ter) with few charred grains and suggesting sedimentation between high energy cross-laminated sandstone units, while shallow marine conditions prevailed in the basin.

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Estimation of source parameters for 14 March 2005 earthquake of Koyna–Warna region

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The source parameters for the 14 March 2005 earthquake in the Koyna–Warna region have been estimated using data from three broadband seismological observatories installed by us at regional distances in the Indian Peninsular shield. Spectral analysis of SH-waveform on transverse component of the three-component seismograms is performed. The estimated seismic moment (M_0), source radius (*r*), stress drop ($\Delta\sigma$) and moment magnitude (M_w) for this earthquake are 3.9×10^{16} N-m, 975 m, 19 MPa and 5.1 respectively. The near-surface attenuation factor (κ) is found to be of the order of 0.01 for the stable shield region, suggesting a thin low-velocity sediment beneath the region. The estimated stress drop of the earthquake is higher compared to the other intraplate earthquakes in India. The focal mechanism solution estimated for this event using amplitudes and polarities of direct P- and S-waves suggests the fault plane with strike N312°, dip 36° and rake 248°.

Keywords: Earthquake, Koyna–Warna region, source parameters, stress drop.

THE Indian Peninsular shield, hitherto considered a stable intraplate environment, appears to be moderately active in the recent times with earthquakes of M 5.0 occurring

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in almost regular intervals of time. For example, the 1967 Koyna earthquake (*M* 6.0), 1969 Bhadrachalam (*M* 5.7), 1970 Broach (*M* 5.2), 1993 Latur (*M* 6.2), 1997 Jabalpur (*M* 5.8) and more recently, the 2001 Bhuj earthquake (*M* 7.7). However, estimation of source parameters like focal mechanism from wave-form modelling or stress drop using digital data could not be attempted due to the absence of a network of digital broadband stations in the Indian shield before 1997, except for Hyderabad (HYD) broadband station of NGRI. In the aftermath of the Latur earthquake in 1993, a digital broadband seismic network of the country has been in existence since 1997, bringing down the threshold of location capabilities to $M < 3$, and the 1997 Jabalpur earthquake was the first digital recorded event by the network[1].

Several workers have attempted determination of source parameters for small and moderate earthquakes and suggested that fairly complete source information can be extracted from a single seismic station given certain conditions. Langston[2] used P- and SH-waveforms to discriminate between fault types. Ekstrom *et al.*[3] applied the centroid moment tensor (CMT) method to retrieve the focal mechanism of large events and Jimenez *et al.*[4] developed a technique utilizing the regional distance surface waves.

Koyna region has been seismically active for more than four decades and moderate earthquakes continue to occur at regular intervals. The seismicity patterns in the region show segmentation of fault system, with earthquakes distinctly occurring along three fault zones[5]. After the 1967 earthquake of *M* 6.3, the region has experienced 20 earthquakes of $M > 5$ and about 170 earthquakes of $M > 4$. On 14 March 2005, an *Mb* 5.1 earthquake occurred close to the Warna reservoir located 25 km south of the Koyna dam in western India. Here we estimate its source parameters like focal mechanism, stress drop and source radius obtained from local and regional digital network and discuss the tectonic implications.

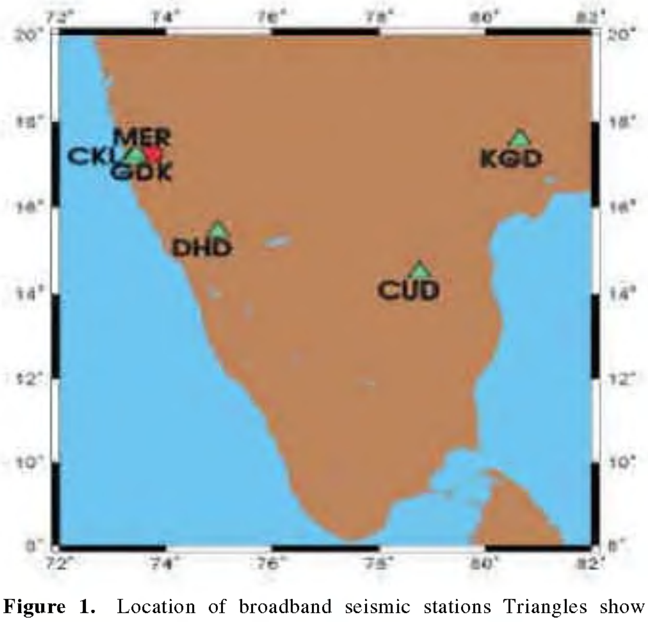

Figure 1. Location of broadband seismic stations Triangles show seismic station locations and red circle shows the Koyna region where the earthquake of *Mb* 5.1 occurred on 14 March 2005.

A high quality dataset of local and regional seismograms recorded at the broadband and short-period digital stations in the Indian shield (Figure 1) provided the data for our study. The three broadband stations, Cuddapah (CUD), Dharwar (DHD), and Kothagudem (KGD) are equipped with CMG 40T broadband sensors of (up to 30 s) period and are part of the regional network in the shield region. The other three stations, Chikli (CKL) with CMG 3ESP, Koyna (MER) and Gadghope (GDK) with L4-3D short-period sensors belong to the local network in the Koyna–Warna area. The data-loggers at all these stations are of REFTEK-make and data have been recorded at 100 samples per second.

Hypocentral parameters for the 14 March 2005 earthquake in the Koyna–Warna region have been estimated using the P- and S-wave data from the stations shown in Figure 1. These parameters were determined using HYPOCENTER program[6]. The average velocity model for the crust given by Singh[7] was considered, and for the mantle we have used the IASPEI97 model. The estimated hypocentral parameters are 17.156°N, 73.739°E and 9 km focal depth. The seismicity patterns shown in Figure 2 have been obtained by relocating about 600 earthquakes using the double difference method[5]. This and an earlier study have shown

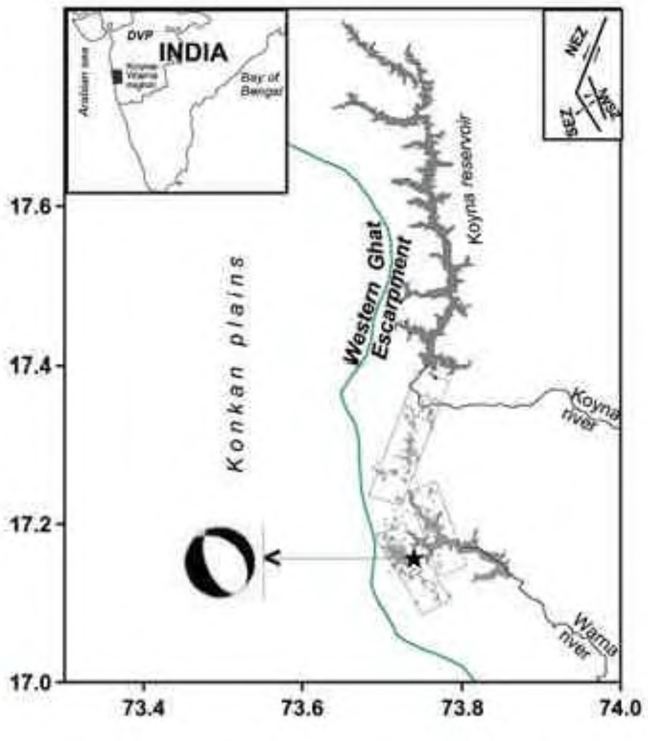

Figure 2. Location and focal mechanism of 14 March 2005 Koyna earthquake.

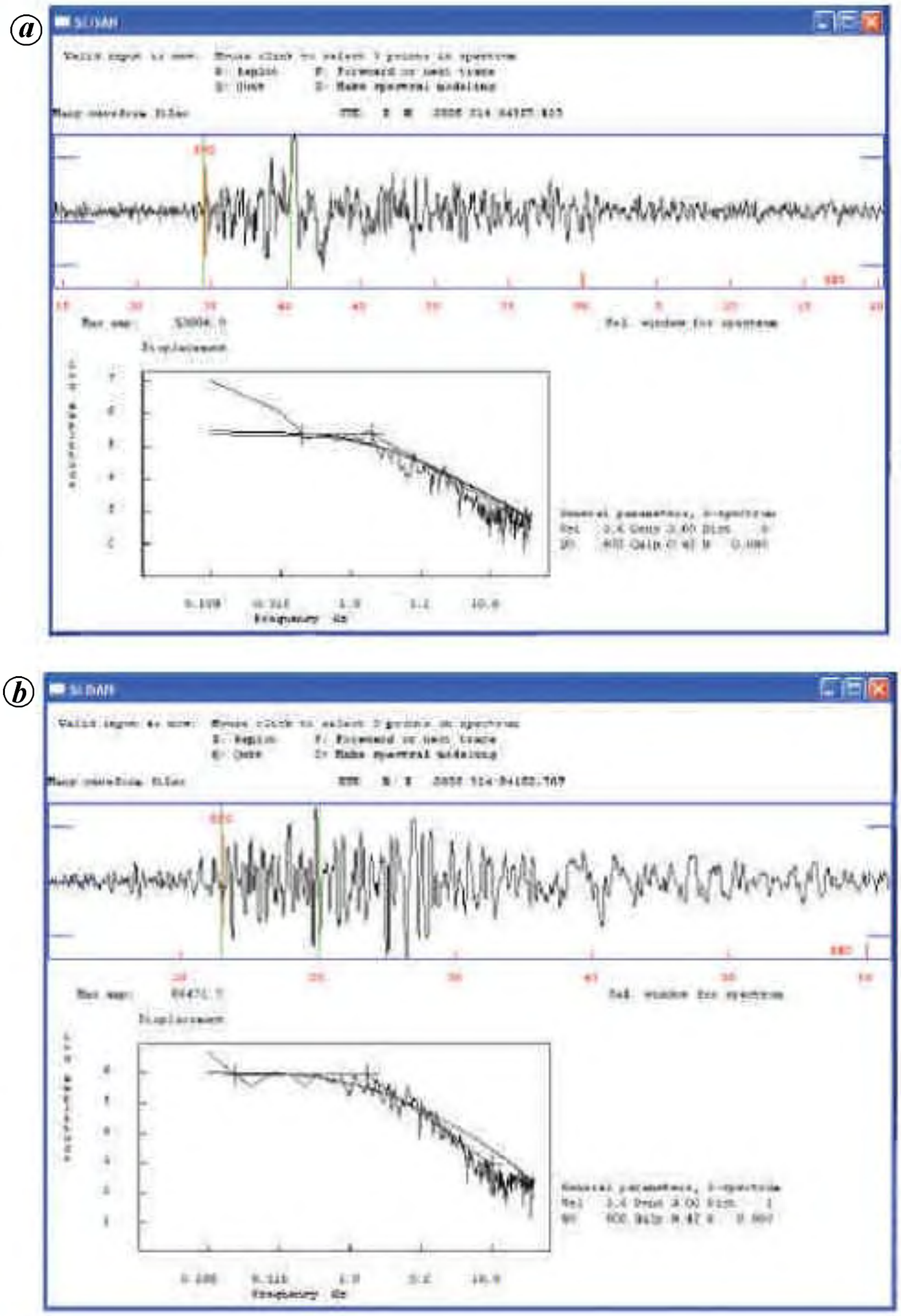

Figure 3. S-wave displacement spectrum of Warna earthquake recorded at (***a***) Cuddapah station and (***b***) Kothagudem station.

that the Koyna region is conspicuous by fault segmentation, namely the north escarpment zone (NEZ), south escarpment zone (SEZ) and Warna seismic zone (WSZ)[8,5]. The 14 March 2005 earthquake is located in the SEZ and is shown in Figure 2.

Seismic moment, size of the rupture plane, source dislocation and stress drop have been estimated using the S-wave displacement spectrum. The instrument response from the original seismograms was removed to obtain true ground motion (displacement). At each station the vertical, N–S and E–W components are rotated to great circle projection to get radial and transverse components. The S-wave spectrum is computed from the transverse component and corrected for attenuation and path effects using the average attenuation relation for Indian shield[9]. The S-wave spectra for CUD and KGD are shown in Figure 3 *a* and *b*; the amplitude level at low frequencies is constant, while it decays for higher frequencies with decay constant as ω^2.

The displacement spectrum is approximated by two straight lines, the first represents a constant amplitude level u_0 at low frequencies and the second is the approximation of decay spectrum at higher frequencies. The intersection of these two straight lines gives the corner frequency f_c. The source parameters are computed using u_0 and f_c applying the circular source model[10]. The relation between seismic moment M_0 and u_0 with average S-wave velocity is given as:

$$M_0 = 4\pi r V_S^3 \tilde{n} u_0/(\Theta S_a), \quad (1)$$

where r is the hypocentral distance, V_S shear velocity, ρ density, u_0 low frequency spectral level, Θ averaged radiation pattern, S_a free surface amplification.

The source radius (R) depends on f_c, and the relation is as follows:

$$R = V_S K_S/2\pi f_{cS}, \quad (2)$$

in which K_S is model constant, and f_{cS} is corner frequency for the shear wave.

The area of the rupture plane is calculated after obtaining the radius of the source (R) as

$$A = \pi R^2. \quad (3)$$

The fault displacement (D) or average source dislocation is directly proportional to the seismic moment (M_0) and inversely proportional to the rigidity and area of the rupture plane:

$$D = M_0/\mu A, \quad (4)$$

where μ is the shear modulus.

The stress drop is determined using the relationship[11]:

$$\Delta\sigma = 7M_0/(16R^3).$$

We estimated the seismic moment M_0, corner frequency f_c, moment magnitude M_W and stress drop Δσ for the 14 March 2005 Warna earthquake. The M_0 values range from 1×10^{15} to 4×10^{16} and f_c values are between 1.7 and 2.3. The f_c values for the stations at CUD and KGD have been obtained from the spectrum shown in Figure 3 *a* and *b*. M_w is estimated as 5.1 and the stress drop values range between 16 and 19 MPa.

Using the program INVRAD[12], focal mechanism was computed. A minimum of five station data are needed to use this program in the calculation of source mechanism. The program is developed for moment tensor formulation. Only the direct up-going P- or S-phases are used in this method, so that the interaction with the crustal structure along the travel path is not distorted by phase shift. The instrument response has been removed from the observed waveform. Here, the amplitudes and polarities of direct waves are inverted for earthquake source mechanism. We have used both P- and S-wave amplitudes and polarities from Dharwar (DHD), Kothagudem (KGD), Chikli (CKL), Gadkope (GDK) and Koyna (KOY) dam. The focal mechanism shows a normal faulting with a small strike-slip component (Figure 2). The focal mechanism parameters are given in Table 1. Earlier source mechanisms for earthquakes in the region were attempted mostly using first motion data from analogue seismograms and digital data[13–15] to constrain the solution. Source studies using short-period digital data from Koyna digital network show that the earthquakes located within the SEZ are conspicuous by normal faulting[5,7].

The Koyna–Warna region is unique as it exhibits protracted seismicity for more than four decades. The source mechanism for the earthquakes in the region shows two distinct styles of faulting, viz. strike-slip along a NNE–SSW trend and normal faulting along NW–SE. The installation of broadband network in the Indian Peninsular shield provided an opportunity to study the source parameters of the M_w 5.1 magnitude earthquake on 14 March

Table 1. Nodal plane solutions for 14 March Koyna earthquake

	Strike	Dip	Slip
Fault plane 1	312	36	248
Fault plane 2	159	57	–75
	Azimuth	Plunge	
Pressure axis	238	11	
Tension axis	109	73	

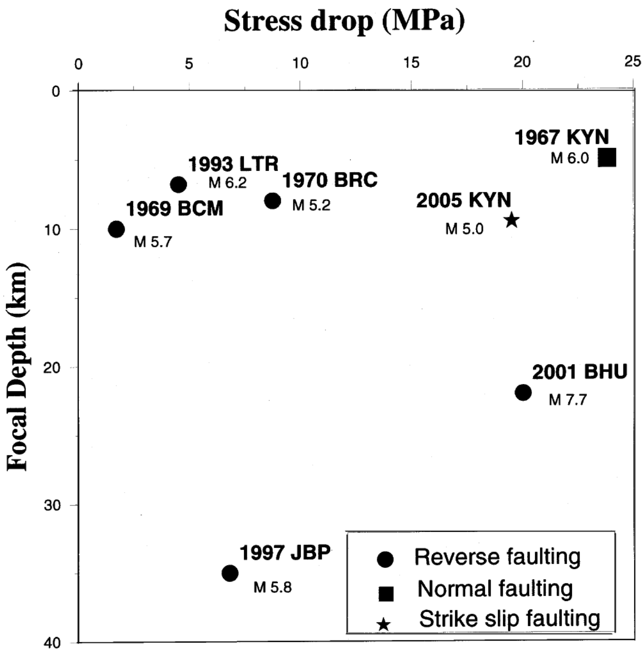

Figure 4. Stress drop for some significant earthquakes with magnitudes ≥5.0 during the last 40 years in the shield region.

2005 (M_w computed in the present study). The earthquake was located in the SEZ in the Koyna region and this fault is conspicuous with normal faulting earthquakes[5]. The seismic moment for this earthquake is estimated to be 3.9×10^{23} dyn-cm. The circular radius of the rupture of the fault plane is about 960 m. Stress drop of this event varies between 16 and 19 MPa. Kanamori and Anderson[16] demonstrated that the average stress drop is higher for intraplate earthquakes compared to inter-plate earthquakes. The stress drop has been estimated by several workers for the 1993 Latur (*M* 6.2), 1997 Jabalpur (*M* 5.8), 1969 Bhadrachalam (*M* 5.7), 1970 Broach (*M* 5.2) and Koyna earthquakes and is found to vary between 2 and 25 MPa (Figure 4). A maximum stress drop of 19 MPa obtained for the 14 March earthquake is comparable to the results which have been obtained from an earlier study[17]. The stress drop for the Koyna–Warna earthquakes (magnitude 1.5–4.7) was estimated to be in the range 0.03 to 19 MPa, with the *M* 4.7 earthquake having the maximum stress drop of 19 MPa. In general, the Koyna–Warna region is conspicuous with higher stress drop in comparison to other source regions in the Peninsular shield. A probable explanation for the high stress drop is due to the presence of competent material within the source volume. Velocity tomography study[18] has revealed the presence of high velocity zone in the Koyna–Warna seismic source region and this high velocity was interpreted in terms of competent material.

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Coastal processes along the Indian coastline

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Based on the measured data, wave height and current speed at a few locations are presented along with the estimated sediment transport rates. The maximum significant wave height recorded during the passage of a cyclone along the west coast in a water depth of 27 m was 6 m. The current measurements show that the maximum currents vary from about 1.4 m/s in the open ocean to about 3.2 m/s in the Gulf of Khambhat. The gross longshore sediment transport rate was about 1×10^6 m^3 per year along south Kerala and south Orissa. The estimated longshore sediment transport rates show that net transport along the east coast of India is towards the north, whereas along the west coast it is mostly towards the south.

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