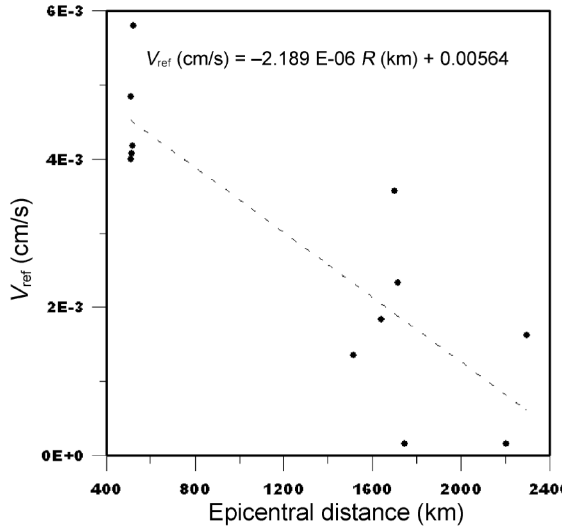
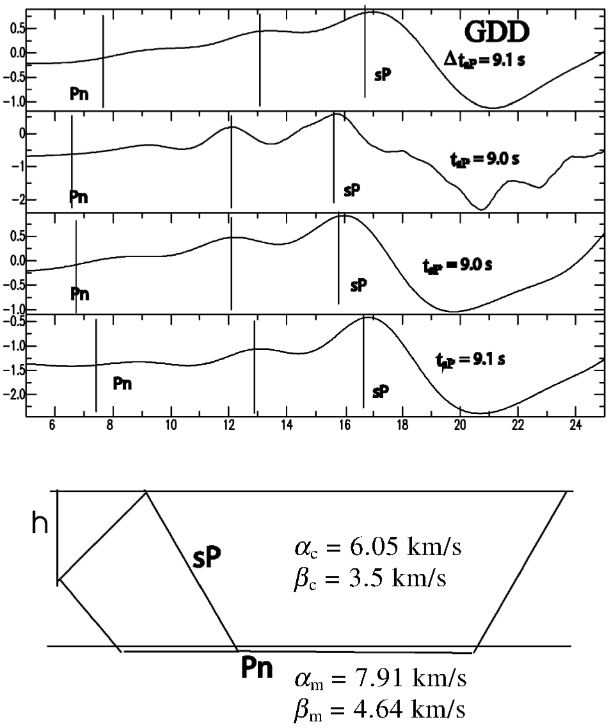


Figure 8. Standard curve for V_{ref} designed using 12 Indian earthquakes of $M_w \geq 5$.

Table 1. Estimated parameters for computing long-period magnitude for four stations in Kachchh

Station	Z (cm/s)	NS (cm/s)	EW (cm/s)	Distance (km)	V_r/V_{ref}	M_0 (dyne-cm)	M_w
GDD	0.12	0.064	0.23	1222	90.5	9.1E + 26	7.24
KVD	0.16	0.12	0.20	1243	90.7	9.7E + 26	7.26
VJP	0.20	0.25	0.23	1252	137	1.4E = 27	7.36
TPR	0.16	0.19	0.22	1296	119	9.7E + 26	7.26

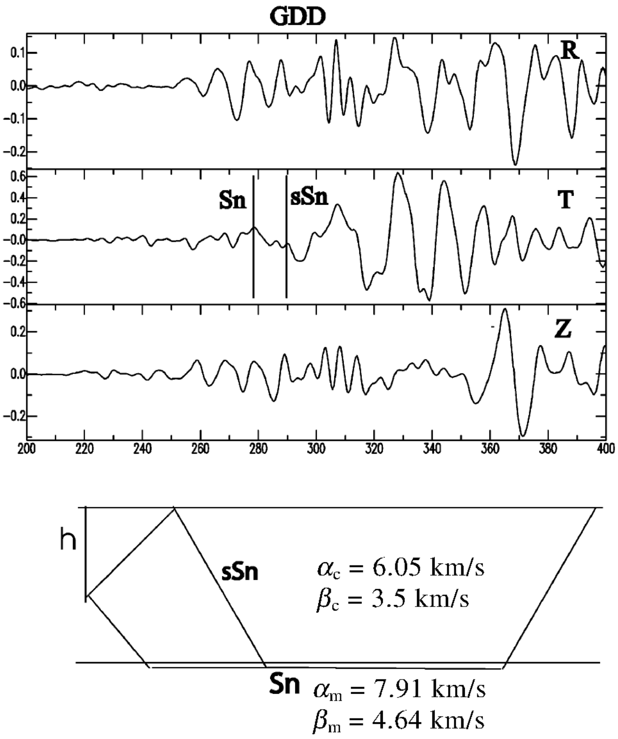


$$\eta_\beta = \left(\frac{1}{\beta_c^2} - \frac{1}{\beta_m^2}\right) = 0.1876 \qquad \eta_\alpha = \left(\frac{1}{\alpha_c^2} - \frac{1}{\alpha_m^2}\right) = 0.1063$$

$$(\eta_\alpha + \eta_\beta) = 0.2939 \qquad \Delta t_{sP} = h(\eta_\alpha + \eta_\beta)$$

Focal depth (h)
GDD: 30.96 km; KVD: 30.62 km; VJP: 30.62 km; TPR: 30.96 km

Figure 9. Bandpass-filtered (0.02–0.25 Hz) Kashmir main shock displacements as a function of time showing P_n and regional crustal sP phase on the vertical component of displacement at all four stations in Kachchh.



$$\eta_\beta = \left(\frac{1}{\beta_c^2} - \frac{1}{\beta_m^2}\right) = 0.1876$$

$$\Delta t_{sSn} = 2h$$

Figure 10. Bandpass-filtered (0.02–0.25 Hz) Kashmir main shock displacements as a function of time showing S_n and regional crustal sSn phase on the radial, transverse and vertical components of displacement at Gadhada station.

where

$$\eta_\alpha = \left(\frac{1}{\alpha_c^2} - \frac{1}{\alpha_m^2}\right)^{1/2}, \tag{9}$$

and

$$\eta_\beta = \left(\frac{1}{\beta_c^2} - \frac{1}{\beta_m^2}\right)^{1/2}. \tag{10}$$

Figures 9–11 show filtered (0.02–0.25 Hz) Kashmir main shock displacements as a function of time. The P waveforms are relatively complicated, but clearly show P_n, sP, S_n and sS_n group on the vertical, radial and transverse components of displacement at all the four stations (Figures 9–11). The sP group contains sP_n and sP_g. sP and sS_n phases are direct indicators of depth. sP is a major phase in regional earthquake seismograms because the P-wave reflection coefficient at the free surface is minimum for regional P-wave ray parameters. The combination of the S- to P-conversion coefficient being near its maximum and earthquake radiation pattern being very efficient for S-wave radiation produces large sP phases[33]. Generation of sP phase also depends on near-surface velocity struc-

Table 2. Estimated time differences for regional crustal phases and focal depths

Station	$\Delta t\ (S_n - P_n)$ (s)	ΔtsP (s)	Z (km) (sP)	ΔtsS_n (s)	Z (km) (sS_n)	Epicentre distance (km)
GDD	123.0	9.1	30.96	11.5	30.65	1222
KVD	127.5	9.0	30.62	11.5	30.65	1243
TPR	124.1	9.1	30.62	11.6	30.91	1296
VJP	132.0	9.0	30.96	11.7	31.18	1252

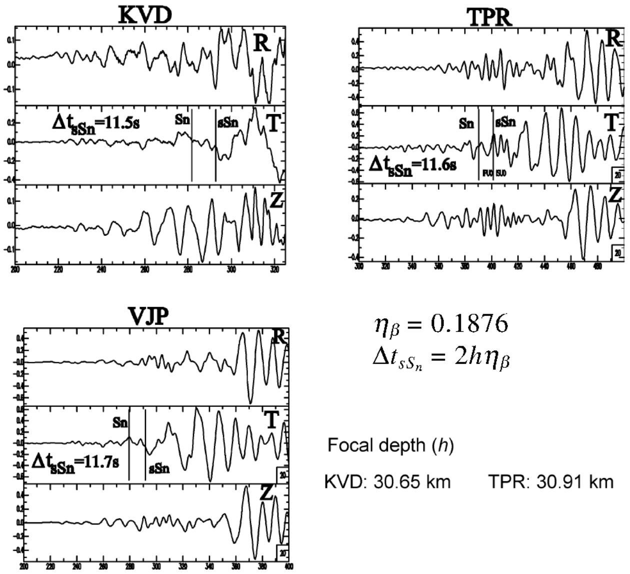


Figure 11. Bandpass-filtered (0.02–0.25 Hz) Kashmir main shock displacements as a function of time showing S_n and regional crustal sS_n phase on the radial, transverse and vertical components of displacement at Kavada, Tapar and Vajepar stations.

ture (Figure 9). sS_n phase is found to be useful in estimating the focal depth of an earthquake (Figure 10). The travel time differences, i.e. $\Delta t(S_n - P_n)$, ΔtsP and ΔtsS_n have been estimated from the filtered displacement seismograms at all the four stations (Figures 9–11), and are listed in Table 2.

From average regional velocity structure as obtained by the surface wave dispersion study[20], the average crustal P-wave velocity (α_c) and S-wave velocity (β_c) were 6.05 and 3.50 km/s respectively. The mantle P-wave velocity (α_m) and S-wave velocity (β_m) were 7.91 and 4.64 km/s respectively. Using this velocity structure and the above-mentioned equations, we obtain $\eta_\beta = 0.1876$, $\eta_\alpha = 0.1063$ and $(\eta_\alpha + \eta_\beta) = 0.2939$ respectively.

Using the above-mentioned values, equations and estimated ΔtsP, and ΔtsS_n times from the filtered displacement seismogram of the main shock (Figures 9–11, and Table 2), the focal depth (h) has been estimated. The mean depth obtained using data from four stations was:

$$\text{Focal depth } (h) = 30.8 \text{ km from } sP \text{ phase analysis}$$
$$= 30.8 \text{ km from } sS_n \text{ phase analysis.} \quad (11)$$

Thus, from our regional crustal sP and sS_n phase analysis for the four stations, the estimated average focal depth for the 2005 Kashmir earthquake was 30.8 km, which is more than the reported focal depth of 20 km for this earthquake (USGS).

Discussion and conclusion

The crustal and sub-crustal structure of the central and western parts of the Indian peninsula have been estimated using the inversion of surface wave dispersion curves of Rayleigh and Love waves. In both these cases the granitic layer was quite thin compared to the basaltic layer, as generally observed for stable old cratons. Well-developed surface waves and clear P_n as well as S_n phases suggest that the seismic waves travelled mostly through the homogeneous upper mantle and the earthquake was of crustal origin. Our best model suggested a two-layered crust: the upper crust 13.8 km thick with a shear velocity (V_s) of 3.2 km/s; the corresponding values for the lower crust being 24.9 km and 3.7 km/s. The shear velocity for the upper mantle was found to be 4.65 km/s. Based on this structure, we performed MT inversion of the bandpassed (0.05–0.02 Hz) seismograms of the Kashmir earthquake. The best fit was obtained for a source located at a depth of 30 km, with a seismic moment $M_0 = 1.6 \times 10^{27}$ dyne-cm, and a focal mechanism with strike 19.5°, dip 42° and rake 167°. The procedure for estimating the long-period magnitude for large earthquakes ($M \geq 4.5$) was found to be quite appropriate and fast. The estimated long-period magnitude was equivalent to M_w. Thus, we obtained an appropriate and fast estimation of M_w. The estimated M_w for the 2005 Kashmir earthquake was found to be (7.310 ± 0.064). This value is 0.3 units less than that obtained by the Harvard CMT inversion. An analysis of well-developed sP_n and sS_n regional crustal phases from the bandpassed (0.02–0.25 Hz) seismograms of this earthquake at four stations in Kachchh suggested a focal depth of 30.8 km, which is of relatively deeper crustal origin in comparison to the other crustal earthquakes along the Himalayan arc, suggesting a different source process. Thus, it can be inferred that the regional earthquake data from the Indian regional networks can be used to obtain much better understanding about the many intriguing questions related to Indian seismicity, in general and Himalayan seismicity, in particular.

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